The Rising Value of Water Due To Scarcity in Sao Paulo, Brazil

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ABSTRACT

The Great São Paulo Metropolitan Region (GSPMR) is already facing episodes of water shortage. Presently, around 18 million people living in the metropolis are being supplied by 7 systems located in a Green Belt that surrounds the urban area. Alternatives for increasing the water supply in the future include imports from distant systems and/or water reuse projects.

This study evaluates the rising value of a natural resource due to scarcity. This work proposes that the increase in water values is proportional to the efforts required to get it. These efforts include all environmental and economic for water availability. Emergy analysis was used to compare two alternative water supply systems - Juquitiba and Capivari. Also, an expeditious methodology for evaluating losses in species diversity in the Atlantic Rainforest was proposed.

Results indicated that, although the monetary costs of the construction of the Capivari project were smaller than the Juquitiba project, the Emergy evaluation of these projects showed that the Capivari project demands greater environmental resources than the Juquitiba alternative, which was not well accounted for in the conventional economic evaluation. Emergy values of water for different hypothetical stages of development displayed an exponential growth pattern, varying from 1.0E11 sej/m³ to 14.3E11 sej/m³ for the Capivari project to 2.6 E11 sej/m³ to 19.5E11 sej/m³ for the Juquitiba project.

INTRODUCTION

The Great São Paulo Metropolitan Region (GSPMR) is one of most densely populated areas in the world. Around 18 million people, representing 10% of the Brazilian population, live in 0.1% of this Brazilian territory. It is also a very developed area, with a gross internal product of 99.1 billion dollars, which represents 16.7% of the Brazilian GNP (Emplasa, 2004).

To support this very high Emergy center resources coming from more distant and pristine areas are required. Valuable resources are demanded to cope with the intensive development of the region. Freshwater is one of those resources currently in short supply.

Water Values

Historically, Sao Paulo city obtained water from the tributaries of the Tiete River, which is the main river crossing the urban area. In the late 1960s, following a large increase in population and industry, a major project, Cantareira, was constructed to withdraw water from a distant river basin (Piracicaba River basin).
Presently, seven systems supply 60 m$^3$s$^{-1}$ of treated water to the GSPMR, as depicted in Figure 1. About half of the water is provided by tributaries of the Tiete River and the rest is diverted from the Piracicaba River basin. This is causing economic constraints and environmental problems to the downstream municipalities along this river basin.

As growth took place in the GSPMR, more valuable resources were required to match the increasing Emergy density of the area. Water is one of the major resources required to support development in the metropolis. As water became scarce, its value increased.

This study proposes that the increase in the value of water is proportional to the efforts required to get it. More natural and economic resources are required to concentrate, purify and transport water. Emergy is a very suitable measure to assess the total costs of proposed water projects because it can quantify both natural and economic resources on a common basis. Therefore, to assess the rising value of the water to be provided to the Great Sao Paulo Metropolitan Region, an Emergy analysis of two new alternative water supply systems was performed.

*Figure 1. Map of the Great São Paulo Metropolitan Region, where the existing (dotted lines) and proposed (dashed lines) water supply systems are displayed.*
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Systems Examined

Alternative solutions that have been proposed to supply water to GSPMR include two projects that divert water from upland tributaries of two coastal watersheds. One of these watersheds is the Juquia–Ribeira River basin, where water would be taken from the Juquitiba River. The other is the Itanhaem River basin, where water would be withdrawn from the Capivari River (Figure 1).

Those tributaries, located in the highlands of the coastal watersheds, take advantage of the moisturized air that rises from the ocean and precipitates on the ridge of the flat plateau where Sao Paulo sits. Heavy and year round rain falls in those areas where average annual precipitation is around 2.2 meters.

Description of the Projects

The Juquitiba Project

Approximately 4.7 m$^3$s$^{-1}$ of river water will be withdrawn from Juquia river watershed and pumped upward 170 m to be discharged in the Guarapiranga reservoir that already serves as a supply system to Sao Paulo region. The design includes the following units: lifting station (22,000 HP), pipeline (15,700 m), tunnel (6,760 m), a channel, and a water treatment plant.

The headwater of the Juquia watershed consists of rainforest and suburban developments. Downstream, close to Juquitiba city, the river is full of rapids, permitting the practice of water sports (rafting, canoeing, fishing, etc.). Further downstream, where the terrain drops very steeply, six small hydroelectric dams are found.

The Capivari Project

The project includes the construction of two dams (Alto and Medio Capivari dams) in the headwaters of the Capivari River to hold and revert water back to the GSPMR. A total of 3.9 m$^3$s$^{-1}$ will be diverted from the Capivari-Itanhaem River systems. The design includes the following units: Medio Capivari dam (5 km$^2$ reservoir), Alto Capivari dam (9 km$^2$ reservoir), lifting station (3,750 HP), Embura dam (0.3 km$^2$) and Embura channel.

The planned reservoirs are located in an area covered by very dense Atlantic Forest. Downstream the Capivari River crosses a natural park and Indian lands. Further downstream, in the estuary, mangrove forests spread across the floodplain.

METHODOLOGY

Emergy Diagrams

The Emergy analysis of the two alternative water supply systems was done according to the following steps. First, diagrams were drawn using Odum’s energetic language (Figures 2 and 3) to identify major natural and economic inputs required for the construction and operation of each alternative. Those resources included river water captured and processed in the uplands of these coastal watersheds; economic and human resources required to construct and operate the water supply project; and natural and economic resources that will be affected by the construction and operation of the projects, such as the downstream losses in the natural and economic production processes and declines in diversity and forest production.

Each alternative was depicted as three sub-systems: the watersheds from which water will be taken; the water supply projects to be constructed and operated; and the GSPMR, where the water resources will be used. For the Juquitiba alternative the watershed sub-system diagram (Figure 2) shows the uplands, covered by Atlantic Forest, and the middle reaches of the Juquia River where aquatic sports and electrical power generation will be affected by the project. For the Capivari
Figure 2. Emergy diagram for the proposed Juquitiba system showing the watershed scale, the water supply project and the Great Sao Paolo Metropolitan Region.
Figure 3. Emergy diagram for the proposed Capivari system showing the watershed scale, the water supply project and the Great Sao Paolo Metropolitan Region.
alternative the major processes in the watershed are depicted as the upper reaches dominated by the dense Atlantic Forest where water will be taken, the middle reaches where the riverine productivity is relevant for the Indian reserve, and the estuarine ecosystem where river waters support mangrove, fisheries, and tourism development (Figure 3). Diagrams of the water supply project (Figure 2 and 3) show major inputs for their construction (fuel, equipment, and labor) and for operation (chemicals and electricity). The GSPMR is represented by a single autocatalytic process where water is one of the major inputs required to support development and provide services to the larger system (Figure 2 and 3).

Data Collection

Data were collected from two main sources: HIDROPLAN (Consortio HIDROPLAN 1995a, 1995b)- a water development plan developed in 1995 for the Sao Paulo metropolitan region and three neighboring watersheds (Baixada Santista, Piracicaba/Capivari/Jundiai, and Medio Tiete) and EISs (Environmental Impact Statements) prepared for the Juquitiba and Capivari water supply projects (Multiservice Engenharia 1992, SABESP 1996).

Emergy Tables

Emergy tables were constructed for the Juquitiba and Capivari water supply projects (see Appendix, Tables A1 and A2). A 30 year- life span for the water supply projects was assumed. Therefore, to estimate the total inputs required by the projects, the annual inputs required for the operation of the projects were multiplied by 30 and then added to the inputs required for construction of the projects.

Evaluation of the affected diversity of Atlantic Forest

The Atlantic Forest is a very diverse and endangered ecosystem (Stotz et al. 1996). It has been indicated as one of the top five priority ecosystems for conservation in the world (Mittermeir et al. 2000). An opening in the forest, as predicted in the Capivari project, is expected to adversely affect the diversity of the ecosystem due to impacts on plant and animal populations (Brooks et al. 1997). To calculate the Emergy of the affected diversity of the Atlantic Forest due to the development of the Capivari water supply project the following procedure was applied:

- It was proposed that it took the whole original area of the forest to shelter the diversity that is found in the present coverage. Considering that the present coverage of the Dense Rainforest, located in the bio-geographic sub-region of Meridional Atlantic Forest, is about 17.7% of the original one (D’Horta, F. personal communication), it was calculated that it took 5.65 ha of the pristine forest to obtain the species diversity of one hectare of the present forest.
- The forested area impacted by the project was estimated as 1,235 ha. Following the rationale presented above, it was assumed that to obtain the diversity of the impacted area (1,235 ha), it would be necessary to allow regeneration of an area 5.65 times larger. Therefore, 6,983 ha (1,235 x5.65) of area multiplied by an estimated regeneration period of 250 years would yield the equivalent species diversity that will be affected by the project.

Therefore, considering that the major input supporting this regeneration process would be chemical potential energy of rain, the Emergy of the affected diversity was calculated by multiplying the total rain falling in the 6,983 ha for 250 years by the transformity of the rain.
RESULTS

Emergy Tables

The Emergy evaluation tables for the two alternative water supply systems are presented in the Appendix as Tables A1 and A2. The evaluation took into consideration major natural and economic resources required for the construction and annual operation of the projects.

For the Juquitiba construction, the Emergy analysis included ecosystem resources affected by the construction; inputs needed for the pipeline production, transportation and construction; material and energy resources for the civil works; and labor and services. The greatest inputs were those related to services (53.58E18 sej), followed by material (concrete, 190.41E18 sej) and energy (electricity for pipeline production, 76.87E18 sej).

The empower of the water that will be supplied to GSPMR was included in the evaluation of the operation of the projects. It was estimated as the annual Emergy of the rain falling in the basin area that drains to the withdrawal point and totaled 83.75E18 sej/yr for the Juquitiba project and 15.40E18 sej/yr for the Capivari project.

The Emergy evaluation of the operational phase of the projects took into consideration resources required for treating and lifting the water and also losses in downstream natural and socioeconomic processes due to the water diversion. In the Juquitiba project, it included socioeconomic impacts due to impediment to rafting activities and reduction in electrical power generation, aside from losses in riverine and estuarine primary productivity. For the Capivari project, computed losses included riverine and estuarine aquatic primary productivity, as well as mangrove productivity.

Electricity was a major input to the operation of the Juquitiba project (Table A1) as it amounted to 59.26E18 sej/yr to lift the river water to GSPMR and 90.78E18 sej/yr in losses of potential electricity production due to the river diversion. Losses in riverine and estuarine productivity (29.2E18 sej/yr) were a major input for the Capivari river operation (Table A2).

Comparisons

Construction Inputs

Figure 4 displays the comparison between inputs required by the construction of the Juquitiba and Capivari projects. Emergy inputs were divided into 3 categories: environmental (natural resources and community impacts), material and energy, and labor and services.

Results indicated that the construction of the Capivari project demanded 376 times more environmental resources than the Juquitiba project. The requirement of material and energy resources, which can ultimately be accounted for as environmental resources too, were 352 percent greater in the Capivari project due to the large quantity of concrete and clay for the construction of the dams.

Operation Inputs

When considering the inputs for the annual operation of the projects, Juquitiba demanded four times more empower of material, energy and services than Capivari, as shown in Figure 5. Those results are due to the fact that the water from Juquitiba River has to be lifted approximately 170 m to reach the GSPMR, which represents four times the water head required by the Capivari project. Water Values

Figure 6 shows the rising value of the water supplied to GSPMR, based on the following rationale. Using the data presented in Tables A1 and A2 four hypothetical scenarios were evaluated: 1) W- river water readily available to consumers- evaluating water that can be taken from the rivers. This was estimated as the Emergy of rain falling in the river basin that contributes to the uptake points; 2) W+T- river water has to be dammed and treated to be available to consumers – calculated as
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**Figure 4.** A comparison of the different categories of resources needed for the construction of the water supply projects.

**Figure 5.** Comparison of the annual resources required for the operation of the two water supply projects.
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Figure 6. Evaluating the rising value of water for different scenarios in Emergy/m³. The scenarios evaluated included: W - water taken directly from river; W+T - river water dammed and treated; W+T+P - river water dammed, treated and pumped; W+T+P+E - river water dammed, treated, pumped where environment impacts are taken in consideration.

The raw water value (W) plus Emergy inputs needed to concentrate additional water with dams. This included material, energy and services of construction, plus chemicals inputs of the water treatment; 3) W+T+P - river water dammed, treated and pumped to be available to consumers, in addition to the previous two scenarios, this value included the Emergy of the resources required for pumping water; 4) W+T+P+E - river water dammed, treated and pumped, and the environment impacts, in addition to the previous three scenarios, this value included the Emergy of the environmental resources (E) affected due to each water supply alternative.

These four scenarios are related to different stages of urban development, from primitive conditions to modern society. Figure 6, showing the value of water along different development scenarios, displays an exponential growth pattern, especially when considering the Juquitiba alternative.

DISCUSSION

The relevance of the Emergy evaluation for comparing alternatives projects

As displayed in Figures 4 and 5, Emergy analysis is a very helpful tool for comparing projects alternatives. It allows for a holistic view of the costs and effects of the projects when compared to traditional technical and economic analyses regularly performed in engineering project appraisals.

For example, when comparing the construction costs, the estimated cost of US$116 million for the Juquitiba project was approximately two-fold the cost of the Capivari project (US$62 million) (Consorsio HIDROPLAN 1995b). However, when projects were compared using Emergy values, the inputs to construction for the Capivari project (44.7E20 sej) were 4.5 times higher than those contributing to the construction of the Juquitiba project (9.50E20 sej). As seen in Figure 4, this is
because the Capivari project required high quality inputs (e.g., biodiversity of the Atlantic Forest and large amounts of concrete and clay) that are undervalued in the economic cost of projects. When doing the Emergy evaluation of the projects operation, only a small fraction of the annual inputs to the projects had monetary basis, which represented only 10% of total annual Emergy for the Juquititba project and 5% for the Capivari project.

**The rising value of water**

Presently, there is a general feeling in the population that water is a valuable and limiting resource. People are starting to condemn wasteful practices of water. Industries are beginning to practice water reuse.

The Emergy evaluation done with the Juquititba and Capivari projects allowed us to estimate Emergy values for different hypothetical stages of development. From a primitive stage, where men were sitting by the river and water was abundant to a modern world, to the current situation, where river water has to be diverted from its original watershed, pumped and treated, the value of water increased 4 to 14 times for the Juquititba and Capivari projects respectively. It varied from 1.0E11 sej/m³ to 14.3E11 sej/m³ for the Capivari project to 5.6E11 sej/m³ to 22.6E11 sej/m³ for the Juquititba project (Figure 6).

These higher figures are comparable to the potable water values estimated by Buenfil (1999) for water treatment systems of Florida. According to that evaluation the Emergy per cubic meter of potable water ranged from 9.11E11 sej to 53.9E11 sej.

**Evaluating losses in Atlantic Forest diversity**

There is a need to include conservation values in an Emergy evaluation of a preserved forest. This study proposes a methodology to evaluate the effects of the Capivari project in the diversity of the Atlantic Forest. It combines bio-geographical information about the original and present extension of the sub-region of the Meridional Atlantic Forest and the Emergy evaluation of the inputs required to obtain a forested area with equivalent diversity. The impact on the conservation values of the forest was evaluated at 1.72E18 sej/ha. Using the Brazilian Emergy-dollar ratio of 4.62E12 sej/$ (estimated for the year 2003), losses of Atlantic Forest were estimated at $372,400 dollars/ha. This figure is a little bit higher than the value assigned for 1 ha of wetlands ($50,000-$100,000) (Edwards and Abivardi 1998), but smaller than replacement values of $ 600,000 to $1,500,000 estimated by Bardi and Brown (1999) for one hectare of different types of wetlands.

**REFERENCES**


D’Horta, F. 2004- Personal communication


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APPENDIX

Table A1. Emergy analysis of the Juquitiba water supply system.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
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Footnotes

Natural Resources
1. Forest Biomass Losses
Deforestation of 28 ha (2 ha right of way + 20 ha for the water treatment plant + 6 ha of the riparian forest in the channel area)
Standing Biomass of tropical rainforest= 42 kg/m² (Deshmukh, 1986)
Biomass energy content= 3.6 kcal/g (Prado & Brown 1997)
Forest Biomass energy= area (ha)*61E+04m²/ha* biomass (kg/m²)*(1E+03g/kg)*(3.6kcal/g)*4,168J/Kcal=
Forest Biomass energy= 28 (ha)*1E+04m²/ha*42 (kg/m²)*(1E+03g/kg)*(3.6kcal/g)*4,168J/Kcal=
Forest Biomass energy= 1.77E+14J
Rain ET= 1.8 m/yr (assumed)
Rain Gibbs Free Energy= 4.94 J/g
Transformity of rain= 1.54E+04 sej/J (Odum, 1996)
Turnover time of forest= 100 years (assumed)
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Transformity of forest biomass = \( \frac{\text{rain ET(m/yr)} \times 1E+6 \text{g/m}^3 \times \text{rain Gibbs Free energy (J/g)} \times \text{Transformity of rain (sej/J) \times \text{turnover time}}}{(\text{biomass (kg/m}^2) \times 1,000 \text{g/kg} \times 3.6 \text{kcal/g} \times 4,186 \text{ J/kcal})} \)

Transformity of forest biomass = \( \frac{1.8 \text{ m/yr} \times 1E+6 \text{g/m}^3 \times 4.94 \text{J/g} \times 15,400 \text{sej/J} \times 100}{42 \text{kg/m}^2 \times 1,000 \text{g/kg} \times 3.6 \text{kcal/g} \times 4,186 \text{ J/kcal} \)}

Transformity of forest biomass = \( 2.84 \times 10^4 \text{ sej/J} \)

2. Forest GPP affected (30 yrs)

Deforestation area = 28 ha

Gross Primary Production = NPP/0.20 = 11,500 g/m\(^2\)/yr

Biomass energy content = 3.6 kcal/g

Energy of affected forest GPP (30 yrs) = \( \frac{\text{GPP (g/m}^2\text{/yr) \times \text{area (ha)} \times (3.6 \text{kcal/g}) \times (4,186 \text{ J/kcal})}{(\text{30yr losses})} \)

Energy of affected forest GPP (30 yrs) = \( \frac{11,500 \text{ g/m}^2\text{/yr} \times 28 \text{ha} \times 3.6 \text{kcal/g} \times 4,186 \text{ J/kcal}}{100} \)

Energy of affected forest GPP (30 yrs) = 1.46E+15 J

Rain ET = 2 m/yr

Rain Gibbs free energy = 4.94E+03 J/kg

Transformity of the chemical potential of the rain = 1.54E+04 sej/J

Transformity of forest GPP = \( \frac{\text{ET (m/yr)} \times (1,000 \text{g/m}^2) \times \text{rain Gibbs Free Energy (J/kg)} \times \text{Transformity of rain ET (sej/J))}{(\text{GPP (g/m}^2\text{/yr) \times (3.6 \text{kcal/g}) \times (41,86 \text{J/kcal})}} \)

Transformity of forest GPP = \( \frac{2 \text{m/yr} \times 1,000 \text{g/m}^2 \times 4.94 \times 10^3 \text{J/kg} \times 15,400 \text{sej/J}}{11,500 \text{g/m}^2\text{/yr} \times 3.6 \text{kcal/g} \times 4,186 \text{ J/kcal}} \)

Transformity of forest GPP = 8.78E+02 sej/J

3. Pasture Biomass Losses

Clearing of the pasture area = 48.32 ha (45 ha of the water treatment plant + 1.8 ha from the lifting area + 1.0 ha of the tunnel entrances + 0.52 ha of the right of way)

Standing Biomass of Savanna = 2.2 kg/m\(^2\) (Deshmukh, 1986)

Biomass energy content = 3.6 kcal/g

Pasture biomass energy = area (ha) \times 4.82 \text{ ha} \times \text{standing biomass (kg/m}^2\text{)} \times (3.6 \text{kcal/g}) = 4,186 \text{J/kg}

Pasture biomass energy = 48.32 \text{ ha} \times 4.82 \text{ ha} \times 2.2 \text{ kg/m}^2 \times 100 \text{g/kg} \times 3.6 \text{kcal/g} \times 100 \text{J/kcal} = 4,186 \text{J/kg}

Pasture biomass energy = 1.60E+13 J

Rain ET = 1 m/yr (assumed)

Rain Gibbs free energy = 4.94E+03 J/kg

Transformity of the chemical potential of the rain = 1.54E+04 sej/J

Turnover time of pasture = 1.5 years (Prado & Brown 1997)

Transformity of pasture biomass = \( \frac{\text{ET (m/yr)} \times (1,000 \text{g/m}^2) \times \text{rain Gibbs Free Energy (J/kg)} \times \text{Transformity of rain ET (sej/J))}{(\text{GPP (g/m}^2\text{/yr) \times (3.6 \text{kcal/g}) \times (41,86 \text{J/kcal})}} \)

Transformity of pasture biomass = \( \frac{2 \text{m/yr} \times 1,000 \text{g/m}^2 \times 4.94 \times 10^3 \text{J/kg} \times 15,400 \text{sej/J}}{11,500 \text{g/m}^2\text{/yr} \times 3.6 \text{kcal/g} \times 4,186 \text{ J/kcal}} \)

Transformity of pasture biomass = 6.88E+03 sej/J

4. Pasture GPP affected (30 years)

Area = 47.8 ha

Net Primary Production (NPP) = 2,300 g/m\(^2\)/yr (Schlesinger, 1991)

Gross Primary Production = NPP/0.3 = 7,666.7 g/m\(^2\)/yr

Biomass Energy content = 3.6 kcal/g

Energy of the pasture GPP affected (30yrs) = GPP(g/m2/yr)*Area (ha)*(1E+04 m2/ha)*(3.6kcal/g)*(4,186 J/kcal)*(4yrs)

Energy (30yrs) = 2.21E+14 J

Rain ET = 1 m/yr

Rain Gibbs free energy = 4.94E+03 J/kg

Transformity of the chemical potential of the rain = 1.54E+04 sej/J

Transformity of pasture GPP = \( \frac{\text{ET (m/yr)} \times (1,000 \text{g/m}^2) \times \text{rain Gibbs Free Energy (J/kg)} \times \text{Transformity of rain ET (sej/J))}{(\text{GPP (g/m}^2\text{/yr) \times (3.6 \text{kcal/g}) \times (41,86 \text{J/kcal})}} \)

Transformity of pasture GPP = 6.58E+02 sej/J

5. Soil Losses

Soil Organic Matter (2 years)

Area of bare soil = 77.79 ha (area of lifting unit + tunnel entrance + pipeline + water treatment plant)

Soil Losses (10% slope) = 60 ton/ha/yr

Energy of soil losses (2 yrs) = soil losses (ton/ha/yr) \times area (ha) \times 1E+06 g/ton \times 0.02 organ. matter \times 5.4 kcal/g \times 41,86 J/kcal

Energy of soil losses (2 yrs) = 60 ton/ha/yr \times 77.79 ha \times 1E+06 g/ton \times 0.02 organ. matter \times 5.4 kcal/g \times 41,86 J/kcal

Energy of soil losses (2 yrs) = 4.22E+13 J

Transformity of top soil organic matter = 7.4E+04 sej/J (Odum, 1996)

Pipeline production/transportation/construction

Steel

Length of pipeline = 1.62E+04 m (SABESP, 1996)

Thickness = 1.43 cm

Steel density = 7,580 kg/m\(^3\)

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Specific weight = 510 kg/m
Pipeline total weight= length* specific weight=8.26E+06 kg
Pipeline total weight= total weight (kg) * 1E3g/kg= 8.26E+09 g
Transformity of steel= 3.78E+09 sej/g (Bargigli & Ulgiati, 2001)

7. Electricity
Energy requirement to produce steel pipe from ore= fuel production energy + energy content of fuels= 54.73 MJ/kg
(Bousted & Hancock, 1979)
Pipeline total weight= 8.26E+06 kg (footnote 6)
Energy requirement to pipe production= 54.73E+06 J/kg* pipeline total weight= 4.52E+14J
Transformivity of electricity = 1.70E+05 sej/J (Odum, 1996)

8. Labor
50 people with average 6 years of education working for 3 months
Energy / worker educational level= 1.53E+16 sej/3 months/6yr-education
(estimated as annual country Emergy divided by the number of Brazilian people with average 6 yrs of education)

9. Services
Pipeline costs= 674.12 $/m (Consorsio HIDROPLAN, 1995b)
Length of pipeline= 1.62E+04 m
Total Cost= length* cost/m= 1.09E+07$

10. Fuel used in transportation
Assuming that all pipes were transported by trucks
Route= 1.62E+04 m
Number of tubes= 1.35E+03 (tubes of 12 m)
Average trip length= 200 km (assumed)
Number of trips= 1.50E+02
Total trip length= 6.0E+04 Km
Diesel consumption= 3.0 km/l(Romitelli, 1999)
Diesel consumption= 2.0E+04 l
Energy= 37.71 MJ/l*consumption= 7.54E+11 J/yr
Transformity of fuel = 6.60E+04 sej/J (Odum,1996)

11. Heavy Machines – Material
Depreciation of heavy machine due to pipeline construction
Average weight of heavy machine = 20,000 kg/machine (assumed)
Number of machines = 20 units (assumed)
Total weight of machines= 4.00E+05 kg
Used material in one year of work= 4.00E+04 kg (assuming average life of the machines as 10 yr)
Used material in one year of work= 4.00E+07 g
Transformity of steel= 3.78E+09 sej/g (Bargigli & Ulgiati, 2001)

12. Heavy Machines- energy
Electricity to make the machines= 50MJ/kg (Bousted & Hancock, 1979)
Energy on “used machine”= used material * 50 MJ/kg=2.00E+12 J
Transformivity of fuel = 6.60E+04 sej/J (Odum,1996)

13. Fuel used in construction
Fuel/month/kg of machine= 0.060697 l/month/kg of machine (Romitelli, 1999)
Total weight (20 machines)= 4.00E+05 kg (as indicated in footnote 11)
Months of implementation= 6 months
Diesel used= 0.060697 l/month/kg of machine* 6 months*4.00E+05 kg=
Diesel used= 145,673.1 liters
Energy on diesel used= 37.71 MJ/Liter*145673.1 liters of diesel= 5.49E+12J
Transformity of fuel = 6.60E+04 sej/J (Odum, 1996)

Civil Work

14. Concrete
Volume of concrete = 53,760 m$^3$ (assumed – 7,000 m$^3$ of the lifting unit + 9,960 m$^3$ of the tunnel + 36,800m$^3$ for the water treatment plant)
Concrete density= 2,300 kg/m$^3$
Total concrete weight= 1.24E+08 kg= 1.24E+11g
Concrete transformity= 1.54E+09 sej/g (Brown & Buranakarn, 1999)

15. Diesel used (transportation of the crushed rock)
Volume of grinded rock= 9.00E+04 m$^3$
Assuming hauling the grinded rock for 100 km
Volume transported for trip= 1.20E+01 m$^3$
Number of trips= 7.50E+03
Total length= 1.50E+06 km
Diesel consumption= 3.00E+00 km/l (Romitelli, 1999)
Diesel used= 5.00E+051
Energy on diesel used = 37.71 MJ/Liter * liters of diesel
Energy on diesel used = 1.89E+13 J
Transformity of fuel = 6.60E+04 sej/J (Odum, 1996)

**Labor and Services**

16. Labor
24 months for the construction = 2 years
Workers = 600 workers
Energy/person (4 yr education) = 3.66E+16 sej/yr (Romitelli, 1999)
Energy from labor = 4.39E+19 sej

17. Services
Cost of the project = 1.17E+08 $ (Consortio HIDROPLAN 1995b)

**Operation**

18. Energy of pumped water
Drainage area = 517 km² (SABESP, 1996)
Rain in the area = 1.8 m/yr
Total rain = 9.31E+08 m³/yr
Total rain = 9.31E+14 g/yr
Emergy of the rain/m³ = 9.00E+03 sej/yr/m³ (Romitelli, 1997)
Total Emergy in Juquitiba watershed = 8.38E+19 sej/yr

19. Electricity for pumping water
Elevation head = 168 m (SABESP, 1996)
Flow = 4.7 m³/s
Electrical energy for pumping = 1.11E+07 J/s = 3.49E+14 J/yr
Transformity of electricity = 1.70E+05 sej/J (Odum, 1996)

20. Electricity costs
Cost of electricity (industrial) = 2.02E+01 US$/bep (MME, 2002)
1 bep = 6.24E+09 J/bep
Cost of electricity = 3.24E+09 US$/J Total cost = 1.13E+06 $/yr

21. Chemicals for water treatment
Typical concentration (Chlorine = 2 mg/l, Aluminum sulfate = 15 g/m³, Lime = 7 g/m³, Polyelectrolyte = 0.7 g/m³) (Azevedo Netto et al. 1978)
Taken aluminum and lime = 22 g/m³
Chemicals used = 0.1034 kg/s
Chemicals used = 3.26E+06 kg/yr = 3.26E+09 g/yr
Transformity of chemicals = 1.00E+12 sej/Kg (Buenfil, 1999)

22. Chemicals costs
Cost of aluminum sulfate = 0.62 R$/kg
Total cost = 2.02E+06 R$/yr = 6.97E+05 US$/yr (assuming 1 dollar = 2.9 reais)

**Downstream effects**

23. Losses on Primary Productivity
(measured as chemical potential Emergy of the uptake water)
Available chemical potential energy = river flow (m³/s) * (1E+06 g/m³) * G
Flow withdrawn = 4.70E+00 m³/s
G = Gibbs Free Energy of Clean water = 4.94 J/g
Available Chemical Potential Energy = 4.7 m³/s * 1.0E+06 g/m³ * 4.94 J/g = 2.32E+07 J/s
Available Chemical Potential Energy = 7.32E+14 J/yr
Transformity of river chemical potential energy = 4.85E+04 sej/J (Odum, 1996)

24. Losses due to rafting impediment
Estimated annual number of tourists = 4.55E+04 persons
(Considering 3 trips a day w/ 12 boats with 6 people each during 6 days/week during summer time and 3 trips a day w/ 10 boats and 6 people each during 3 days/ week during low season. This number was raised by 30% due to holidays)
Average expenditure = 200 reais/person (assumed)
Total gain w/ rafting = 9.10E+06 R$ Total gain w/ rafting = 3.14E+06 US$ (1 US$ = 2.90 R$)

25. Losses in electrical power generation
6 hydro power plants downstream
Total drop in elevation = 525.2 m (being 82 m of UHE França; 110.2m of UHE Fumaça; 79m of UHE Barra; 64.5m of UHE Porto Raso; 146.5m of UHE Alcim; 43m of UHE Serraria) (Secretaria do Estado do Meio Ambiente, 1999)
Loss in electricity generation = diverted flow * drop in elevation = 1.69E+07 W
Loss in electricity generation = 1.69E+07 W
Loss in electricity generation = 16,933.5 kW
Annual loss in electricity generation = 5.34E+14 J/yr
Transformity of electricity = 1.70E+05 sej/J (Odum, 1996)
26. Losses in electricity revenue
Cost of electricity (industrial)= 2.02E+01 US $ bep (MME, 2002)
1 bep= 6.24E+09 J
Cost of electricity= 3.24E-09 U$/J
Total cost= 1.73E+06 $/yr

Table A2 - Emergy analysis of the Capivari water supply system

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Data</th>
<th>Transformity</th>
<th>Solar Emergy</th>
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<td>Clay for Embankment</td>
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<td>OPERATION (annual inputs)</td>
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<td>Raw Water Energy</td>
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<td>River/Estuarine PP</td>
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<td>Losses in Mangrove</td>
<td>1.42E+14</td>
<td>J/yr</td>
<td>1.11E+04</td>
</tr>
</tbody>
</table>

Footnotes

Natural Resources

1. Rain Forest Diversity Losses
Area to be deforested = 1,235 ha
Atlantic forest covers 17.7% of the original forest (D’Horta, personal communication), therefore each ha of the present forest represents 5.56 ha of the original forest.
Area of equivalent diversity= (area to be deforested)*5.56 ha of equivalent original area) = 6,982.5 ha = 6.98E+07 m2
Time needed for forest restoration to original conditions= 250 yr
Rain ET = 1.6 m/yr (assumed)
Gibbs Free Energy of the rain = 4.94J/g
Transformity of the chemical potential energy of the rain= 15,400 sej/J
Energy of the affected conservation values= annual rain ET* area of equivalent diversity* 1E6g/m3 * Gibbs Free Energy of rain* Transformity of rain*250 yrs
Energy of the affected conservation values= 1.6m/yr*6.98E+7m3*1E+06g/m3*4.94J/g*15,400 sej/J*250 yr

2. Rainforest Biomass Losses
Affected area = 1,235 ha of Atlantic Forest* 1.5 (assuming additional 50% of affected area due to border effect)= 1,852.5 ha
Tropical forest standing biomass = 42 kg/m2 (Deshmukh, 1986)
Plant energy content= 3.6 kcal/g (Prado & Brown, 1997)
Rain ET = 1.6 m/yr
Gibbs Free Energy of the rain = 4.94J/g
Transformity of the chemical potential of the rain = 15,400 sej/J

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Turnover time of the forest = 100 yrs (assumed)

Rainforest biomass energy = affected area (ha) * 1E+4 m²/ha * standing biomass (kg/m²) * (1E+3 kg/Kg) * energy content (Kcal/g) * 4,168 J/Kcal

Rainforest biomass energy = 1,852.5 ha * 1E+04 m²/ha * 42 kg/m² * 1E+03 g/Kg * 3.6 kcal/g * 4,168 J/Kcal

Rainforest biomass energy = 1.17E+16 J

Transformity of the forest biomass = (rain ET (m/yr) * 1E+06 g/m³ * Gibbs Free Energy (J/g) * Transformity of the rain ET (sej/J) * turnover time) / (biomass (kg/m²) * 1E+03 g/Kg * 3.6 kcal/g * 4,168 J/Kcal)

Transformity of the forest biomass = 1.6 m/yr * 1E+06 g/m³ * 4.94 J/g * 15,400 sej/J * 100 yrs / (42 kg/m² * 1E+03 g/Kg * 3.6 kcal/g * 4,168 J/Kcal)

Transformity of the forest biomass = 2.52E+04 sej/J

3. Rainforest GPP affected (30 yrs)

Affected area = 1,235 ha of Atlantic Forest * 1.5 (assuming additional 50% of affected area due to border effect) = 1,852.5 ha

Tropical forest net primary production (NPP) = 2,300 g/m²/yr (Deshmukh, 1986)

Tropical forest gross primary production (GPP) = NPP / 0.8 = 11,500 g/m²/yr

Plant energy content = 3.6 kcal/g (Prado & Brown, 1997)

Rain ET = 1.6 m/yr

Gibbs Free Energy of the rain = 4.94 J/g

Transformity of the chemical potential of the rain = 15,400 sej/J

Rainforest GPP energy = affected area (ha) * 1E+04 m²/ha * GPP (g/m²/yr) * energy content (Kcal/g) * 4,168 J/Kcal * 30 yrs losses

Rainforest GPP energy = 1,852.5 ha * 1E+04 m²/ha * 11,500 g/m²/yr * 3.6 kcal/g * 4,168 J/Kcal * 30 yrs

Rainforest GPP energy = 9.66E+16 J

Transformity of the forest GPP = (rain ET (m/yr) * 1E+06 g/m³ * Gibbs Free Energy (J/g) / Transformity of the rain ET (sej/J)) / (GPP (g/m²/yr) * 3.6 kcal/g * 4,168 J/Kcal)

Transformity of the forest GPP = 9.66E+02 sej/J

4. Land Acquisition

Cost of land + right of way = 1.44E+07 $ (Consorsio HIDROPLAN, 1995b)

5. Families Displacement

Jobs affected = 7.28E+02 jobs (assuming 2 jobs per occupied house in the affected area of the project)

Average salary + fringe benefits = 600 R$/month (assumed)

Months to find a new job = 12 months (assumed)

Expenditures with family resettlement = (number of jobs * average salary * months to find a job) = 5.24E+06 R$

Expenditures with family resettlement = 1.81E+06 US$ (assuming 1 US$ = 2.90 R$)

6. Clay used for embankment

Volume of clay = 5.98E+05 m³

Density = 1.2 ton/m³

Weight of Clay = 7.18E+11 g

Transformity of the clay from weathering = 1.70E+09 sej/g (Odum, 1996)

7. Concrete

Total volume = 104,055 m³ (76,890 m³ of Alto Capivari and 27,075 m³ of Médio Capivari) (Consorsio HIDROPLAN, 1995)

Density = 1.2 ton/m³

Weight of concrete = 2.39E+11 g

Concrete transformity = 1.54E+09 sej/g (Brown & Buranakarn, 1999)

8. Steel used on excavation

Excavated material = 8.21E+05 m³ (6.29E+5 m³ of soil and 1.92E+05 m³ of rock from dams and channel construction)

Material used for m³ transported = 1.06E-01 Kg of steel per m³ transported (index estimated using transportation data from Immigrants highway and machinery use from Romitelli, 1999)

Material on steel used = 8.21E+05 m³ * 1.06E-1 Kg/m³ = 8.71E+04 kg

Transformity of steel = 3.78E+09 sej/g (Bargigli & Ulgiati, 2001)

9. Energy of used machinery

Electricity to make the machines = 50 MJ/Kg (Boustead & Hancock 1979)

Weight of transported material = 8.71E+04 kg (footnote 8)

Energy on used machine = 50 MJ/Kg * 8.71E+04 kg = 4.35E+12 J

Transformity of fuel = 6.60E+04 sej/J (Odm, 1996)

10. Transport of excavated material

Total distance = 4.10E+06 Km (considering the 8.21E+05 m³ the volume to be transported; 12 m³/truck; 60 km the length of the round trip)

Diesel consumption = 3 Km/liter of diesel (Romitelli, 1999)

Volume of diesel = 1.37E+06

Energy on diesel used = 37.71 MJ/Liter * liters of diesel

Energy used for transporting excavated material = 5.16E+13 J

Transformity of fuel = 6.60E+04 sej/J (Odm, 1996)
11. Labor
Workers (direct and indirect)= 700 workers for 1.5 years
Assuming an average education of 4 years= 3.66E+16 sej/year (Romitelli, 1999)
Economy on labor= 3.84E+19 sej= 2.95E+07 dollars

12. Services
Total service (direct cost-land + construction + interests)= 4.9E+07 US (Consorsio HIDROPLAN, 1995)

13. Raw water Emergy
Drainage area= 95 Km² (Multiservice, 1992)
Rain in the area= 1.8 m/yr
Total rain= 9.5E+07*1.8m/yr=1.71E+08 m³/yr
Total rain = 1.71E+14g/yr
Energy/g of rain water= 9.00E+04 sej/g (Romitelli, 1997)
Total raw water emergy= 1.54E+19 sej/yr

14. Electricity for pumping the water
Elevation head= 42 m
Flow= 3.9 m³/s
Energy required for pumping water= 2.29E+06 J/s= 7.23E+13 J/yr
Transformity of electricity = 1.70E+05 sej/J (Odum, 1996)

15. Electricity costs
Cost of electricity (industrial)= 2.02E+01 US$/bep (MME, 2002)
1 bep= 6.24E+09 J/bep
Cost of electricity= 3.24E-09 US$/J
Electricity costs= 7.23E+13J/yr*3.24E-09US$/J= 2.34E+05 $/yr

16. Chemicals for water treatment
Typical concentration (Chlorine= 2 mg/l, Aluminum sulfate= 15 g/m³, Lime= 7 g/m³, Polioletoelectyte= 0.7 g/m³) (Azevedo Netto et al., 1978)
Taken aluminum and lime= 22 g/m³
Chemicals used= 3.9 m³/s*2.2 E-02kg/m³=0.0858 Kg/s
Chemicals used= 2.71E+06 Kg/yr = 2.71E+09 g/yr
Transformity of chemicals= 1.00E+12sej/Kg (Buenfil, 1999)

17. Chemicals costs
Cost of aluminum sulfate= 0.62 R$/Kg
Chemical costs= 2.71E+06kg/yr*0.62R$/kg=1.68E+06 R$/yr
Chemical costs= 5.78E+05 US$/yr (assuming 1US$= 2.9 R$)

Downstream Losses
18. Riverine/ estuarine Primary Production
Measured as the river chemical potential energy of the water diverted
Water withdrawn from the basin= 3.9 m³/s
River Chemical Potential Energy= volume*density* Gibbs Free energy=
River Chemical Potential Energy= 3.9 m³/s*1E+06g/m³* 4.94J/g=
River Chemical Potential Energy= 6.03E+14 J/yr
Transformity of river chemical potential energy = 4.85E+04 sej/J (Odum, 1996)

19. Losses in Mangrove Production
Mangrove area= 150 Km²
Mangrove productivity=1,000 g/m²/yr (Odum et al., 1982)
Total annual production= 150 km²*1E+06m²/km²*1.0kg/m²/yr=1.50E+08 kg/yr
Average flow reduction= 6.33% of total flow
Considering equivalent impact in mangrove annual production
Losses in mangrove annual production=1.50E+08Kg/yr*0.0633= 9.50E+06 kg/yr
Energy of mangrove production lost= (GPP(kg/yr)*(1,000kg/kg)*(3.6kcal/g)*(4,186J/kcal)=
Energy of mangrove production lost= (9.5E+06kg/yr)*(1,000kg/kg)*(3.6kcal/g)*(4,186J/kcal)=
Energy of mangrove production lost = 1.42E+14J
RainET= 2 m/yr
Rain Gibbs free energy= 4.94 J/g
Transformity of rain= 15,400 sej/J
Transformity of forest GPP= (ET(m/yr)* (1,000kg/m²)*Rain Gibbs Free energy (J/kg)* Transformity of rainET
(see/J)*(GPPg/m²/yr)*(3.6kcal/g)*(4,186J/Kcal))
Transformity of forest GPP= (1,000kg/m²)*(4.94J/kg) (15,400se/J)*(1,000g/m²/yr)*(3.6kcal/g)*(4,186J/Kcal))
Transformity of forest GPP= 1.11E+04 sej/J