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Geomorphological maturity profile of the Paracatu river basin

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ABSTRACT

An assessment of the maturity of the geomorphological profile of the Paracatu River Basin, a tributary of the São Francisco River, is presented. The relationship between length and average stream fall for each order using the Strahler method is analysed using empirical laws for a comparison to a theoretical profile of maximum equilibrium. The results show that the Paracatu River Basin is close to its maximum stage of maturity, though it has not achieved it completely. Based on this study, reflections are made about the possibilities to study this watershed based on entropy approaches, metastability, geological vulnerability and geomorphological evolution.

Keywords: Equilibrium profile, entropy, metastability, geovulnerability, geomorphological evolution, Paracatu.

Perfil geormofológico de maturidade da bacia do rio Paracatu

RESUMO

Apresenta-se uma avaliação da maturidade do perfil geomorfológico da Bacia do Rio Parcatu, afluente do Rio São Francisco. As relações entre comprimento e queda média dos seguimentos de rios para cada ordem pelo método de Strahler são analizados por leis empíricas para comparação com um perfil teórico de máximo equilíbrio. Os resultados demonstram que a Bacia do Rio Paracatu está próxima de seu estágio máximo de maturidade, embora ainda não o tenha alcançado completamente. A partir do estudo aplicado, são tecidas reflexões sobre as possibilidades de investigação de bacias hidrográficas com base em abordagens de entropia, meta-estabilidade, geovulnerabilidade e evolução geomorfológica.

Palavras-chave: Perfil de equilíbrio, entropia, meta-estabilidade, geovulnerabilidade, evolução geomorfológica, Paracatu.

Introduction

Horton (1945) presents a quantitative description of river morphology and proposes an ordering system for river networks that includes the laws of stream order, number of channels and number of bifurcations, among others. A description of a watershed using the empirical laws of Horton (1945), interpreted according to the ordering criterion of Strahler (1964)[1], allows predictions of the exchange of matter and energy between its waterways.

In 1962, Leopold and Langbein (1964) introduced the concept of entropy in the evaluation of river morphology. They postulated that a geomorphological system (such as a river network) is an open system in a steady state analogous to thermodynamic entropy. This entails two generalizations about the most probable energy distribution, which would be an intermediate state between two states or tendencies: a state in which the energy dispersion rate is uniformly distributed; and a state in which the system performs minimum work.

Yang (1971) applied the entropy concept to these relationships, showing that in the evolution towards the final static equilibrium, the basin reaches one or more states of dynamic equilibrium in which the fall per sub-basin is constant. Yang verified this property for 14 basins in North America with sufficient accuracy to study the distribution of the water potential for each sub-basin. For the closed system, the application of the

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[1] The Strahler criterion considers single streams as order 1. The joining of 2 streams of order 1 produces a stream of order 2 and so on.

Law of Entropy to the water mass unit leads to the conclusion that the average fall per sub-basin is independent of the order. For an open system, it is concluded that the potential energy per sub-basin is also independent of the order.

The method of Yang (1971) allows analysis of the state of maturity of a watershed, based on the concept of jointly considering relief potential energy and river morphology. This method leads, in a transdisciplinary way, to the idea of entropy as the metastable state of greater dynamic equilibrium that the relief should be at for a given basin at the end of a morphogenic stage.

In this theoretical framework, two laws are useful to describe this state of affairs:

[**1**] Law of average stream fall – "under dynamic equilibrium conditions, the ratio between the average gradients of two streams of different orders in the same basin is close to unity"
[**2**] Law of minimum energy expenditure - "during the evolution of a basin towards the equilibrium condition, a natural stream makes its way so that the rate (power) of potential energy use per water mass unit along the path is at a minimum".

The underlying idea is that a basin can be in a state of equilibrium, which means the state of greater maturity for a certain phase is the conjugation of the factors of crustal uplift and rainfall effect, factors that act against each other. To be in the condition of maximum entropy or operating at the lowest possible geopotentials for the situation, the basin must have reached the maximum ratio of geopotentials loss in all compartments.

The objective of this article is to use the method of Yang (1971) to study the maturity of the hydro-geomorphological profile of the Paracatu River basin.

Materials and methods

The area of Paracatu River Basin (Figure 1) is 45,154 km^2 and it is the largest basin among the direct tributaries of the São Francisco River. It is almost entirely within the state of Minas Gerais (Northeast Region), with small areas at the top of the basin entering Goiás state and the Federal District.

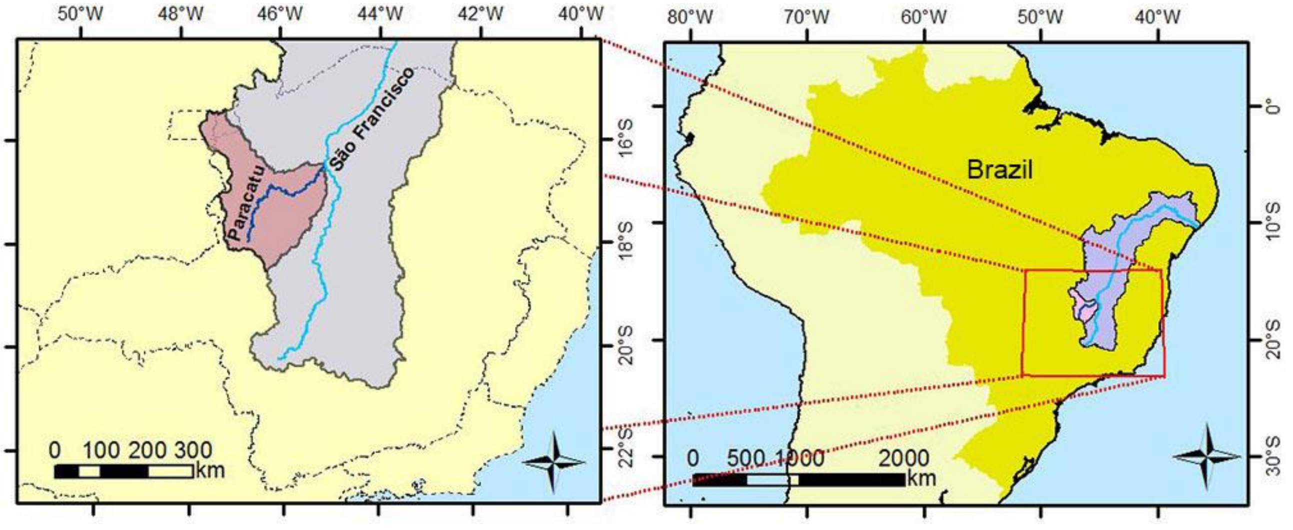

Figure 1. Location of the Paracatu River Basin

The data required to calculate the parameters of the empirical laws were obtained from topographical maps from the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística – IBGE) at the 1:100,000 scale, with information that corresponded to each Strahler order, namely: number of streams (N_U), average stream length (L_U), average stream fall (Y_U) and average drainage area (Ad_U) (Figure 2).

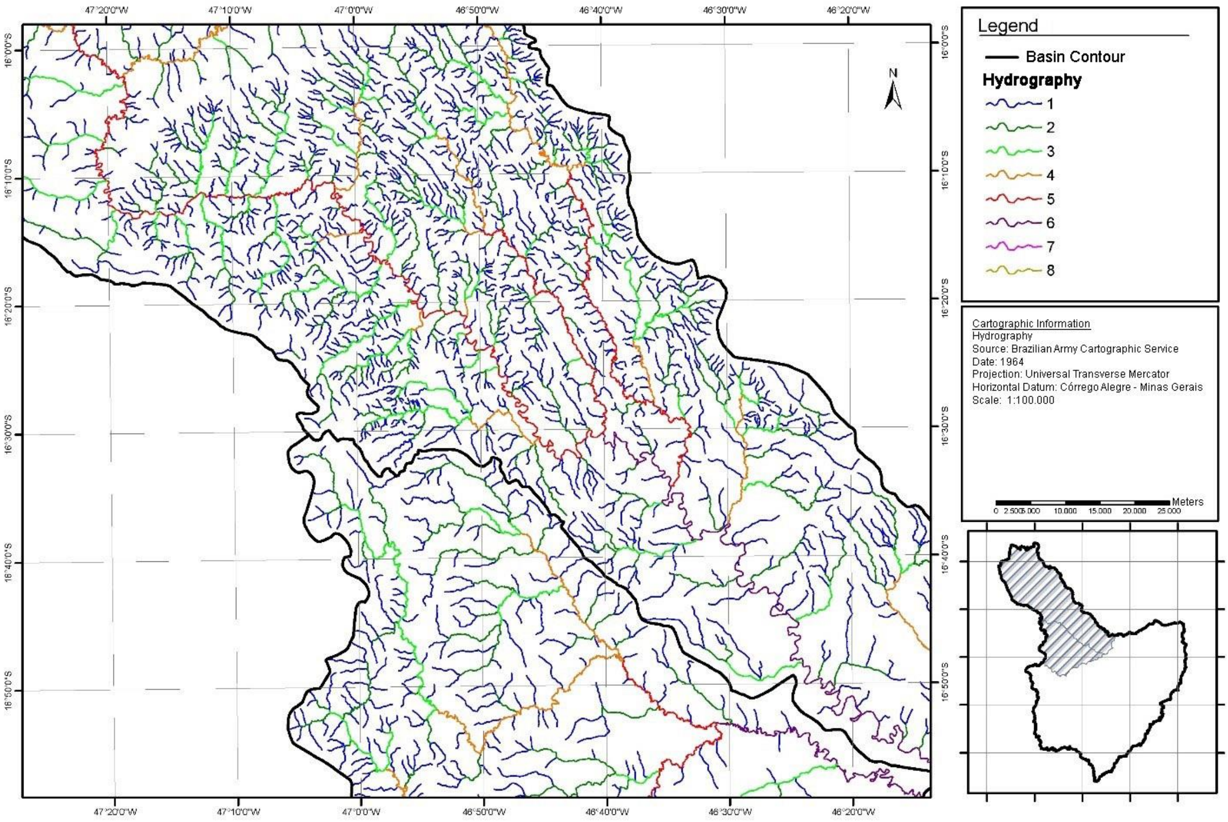

Figure 2. Map of the sub-basins of the Entre Ribeiros and Escuro River in the Paracatu Valley showing the streams of various orders based on the Strahler method. Cartographic basis: Martins Junior et al. (2006)

The average values per sub-basin are fitted to empirical laws:

$\ln Nu = A - B.u$
$\ln Lu = C - D.u$
$\ln Yu = G - H.u$

Using these equations, it is possible to establish a relationship between the virtual course of flow and the fall per sub-basin by considering the sub-basin to be a single watercourse characterized by the average values of the respective parameters.

Adding virtual pathways from the beginning of the stream of order 1 until the end of the stream of order u provides the x-coordinate of the fall diagram for the entire basin. By adding the falls, the respective y-coordinates are obtained. Following the same procedure, the diagram of cumulative fall in the basin in the dynamic equilibrium state is obtained given that, according to the Yang model, the total fall in the basin (from the head of the stream of order 1 to the mouth of stream u) in the dynamic equilibrium state is equally distributed over the sub-basins, i.e., the fall Y_U does not depend on the value of u. Finally, a diagram of the fall observed in the basin is constructed with the unadjusted data from the parameters, in which $X_u = \Sigma_1^u Lu$ and $Y_u = \Sigma_1^u Y_{observ}$.

Results

The average fluviomorphological data for the Paracatu Rio Basin are shown in Table 1.

Figure 3 shows the results of the empirical laws for the sub-basins grouped by each Strahler order.

By summing up the virtual courses of flow of the Paracatu River Basin, the following coordinates for the fall diagram are obtained:

$$\mathbf{X_u} = \Sigma_1^u X_u = \Sigma_1^u\ e^{6.77 + 0.822\,u} = e^{6.77}\, \Sigma_1^u\ e^{0.822\,u}$$

$$\mathbf{Y_u} = \Sigma_1^u\ e^{3.86 + 0.0496u} \text{ and } {}^{3.86}\, \Sigma_1^u\, e^{0.0496\,u}$$

The diagram of the cumulative fall in the basin in the dynamic equilibrium state was obtained using the X_u equation above, along with $Y_u = e^{3.86} x\ \Sigma_0^u\ 1 = 47.5$ u. Figure 3 shows the cumulative falls due to the course of flow of the streams. To facilitate a comparison of the results between this study and others, the cumulative fall diagram is converted into a longitudinal profile with the highest observed fall as the reference point and successively deducting the falls per sub-basin from the reference point (Figure 4.B)

Table 1. Parameters of the empirical laws

Orders of water courses	Number of water courses N_u	Average length L_u (m)	Average fall Y_u (m)	Slope average S_u	Drainage area average Ad_u (km^2)
1	5,439	2,518	66.9	0.0266	4.53
2	1,295	3,699	37.6	0.0102	6.59
3	285	9,425	55.8	0.0059	18.02
4	63	23,794	62.4	0.0026	44.57
5	17	63,176	66.5	0.00105	127.06
6	6	82,000	40.0	0.00049	181.83
7	1	363,000	53.0	0.00015	1270.00

m/m (*dimensionless*).

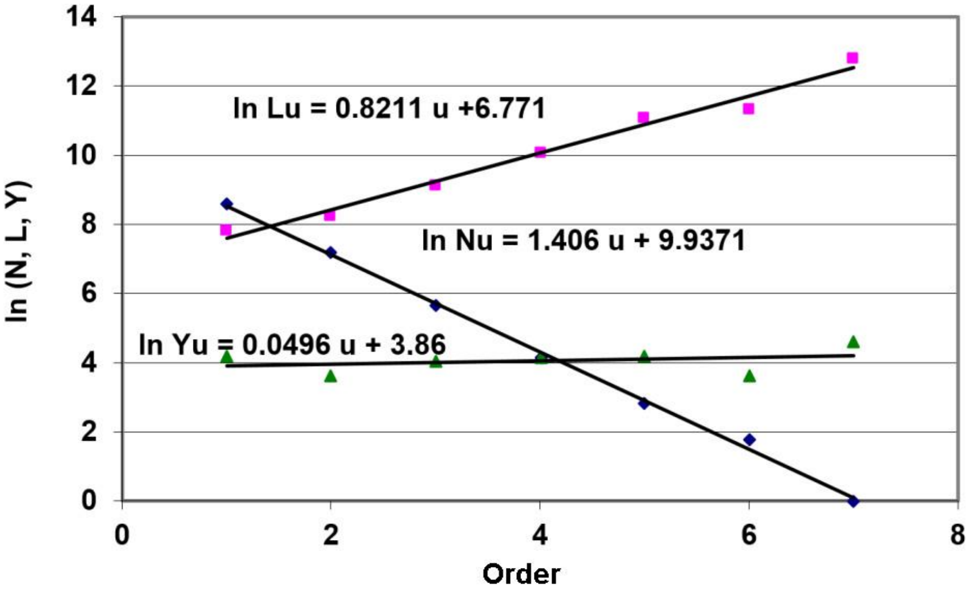

Figure 3. Results of the empirical laws for the Paracatu River Basin

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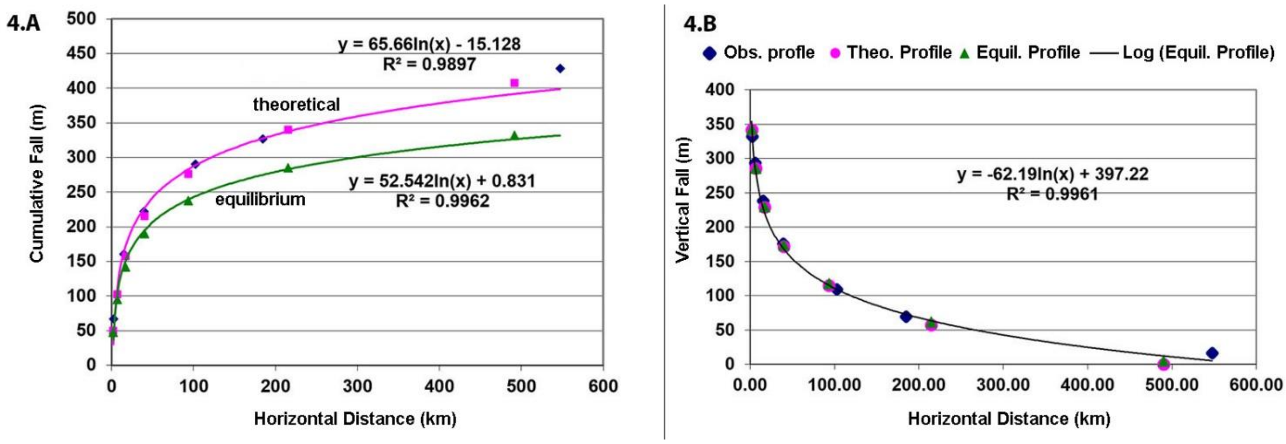

Figure 4. Cumulative fall in the Paracatu River Basin.

Figure 4.B, corresponding to the profile of the Paracatu River Basin, shows agreement between the theoretical and actual profiles, indicating that the Paracatu River Basin is at the maximum maturity or maximum entropy stage of its evolution for the current phase of tectonic and climatic evolution.

For comparison, Figure 5 is presented, which displays a diagram of the longitudinal profiles of the Santo Antonio River (Moreira et al., 2002).

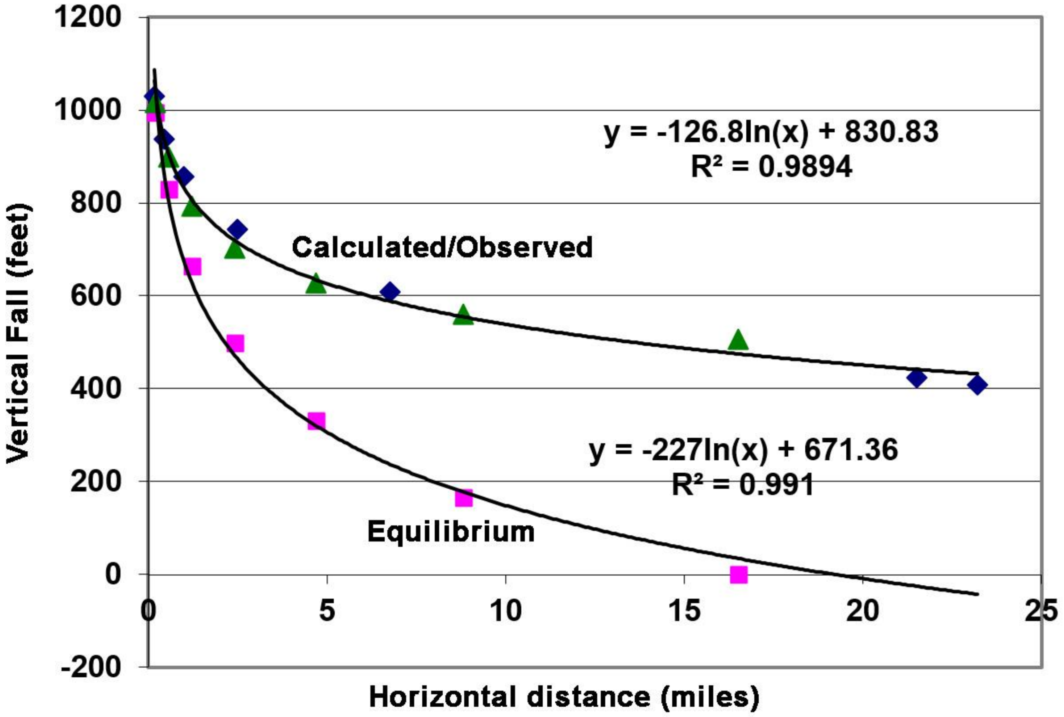

Figure 5. Longitudinal profiles of the Santo Antônio River Basin

Discussion

Given the example shown in this article for the morphological profile of the Paracatu River Basin, it is important to define stability in relation to geovulnerability, because both the concepts and phenomena are not easy to discriminate.

Every natural system is transient and does not operate in a steady state. There is no stationarity; therefore, geovulnerability must be defined as a function of these transient conditions.

During a particular time period, it is possible to make an assumption that a subsystem is stable or, more appropriately, metastable. Metastability means that the subsystems might be operating in the condition of maximum entropy, i.e., greater stability in its current state of evolution. A subsystem is always in a metastable condition without necessarily being at maximum entropy and has stabilized because of the effects of a series of elements from the existing ecosystems that stabilize the structure of the system.

Stability occurs when the total balance of internal forces of the macrosystem, or forces that act on this system, allow it to be away from equilibrium with little discernible losses, such that, on average, it still behaves like it is in equilibrium. For example, a change in the subsoil occurs that compensates for the loss of soils and/or nutrients outside of the system with the formation of neo-soils that replace the lost soils. This formation should represent the soil losses to the degree that the different geological processes are observed.

In another sense, presence of life as an agent of stability is a key function of metastability. The presence of life is an "active geological agent (⇒)" when it builds the geological environment and a "passive agent (⇐)" when it resists the production of entropy on the continent as a macrosystem. The atmosphere must be included as an agent of high mechanical efficiency (⇓⇒) and production of entropy and new patterns of ordination.

Vegetation, in turn, is largely responsible for maintaining a certain state-situation, as a form of resistance to evolution towards maximum entropy. Without it, the system would tend towards complete levelling of the structure of a river basin and major fluctuations of the relief within it, which is the state of full maturity of a basin and relief. The state of maturity can only be reactivated, i.e., have new geopotentials generated via three types of events:

- continental uplift or epeirogeny (an example is the broad uplift at the end of the Cretaceous period that allowed the geoforms to evolve to their current state),
- eustatic variation in sea level with a decrease or increase in the level,

- compartmentalised tectonic movement in an area, producing unevenness or new geopotentials.

Geovulnerability is an indicator of "how events can move a sub-basin away from its condition of metastability to a lower level of available geopotential to a new meta-stability state".

Clearly, any management strategy should consider that human intervention can and should benefit from the natural heritage of production processes without producing irreversibility that leads the basin to a new metastable state. Therefore, human intervention causes the metastable state to be less organized or with less potential than the current existing state.

Geovulnerability is more easily recognized at the *system nodes* level, i.e., each *node* or *crisscrossing* or *intersection* of systems, where the cybernism can be changed beyond the *fluctuation state inherent and normal to the system*, that is, the *fluctuation state* that does not take the system away from its own equilibrium condition or, at most, takes it to a fluctuation very close to equilibrium.

From an environmental management perspective, such a situation may indicate four issues:

- the basin is in equilibrium, thus considerable erosion cannot occur spontaneously;
- the basin is in non-equilibrium, thus some of its areas are highly susceptible to spontaneous erosion;
- any climatic change can change the equilibrium relationships of the maturity profile of a basin, particularly if rains increase in intensity, either along the entire hydrological year or specifically during the most rainy season;
- human intervention must not change the equilibrium state of the basin, whatever its current stage.

Finally, the condition of no-change will be valid as long as the current geotectonic conditions and/or prevailing climatic conditions remain. The natural forces are obviously uncontrollable, but the effects can be minimized by the natural vegetation and through agricultural projects implemented using soil and water conservation measures.

Conclusion

The analysis of the Paracatu River Basin using the Yang method reveals that opposing geopotential processes that create (+) and destroy (-), i.e., the regional crustal uplift (+) and the erosive effect of rainfall (-), have reached a level very close to maximum entropy.

The graphs presented show good agreement between the observed and theoretical profiles, which indicates the adequacy of the empirical laws for describing the morphology of the Paracatu River Basin. However, the theoretical profile is relatively far from the equilibrium profile, which suggests that a steady state has not been achieved. Using the criterion of distribution of falls per sub-basin with the data from Figure 1 (adjusted straight line), the average ratio between successive falls (Y_u/Y_{u+1}) is calculated to be 0.951, which confirms the state is in non-equilibrium.

It is also observed that the equilibrium profile is above the theoretical profile, contrary to what was observed in the Santo Antonio River Basin (ratio of 1.166), which was studied using the same method. Different processes were at work in these two basins to reach the respective high or low side of dynamic equilibrium.

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