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CALCULATING BEDLOAD TRANSPORT IN RIVERS: CONCEPTS, CALCULUS ROUTINES AND APPLICATION

CALCULANDO TRANSPORTE DE CARGA DE FUNDO EM RIOS: CONCEITOS, ROTINA DE CÁLCULO E APLICAÇÃO

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Palavras-chave:
Transporte de Carga de Fundo; Van Rijn; Modelo Matemático; Microsoft Excel; Rio Paraná.

Abstract:

Rivers are immensely important to human activities such as water supply, navigation, energy generation, and agriculture. They are also an important morphodynamic agent of erosion, transport and deposition. Their capacity to transport sediment depends on their hydraulic characteristics and can be predicted by mathematical models. Several mathematical models can be used to compute bed-load transport. Each one is appropriately better for certain conditions. In this paper, we present an application built in Microsoft Excel to compute the bed-load transport in rivers based on the Van Rijn mathematical model. The Van Rijn model is appropriate for rivers transporting sandy sediments in conditions of subcritical flow. Hydraulic parameters such as channel slope, stream power, and Reynolds and Froude numbers can be calculated using the application proposed here. The application was tested in the Paraná River and results from the calculations are consistent with data obtained from fieldwork surveys. The error of the application was only 20%, which shows good agreement of the model with survey values.

Resumo:

Rios são imensamente importantes para atividades humanas tais como navegação, geração de energia e agricultura. Eles também são um importante agente morfodinâmico de erosão, transporte e deposição. Sua capacidade para transportar sedimento depende de suas características hidráulicas e pode ser predita por modelos matemáticos. Diversos modelos matemáticos podem ser usados para se computar o transporte de carga de fundo. Cada um é mais bem apropriado para certas condições. Neste artigo, nós apresentamos um aplicativo, construído no Microsoft Excel, para computar o transporte de carga de fundo em rios, baseado no modelo matemático de Van Rijn. Esse modelo é apropriado para rios transportando sedimento arenoso em regime de fluxo subcrítico. Parâmetros hidráulicos tais como declividade, potência do canal, números de Reynolds e Froude podem ser calculados usando o aplicativo aqui proposto. O aplicativo foi testado no rio Paraná e os resultados dos cálculos são consistentes com dados obtidos em trabalho de campo. O erro do aplicativo foi de apenas 20 %, o qual mostra boa concordância do modelo com os valores medidos.

1. Introduction

Rivers are important surface agents that transport sediment and sculpt bed topography to produce the landscape. Therefore, knowing the rates of sediment transport is important for geomorphology research and to human activities such as navigation, damming (i.e., energy generation), and agriculture. Several studies have attempted to mathematically model the sediment transport in rivers from these perspectives.

Suspended load transport occurs when particles are sufficiently light to "float" by flow turbulence. On the other hand, a bed-load transport particle is supported by a complex arrangement of fluid forces that move them intermittently or continuously in three modes: by rolling, sliding or saltation (ABBOTT; FRANCIS, 1977). However, the division between bed-load and suspended load is inaccurate. Some authors assume that the thickness of the bed-load layer is only twice that of the bed-load grain size (EINSTEIN, 1950). Others assume that the limit between suspended load and bed-load is a distance of approximately 10 particle diameters just above the bed (ABBOTT; FRANCIS, 1977; FRANCIS, 1973).

There are several models to calculate sediment transport. For example, the Einstein model (EINSTEIN, 1950), which computes the total sediment transport (bed-material load), presents a method that combines an equation of drag transport with another that computes the solid discharge in suspension. In a similar way, Van Rijn proposed (VAN RIJN, 1984a) a model to calculate total sediment transport by separately calculating the bed-load and suspended load transport (VAN RIJN, 1984b; VAN RINJ, 1984c).

When we analyze models to compute sediment transport, we perceive that each proposed model is appropriate for a particular condition. Kalinske (1947) developed a formula to calculate bed-load transport for a uniform grain size based on a continuity equation in which the bed-load is equal to the product of mean particle velocity, particle weight, and number of particles. Another example is the proposal of Rottner (1959) that applied regression to determine the effect of relative roughness. However, his equation does not consider the wall effect and the bed cross-section and is not applicable when limited material quantities are moving. The sediment transport formula presented by Meyer-Peter and Müller (1948) was designed for fine gravel grains and is based on the following premises: a) the slope of the energy line is a characteristic of the iteration between both solid and fluid movement of a stream during sediment transport; b) the same phenomenon governs the sediment transport and the start of motion. Many years later, Yang (1973) proposed a method to calculate bed-load transport using two options: the first is used when the bed-load is composed of sand with grain size expressed by D_{50} (the size at which 50% of the sample is finer), and the second is implemented when the bed-load is composed of sand and gravel. Some authors use the stream power concept of Bagnold (BAGNOLD, 1966) (e.g. ACKERS; WHITE, 1973; ENGELUND; HANSEN, 1967). More recently, other researchers have estimated the sediment transport using a 2D depth-averaged hydrodynamic model (ABAD *et al.*, 2008), which estimates the sediment transport using only hydrodynamic characteristics (e.g., velocities and turbulence). All these models require the recognition of such sediment, flow and channel characteristics as specific sediment weight, specific water weight, mean flow velocity, grain size, hydraulic radius, kinematic viscosity, and channel width.

This paper presents an applied calculus project based on the Van Rijn mathematical model (VAN RIJN, 1984b). The project was built in a Microsoft Excel spreadsheet that was formatted to compile the Van Rijn equations. To evaluate its reliability in calculating the bed-load transport, the project was tested in the reach of the Paraná River near the city of Porto Rico, PR, Brazil. This section of the Paraná River was chosen because an estimate of sediment transport by the dune displacement method is available (STRUCKRATH, 1969; MARTINS, 2008), which was used to validate the program.

2. Fundamentals of Particle Transport

The distinction between suspended load transport and bed-load transport depends on the size of the bed material particles and the flow conditions. If the flow (energy) is less than the bed-shear velocity, no particle will move. However, if the flow velocity is slightly higher than bed-shear velocity, the particles will move by rolling, sliding or both. As flow velocity increases, the particle will move by almost regular jumps, called *saltation*. In the current analysis, bed-load particles are those that move by rolling, sliding, and saltation.

A particle in a bed-load can become suspended when jump length reaches a dimension larger than a few grain diameters (EINSTEIN, 1950; ENGELUND; FREDSøE, 1967). On the other hand, Bagnold assumes that the bed-load particle is dominated by gravity forces, whereas the effect of turbulence on the overall particle trajectory is of minor importance (BAGNOLD, 1941; BAGNOLD, 1973). Therefore, we will limit the bed-load to transport by fluid drag forces because the successive contact of the particles with the bed are strictly limited by the effect of gravity, and we will define the suspended load as the particles transported by a random succession of upward impulses (eddies).

A body in water flow experiences a lift force due to the velocity gradient in the sheared flow near the bed; therefore, the particle will move by bed-load. When the flow conditions are sufficiently strong to move the particle by saltation the forces shown in Fig. 1a take effect. The gravitational and fluid drag forces are directed downward on the rise of the particle trajectory. The lift force is directed upward during the entire trajectory. The vertical component of the fluid drag force opposes the gravitational force on the falling part of the particle trajectory.

Therefore, there are three basic forces acting on a saltating particle: gravitational force (F_G), lift force (F_L), and drag force (F_D). A component of the particle velocity relative to the flow (V_r) remains and opposes F_D. F_L is in the normal direction of the V_r–F_D vectors.

Having discussed the characteristics of particle saltation, we now present the equation of motion that is represented by the following expressions, according to White and Schultz (1977):

$$m\ddot{x} - F_L\left(\frac{\dot{z}}{V_r}\right) - F_D\left(\frac{u-\dot{x}}{V_r}\right) = 0 \qquad (1a)$$

$$m\,\ddot{z} - F_L\left(\frac{u-\dot{x}}{V_r}\right) - F_D\left(\frac{u-\dot{z}}{V_r}\right) + F_G = 0 \qquad (1b)$$

where m is the particle mass and added fluid mass calculated by the equation $m = \frac{1}{6}(\rho_s + \alpha_m \rho)\pi D^3 P$, in which α_m is the added mass coefficient, ρ_s is the density of sediment, ρ is the density of water, and D is the particle size; V_r is equal to $[(u - \dot{x})^2 + (\dot{z})^2]^{0.5}$; u is the local flow velocity; $\dot{x}$ and $\dot{z}$ are the longitudinal and vertical particle velocities, respectively; and $\ddot{x}$ and $\ddot{z}$ are the longitudinal and vertical particle accelerations, respectively.

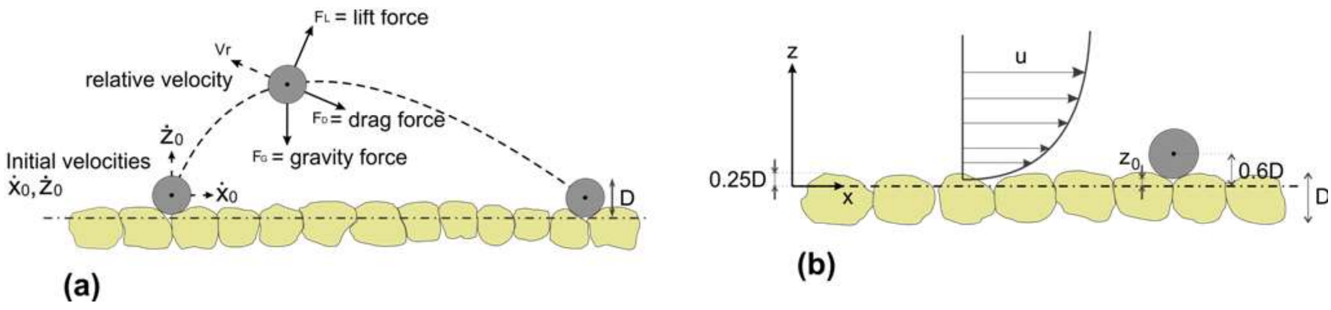

Figure 1 - Scheme of particle saltation (a) and initial position of a particle (b). (after Van Rijn, 1984a)

The *drag force* is expressed by equation 2:

$$F_D = \frac{1}{2} c_D \, \rho \, A \, V_r^{\,2} \tag{2}$$

where C_D is the drag coefficient and A is the cross-sectional area of the sphere, which is equal to $A = {}^1/_4 \, \pi \, D^2$. The drag coefficient can be determined from the expression given by Morsi and Alexander (1972).

To calculate the *lift force*, the expression derived by Saffman (1968) may be used:

$$F_L(shear) = \alpha_L \, \rho \, \nu^{0.5} D^2 V_r \left(\frac{\partial u}{\partial z}\right)^{0.5} \tag{3}$$

where α_L is the lift coefficient (= 1.6 for viscous flow); ∂_u/∂_z is the velocity gradient; and ν is the kinematic viscosity (which can be calculated from water temperature: $\nu = -0.000138t^3 + 0.0146t^2 - 0.675t + 19.107$).

The submerged weight can be calculated by

$$F_G = \frac{1}{6} \, \pi \, D^3(\rho_s - \rho) \, g \tag{4}$$

where g is the gravitational acceleration (≈ 9.8 m/s²).

Additionally, it is necessary to calculate the vertical flow velocity distribution described by equation 5:

$$u(z) = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right) \tag{5}$$

where u_* is the bed-shear velocity; k is the constant of Von Karman (= 0.4); and z_0 is the zero-velocity level above the bed given by $z_0 = 0.11(\nu/u_*) + 0.03k_s$, in which k_s is the equivalent roughness height of Nikuradse.

The conditions shown in Fig. 1b are necessary for these equations to be consistent. The bed level is assumed to be a distance of 0.25D from the bottom to the top of the particles. The initial position that is most stable is located where the center of the particle rests approximately 0.60D above the bed level.

Solving equation 1 requires knowledge of the initial longitudinal and vertical particle velocities. For equation 1, these values will be considered equal to $2u_*$, according to measurements made by Abbott and Francis (1977) and Francis (1973).

3. VAN RIJN MATHEMATICAL MODEL

Although Van Rijn defines water flow and sediment particles by seven parameters (density of water, density of sediment, dynamic viscosity coefficient, particle size, flow depth, channel slope, and acceleration of gravity), he assumes that the bed-load transport can be described by only two dimensionless parameters. The author uses an expression similar to one used by Acker and White (1973) and Yalin (1972):

A) Particle Parameter,

$$D_* = D_{50}\left[\frac{(s-1)g}{\nu^2}\right]^{1/3} \tag{6}$$

where D_{50} is the size at which 50% of the sample is finer than D_{50}; s is the specific density (ρ_s / ρ); g is the acceleration of gravity; and ν is kinematic viscosity (μ / ρ).

B) Transport Stage Parameter,

$$T = \frac{(u'_*)^2 - (u_{*,cr})^2}{(u_{*,cr})^2} \qquad (7)$$

where u'_* is the bed-shear velocity related to grains, equal to ($g^{0.5}/C'$)ū, in which C' is the Chezy-coefficient related to grains ($C'=18log[(12R_b)/3D_{90}]$), where R_b is the hydraulic radius and D_{90} is the size at which 90% of the sample is finer); ū is the mean flow velocity; and $u_{*,cr}$ is the critical bed-shear velocity, equal to $u_{*,cr} = \sqrt{\theta_{cr}[(s-1)\, g\, D_{50}]}$ according to Fig. 2, where θ_{cr} is the critical particle mobility parameter.

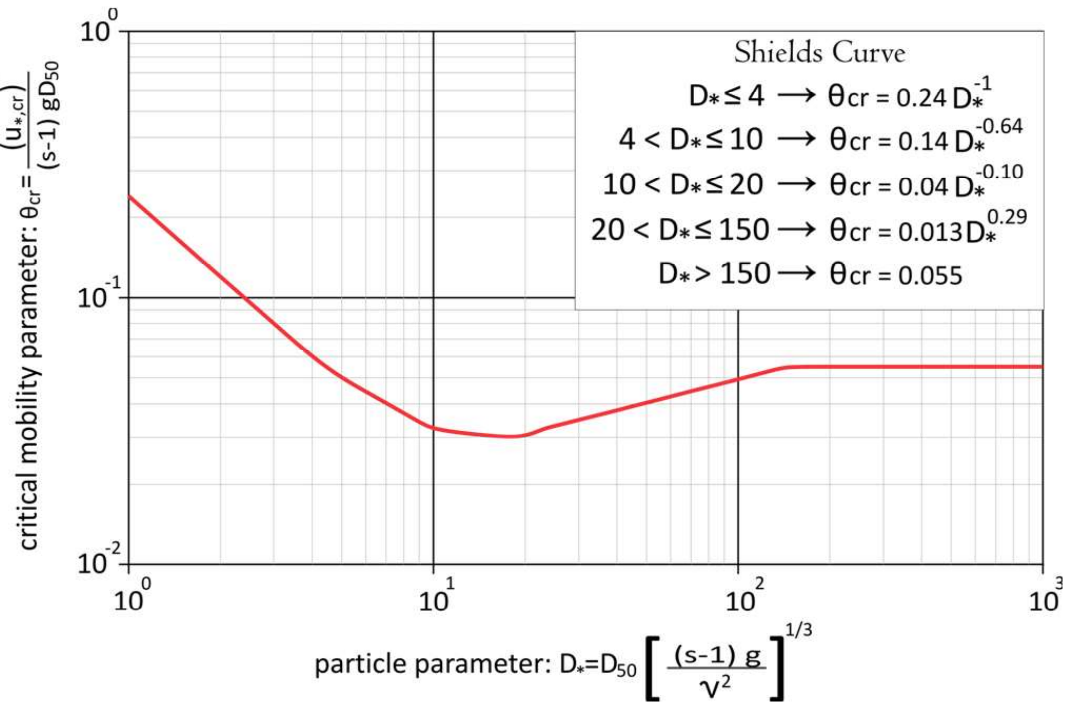

Figure 2 - Critical mobility parameter as a function of particle parameter (D). (after Van Rijn, 1984a)*

The Van Rijn model was calibrated using the experiments of Fernandez Luque and Beek (1976), which involved flume experiments on bed-load transport, and compared these experiments with other authors (KAMPHUIS, 1974; MAHMOOD, 1971; HEY, 1979; GLADKI, 1975).

Initially, the lift coefficient (α_L) and the equivalent roughness of Nikuradse (k_s) were used to calibrate the model. Other parameters were also used: particle diameter = 1.8 mm; density of sediment = 2.65 kg/m³; bed-shear velocity = 0.04 m/s; kinematic viscosity = 1.10^{-6} m²/s; and initial longitudinal and vertical particle velocities = 0.08 m/s.

Both calibration parameters strongly influence the computed trajectory; however, the best agreement between measured and computed values was obtained for $\alpha_L = 20$ and $k_s = 2D$ to 3D. Similar results were found by the previously mentioned authors.

In addition to both parameters, the model was also calibrated to small particles (0.1 mm) and the flow conditions were set equal to those of a 1.8 mm particle diameter (FERNANDEZ LUQUE; BEEK, 1976). It was observed that the saltation height and length are relatively sensitive to the α_L value and vary according to the grain size (1.8 mm to 0.1 mm).

After calibrations, the saltation characteristics were computed for various flow conditions. The objective was to relate the saltation characteristics with two dimensionless parameters, D_* and T. The following assumptions were used: grain size D = 0.1 mm – 2 mm; flow condition $u_* = 0.02 - 0.14$ m/s; $k_s = 2D$; $(\dot{x}_0) = (\dot{z}_0) = 2u_*$; $z_0 = 0.6D$; $\rho_s = 2.65$ kg/m³; ν = 1.10^{-6} m²/s; $\alpha_m = 0.5$; $\alpha_L = 1.6$ for Reynolds numbers ≤ 5; $\alpha_L = 20$ for Reynolds numbers ≥ 70; $\alpha_L = 1.6$ to 20 (linear) for Reynolds numbers between 5 and 70; and k = 0.4.

3.1 Saltation Height

Both the particle parameter (D_*) and the transport stage parameter (T) were computed for the set of hydraulic conditions previously mentioned and related to the (dimensionless) saltation height. The relationship between saltation height and particle size can be approximated with an accuracy of approximately 90% by the following equation:

$$\frac{\delta_b}{D} = 0.3{D_*}^{0.7}T^{0.5} \quad (8)$$

where δ_b is the saltation height.

Both parameters (D_* and T) influence the dimensionless saltation height depending on particle size. the results of equation 8 are similar to results of experiments of Williams (1970) and Reizes (1978).

3.2 Particle Velocity

Van Rijn computed the particle velocity (Eq. 1) as a function of the flow conditions and particle size to obtain equation 9 with an accuracy of approximately 90%, in which θ is the particle mobility parameter (${u_*}^2/[(s-1)gD]$):

$$\frac{u_b}{u_*} = 9 + 2.6\, logD_* - 8\left[\frac{\theta_{cr}}{\theta}\right]^{0.5} \quad (9)$$

However, when the equation results are compared with the measured data, the particle parameter does not influence the particle velocity. Therefore, the computational particle velocities were approximated by equation 10 with an accuracy of approximately 80%:

$$\frac{u_b}{[(s-1)gD]^{0.5}} = 1.5\, T^{0.6} \quad (10)$$

3.3 Bed-Load Concentration

Van Rijn defined the bed-load concentration using measured bed-load transport of 130 flume experiments with particle sizes ranging from 0.2 mm to 2 mm. The author adopted the premise that the bed-load transport rates are equal to bed-load saltation multiplied by particle velocity and by bed-load concentration. Equation 11 thus defines the bed-load concentration:

$$C_b = \frac{q_b}{u_b \delta_b} \quad (11)$$

where q_b is the bed-load transport rate.

The data of Guy *et al.* (1966), Falkner (1935), Gilbert (1914), Tsubaki and Shinohara (1959), Fernandez Luque (1974), Willis (1979) and Williams (1970) were utilized for this purpose. The bed-load concentration was approximated by equation 12 with an accuracy of 80%:

$$\frac{C_b}{C_0} = 0.18\, \frac{T}{D_*} \quad (12)$$

where C_0 is the maximum bed concentration (= 0.65).

3.4 Computation and Verification of Sediment Transport Rate

From the premise that the sediment transport is equal to $q_b = C_b u_b \delta_b$ and using equations 8, 10 and 12, the bed-load transport (in m²/s) for particles in the range of 0.2 mm–2 mm can be computed by equation 13:

$$q_b = 0.053\, \frac{T^{2.1}}{{D_*}^{0.3}}[(s-1)g]^{0.5}{D_{50}}^{1.5} \quad (13)$$

The input data are mean flow velocity ($\bar{u}$), hydraulic radius (Rb), particle diameter (D_{50} and D_{90}), density of water and sediment (ρ, ρ_s), kinematic viscosity (ν), and the acceleration of gravity. The follow computational sequence must be performed:

1) Compute particle parameter using equation 6;

2) Compute critical bed-shear velocity according to Fig. 2;

3) Compute Chezy-coefficient related to grains (C') using equation given above in opening chapter;

4) Compute effective bed-shear velocity (u'_*);

5) Compute transport stage parameter, using equation 7;

6) Compute bed-load transport, using equation 13;

To verify Eq. 13 a total of 524 flume experiments were used and compiled from Peterson and Howells (1973), Guy et al. (1966), Stein (1965) and Delft Hydraulics Laboratory (1979). Moreover, three field data sets were used (TSUBAKI; SHINOHARA, 1959; EINSTEIN, 1944; HANSEN, 1966). The results are compared with Engelund and Hansen (1967); Ackers and White (1973); Meyer-Peter and Müller (1948) and are shown in Table 1.

As Table 1 illustrates, it is possible to compute the bed-load transport rate using the mathematical model proposed by Van Rijn with an accuracy of approximately 77% over the discrepancy range (r) of one-half to twice the measured values.

Table 1: Scores (percentage) of predicted bed-load in the discrepancy range. (modified from Van Rijn, 1984b)

$0.75 \leq r \leq 1.5$				$0.5 \leq r \leq 2$				$0.33 \leq r \leq 3$			
Van Rijn	Engelund-Hansen	Ackers-White	Meyer-Peter and Müller	Van Rijn	E-H	A-W	M-P-M	Van Rijn	E-H	A-W	M-P-M
42%	43%	48%	23%	77%	76%	77%	58%	93%	90%	92%	76%

4. The Bedload Calculus Project

As previously mentioned, the application is a Microsoft Excel spreadsheet formatted to calculate the bed-load transport using the Van Rijn mathematical model. The universal availability of Microsoft Excel will enable the use of the BEDLOAD program by many researchers, which permits an easier estimation of bed-load transport in rivers that do not have such information. The BEDLOAD 1.0.xlsx program is compatible with Microsoft Excel 2007 and will be compatible with any newer version.

The data that must be input are: particle size analysis, water temperature, sediment density, mean flow velocity, wetted perimeter and area, section width, bathymetric data (the three previous data types are not required if bathymetric data are available). After inputting these data, the BEDLOAD program will calculate the transport stage and particle parameters, kinematic viscosity and the density of water. For the last two parameters, the program uses equations 14 and 15:

$$\nu = -0.000138t^3 + 0.01461t^2 - 0.67520t + 19.10679 \quad (14)$$

$$\rho = 0.00002t^3 - 0.00604t^2 + 0.02477t + 999.95409 \quad (15)$$

where t is the water temperature.

The user is required to input the mass (in grams) retained on a specific sieve on the particle size analysis screen. After applying the grain size analysis, the user must specify the water temperature, density of sediment, mean flow velocity and bathymetric data by clicking on the blue buttons.

After specifying the input data, the application will calculate the D* and T parameters and, consequently, the bed-load transport. Moreover, the program also calculates some hydraulic parameters such as Reynolds number, Froude number, overall Chezy coefficient, Manning roughness coefficient, water surface slope, stream power and specific stream power. With the first two parameters the program classifies the state of flow as turbulent, laminar, or transitional flow and subcritical or supercritical flow.

If the user has suspended load data, the program can also calculate the suspended load transport and compare it to the bed-load transport, thus classifying the river as suspended load dominant or bed-load dominant.

5. Application to the Paraná River Downstream of Porto Primavera DAM

The Paraná River is the major river of the Rio de la Plata basin and runs a distance of 3,965 km from its source on the mouths of the Grande and Paranaiba rivers to its mouth on the Rio de la Plata Estuary (ORFEO; STEVAUX, 2002). The Paraná River basin has an area of 2,800,000 km² and drains all south-central South America (STEVAUX, 1994). The Paraná River alluvial trench is divided into three major parts: an upper course, from its source to the Itaipu Dam near Foz do Iguaçu; a middle course along the Paraguay-Argentina border; and a lower course from the Paraguay River confluence near Corrientes (Argentina) to the Rio de la Plata Estuary (STEVAUX, 1994). The studied section is near the town of Porto Rico (latitude 22 ° 43 ' S, longitude 53 ° 10 ' W), which is between the mouth of the Paranapanema and Ivai Rivers. The Porto São

José gauge station is in this reach and has registered an annual average discharge of 8,912 m^3/s since 1964 and minimum and maximum discharges of 2,551 m^3/s and 33,740 m^3/s, respectively (STEVAUX et al., 2009). The period of flood in this river reach is during the summer (Dec-Feb), and low water levels are in winter and spring (Jul-Nov) for the period 1964-1983. The river hydrology was strongly influenced by dam regulation after 1988, which caused reductions in the hydrograph amplitude and the low peak of flood (op. cit).

Data collected during a survey in the Paraná River (MARTINS, 2008), in front of Porto São José village, Paraná State (Fig. 3), were used in the BEDLOAD program review. The results of sediment transport calculated by the BEDLOAD program were compared with the results of measurements of dune displacement made by Martins (2008). The measurements of dunes displacement were taken to be the real results of sediment transport in Paraná River because there is no direct measurement in this river.

An acoustic Doppler current profiler (ADCP – RiverRay™) was used to measure the flow velocity and water discharge. An Ecosounder device (Furuno™) was also used to survey the river bathymetry. Nine samples of bed-load sediments were collected in this section, spaced 120 m apart from each other. A Van Veen sampler was used to collect bed-load. The bed-load material was sieved with 4, 2.8, 2, 1.4, 1, 0.71, 0.5, 0.355, 0.25, 0.177, 0.125, 0.090, and 0.045 mm sieves (Fig. 4). After inserting the particle sizes, the BEDLOAD software calculates the particle size distribution (Fig. 5). To calculate the bed-load transport, it is necessary to specify water temperature, density of sediment, mean flow velocity, wetted area and perimeter. The water temperature was considered to equal 25º C, and the mean flow velocity was obtained from the ADCP. Wetted area and perimeter were obtained from the bathymetric survey. For this section in the Paraná River the mean flow velocity was 0.80 m/s, the density of sediment was 2.65 ton/m^3, the wetted area was 11,601.65 m^2, the wetted perimeter was 1203.49 m, and the width of section was 1,200 m.

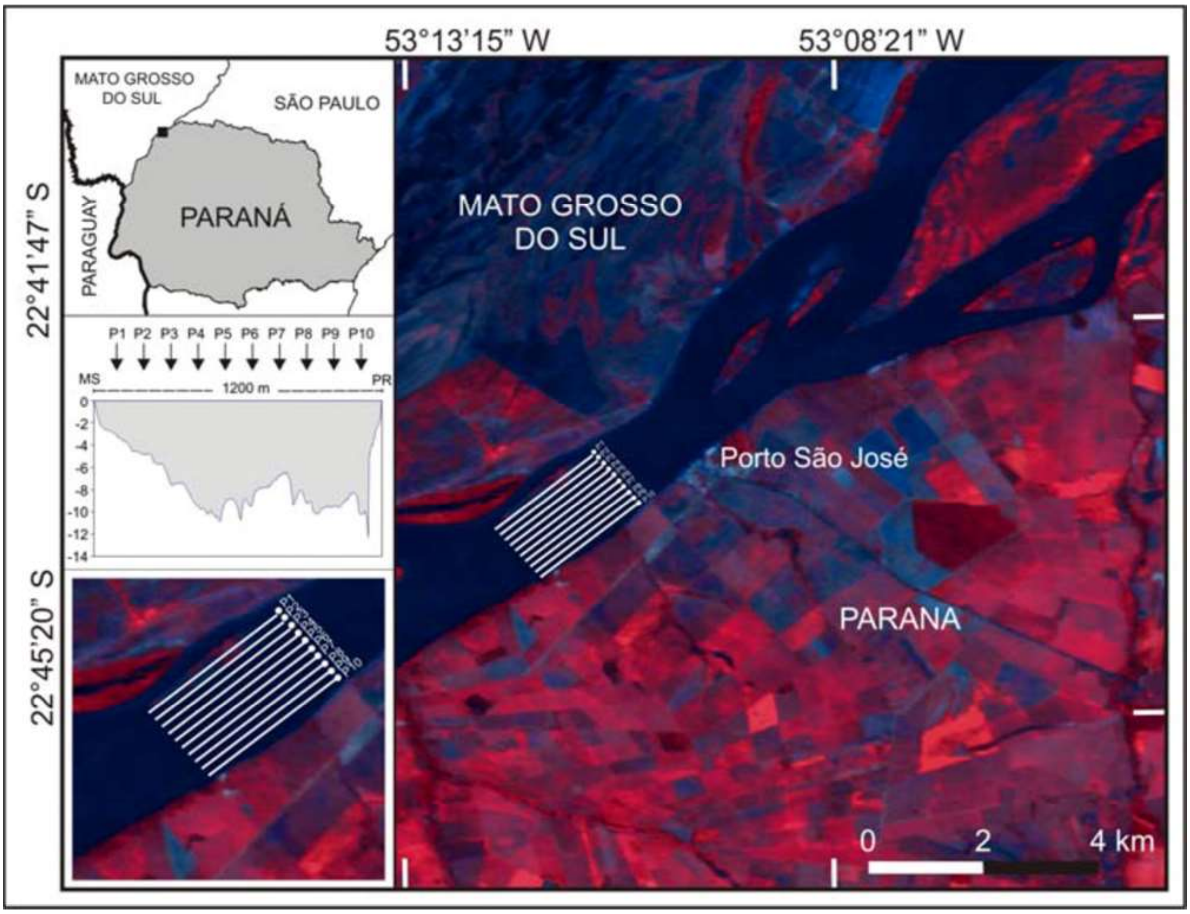

Figure 3 - Section used to validate the program. Surveyed section is in Paraná River in front of Porto São José village in the town of Porto Rico, Paraná State. The lines along the channel are bathymetric long profiles surveyed to measure the bedform's displacement (after Martins, 2008).

Sample Description Data:	001 P9	002 P8	003 P7	004 P6	005 P5	006 P4	007 P3	008 P2	009 P1
APERTURE (mm)	REFRAINED MASS (g)	REFRAINED MASS (g)	REFRAINED MASS (g)	REFRAINED MASS (g)	REFRAINED MASS (g)	REFRAINED MASS (g)	REFRAINED MASS (g)	REFRAINED MASS (g)	REFRAINED MASS (g)
4.000	0	0	0	0	0	0	7.68	6.35	1.68
2.800	0	0	0	0	0	0	2	6.42	3.01
2.000	0	0	0	0	1.06	0.12	24.57	7.73	8.68
1.700									
1.400	0.01	0.24	0	0.21	0.94	0.06	13.35	11.62	19.24
1.180									
1.000	0.04	0.16	0.01	0.13	1.58	0.29	12.95	12.65	26.64
0.850									
0.710	0.11	0.38	0.04	0.6	5.89	1.22	12.63	22.08	38.44
0.600									
0.500	0.78	1.41	0.31	2.46	16.65	10.66	7.2	24.39	35.21
0.425									
0.355	6.44	8.9	3.16	16.06	39.58	43.54	7.11	37.32	37.46
0.300									
0.250	24.44	20.87	19.9	22.48	28.37	37.91	7.43	45	23.63
0.212									
0.177	15.29	15.51	22.01	7	5.38	5.7	4.44	23	5.65
0.150									
0.125	2.65	2.34	4.28	0.98	0.49	0.46	0.58	3.22	0.3
0.106									
0.090	0.22	0.18	0.27	0.08	0.05	0.03	0.04	0.19	0.03
0.075									
0.063									
0.053									
0.045	0.02	0.01	0.02	0	0.01	0.01	0.02	0.03	0.03

Water Temperature | Hydraulic | Bathymetry | Particle Diameter | Statistics granulometry | Wetted Perimeter & Wetted Area | Kinematic Viscosity | Particle Parameter (D.) | Transport Stage (T) | BED-LOAD TRANSPORT

INPUT DATA | REPORTS

Figure 4 - Refrained mass on each sieve used to compute the bed-load transport at Paraná River (the first input screen of the BEDLOAD program).

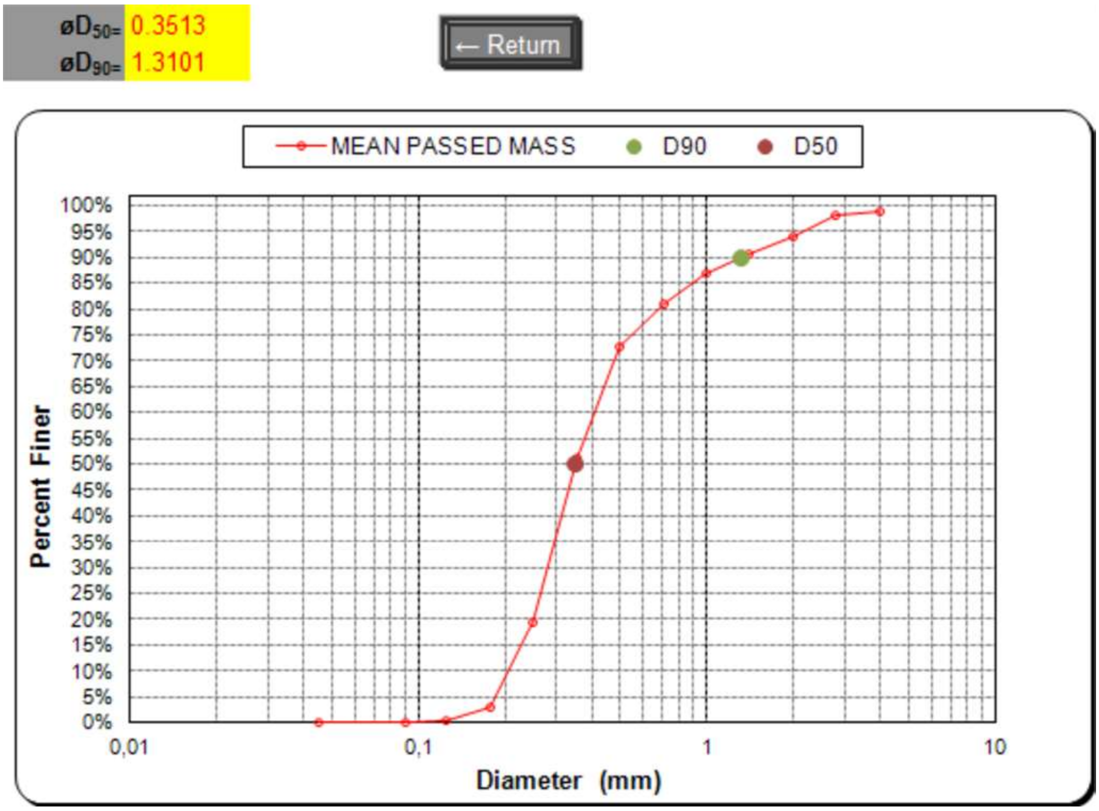

Figure 5 - Grain size distribution of the surveyed section. The program calculates the characteristic sizes (D_{50} and D_{90}) using these data

The results show that the Paraná River in the surveyed section has turbulent-subcritical flow (Rey=8.36x10^{9}; F=0.082). The river is capable of transporting sand only; in spite of the grain size analysis, some particles were bigger than sand grain size (Fig. 4). The presence of this grain size is explained by the fact that this reach of the Paraná River is controlled by the Porto Primavera Dam, which causes an increase of downstream grain size due to sediment captured by the dam. Because the downstream reach does not receive the same sediment load before barrage construction, the river carries out the finer sediment by selective transport due to changes in river hydrology. This phenomenon is well-known in several dammed rivers in the world as the armouring effect (CHIEN, 1985). Changes in the river hydrology are also able to produce several other effects in the channel dynamics such as increase in bank erosion (FERNANDEZ, 1990; DESTEFANI et al., 2004) or threats to benthic fauna (STEVAUX; TAKEDA, 2002).

The bed-load transported calculated by BEDLOAD was 3,803.018 tons/day. The overall Chezy coefficient was 80.771 and the Manning roughness coefficient was 0.027. The Manning roughness is within values estimated by Chow (1959) for floodplain channels that are clean, straight and free of deep depressions (0.025 – 0.033). Sediment transport estimated by measurements of dunes displacement showed results compatible with those calculated by BEDLOAD. The bed-load transport by dunes displacement was 3,157 tons/day, which shows that the bed-load transport calculated by the proposed application has a coherent result. The difference was only 20% (1.20 times) of the estimated result by dunes displacement, which is consistent with the Van Rijn model (77% chance of between twice or half the measured values). However, in our program's estimate, samples with very coarse material (2-4 mm) were considered. This material is probably not fluvially transported and should be disregarded in the calculation. Thus, the results from BEDLOAD (3,239.364 tons/day) would be much closer to dune migration rates, which lead to a difference of only 2.61% (1.0261 times).

Martins (2008) tested two other formulas: Meyer--Peter & Müller; Engelund & Fredsøe, but only the latter resulted in an estimate consistent with the measured dune displacement. The Meyer-Peter & Müller formula had a 45% error and the Engelund & Fredsøe formula had a very low 0.7% error. These results show that each mathematical model is suited to specific conditions. This caveat has also been demonstrated in research on the Nile River (Fattah et al., 2004). In this study, three formulas for calculating bed-load sediment transport were tested: Van Rijn; Bagnold; and Meyer-Peter & Müller. Of the three formulas, the Van Rijn calculation was closest to the measured result. This formula showed a difference (ratio of computed and measured transport rate) of only 1.65 times, whereas Bagnold showed a difference of 4.68 times and Meyer-Peter & Müller showed a difference of 2.48 times.

6. CONCLUSION

Measurements of bed-load transport in rivers are generally scarce worldwide, mainly because of difficulties in measuring this phenomenon. Some ways to measure bed-load transport in rivers are direct methods such as that presented in this paper (dune migration). However, this method consumes much time and, consequently, financial resources. Therefore, mathematical models are of great importance due to their capacity to estimate this important geomorphologic parameter while expending less time and fewer resources because less fieldwork is necessary. Nonetheless, the calculation routine can become expensive and may result in errors. It is extremely helpful if we have tools that can help us avoid calculation errors; the BEDLOAD tool was created to assist us in the calculation of bed-load transport.

There are many models to compute bed-load transport in rivers, and each one is better suited for particular conditions. The model studied in this paper was developed for subcritical flow conditions (Froude number < 0.9) and sand particle sizes ranging from 0.2 mm to 2 mm. These characteristics are similar to those found in the Paraná River; therefore, the Van Rijn model is appropriate to compute bed-load transport in this river. The calculation of sediment transport by the proposed application had an error of only 20%, which indicates good model accuracy.

Additionally, the Van Rijn model performed well in predicting bed-load in the Paraná River conditions. The BEDLOAD program is a quick and accurate tool for those who want to calculate bed-load transport of rivers with subcritical flow and sandy bed-forms. Therefore, this application is an important tool that will assist many researchers who work with fluvial geomorphology worldwide.

SUPPLEMENTARY MATERIAL

Supplementary material related to this article is available online at: https://1drv.ms/f/s!ArdUczeHp2hZhiwtiTmFNrjlmoLO

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