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Evaluation of two hydropower plants in Brazil: using emergy for exploring regional possibilities

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A B S T R A C T

Two Brazilian hydropower plants (Jupiá and Porto Primavera) located in the same watershed were explored in terms of the global resources needed to support these enterprises using a donor-side approach. Emergy theory and methods although commonly used by environmental scientists, may seem difficult to interpret for policy and decision-makers. Because of this, the possibility of transforming emergy flows and indices into money and area measures is explored in the present paper. Both hydropower plants deliver the same power and rely on practically the same infrastructure but involve very different flooded areas. Indirect areas calculated in terms of emergy show the different spatial distribution of resources. Some realistic alternatives for development were explored from both environmental and economic perspectives by using the emergy investment ratio and taking into account the matching between the enterprises emergy flows and the regional ones.

1. Introduction

Diverse aspects of emergy accounting in the production of hydroelectricity have been addressed in previous works. The first approach, which we considered as the more traditional emergy accounting form, identified and quantified all the inputs (defined as all the necessary resources required to construct the infrastructure and keep the hydroelectric plant in operation), in order to obtain the total emergy required to generate electricity via a hydroelectric plant. This former approach was adopted by some authors (Ulgiati and Brown, 2002; Brown and Ulgiati, 2004; Zhang et al., 2014). The emergy of the main product, electricity, is calculated through the addition of the emergy flows of all the inputs considered (without double counting). The transformity of the hydroelectric-generated electricity for the studied plants is calculated by dividing the sum of the emergy flows related to all inputs by the energy (expressed in J) generated.

The second approach focused on the benefits (not only electricity but also others) and costs in emergy terms derived from the hydroelectric plant construction and operation. In this way, benefits and impacts as a consequence of the construction of the dam are identified and quantified (Brown and McClanahan, 1996; Kang and Park, 2002; Cui et al., 2011; Pang et al., 2015). Not only the main product of the enterprise is taken into account but also those indirectly generated as a consequence. Brown and McClanahan (1996) concluded that the loss of sediment was the largest impact while among the benefits, electricity production was the largest followed by irrigation. Within this approach the transformity of hydroelectric-generated electricity is assumed from the literature. Always in emergy accounting, but especially when working under this approach, the system's frame must be well defined in order to clearly establish the extent of positive and externalities considered. In addition, the concept of benefits or cost is plausible of different "readings" according to the expertise of the analyst, pressure of the stakeholders' profile and interests, or subjective economic interests.

In general, benefits include: economic returns, social benefits (employment generation), service of regulating the river flow thus preventing dangerous situations downstream (floods or water shortage), water supply, recreation and fisheries (Von Sperling, 2012). As negative impacts: social disruption, sediment

Abbreviations: DA, direct area; ED, empower density; EIR, emergy investment ratio; EIR_{SP}, emergy investment ratio of São Paulo State; ELR, environmental loading ratio; $Empd_R$, renewable empower density of the region; EMR, emergy per money ratio; Em*R$*, Em real; ESI, emergy sustainability index; EYR, emergy yield ratio; F, purchased resources; HP, hydro power plant; I_j, environmental resources; IA_F, purchased indirect area; IA_N, non-renewable indirect area; N, non-renewable resources; PP, Porto Primavera; R, renewable resources; Y, total emergy requirement.

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deposition, siltation, loss of genetic patrimony, climatic alteration and emission of greenhouse gases, are considered among others (Von Sperling, 2012). The inclusion of one or others of these costs and benefits into the emergy accounting depends on the extent of the system.

Although emergy accounting is today much more adopted as a useful and accurate methodology to access the global use of resources and evaluate environmental impact, a fact evidenced by the huge number of scientific papers published in the last ten years, it may be considered inaccessible for the uninitiated. This fact creates barriers for a straightforward language among researchers, government, policy makers, and the population as a whole. In order to solve that limitation, the translation of emergy terms to more accessible concepts as money and area (Odum, 1996), make the concept more understandable for managers, stakeholders and decision-makers. The latter approach was also explored by some authors to evaluate hydropower through the emergy theory. The topic was explored in terms of an emergy-modified ecological footprint (He, 2012) and in terms of support area (Ulgiati and Brown, 2002).

In the present paper two aspects will be approached since the resource water can be considered from two points of view, not necessarily divergent; its capacity for generating electricity due to potential energy and its intrinsic value since water is a vital natural resource for the survival of humans and ecosystems. Water reservoirs not only represent the capacity of water to store energy but also represent the confinement of the resource, a fact that might lead to the lack of this resource in more deprived regions. The decision of the most important or urgent use of water and its allocation is not trivial and requires a global vision in order to avoid controversial or subjective visions and prioritize objectively the real necessities. Its condition of provider of eco-services should demand a resource management system that assures an adequate and sustainable supply and avoids the deterioration of water ecosystems. In the present paper we treat the duality of water functions as a hydroelectric power source and as an irreplaceable resource in an integrated way.

Emergy accounting enables this interdisciplinary approach to handle the two cited aspects of water and establish a scientific decision-making frame as well as collaborate to develop policy for regional development-planning.

The aim of the present paper is to explore the use of emergy theory and methods to help in the decision-making of water management taking into account the "dual" role of water. For this purpose two hydroelectric plants located in Brazil were studied, one considered as a traditional hydro plant and the other with a smaller reservoir, considered as a Run-of-River with Modified Peaking hydro plant. The traditional emergetic indices were calculated as well as the indirect areas, related to purchased and non-renewable resources. Some alternatives for development in order to attain more sustainable designs were evaluated in terms of the emergy investment ratio (EIR) and by means of the concept of matching energy qualities (Odum, 1996).

2. Materials and methods

2.1. Emergy environmental accounting

Emergy accounting (Odum, 1996), a methodology based on thermodynamics, systems theory and ecology, was developed to account for all the global resources used to accomplish a process, product or service in a common basis as solar energy. It has turned into a scientific sustained tool to help environmental policy and decision-makers.

Since only a brief assessment will be provided here, the reader may refer to other literature (Odum, 1996; Odum et al., 2000).

Solar Emergy is defined as the available solar energy used up directly or indirectly to make a service or product. Its unit is the solar energy joules (sej).

The inputs flows are classified in three categories of resources: R, as renewable resources, N as non-renewable resources and F, coming from the economy (Odum, 1996). The resources contained within the former two categories are provided by the environment and are economically free. The outputs may include products, services and also emissions that are released to the environment. The total emergy requirement, Y is defined as $Y = R + N + F$. the sum of all the independent flows that enter the system.

Evaluation starts with energy systems diagramming, and for doing so, it is necessary to define the boundary of the system as well as the internal components and external sources. Specific symbols are used, where each have energetic and mathematical meanings (Odum, 1996).

Operationally, each input that enters the system has to be quantified and the raw data expressed in compatible units with the transformation factors that will convert, via multiplication, the raw data flows into emergy flows. The transformation factors include solar transformity (the solar energy required to make 1 J of a service or product), solar emergy per mass unit and emergy per money ratio (EMR).

The identification of the flows by the emergy environmental accounting enables the calculation of emergy indices. Only a brief description of the indices is provided here but complete information can be found elsewhere (Odum, 1996; Brown and Ulgiati, 1997). The emergy yield ratio, EYR, is the ratio of the emergy of the output (Y), divided by the emergy of purchased inputs (F). The emergy yield ratio, EYR, is a measure of the ability of a process to exploit and make available local resources by investing outside resources. It provides a measure of the appropriation of local resources by a process, which can be read as a potential additional contribution to the larger economy, gained by investing resources already available (Raugei et al., 2005).

The investment ratio, EIR, is the ratio of purchased inputs (F) to all emergy fluxes derived from local free resources $(R + N)$.

The environmental loading ratio, ELR, is the ratio of non-renewable (local and purchased) to renewable emergy flows. The higher this ratio, the bigger the distance of the technological development from the natural process that could have developed locally. In this sense, we can say that the ELR is a measure of the load on the environment.

The emergy sustainability index, ESI aggregates the measure of yield and environmental loading indices $(ESI = EYR/ELR)$.

The empower density of the enterprise $ED = (R + N + F)/\text{area}$, is the emergy per unit time per unit area and is a measure of activity.

The methodology enables us to convert resource use evaluated in emergy terms into the area demanded to supply those resources. When it is assumed that all the purchased requirements for the enterprise could be substituted by the local renewable resources of the region (Geber and Björklund, 2001), the "indirect area" is expressed as: $IA_F = F/Empd_R$; where $Empd_R$ is the renewable empower density of the region (sej km^{-2} yr^{-1}). According to Geber and Björklund (2001), this allows comparison of the direct and the indirect area demand, the direct area being that area directly occupied by the hydroelectric plants and reservoirs. As in Geber and Björklund (2001), the renewable larger input to the region was the contribution from rain.

Additionally, another indirect area, expressed as $IA_N = N/Empd_R$, is presented here and comparison among the three indices performed to explore to what extent space could substitute for purchased and non-renewable inputs required for hydropower generation. It is thought that the last indirect area could evidence the dual characteristics of hydropower generation, since although systems operation relies on direct use of potential energy of the water stream (a renewable resource), also it implies the degradation and disturbance of areas responsible for eco-services supply.

The evaluation of alternatives for development was performed through exploring the EIR index of potential enterprises and comparing with the regional value (EIR_{SP}, where SP is São Paulo state). For this purpose, some situations were considered, as follows: the original situation before dam construction with subsistence livestock; the actual system; the alternative whose purchased inputs match the attraction value of the region; the alternative that assumes the same purchased inputs as the actual; and the situation when the major environmental flow available was exploited (the chemical potential energy of water) by means of market feedback.

2.2. Study area

The two hydroelectric plants are located along the Paraná River, in the Paraná Basin, specifically in the Upper Paraná River that includes approximately the first third of the river, and lies completely within Brazilian territory. The basin has the largest hydroelectrical power potential of the country. The Upper Paraná River Basin covers an area of 572,480 km^2. The climate in the Upper Paraná region is tropical/sub-tropical. The Eng. Souza Dias plant, known as Jupiá plant, began its construction in 1961, was inaugurated in 1969 and concluded in 1974. The Eng. Sergio Motta plant, known as Porto Primavera (PP), was initiated in 1978, and began to operate in 1998.

The Jupiá plant is classified as Run-of-River with Modified Peaking due to the small reservoir dimension. It can supply 1550.2 MW with a reservoir of 330 km^2. PP plant, a typical impoundment plant, has a reservoir of 2250 km^2 and can provide 1540 MW. The original area before flooding was covered by cerrado biome and natural pasture and by rainforest biome and natural pasture, respectively. Both of them have 14 Kaplan-type turbines in operation and belong to CESP (Companhia Energética de São Paulo).

2.3. Calculation considerations

In order to carry out emergy flux determination, the planetary baseline of 15.83E+24 sej/year was adopted (Odum et al., 2000).

The river flow was not entirely considered in order to calculate the potential energy, but only the portion of the flow that effectively generated electricity by passing through the turbines.

Since evidences of drastic changes in salinity, sediment content and water temperature of downstream rivers were related as a consequence of dam construction (Molisani et al., 2006; Manyari and de Carvalho, 2007), the chemical energy of the river water is compromised. For this reason, we considered sediment retention, while chemical energy changes downstream were not considered in the calculation, neither were other downstream effects. The main portion of sediments consists in clay minerals; the content of organic matter was considered in calculations.

The use of land in the Parana Basin had already strong anthropogenic influence some decades ago. In order to do calculations, the presence of native biomes was considered for the 20% of the area previous to flooding, whereas the other 80% was considered as natural pastures. These considerations are compatible with information on land use cited on the IBGE (Brazilian Institute of Geography and Statistics) in 1995 (Souza, 2005).

The values for evaporation of the reservoirs are extracted from ONS (Operador Nacional do Sistema Elétrico or “Electric System National Operator”) data (ONS, 2004). Although data are previous to the time frame selected for the study, the database has not been updated by the ONS.

The emergy in services is calculated from the emergy money ratio of São Paulo state (Cutrim Demetrio, 2011), expressing flows in the monetary unit of Brazil, the real (*R$*). The EIR_{SP} value was adopted from Cutrim Demetrio (2011).

3. Results and discussion

3.1. Global resources involved in hydroelectricity production

The diagram in Fig. 1 displays the main inputs that cross the system's boundaries to enable the hydropower plants to be constructed and to operate. According to Emergy theory, inputs were classified in R, N and F. Among the renewable flows, rain on the reservoir and the potential energy of the river were accounted for. The N resources include loss of sediments that are usually carried by the river downstream, loss of soil and loss of biomass from native forest and grassland due to the flooded area. The F resources include the flows necessary to construct and to operate. Both calculation with and without services are presented in the text.

Tables 1 and 2 show the emergy flows that support the hydropower plants, the total emergy, the percentage of each resource and the transformity obtained through the present evaluation, for Jupiá and PP plants, respectively.

Renewable inputs account for the main portion of the total emergy flow, representing 83.8% and 63.0% of the total, respectively for Jupiá and PP. On the other hand, the contribution of potential energy due to the river does not differ since river flow and elevation are almost the same. On the contrary, since the reservoir areas are quite different, the PP reservoir being almost 7 times bigger than Jupiá, the rain contribution matches the difference in reservoir area. Fertile soil loss is the main emergy percentage contribution for non-renewable resources for both systems, also reflecting the reservoir area differences (3.2% versus 13.4%). Loss of biomass due to flooded area is the second item for both systems, although presenting different values (2.8% and 12.7%, respectively) due to reservoir area differences. Evaporation is negligible in terms of emergy percentage for Jupiá but it represents 4.4% for PP. The absolute value of evaporation is more than twice greater than the greater N resources for Jupiá. Purchased inputs represent 8.5% and 6.5% respectively. Operation and maintenance is the main flow for the Jupiá plant and concrete for PP plant. The total annual emergy that supports the systems was calculated and is shown on the bottom of Tables 1 and 2, where the value corresponding to PP is 1.6 times the value of Jupiá. Transformity values calculated were 5.04E+04 sej/J and 8.28E+04 sej/J, for the Jupiá and PP plants, respectively. Values are comparable to that presented for a hydropower plant delivering 85 MW, 6.23E+04 sej/J, also with services included (Brown and Ulgiati, 2002). It is important to notice that the last value was calculated with another baseline, and as a result, it should be multiplied by 1.68 (1.04E+05 sej/J) in order to be properly compared. The value of 1.03E+05 sej/J was calculated by Zhang et al. (2014) but for smaller hydropower plant (8 MW).

3.2. Traditional emergy indices

Table 3 displays the values of the emergy indices with and without considering services paid in Brazilian money, R$.

When services are not included in the calculations, F inputs are slightly decreased and the alteration is reflected in the indices values. In the cases under study, characterized by a great inflow of renewable resources, as well as in other cases with the same characteristics, EYR can be interpreted as a “measure of the power plant contribution to the economy beyond its own operation” (Odum, 1996). The high values of EYR reflect the fact that natural sources, generated by previous steps in time, are

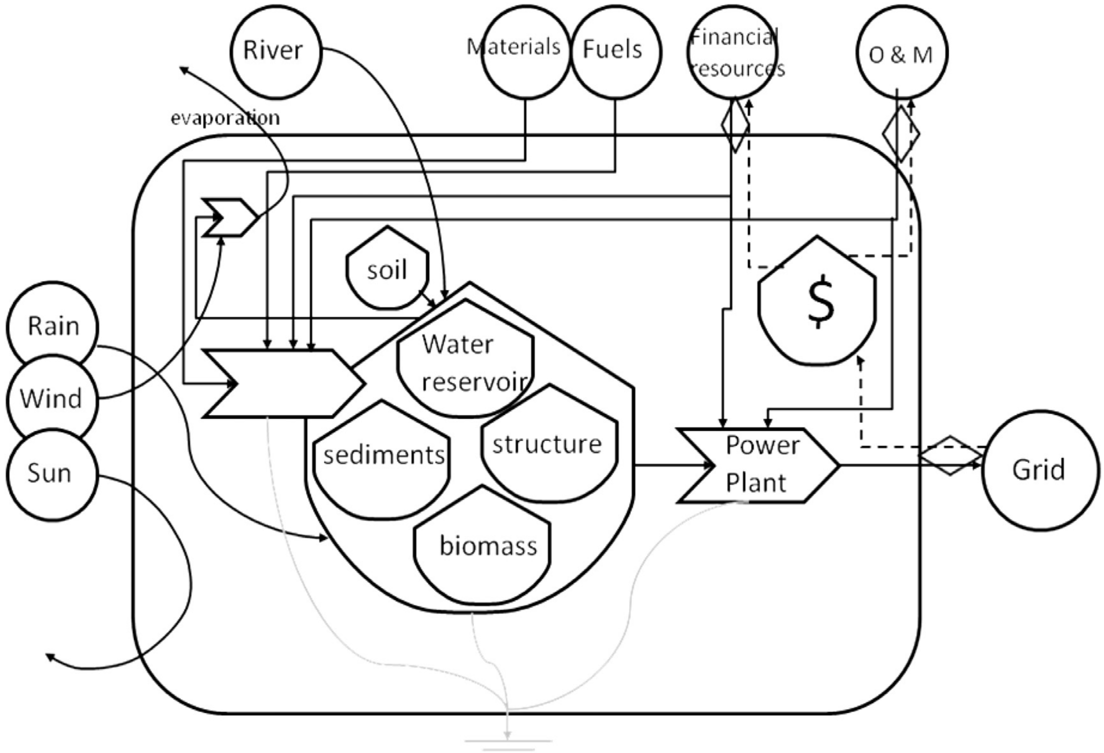

Fig. 1. A conceptual Energy Systems Language diagram of the hydropower generation for Jupiá and Porto Primavera plants (O & M-operation and maintenance).

exploited by a small input from the economy. Values of 10 (Odum, 1996) and 7.65 (Brown and Ulgiati, 2002) are cited in literature for hydropower plants. A value of 22.45 was calculated by Fang and Chen (2014) for a HP plant in China with a capacity of 1500 MW. Even so, the direct comparison of the results is not possible and should be avoided, since calculation considerations made by every group of authors are different. It is important to notice that although at a rapid glance high values of EYR seem to reflect the best situation, this is only true when natural resources involved are in fact, renewable. A deep and complete discussion is found in Raugei et al. (2005). Since potential energy delivered by the elevated water of the river and rain falling on the plant site, can be considered as renewable and continuously assured unless a serious problem occurs upstream, we can affirm that higher values of EYR reflect better situations of system behavior. Although both hydroelectric plants could be considered good examples in terms of EYR, differences between their values rely on different reservoir areas. Purposely, two hydropower plants

Table 1
Emergy annual evaluation of the Jupiá hydropower plant for construction and operation. The area considered (330 km^2) includes the water reservoir.

Item number	Item	Unit	Data (units/year)	Emergy/uni. (sej/unit)	Ref. Emergy/unit	Emergy (sej/year)	% (sej/sej)
	Renewable (R)						
1	Sun	J	2.05E+18	1.00E+00	(1)	2.05E+18	–
2	Rain, Chemical potential*	J	2.96E+15	3.12E+04	(1)	9.23E+19	3.8
3	River Geopotential*	J	4.23E+16	4.66E+04	(2)	1.97E+21	80.0
	Non-renewable (N)						
4	Fertile soil loss	J	6.40E+14	1.24E+05	(3)	7.94E+19	3.2
5a	*Cerrado loss*	J	1.59E+15	1.26E+04	(4)	2.00E+19	<1
5b	*Natural pasture loss*	J	2.81E+15	1.77E+04	(4)	4.98E+19	2.0
5	*Vegetation loss:*					6.98E+19	2.8
6	Sediments loss*	J	4.12E+12	1.06E+05	(2)	4.36E+17	<1
7	Evaporation*	m^3	1.72.E+08	2.44E+11	(5)	4.19E+19	1.7
	Purchased (F)						
8	Financial resources	*R$*	5.46E+07	0.93E+12	(6)	5.08E+19	2.1
9	Operation and maintenance	*R$*	8.15E+07	0.93E+12	(6)	7.58E+19	3.1
10	Structural steel*	kg	3.25E+08	6.97E+12	(7)	2.26E+19	<1%
11	Concrete	kg	3.25E+07	1.81E+12	(8)	5.88E+19	2.4
12	Fuel during implantation	J	9.82E+12	1.13E+05	(9)	1.11E+18	<1
	Total emergy					2.46E+21	100
	Electricity production	J	4.89E+16	***5.04E+04***		2.46E+21	

The bold entry corresponds to the result extracted from the table.
(1) Odum, 1996; (2) Brown and McClanahan, 1996; (3) Odum et al., 2000; (4) Pereira, 2008; (5) Buenfil, 2001; (6) Cutrim Demetrio, 2011; (7) Brown and Buranakarn, 2003; (8) Pulselli et al., 2007; (9) Bastianoni et al., 2005. The emergy/unit values marked with * were corrected to be expressed on the adopted baseline.

Table 2
Emergy annual evaluation of the PP hydropower plant for construction and operation. The area considered (2250 km^2) includes the water reservoir.

Item number	Item	Unit	Data (units/year)	Emergy/unit (sej/unit)	Ref. Emergy/unit	Emergy (sej/year)	% (sej/sej)
	Renewable (R)						
1	Sun	J	1.41E+19	1.00E+00	(1)	1.41E+19	–
2	Rain, chemical potential*	J	1.97E+16	3.12E+04	(1)	6.15E+20	15.3
3	River geopotential*	J	4.13E+16	4.66E+04	(2)	1.92E+21	47.7
	Non-renewable (N)						
4	Fertile soil loss	J	4.36E+15	1.24E+05	(3)	5.41E+20	13.4
5a	*Rainforest loss*	J	1.27E+16	1.33E+04	(4)	1.69E+20	4.2
5b	*Natural pasture loss*	J	1.92E+16	1.77E+04	(4)	3.40E+20	8.5
5	*Vegetation loss:*					5.09E+20	12.7
6	Sediments loss*	J	5.50E+12	1.06E+05	(2)	5.82E+17	<1
7	Evaporation*	m^3	7.29E+08	2.44E+11	(5)	1.78E+20	4.4
	Purchased (F)						
8	Financial resources	*R$*	5.42E+07	0.93E+12	(6)	5.04E+19	1.3
9	Operation and maintenance	*R$*	8.09E+07	0.93E+12	(6)	7.52E+19	1.9
10	Structural steel*	kg	5.30E+06	6.97E+12	(7)	3.69E+19	<1
11	Concrete	kg	5.30E+09	1.81E+12	(8)	9.59E+19	2.4
12	Fuel during implantation	J	3.55E+13	1.13E+05	(9)	4.00E+18	<1
	Total emergy					4.03E+21	100%
	Electricity production	J	4.86E+16	***8.28E+04***		4.03E+21	

The bold entry corresponds to the result extracted from the table.
(1) Odum, 1996 (2) Brown and McClanahan, 1996 (3) Odum et al., 2000 (4) Pereira, 2008 (5) Buenfil, 2001 (6) Cutrim Demetrio, 2011 (7) Brown and Buranakarn, 2003 (8) Pulselli et al., 2007 (9) Bastianoni et al., 2005. The emergy/unit values marked with * were corrected to be expressed on the adopted baseline.

Table 3
Total emergy flow, emergy flows discriminated by resource type and emergy indices for hydroelectricity generation of Jupiá and PP plants, with and without considering services paid in money.

	Jupiá plant	Jupiá plant (without services)	Porto Primavera plant	Porto Primavera plant (without services)
Supporting emergy (sej/year)	2.46E+21	2.34E+21	4.03E+21	3.90E+21
R resources (sej/year)	2.06E+21	2.06E+21	2.54E+21	2.54E+21
N resources (sej/year)	1.92E+20	1.92E+20	1.230E+21	1.23E+21
F resources (sej/year)	2.09E+20	8.25E+19	2.62E+20	1.37E+20
% Renewability (sej/sej)	82.7	88.3	63.0	65.0
EYR	11.8	28.3	15.3	28.5
EIR	0.09	0.04	0.07	0.04
ELR	0.19	0.13	0.59	0.54
ESI	60.6	213.1	26.1	52.9
ED (sej/year m^2)	7.5E+12	7.1E+12	1.8E+12	1.7E+12

with similar values of delivered power and construction infrastructure were selected in order to put in evidence the weight of flooded area. Emergy methodology seems to be sensitive to that.

By referring to the EIR it is useful to remember that it can be expressed as 1/(EYR-1). The denominator makes explicit how much the value of EYR deviates from unity, that is it shows the weight of natural resources exploited to the total emergy flow. Thus, small values of the index evidence great appropriation of natural resources with little injection from economy. PP plant presents lower values of EIR, suggesting a better investment for the economy. But since EIR does not discriminate R or N natural inputs in, a higher value of natural resources involved is not synonymous with "good" investment in the long run in holistic terms.

In this way, it is advisable to use all the indices in a complementary way to compose the complete evaluation. ELR shows the opposite trend, Jupiáś values are slightly smaller than PP. Even so, all the values, with and without services for both the plants are less than 2 considered as the superior limit for low impact according to Brown and Ulgiati (1997). The same value of 0.19 was related for the Manwan HP (1500 MW) (Fang and Chen, 2014). Values corresponding to PP plant are quite similar to the value presented in Brown and Ulgiati (2002) for a hydropower plant.

The ESI is the ratio of the emergy yield per environmental load. Table 3 shows that Jupiá performance is preferable in terms of ESI than PP plant performance (more than twice as high when services are considered, 4 times higher without services). The influence of services on the ESI value is greater for the Jupiá plant. Even so, both plants are considered as being sustainable in the long run according to the range of ESI values (Brown and Ulgiati, 1997). But in the same way as with EYR, the concept of good performance in sustainable terms is subject to the supply of real renewable inputs. The values of the indices, as already discussed elsewhere reflect a picture of the systems and the establishment of short, medium or long-run sustainable behavior is associated with the capacity of the environment to keep supplying the necessary resources to the systems (Bonilla et al., 2010).

ED values when services are considered and when not, are almost 4 times higher for Jupiá than for PP plant. Global resources that sustained electricity generation are more spatially concentrated for Jupiá.

It is noticeable that N flows for PP account for 6.5 times the N inputs of the Jupiá plant. Since the reservoir area of PP is almost 7 times that of Jupiá, it is evident that the N flows with higher contributions are those that are dependent on area.

3.3. Indirect areas

If it is assumed that the whole purchased demand is derived from renewable resources supplied by region empower, the calculated "indirect area", the IA_F will act as a sustainability predictor of long term sustainability. It represents the area required to provide the total emergy requirements to support economic development provided all the inputs were renewable and compatible with the local capacity of supply. As in Geber and Björklund (2001), the renewable empower density of each region was calculated from rain contribution in terms of chemical potential. For the Jupiá area, precipitation was considered as 1815.5 mm/year and 1779.5 mm/year for PP (values adopted for all calculations on the present paper).

Table 4 shows the values of direct and indirect areas, for both Jupiá and PP when services are considered and disregarded.

The trend of behavior observed for IA_F and IA_N for each case is completely different as a consequence of the spatially profile distribution of F and N for each plant.

In this way, IA_N is almost twice the direct area for either Jupiá or PP. The trend of IA_F is not constant and varies according the plant. For instance, it is smaller than the DA for the Jupiá plant when services are disregarded. In contrast, IA_F values are greater than DA for PP, and for Jupiá when services are considered.

The difference relies on the spatially uniform distribution of N whereas F is practically independent of the area occupied by the hydropower plant. Since the inputs that present more weight among the N ones are those that depend on reservoir dimension, non-renewable emergy flow is almost homogeneously distributed across the reservoir area. That means, N flow is almost proportional to flooded area.

3.4. Discussing alternative options for development

Odum (1996) developed the concepts of emergy-matching relating them to the concepts of limiting factors in production systems. He affirmed that self-organizing processes, also including anthropogenic ones, tend to develop designs in order to avoid being subjected to limiting factors. That means, matching emergy inflows to production is equivalent to balancing potentially limiting factors (Odum, 1996). He concluded that the intensity of production that will be sustainable is that whose EIR tends to be that of the region. If the feedback from economy is lower than those that match the regional EIR, the producer will get more from environment and has to purchase less. He will capture the market but on the other side, the area may not be able to maintain that pattern since the potential for economic growth is large and more intensive systems will displace the less intensive (Odum, 1996).

For comparing alternatives, some realistic options were selected (see Fig. 2).

Fig. 2 displays the actual case and the comparison to four situations in terms of emergy inflows of environment resources (expressed as I_j, that correspond to the sum R + N), economic feedback (expressed as F_j), and the whole emergy flow Y_j, that support the enterprise. The proposed alternatives to be analyzed are: i) system **1**, the "original" system (before dams construction), mainly considered as a system of subsistence based on livestock; ii) the "actual" system, expressed as HP plant with its own distribution of resources R + N and F; iii) system **2**, considered as a "potential" investment, which operates by using all the same natural resources (in quantity and distribution) as the "actual" system but using F resources that equal the attraction value (that means that matches the EIR of the region); iv) system **3**, considered as an "alternative" investment, which operates being supported by the same quantity of F flow as the "actual" but with (R + N) flow that matches the EIR_{SP}. Also, another option was analyzed in terms of EIR matching, v) system **4**, that considered the chemical energy of the reservoir water as the main renewable contribution from the environment to attract the alternative investment (calculation in the Appendix), with F resources that match with the EIR_{SP}. The last investment proposed (system **4**) would be any that take advantage of the water quality in terms of its chemical properties, which means, its capacity to dissolve solids.

Table 5 shows all the results in order to enable comparison.

i) System **1** corresponds to the situation before dam construction. Emergy flow at that moment accounted for rain and natural grassland (from Tables 1 and 2, for Jupiá and PP areas, respectively), that enabled subsistence through raising livestock.

For Jupiá, being Y_1 = 1.42E+20 sej/year, and dividing by the EMR_{SP} value, the annual contribution of that situation to regional economy was 153E+06 Em*R$*. For PP, contribution was 1027E+06 Em*R$*. The difference is accounted for the greater size of PP's reservoir.

ii) The actual system developed the area by dam construction in order to generate electricity. The total annual emergy flow (expressed as I_2 + F_1 in Fig. 2) represents (from HYPERLINKTables 1 and 2 and then divided by EMR_{SP} value) 2511E+06 and 4201E+06 Em*R$*, for Jupiá and PP.

iii) System **2** would be supported by the same flow of environmental resources I_2, but with a feedback from the economy that matches the regional attraction value.

For Jupiá, feedback accounts for $I_2 \times EIR_{SP}$ = 1.64E+21sej/year, and Y_2 = 3.89E+21 sej/year, that is equivalent to 4185E+06 Em*R$*.

For PP, feedback accounts for $I_2 \times EIR_{SP}$ = 2.75E+21sej/year, and Y_2 = 6.52E+21 sej/year, that is equivalent to 7013E+06 Em*R$*. Both alternatives present a higher contribution from the economy and generate a flow of emergy and Em-money 1.6 times higher than the hydroelectric plants. According to Odum (1996), when EIR values are well below unity, as in the "actual" systems under study, the poor reinforcing feedback of the economy may result in non sustainable arrangements. When matching with the regional profile, the higher feedback will enable the systems to receive economic support in order to maintain ecosystems that sustain the enterprise.

iv) The possibility exists when the same investment (system **3**) done for the actual system is used for exploiting an environmental flow that matches with the regional EIR. That means that only a portion of environmental resources available will be used as inflows in the enterprise. The Em*R$* flow is well diminished for both Jupiá and PP scenarios.

v) As it explained in the beginning of the work, water presents a dual characteristic, and although its gravitational energy is being exploited during electricity generation, the chemical potential energy of the water stored in the reservoir also could be used. Calculation was done for the whole potential inflow of environmental resources (system **4**) but it will be

Table 4
The direct area (DA), the purchased indirect area (IA_F), the non-renewable indirect area (IA_N) and the ratios between DA and indirect areas, calculated for Jupiá and PP hydropower plants, with and without considering services paid in money.

	Jupiá plant	Jupiá plant (without services)	Porto Primavera plant	Porto Primavera plant (without services)
DA (km^2)	330	330	2250	2250
IA_F (km^2)	747	295	972	507
DA/IA_F	0.44	1.12	2.32	4.44
IA_N (km^2)	685	685	4484	4484
DA/IA_N	0.48	0.48	0.50	0.50

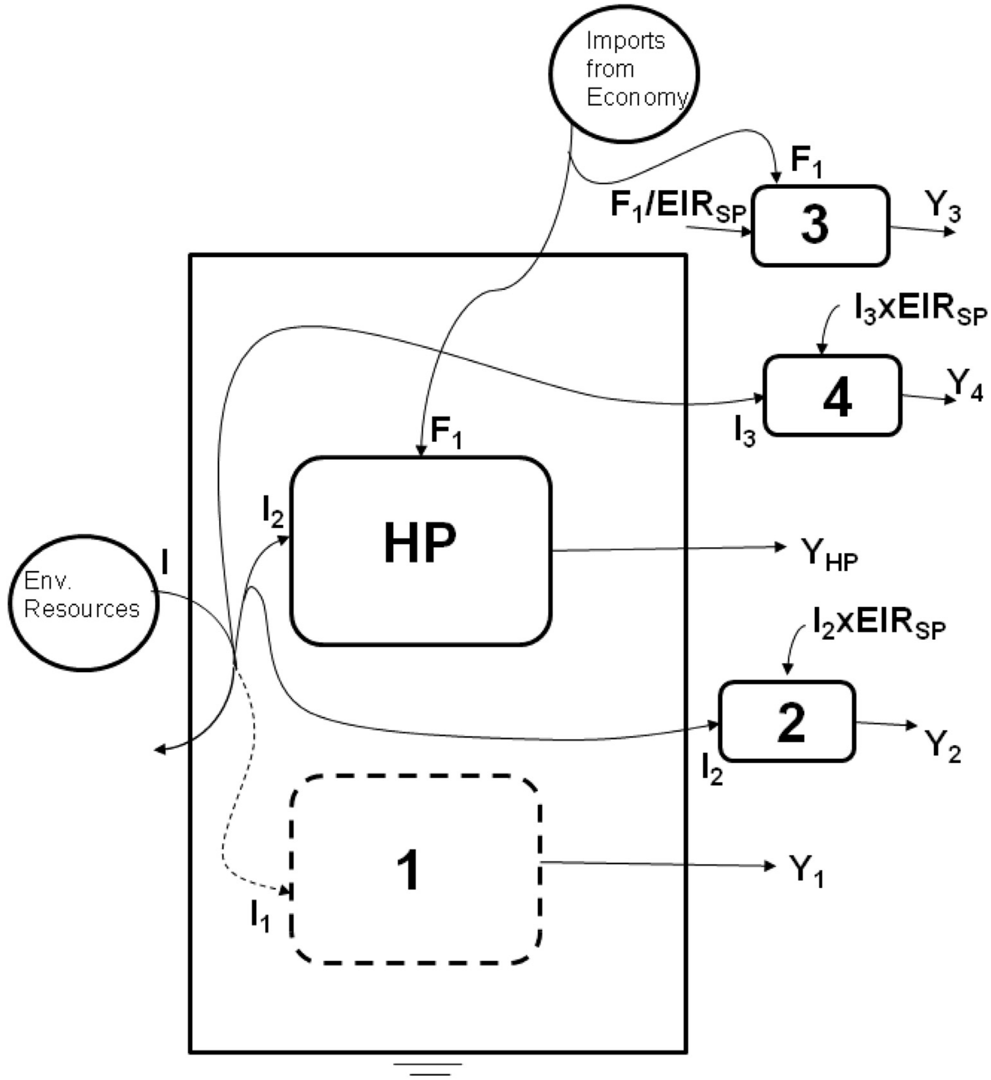

Fig. 2. Diagram for comparing alternatives for development (enterprises **1**, **2**, **3**, **4** and hydropower plant-**HP**). Y_j is the sum of environmental contribution and economical feedback. Y_1 is the flow relating to the original use of the portion of environmental resources I_1. Y_{HP} is the actual total contribution from hydropower investment. Y_2 is the output if the resources exploited by the actual hydropower receive an economic feedback matched with the regional EIR (considered as that of São Paulo State, EIR_{SP}). Y_3 is the output of the alternative use of the actual economic feedback if matched with environmental resources according to the regional EIR_{SP}. Y_4 is a potential output when all of the chemical potential energy of the reservoir is exploited by using a economical inflow according to regional EIR_{SP}.

impracticable to use the total volume since either availability or quality of water would be compromised downstream depending on the enterprise. According to Buenfil (2001), water treatments present an interval of EIR compatible to the regional EIR (from 0.78 to 1.43 from ground and surface water, respectively).

4. Conclusions

Hydropower plants although considered as "environmentally friendly" requires apart from renewable resources for electricity generation, economic resources for construction and operation, as well as the loss of areas due to flooding (including soil and vegetation loss and consequently people reallocation) that are considered as non-renewable resources. Although we agree that a complete hydropower evaluation should include a cost–benefit accounting relating to the services from ecosystems, this resource accounting is not trivial and as it was undertaken by using a donor-side approach with the approach of accounting for the global work of the biosphere. Emergetic theory can embrace various systems, from purely natural to productive processes, yet it is relatively inaccessible for policy and decision-makers due to its complexity. For this reason, the concept of translating and transforming emergy flows in equivalent areas and equivalent currency, enabling an easier comprehension of the scientific theory. Since hydropower plants are widely distributed in Brazil and a drastic growth of this type of electricity generation is expected a methodology to aid in decision and policy-making is urgently needed.

In the particular cases that we studied, the plants were specially selected since they deliver the same power and used up practically the same resources from the economy, but present a great difference in reservoir dimension. Non renewable resources made the difference when indirect areas were calculated since they are spatially distributed and areally dependent.

The exploration of alternatives for the use of watershed resources with a future perspective also contributed to make clear the composition of various but complementary aspects of

Table 5
Comparison of alternatives for development among the "actual" systems, systems **1** (original situation before dam construction) and four other enterprises, as follows: actual system with its own contribution of resources; system **2** that may use the same environmental resources as "actual" but with the feedback equaling SP regional attraction value; system **3**, can invest the same quantity of economic resources in exploiting environmental resources that match the regional EIR_{SP}; system **4** can explore the maximum use of chemical potential environmental resources by using a economic feedback equaling attraction value. j sub indices match with those used in Fig. 2

System		I_j (sej/year)	Fj (sej/year)	Yj (sej/year)	Em*R$* (Em*R$*/year)
1	Jupiá's area	1.42E+20 j = 1		1.42E+20 j = 1	153E+06
	PP's area	9.55E+20 j = 1		9.55E+20 j = 1	1027E+06
Actual	Jupiá's area	2.25E+21 j = 2	0.83E+20 j = 1	2.34E+21 j = HP	2511E+06
	PP's area	3.77E+21 j = 2	1.37E+20 j = 1	3.91E+21 j = HP	4201E+06
2	Jupiá's area	2.25E+21 j = 2	1.64E+21 (1)	3.89E+21 j = 2	4185E+06
	PP's area	3.77E+21 j = 2	2.75E+21 (1)	6.52E+21 j = 2	7013E+06
3	Jupiá's area	1.14E+20 (2)	0.83E+20 j = 1	1.97E+20 j = 3	211E+06
	PP's area	1.88E+20 (2)	1.37E+20 j = 1	3.25E+20 j = 3	349E+06
4	Jupiá's area	7.84E+22 j = 3	5.72E+22 (3)	1.36E+23 j = 4	146,237E+06
	PP's area	8.77E+22 j = 3	6.40E+22 (3)	1.52E+23 j = 4	163,141E+06

(1) Equals $I_2 \times EIR_{SP}$; (2) equals F_1/EIR_{SP}; (3) equals $I_3 \times EIR_{SP}$.

development. We examined both quantitatively and qualitatively the distribution of resources needed, the spatial distribution of emergy flows, the interval of values of the emergy indices, and finally, the examination of potential enterprises and/or different options to manage available environmental resources and economic feedback in a more holistic way.

Appendix

A) I_3 calculation for Jupiá scenario
Reservoir volume = 3680E+06 m^3
Reservoir mass = 3680E+06 $m^3 \times$ 1E+06 g/m^3
(CESP, available in: http://www.cesp.com.br/portalCesp/biblio.nsf/V03.01/Livro_40_Peixes.pdf/$file/Livro_40_Peixes.pdf)
Turn-over time = 6.9 days.
Gibbs Free Energy = 4.94 J/g
Transformity = 8.13E+04 sej/J (Odum, 1996)
Annual flow in emergy = 7.82E+22 sej/year
N = 1.92E+20 sej/J (from Table 3)
I_3 = 7.82E+22 sej/J + 1.92E+20 sej/J = 7.84E+22 sej/J
B) I_3 calculation for PP scenario
Reservoir volume = 20000E+06 m^3
Reservoir mass = 20000E+06 $m^3 \times$ 1E+06 g/m^3
(CESP, available in: http://www.cesp.com.br/portalCesp/biblio.nsf/V03.01/Livro_40_Peixes.pdf/$file/Livro_40_Peixes.pdf)
Turn-over time = 33.9 days
Gibbs Free Energy = 4.94 J/g
Transformity = 8.13E+04 sej/J (Odum, 1996)
Annual flow in emergy = 8.65E+22 sej/year
N = 1.23E+21sej/J (from Table 3)
I_3 = 8.65E+22 sej/J + 1.230E+21 sej/J = 8.77E+22 sej/J

References

Bastianoni, S., Campbell, D., Susani, L., Tiezzi, E., 2005. The solar transformity of oil and petroleum natural gas. Ecol. Model. 186 (2), 212–220.
Bonilla, S.H., Guarnetti, R.L., Almeida, C.M.V.B., Giannetti, B.F., 2010. Sustainability assessment of a giant bamboo plantation in Brazil: exploring the influence of labour, time and space. J. Clean. Prod 18, 83–91.
Brown, M.T., Buranakarn, V., 2003. Emergy indices and ratios for sustainable material cycles and recycle options. Resour. Conserv. Recycl. 38 (1), 1–22.
Brown, M.T., McClanahan, T.R., 1996. EMergy analysis perspectives of Thailand and Mekong River dam proposals. Ecol. Model. 91, 105–130.
Brown, M.T., Ulgiati, S., 1997. Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. Ecol. Eng. 9, 51–69.
Brown, M.T., Ulgiati, S., 2002. Emergy evaluations and environmental loading of electricity production systems. J. Clean. Prod. 10, 321–334.
Brown, M.T., Ulgiati, S., 2004. Emergy analysis and environmental accounting. Encycl. Energy 2, 329–354.
Buenfil, A.A., 2001. Emergy Evaluation of Water (PhD dissertation). University of Florida, USA.
Cui, B., Hu, B., Zhai, H., 2011. Employing three ratio indices for ecological effect assessment of Manwan dam construction in the Lancang River, China. River Res. Appl. 27, 1000–1022.
Cutrim Demetrio, F.J., 2011. Avaliação de Sustentabilidade Ambiental do Brasil com a Contabilidade em Emergia (PhD dissertation). Paulista University (UNIP), Brazil (in Portuguese).
Fang, D., Chen, B., 2014. Environmental accounting of hydropower construction in Upper Mekong River: an emergy perspective. Energy Procedia 61, 216–219.
Geber, U., Björklund, J., 2001. The relationship between ecosystem services and purchased input in Swedish wastewater treatment systems – a case study. Ecol. Eng. 18, 39–59.
He, C.L., 2012. A modified ecological footprint and its application in hydropower project. Adv. Mater. Res. 356–360, 2349–2357.
Kang, D., Park, S.S., 2002. Emergy Evaluation perspectives of a multipurpose dam proposal in Korea. J. Environ. Manag. 66, 293–306.
Manyari, W.V., de Carvalho, O.A., 2007. Environmental considerations in energy planning for the Amazon region: downstream effects of dams. Energy Policy 35, 6526–6534.
Molisani, M.M., Kjerfve, B., Silva, A.P., Lacerda, L.D., 2006. Water discharge and sediment load to Sepetiba Bay from the anthropogenically-altered drainage basin, SE Brazil. J. Hydrol. 331, 425–433.
Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley & Sons, Inc., New York.
Odum, H.T., Brown, M.T., Brandt-Williams, S., 2000. Handbook of Emergy Evaluation – a Compendium of Data for Emergy Computation Issued in a Series of Folios. Fólio # 1: Introduction and Global Budget. Center for Environmental Policy – Environmental Engineering Sciences. University of Florida.
ONS, 2004. Evaporações líquidas nas usinas hidroelétricas, RE 3/214/2004. Available at: http://www.ons.org.br/download/operacao/hidrologia/rel_evapora%C3%A7%C3%A3o_08_02_2006.pdf (accessed Sept/2015.).
Pang, M., Zhang, L., Ulgiati, S., Wang, C., 2015. Ecological impacts of small hydropower in China: insights from an emery analysis of a case plant. Energy Policy 76, 112–122.
Pereira, L.G., 2008. Síntese dos Métodos de Pegada Ecológica e Análise Emergética para Diagnóstico da Sustentabilidade de Países – O Brasil como um Estudo de Caso (PhD dissertation). Universidade Federal de Campinas (UNICAMP), Brazil (in Portuguese).

Pulselli, R.M., Simoncini, E., Pulselli, F.M., Bastianoni, S., 2007. Emergy analysis of building manufacturing, maintenance and use: em-building indices to evaluate housing sustainability. Energy Build. 39, 620–628.
Raugei, M., Bargigli, S., Ulgiati, S., 2005. Emergy "yield" ratio: problems and misapplications. In: 3rd Biennial Emergy Research Conference, Book of Proceedings, Emergy Synthesis 3: Theory and Applications of the Emergy Methodology, pp. 159–164.
Souza, E.A., 2005. Reordenamento sócio-econômico e cultural das famílias atingidas pela UHE Eng. Sérgio Motta: Reassentamentos Pedra Bonita e Santa Emília/Santana Brasilândia-MS (Master thesis). Universidade Estadual de São Paulo (UNESP), Brazil (in Portuguese).
Ulgiati, S., Brown, M.T., 2002. Quantifying the environmental support for dilution and abatement of process emissions. The case of electricity production. J. Clean. Prod. 10, 335–348.
Von Sperling, E., 2012. Hydropower in Brazil: overview of positive and negative environmental aspects. Energy Procedia 18, 110–118.
Zhang, L.-X., Pang, M.-Y., Wang, C.-B., 2014. Emergy analysis of a small hydropower plant in southwestern China. Ecol. Indic. 38, 81–88.