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ORIGINAL ARTICLE

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Morphometric analysis of a subtropical Andean basin (Tucumán, Argentina)

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Abstract A morphometric analysis was done to determine the drainage characteristics of Lules River basin using land-sat imageries and topographical maps. This catchment was divided into seven sub-basins for the analysis: Liquimayo, Hoyada, Ciénaga, De Las Tablas, Siambón, Potrerillo and San Javier. Yungas ecoregion covers almost all the watershed. The drainage patterns of the sub-basins are dendritic and parallel. The basin includes seventh order stream and lower streams order mostly dominate the basin. The development of stream segments is affected by slope and local relief. The mean bifurcation ratio indicates that the drainage pattern is not much influenced by geological structures. The shape parameters also reveal the elongation of the basin and sub-basins.

Keywords Lules River basin · Yungas · Basic parameters · Shape parameters · Argentina

Introduction

Geology, relief and climate are the primary determinants of running water ecosystems functioning at the basin scale (Lotspeich and Platts 1982; Frissel et al. 1986). Morphometric descriptors represent relatively simple approaches to describe basin processes and to compare basin characteristics. Anthropogenicals changes have led to widespread modifications in physical structure of rivers, biotic communities and ecological functioning of aquatic ecosystems around the world (Thompson et al. 2001). In this sense, this study allows the description of the physical changes in a drainage system over time in response to natural disturbances or human impacts (Thompson et al. 2001). This is an important aspect considering the contamination in the lower part of the study catchment as well as the lack of data recorded in the hydrologic system for ecosystem management in northwestern of Argentina (Fernández and Molineri 2006).

The drainage characteristics of Lules River basin (Lrb) and sub-basins were studied to describe and evaluate their hydrological characteristics by analysing topographical maps and land-sat imageries.

Study area

The Lrb covers an area of 787 km^2 considering the Instituto Geográfico Militar toposheet number 2766-II on a scale of 1:250,000 (Fig. 1). The basin lies between latitudes 26°36′21″ and 26°55′09″N and longitudes 65°45′36″ and 65°19′35″W. It belongs to Salí-Dulce River basin (Tucumán, Argentina) and is characterized by a seasonal rainfall regime. This basin is to the east of Cumbres Calchaquíes Range (4,500 m) and includes some important orographics systems as San Javier, Taficillo, Periquillo and Siambón hills. The maximum elevation basin ranges from 4,488 m in the northwestern to 408 m in the southeastern. The Yungas phytogeographical province covers almost all the basin area. This is a high species diversity ecoregion typical of the mountainous subtropical region, and it extends in Argentina between 22° and 28° of south latitude covering an area of approximately 3,900,000 ha (Brown 2000).

Climate

The relief is an important factor that influences the climate of Lrb. Basically there are two types (Minetti and Poblete 2003): Cwb, which corresponds to a mountainous climate, template and moist, with template summer and dry winter; and Cwa, template, warm and moist, with warm summer and dry winter. A statistical summary of meteorological data related to Lrb for the period 1961–1990 indicates that the average air minimum temperature is 12°C in July, and the maximum temperature is 25.5°C in January. The annual temperature value is 19°C. Rainfall data for the same period indicates that the precipitation occurs mainly during 5 months, from November to March, with an average maximum 226 mm in January. The minimum average value is in August, with 12 mm. The precipitation annual value is 1,141 mm (data recorded by "Obispo Colombres" experimental station of Tucumán). The rainfall regimes could be defined as predictable considering studies based on constancy and contingency (Fernández 2003).

Vegetation

The Lrb includes several vegetation belts: premontane subtropical forest between 350 and 600 m, characterized for cebil (*Anadenanthera macrocarpa*) and pacará (*Enterolobium contortisiliquum*) species. This forest once formed the natural vegetation and has now been completely replaced by sugarcane and citrus plantations (Hunzinger 1997). The subtropical montane forest is above 600 m (Yungas forest) and is characterized by highest rainfall and biodiversity (Brown and Grau 1993). Two other altitudinal levels can be recognized: between 600 and 1,000 m, tipa (*Tipuana tipu*) and laurel (*Phoebe porphyria*) forest occurs, and between 1,000 and 1,500 m, myrtaceous forest with species *Eugenia uniflora* and *Blepharocalyx gigantea* is dominant. Above 1,500 m, pine forest (*Podocarpus parlatorei*) and mountain alder (*Alnus acuminata*) are found. These last species form pure stands above 2,000 m up the timberline at 2,800 m in higher mountains (Hunzinger 1997). These altitudinal vegetation levels form the Yungas biogeographical province which ranges from Venezuela and Colombia to Tucumán province in Argentina (Brown and Grau 1993).

Geology

The Lrb shows a wide range of geologic units. The oldest ones are metamorphic basement rocks of low, medium and very low grade of metamorphism, mainly composed of metagreywackes and schists. According to their fossiliferous content, these rocks are Upper Precambrian–Lower Cambrian in age. The basement metamorphites are correlated to Puncoviscana Formation. At the southern part of the basin area, there are some granitoid emplacements. The lower paleozoic units were unconformably overlain by cretacic and tertiary sedimentary units, composed of conglomerates, sandstones, limestones, gypsum and calcareous levels. Modern deposits occupy the valleys and rivers beds at the same basin. They are integrated by conglomerates, sands, limes and clays (González et al. 2000).

Materials and methods

A topographic map of 1:250,000 scale was used as a base for the delineation of Lrb and sub-basins. The morphometric analysis was based on land-sat imageries on a 1:75,000 scale. The morphometrics parameters were divided in three categories: basic parameters, derived parameters and shape parameters. The data in the first category includes area, perimeter, basin length, stream order, stream length, maximum and minimum heights and slope. Those of the second category are bifurcation ratio, stream length ratio, RHO coefficient, stream frequency, drainage density, drainage texture, basin relief and relief ratio. The shape parameters are elongation ratio, circularity index and form factor. The drainage network of the basin was analysed as per Horton's (1945) laws and the stream ordering was made after Strahler (1964).

Results and discussion

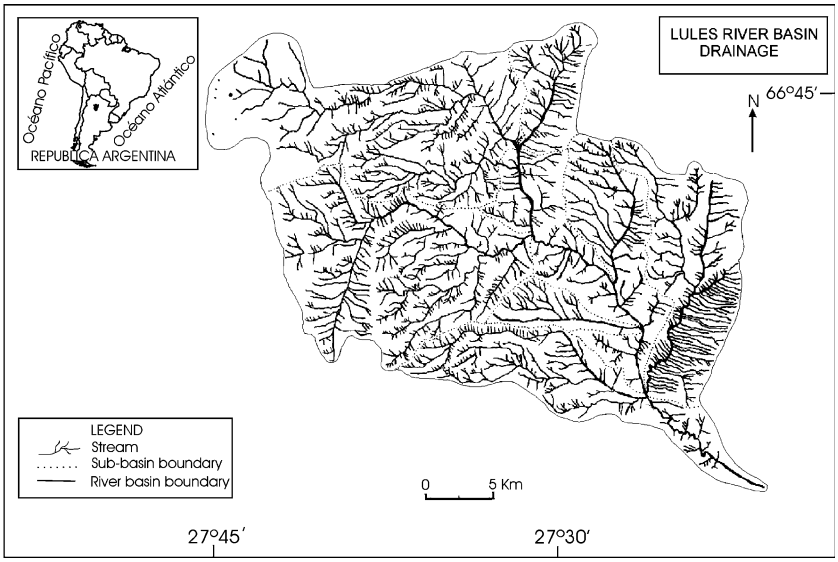
The total drainage area of Lrb was divided into seven sub-basins for the analysis (Fig. 1): Liquimayo (Ls), Hoyada (Hs), Ciénaga (Cs), De Las Tablas (Ts), Siambón (Ss), Potrerillo (Ps) and San Javier (Js).

Basic parameters

Area (A)

The entire area was considered between the divide line and the outfall with all sub- and inter-basin areas. The total drainage area of Lrb is 787 km^2, and the areas of each sub-basin are shown in Table 1. Ps is the smaller sub-basin ($A < 24$ km^2) and Ls is bigger than the others ($A > 200$ km^2).

Fig. 1 Drainage density of Lules River basin



Perimeter (P)

The perimeter is the total length of the drainage basin boundary. The perimeter of Lrb is 188 km, and the *P* of the seven sub-basins is shown in Table 1. Ls has the higher value ($P > 85$ km) and coincides with the higher value of *A*, while the perimeter of Ps is less ($P < 32$ km) than the other sub-basins.

Basin length (L)

The basin length corresponds to the maximum length of the basin and sub-basins measured parallel to the main drainage line. The basin length of Lrb is 54.97 km and the values of *L* for the seven sub-basins are shown in Table 1. Ls and Js are the longer sub-basins ($L > 20$ km) while Hs has the minimum value of *L* ($L < 11$ km).

Table 1 Basic parameters of Lules River basin

Basic parameters	Sub-basins							Basin
	Ls	Hs	Cs	Ts	Ss	Ps	Js	Lrb
A (km^2)	204.6	41.3	175.7	75.5	47.7	23.1	113.8	787
P (km)	85.17	35.78	67.32	47.48	32.42	31.32	66.8	188
L (km)	24.53	10.32	18.4	18.63	11.55	11.94	20.14	54.97
N1	1,520	378	1,562	607	237	113	708	5,699
N2	266	67	269	116	52	27	114	1,038
N3	60	18	45	26	12	6	27	214
N4	15	3	11	6	2	2	6	48
N5	4	1	2	2	1	1	2	12
N6	2	0	1	1	0	0	1	5
N7	0	0	0	0	0	0	0	1
Nt	1,867	467	1,890	758	304	149	858	7,016
L1 (km)	0.25	0.24	0.24	0.21	0.24	0.24	0.28	0.23
L2 (km)	0.54	0.67	0.56	0.43	0.55	0.70	0.79	0.57
L3 (km)	1.32	0.99	1.30	1.25	1.61	1.00	1.34	1.28
L4 (km)	2.98	3.47	3.79	3.15	3.63	3.45	2.95	3.14
L5 (km)	3.47	6.00	9.48	3.26	7.65	5.25	3.45	4.92
L6 (km)	4.42	0	4.20	10.50	0	0	8.62	6.43
L7 (km)	0	0	0	0	0	0	0	39
LT1 (km)	381.37	90.67	377.85	129.37	56.77	27.75	198.97	1,342.12
LT2 (km)	142.95	45.45	150.975	50.25	28.50	18.90	90.67	590
LT3 (km)	79.27	17.77	58.35	32.55	19.35	6.00	36.22	273
LT4 (km)	44.7	10.42	41.70	18.9	7.27	6.90	17.7	150.97
LT5 (km)	13.87	6.00	18.97	6.52	7.65	5.25	6.90	59
LT6 (km)	8.85	0	4.20	10.50	0	0	8.62	32.17
LT7 (km)	0	0	0	0	0	0	0	39
LT (km)	671.02	170.32	625.05	248.1	119.55	64.80	359.10	2,486.27
H (km)	4.719	2.760	4.376	3.138	2.090	2.100	1.541	4.488
h (km)	1.339	1.309	1.114	699	861	787	685	408

Stream order (Nu)

Stream order, or classification of streams based on the number and type of tributary junctions, has proven to be a useful indicator of stream size, discharge and drainage area (Strahler 1957). The number of streams (N) of each order (*u*) is presented in Table 1. The details of stream characteristics confirm Horton's first law (1945) "law of stream numbers" which state that the number of streams of different orders in a given drainage basin tends closely to approximate an inverse geometric ratio. This inverse geometric relationship is shown graphically in the form of a straight line when log values Nu are plotted on an ordinary graph (Fig. 2). Lrb is designated as a seventh order basin; Ls, Cs, Ts, Js are sixth order while Hs, Ss and Ps are fifth order sub-basins (Horton 1945; Strahler 1964).

Stream length (Lu)

The values of length (Lu) and total stream length (Lt) are shown in Table 1. The stream length characteristics of the sub-basins confirm Horton's second law (1945) "laws of stream length," which states that the average length of streams of each of the different orders in a drainage basin tends closely to approximate a direct geometric ratio. This geometric linear relationship is shown graphically when log values of these variables are plotted on an ordinary graph (Fig. 3). Most drainage networks show a linear relationship with a small deviation from a straight line (Chow 1964).

Maximum and minimum heights (H, h)

The maximum and minimum height corresponds to the highest and lowest point of the basin and sub-basins.

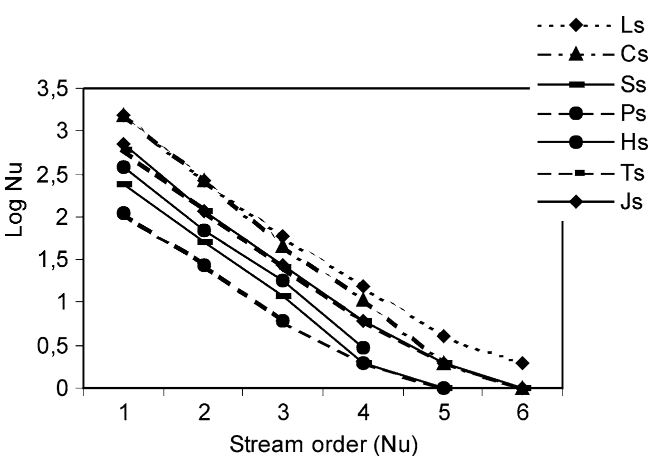


Fig. 2 Horton's first law using Lules River basin data

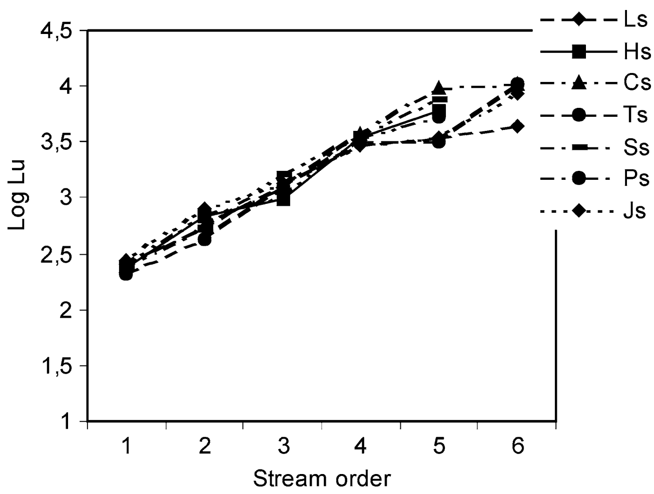


Fig. 3 Horton's second law using Lules River basin data

The maximum height of Lrb is 4,488 m in the northwestern sector, and the minimum height is 408 m in pedemontane zone (southeastern sector). The *H* and *h* values for the seven sub-basins are shown in Table 1.

Slope

The slope angle of a basin is a morphometrical factor of hydrological relevance. Steep slopes generally have high surface run-off values and low infiltration rates. Sediment production thus tends to be high except when largely barren slopes are concerned (Verstappen 1983). The basin slope was calculated applying the following formula:

$$\mathrm{Sb} = \frac{H - h}{L'}$$

where *H* and *h* are the maximum and minimum basin heights, respectively; and L' is the horizontal length of the basin.

The Lrb slope is 6°11′. This value is in relationship with the steep mountainous topography of the basin area.

Derived parameters

Bifurcation ratio (Rb)

This is an adimensional parameter that expresses the ratio of the number of streams of any given order (Nu) to the number in the next lower order (Nu + 1) (Horton 1945). Therefore, it is defined as:

$$\mathrm{Rb} = \frac{\mathrm{Nu}}{N(u+1)}$$

This is a very important parameter that expresses the degree of ramification of the drainage network. The Rb of Lrb is 4.37 and the values of the seven sub-basins vary from 3.4 to 4.7 (Table 2).

Stream length ratio (Rl)

The basin and sub-basins stream length ratios have been calculated by applying the following formula:

$$\mathrm{Rl} = \frac{\mathrm{Lu}}{\mathrm{Lu} - 1}$$

where Rl = stream length ratio, Lu = stream length order u and Lu-1 = stream segment length of the next lower order. Rl between successive streams orders varies due to differences in slope and topographic conditions, and has an important relationship with the surface flow discharge and erosional stage of the basin (Sreedevi et al. 2004).

The values of Rl for the seven sub-basins vary from 1.86 to 2.42, while the Rl of Lrb is 2.4 (Table 2).

RHO coefficient (RHO)

This parameter was defined by Horton (1945) as the ratio between the stream length ratio (Rl) and the bifurcation ratio (Rb):

$$\mathrm{RHO} = \frac{\mathrm{Rl}}{\mathrm{Rb}}$$

It is an important parameter that determines the relationship between the drainage density and the physiographic development of the basin, and allows the evaluation of the storage capacity of the drainage network (Horton 1945). It is influenced by climatic, geologic, biologic, geomorphologic and anthropogenic factors. The RHO of the basin and sub-basins varies from 0.45 to 0.68 (Table 2). Ps has the higher value (RHO > 0.67), so it will have higher hydric storage during flood periods and it attenuates the erosion effects during elevated discharge.

Stream frequency (Fs)

The stream frequency (Fs) was defined by Horton (1945) as the ratio between the total number of stream segments of all orders in a basin and the basin area:

$$\mathrm{Fs} = \frac{\sum \mathrm{Nu}}{A}$$

where $\sum \mathrm{Nu}$ = total number of stream segments of all orders, and A = basin area.

The Fs of the whole basin is 8.91 km^{-2}, while the Fs for the sub-basins are shown in Table 2.

Drainage density (Dd)

According to Horton (1945), the drainage density (Dd) is defined as the total length of streams per unit area

Table 2 Derived parameters of Lules River basin

Derived parameters	Sub-basins							Basin
	Ls	Hs	Cs	Ts	Ss	Ps	Js	Lrb
Rb 1	5.74	5.64	5.80	5.23	4.56	4.18	6.21	5.49
Rb 2	4.43	3.72	5.98	4.46	4.33	4.50	4.22	4.85
Rb 3	4.00	6.00	4.10	4.33	6.00	3.00	4.50	4.46
Rb 4	3.75	3.00	5.50	3.00	2.00	2.00	3.00	4.00
Rb 5	2.00	0	2.00	2.00	0	0	2.00	2.40
Rb 6	0	0	0	0	0	0	0	0
Rb	3.98	4.59	4.68	3.80	4.22	3.42	3.99	4.37
Rl 2-1	2.15	2.82	2.33	2.05	2.29	2.91	2.82	2.47
Rl 3-2	2.45	1.45	2.32	2.90	2.93	1.43	1.70	2.24
Rl 4-3	2.26	3.50	2.91	2.52	2.75	3.45	2.20	2.45
Rl 5-4	1.17	1.72	2.50	1.03	1.72	1.52	1.17	1.57
Rl 6-5	1.27	0	0.44	3.22	0	0	2.50	1.31
Rl 7-6	0	0	0	0	0	0	0	6.10
Rl	1.86	2.37	2.10	2.34	2.42	2.32	2.08	2.4
RHO	0.47	0.52	0.45	0.61	0.57	0.68	0.52	0.55
Fs (km^{-2})	9.12	11.3	10.76	10.04	6.37	6.45	7.54	8.91
Dd (km^{-1})	3.28	4.12	3.56	3.29	2.51	2.80	3.15	3.16
T (km^{-1})	29.91	46.55	38.30	33.03	15.99	18.06	23.75	28.15
R (m)	3,380	1,451	3,262	2,439	1,229	1,313	856	4,080
Rr (m km^{-1})	137.80	140.60	177.28	130.92	106.41	109.96	42.50	74.22

divided by the area of drainage basin. It is expressed as:

$$\mathrm{Dd} = \frac{\sum \mathrm{Lt}}{A}$$

where Lt = total length of all the ordered streams, and A = area of the basin.

Dd is a measure of the degree of fluvial dissection and is influenced by numerous factors, among which resistance to erosion of rocks, infiltration capacity of the land and climatic conditions rank high (Verstappen 1983).

The Dd of Lrb is 3.16 while those of the seven sub-basins are shown in Table 2.

Drainage texture (T)

The drainage texture (T) is an expression of the relative channel spacing in a fluvial dissected terrain. It depends upon a number of natural factors such as climate, rainfall, vegetation, rock and soil type, infiltration capacity, relief and stage of development of a basin (Smith 1950). It can be expressed by the equation (Smith 1950):

$$T = \mathrm{Dd} \times \mathrm{Fs}$$

where Dd = drainage density, and Fs = stream frequency.

The value of T for the basin and the seven sub-basins are shown in Table 2.

Basin relief (R)

Basin relief is the difference in elevation between the highest and the lowest point of the basin:

$$R = H - h$$

The R controls the stream gradient and therefore influences floods patterns and the amount of sediment that can be transported (Hadley and Schumm 1961).

The relief of Lrb is 4,080 m and the seven sub-basins are shown in Table 2. The Lrb and the sub-basins have high values of R due to physiographic mountainous structure of the area.

Relief ratio (Rr)

Schumm (1963) exposed that Rr is the dimensionless height–length ratio between the basin relief (R) and the basin length (L):

$$\mathrm{Rr} = \frac{R}{L}$$

The Rr of Lrb is 74.22, while those of the seven sub-basins are shown in Table 2. The values of Rr of the basin as well as the sub-basins are high due to the presence of resistant rocks in the area.

Shape parameters

Elongation ratio (Re)

Elongation ratio (Re) was defined for Schumm (1956) as the ratio between the diameter of a circle of the same area as the basin (D) and basin length (L). The Re is calculated by using the following formula:

$$\mathrm{Re} = \frac{\mathrm{D}}{\mathrm{L}} = 1.128\frac{\sqrt{\mathrm{A}}}{\mathrm{L}}$$

where A = area of the basin, L = basin length, and 1.128 is a constant.

The Re of Lrb is 0.57, while those of the seven sub-basins are shown in Table 3. All of those values are indicative of elongated shapes.

Circularity index (Rc)

The circularity ratio (Miller 1953; Strahler 1964) is expressed as the ratio of the basin area (A) and the area of a circle with the same perimeter as that of the basin (P):

$$\mathrm{Rc} = \frac{4\pi A}{P^2}$$

where Rc = basin circularity, P = basin perimeter, A = area of the basin and 4 is a constant.

The Rc of Lrb is 0.28, while those of the seven sub-basins are shown in Table 3. Those values are indicative of the lack of circularity.

Table 3 Shape parameters of Lules River basin

Shape parameters	Sub-basins							Basin
	Ls	Hs	Cs	Ts	Ss	Ps	Js	Lrb
Re	0.66	0.70	0.81	0.53	0.67	0.45	0.60	0.57
Rc	0.35	0.40	0.49	0.42	0.57	0.29	0.32	0.28
Ff	0.34	0.39	0.52	0.22	0.36	0.16	0.28	0.26

Form factor (Ff)

Horton (1945) proposed this parameter to predict the flow intensity of a basin of a defined area. The Ff of a drainage basin is expressed as the ratio between the area of the basin (A) and the squared of the basin length (L^2). Therefore, the Ff is expressed as:

$$\mathrm{Ff} = \frac{A}{L^2}$$

The Ff of Lrb is 0.26, while those of the seven sub-basins are shown in Table 3. The index of Ff shows the inverse relationship with the square of the axial length and as a direct relationship with peak discharge (Gregory and Walling 1973).

Conclusion

The stream ordering system of Lrb reveals a high hierarchization and high degree of ramification of the watershed (Horton 1945). Lower order streams mostly dominate the basin. The drainage network of the watershed is effective to provide a sufficient superficial draining with a high number of streams of low order that flow directly in the principal collector or in upper order streams.

Rb for the basin and sub-basins are the expected values relative to mountainous or highly dissected areas (Horton 1945). The mean Rb (4.37) indicates that the drainage pattern is not much influenced by geological structures (Strahler 1964). This value also is in relationship with the elongate shape of the basin (Schumm 1956).

The development of stream segments is affected by slope and local relief (Strahler 1964). Those factors produce differences in values of Dd among the sub-basins. The physiographic structure of the basin area produces high surface run-off values and low infiltration rates. The high proportion and velocity of the overland flow easily leads to sheet, rill and gully erosion, and a high amount of sediment can be transported. The Dd of the basin exhibit that the general nature of rocks is impermeable. The general pattern of the sub-basins is dendritic and one sub-basin has a parallel pattern (Js). The shape parameters also reveal the elongation of the basin and sub-basins. Due to this characteristic, the units will tend to have smaller flood peaks but longer lasting floodflows compared to a round basin (Gregory and Walling 1973). This particularity is very important considering the management objective in the basin (reservoir project) and a progressive land use pressures (Fernández et al. 2002; Fernández and Molineri 2006).

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