An Integrated Indicator Based on Basin Hydrology, Environment, Life, and Policy: The Watershed Sustainability Index

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An Integrated Indicator for Basin Hydrology, Environment, Life, and Policy: The Watershed Sustainability Index

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Abstract: Several issues impact the water sustainability of a river basin. Among them are the social, economic, and environmental issues. However, they are often treated separately, and not as an integrated, dynamic process. In order to integrate the hydrologic, environmental, life & policy issues, as well as the existing pressures and policy responses in one quantitative, dynamic, and aggregated indicator, a watershed sustainability index (WSI), which uses a pressure-state-response function, was developed. Applied to a 2,200 km^2 Unesco-HELP demonstration basin in Brazil (S.F. Verdadeiro), the value calculated for WSI was 0.65, which represents an intermediate level of basin sustainability.

Key words: hydrology, environment, life, policy, watershed sustainability index, S.F. Verdadeiro, HELP basin.

1. INTRODUCTION

Several issues impact the water sustainability of a river basin. Among them are the social, economic, and environmental issues. However, they are often treated separately, and not as an integrated, dynamic process (Viessman, 1990).

Additionally, integrated and environmentally sustainable water management requires more than simply carrying out environmental impact assessments. It requires integration of policy formulation, project appraisal, sound water management laws and institutions, across the breath and depth of the decision-making process regarding the use of freshwater resources (Smith & Rast, 1998).

Recently, Unesco's International Hydrologic Program-IHP adopted a framework which includes hydrology, environment, life, and policy issues. With this framework (the HELP platform), one aims to break the so called "paradigm lock", which hinders effective and integrated actions by different basin stakeholders (UNESCO, 2005). Last year, more than 60 operational and demonstration HELP basins existed around the world, providing a platform for sharing water resources management experiences.

The objective of this paper was to develop an integrated index which could incorporate hydrologic, environmental, life, and water policy issues and responses. In its development, several indicator criteria established in the literature were followed.. In order to demonstrate the applicability of the index, the WSI was applied to the S.F. Verdadeiro watershed, a Unesco-HELP operational basin in Southern Brazil.

2. INTEGRATING THE HYDROLOGY, ENVIRONMENT, LIFE, & POLICY ISSUES IN ONE SUSTAINABILITY INDEX

Sustainability assessments should cut across jurisdictional boundaries. Although they are the natural water resources planning unit, watersheds generally do not align themselves with political governance (Nyerges, 2002). However, seldom are watersheds used as planning and management unit.

Though it is recognized that the sustainability of the water resources in a given basin is directly related to its hydrologic, environmental, life, and policy conditions, a few attempts have been made to integrate them in one single and comparable number. Integrated indices are used for survey and planning purposes. The United Nations has been using the Human Development Index-HDI (UNDP, 1998) for several years. It integrates educational, life expectancy, and income information for municipalities, states and countries. Varying from 0 to 1, the HDI is simple to use, robust and applied worldwide.

Aiming at the estimation of the water scarcity in world countries, Lawrence et al. (2002) developed a Water Poverty Index-WPI. Varying from 0 to 100, this index uses as indicators information about the water resources, access, use, and environment. The authors applied the WPI to several countries, but found that it was highly correlated with the HDI (R=0.81). A variation of the WPI is the Climate Variability Index-CVI (Meigh & Sullivan, 2005), which estimates the vulnerability of countries, regions, and communities in relation to water resources. Although both indices are integrative, their indicators are subjective and not basin-specific.

More recently, an Environment Sustainability Index (ESI) was proposed (Esty & Levy, 2004). This index uses 5 components, comprising 21 indicators and 76 variables. Although it was applied to several countries, the high number of indicators and variables reduce its applicability in data-scarce regions. In addition to being non-watershed specific, the above indices do not take into account cause-effect relationships, or consider the policy responses that are implemented in a given watershed, in a given period.

Sustainability indicators and parameters shall meet some basic criteria if they are to be useful. According to HCTF (2003), watershed indicators shall be:

- <u>Available</u>: the indicator data shall be available and easily accessible. They shall be collected throughout the watershed, published in a routine basis, and made available to the public;
- <u>Understandable</u>: indicators shall be easily understood by a diverse range of non-technical audiences;
- <u>Credible</u>: indicators shall be supported by valid, reliable information, and interpreted in a scientifically defensible manner;
- <u>Relevant</u>: indicators shall reflect changes in management and in activities in the watershed. They shall be able to measure changes over time;
- <u>Integrative</u>: indicators shall demonstrate connections among the environmental, social & economical aspects of sustainability.

Additionally, quantitative indicators or parameters shall be preferred as much as possible over qualitative indices, to avoid subjectiveness. Applied to watersheds, an index formed by indicators meeting the above criteria could be universally applied, which would significantly increase their usefulness in establishing the sustainability of water resources in river basins.

Considering that the water management is dynamic process, and assuming that the water sustainability of a basin is a function of its hydrology (H), environment (E), life (L), and policy (P), a dynamic, pressure-state-response model (OECD, 2003) was applied to those four indicators (H, E, L, P) in a matrix scheme. As a result, a watershed sustainability index-WSI was obtained. Numerically, the WSI is given by:

$$WSI = (H+E+L+P) / 4 \quad [1]$$

Where WSI (0-1) is the watershed sustainability index; H (0-1) is the hydrologic indicator; E (0-1) is the environment indicator; L (0-1) is the life (livelihood) indicator; and P (0-1) is the policy indicator. As seen from equation [1], all indicators have the same weight, since there is no evidence that it be otherwise (Harr, 1987).

The linear and additive structure of equation [1] allows for error compensation in the indicators, reducing the potential of sub and super-estimation of WSI. The logic behind this is the fact that, if one of the indicators of equation [1] is overestimated, there is a good chance that another would be underestimated, compensating (at least) part of the overall error. This is an important issue in model development, but often overlooked by modelers (Chaves & Nearing, 1991).

Since basin management at the local and regional level is more effective in watersheds up to 2,500 km^2 (Schueler, 1995), this is the upper limit suggested for the application of WSI in the estimation of basin sustainability.

Table 1 below presents the WSI parameters relative to each of the four indicators (H,E,L,P). These, in turn, are divided in 3 columns, comprising *Pressure*, *State* and *Response*. The advantage of using a PSR model is that it incorporates cause-effect relationships, helping stakeholders and decision-makers to see the interconnections between the parameters (OECD, 2003).

Table 1. Indicators and parameters of the Watershed Sustainability Index

	Pressure	***State***	***Response***
Indicators	*Parameters*		
Hydrology	- Variation in the basin's *per capita* water availability in the last 5 years; - Variation in the basin BOD5 (last 5 years)	- Basin *per capita* water availability - Basin BOD5 (yearly average)	- Improvement in water-use efficiency (last 5 yrs.); - Improvement in sewage treatment/ disposal (last 5 yrs.)
Environment	- Basin's EPI (Rural & urban)	- % of basin area with natural vegetation	- Evolution in basin conservation (Protected areas, BMPs)
Life	- Variation in the basin per capita GDP in the last 5 yrs	- Basin HDI (weighed by county pop.)	- Evolution in the basin HDI (last 5 yrs.)
Policy	- Variation in the basin HDI-Ed in the last 5 years	- Basin institutional capacity in WRM	- Evolution in the basin's WRM expenditures in the last 5 years

To each combination of indicators and parameters, a value between 0 and 1 is assigned. A value of 0.25 is assigned to poorer levels, and 1.00 to optimum conditions. The full description of levels and values of all WSI parameters is presented in Tables 2, 3, and 4, respectively.

Table 2. Description of WSI Pressure parameters, levels, and values.

Indicator	*Pressure Parameters*	*Level*	*Value*
Hydrology	Δ1- Variation in the basin *per capita* water availability in the last 5 years (m^3/person.yr)	$\Delta1 < -10\%$ $-10\% < \Delta1 < 0\%$ $0 < \Delta1 < +10\%$ $\Delta1 > +10\%$	0.25 0.50 0.75 1.00
	Δ2- Variation in the basin BOD5 (last 5 years)	$\Delta2 > 10\%$ $0 < \Delta2 < 10\%$ $-10\% < \Delta2 < 0\%$ $\Delta2 < -10\%$	0.25 0.50 0.75 1.00
Environment	- Basin E.P.I. (Rural & urban)	EPI > 10% 10%<EPI<5% 5%<EPI<0% EPI<0%	0.25 0.50 0.75 1.00
Life	- Variation in the basin per capita HDI-Inc in the last 5 years	$\Delta < -10\%$ $-10\% < \Delta < 0\%$ $0 < \Delta < +10\%$ $\Delta > +10\%$	0.25 0.50 0.75 1.00
Policy	- Variation in the basin HDI-Ed in the last 5 years	$\Delta < -10\%$ $-10\% < \Delta < 0\%$ $0 < \Delta < +10\%$ $\Delta > +10\%$	0.25 0.50 0.75 1.00

Table 3. Description of WSI *State* parameters, levels, and values.

Indicator	*State Parameters*	*Level*	*Value*
Hydrology	- Basin *per capita* water availability (m^3/person.yr)	Wa < 1,700 1700<Wa<3,400 3400<Wa<5,100 Wa>5,100	0.25 0.50 0.75 1.00
	- Basin Ave. BOD_5 (mg/l)	BOD>10 10<BOD<5 5<BOD<3 BOD<3	0.25 0.50 0.75 1.00
Environment	- % of basin area under natural vegetation (Av)	0 < Av < 10 10 < Av < 25 25 < Av < 40 Av > 40	0.25 0.50 0.75 1.00
Life	- Basin HDI (weighed by county pop.)	HDI <0,6 0,6<HDI<0,75 0,75<HDI<0,9 HDI >0,9	0.25 0.50 0.75 1.00
Policy	- Basin institutional capacity in WRM (legal & organizational)	Poor Medium Good Excellent	0.25 0.50 0.75 1.00

Table 4. Description of WSI Response parameters, levels, and values.

Indicator	*Response Parameters*	*Level*	*Value*
Hydrology	- Improvement in water-use efficiency (last 5 yrs.)	Poor Medium Good Excellent	0.25 0.50 0.75 1.00
	- Improvement in adequate sewage treatment/ disposal (last 5 yrs.)	Poor Medium Good Excellent	0.25 0.50 0.75 1.00
Environment	- Evolution in basin conservation areas (Protected areas & BMPs) in the last 5 yrs.	Δ < -10% -10%< Δ< 0% 0 < Δ < +10% Δ > + 10%	0.25 0.50 0.75 1.00
Life	- Evolution in the basin HDI (last 5 yrs.)	Δ < - 10% -10%< Δ< 0% 0 < Δ < +10% Δ > + 10%	0.25 0.50 0.75 1.00
Policy	- Evolution in the basin's WRM expenditures in the last 5 years	Δ < -10% -10%< Δ< 0% 0 < Δ < +10% Δ > +10%	0.25 0.50 0.75 1.00

In the **Hydrology** indicator, there are 2 sets of variables: one relative to water quantity and the other to water quality. In the case of *water quantity*, the parameter is the per capita water availability per year. According to Falkenmark & Widstrand (1992), water stress occurs when water availability falls below 1,700 m^3/person.yr. Therefore, 4 levels of per capita water availability were used: a) $W_a < 1,700$ m^3/inhab.yr, b) $1,700 < W_a < 3,400$; c) $3,400 < W_a < 5,100$; and d) $W_a > 5,100$ m^3/person.yr, corresponding to poor, medium, good, and excellent water availability, respectively.

In the case of *water quality*, since biochemical oxygen demand (BOD_5, in mg/l) information is often available in watersheds, and due to its high correlation with other important water quality data (dissolved oxygen, turbidity), it was selected as the quality parameter. Non point loadings, such as pollution by nutrients and pesticides are often associated to high BOD values. Figure 1 shows the correlation of BOD_5 with other water quality parameters.

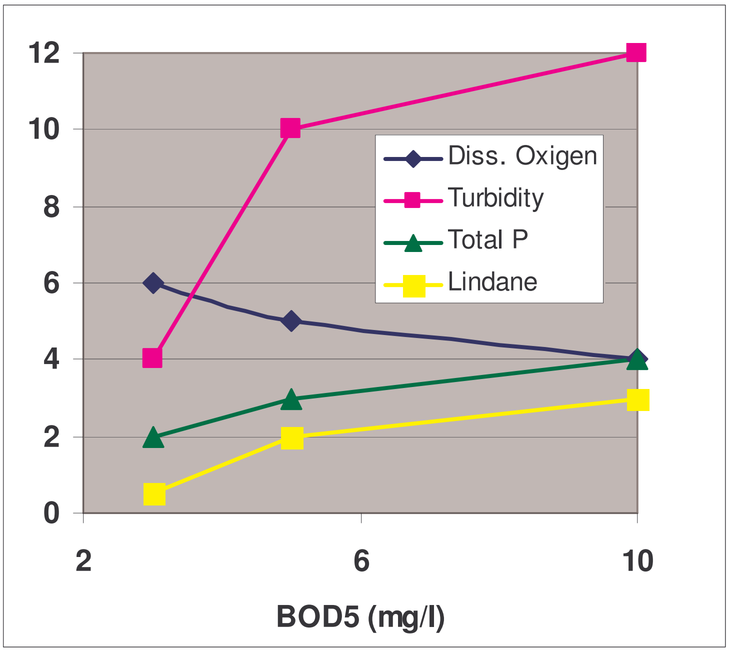

Figure 1. Correlation of maximum tolerance limits of water quality parameters with BOD5 (normalized values). Source: Braz. Environment National Council Res. # 357/05.

Since it compares the latest water availability information (5 years) with the long-term average, the hydrologic *Pressure* parameters have the advantage of incorporating eventual climate variability/change impacts which, in certain conditions, could significantly affect water availability in the watersheds.

In Table 2, the *Pressure* parameter for the **Environment** indicator is the *Environment Pressure Index-EPI*, estimated by the averaged variation of the basin agricultural area and urban population in a 5-year period (in percent). The proportion of agricultural and urban areas is a given basin is correlated with water quality (Hunsaker & Levine, 1995), and are easy to obtain from agricultural and population censuses.

The EPI used here is a modification of the Anthropic Pressure Index, developed by Sawyer (1997). The EPI, estimated for a 5 yr period, is given by:

$$\text{EPI} = (\text{\% variation of basin agric. area} + \text{\% variation of basin urban pop.}) / 2 \qquad [2]$$

EPI can be positive, negative, or zero. Positive values indicate higher pressures over the remaining natural vegetation of the basin (Environmental *State*). This *State* parameter is, in turn, highly correlated to flora and fauna biodiversity, being an indicator of the basin overall environmental integrity.

The **Life** parameters of the WSI are the basin human development index-HDI (in the *State* column), and its evolution in a 5-year period (*Response*). The *Pressure* parameter is given by the % variation of the HDI-Income, i.e., the variation of the basin per capita income in the 5-year period studied. Negative values of this parameter indicate that the population got poorer, and vice-versa, which would impact the basin's resources and sustainability.

In the case of the **Policy** parameters, the *Pressure* is given by the variation in the basin *HDI-Education* indicator, in the 5-yr period studied. Since this indicator measures the population educational level, positive values of HDI-Ed would indicate that the basin population became more participative in WRM, which puts more pressure on the decision-makers.

The *State* policy parameter reflects the present basin institutional capacity in WRM, given by the level of adequate legal and institution framework, as well as participatory management. It is one of the few qualitative parameters of the index, varying form poor (0.25) to excellent (1.0).

The *Response* parameter is estimated by evolution in the basin WRM expenditures in the 5 yr. period studied. This reflects the pressure applied by basin stakeholders to the decision-makers. The greater the spending in WRM, the higher the chances the basin will meet its water-related objectives.

After all indicators are obtained, and selecting a 5-year period for the pressure, state & responses, the WSI is calculated, according to equation [1]. The advantage of the WSI is that its framework provides for comparative measurements of the basin sustainability in different time frames and scenarios, including climate variability.

3. APPLYING THE WSI TO THE S.F. VERDADEIRO RIVER BASIN

To exemplify the utilization of the WSI, it was applied to the SF Verdadeiro River basin, a 2,200 km^2-wide watershed in Southern Brazil. The period studied was the 5 years between 1996 and 2000, where environmental and social data were available. Since WSI is formed by 4 indicators, each of them will be presented separately, and the overall sustainability index computed in the end.

3.1 Hydrology Indicator

The hydrology indicator is simply the average of the basin's quantity and quality parameters. In the case of the quantity sub-indicator, since the dominant water use in the basin is surface water, the per capita water availability (*State*) is simply the long-term river mean flow rate, divided by the basin population.

Figure 2 shows SF Verdadeiro river mean monthly flow rates, with a long term average of 39 m^3/s. Divided by a total basin population of 167,083 inhabitants (year 2000 basis), the per capita water availability (*Wa*) was 33,600 m^3/person.yr. According to Table 4, the value for the *State* quantity parameter is 1.0 (excellent).

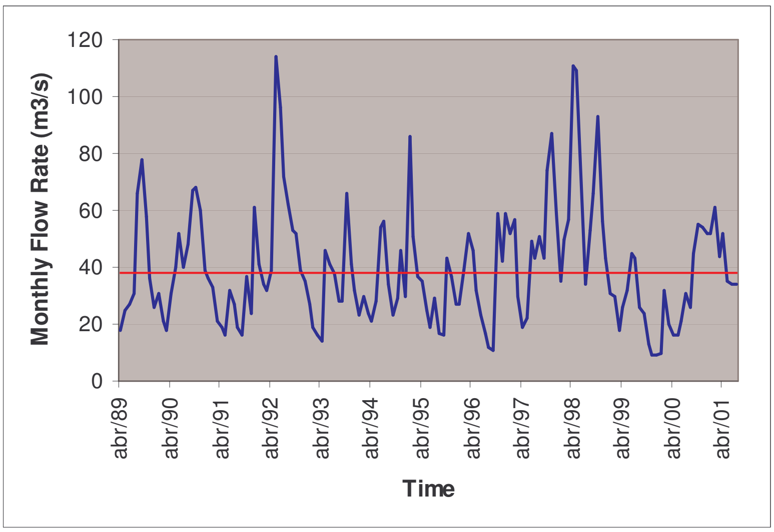

Figure 2. Monthly flow rates of the SF Verdadeiro river, and the long-term average flow rate.

In the case of the quantity *Pressure* parameter, the variation in W_a in the 5 yr period studied, with respect to the long-term average, was + 4.8%. This, according to Table 2, results in a pressure value of 0.75. In the case of *Response*, in the 5 yr period considered, there was a medium improvement in water use efficiency in the basin, which corresponds to a value of 0.5. Therefore, the averaged *Pressure*, *State*, and *Response* parameters for quantity was (1.0 + 0.75 + 0.5) /3 = 0.75.

In the case of the *quality* sub-indicator, *Pressure* corresponds to the variation in the basin BOD_5 in the 5 yr period (+4.6%), yielding, according to Table 3, a value of 0.5. The *State* parameter for quality (the basin's BOD5 long-term average) is equal to 1.3 mg/l (Figure 3). This results in a *State* value of 1.0.

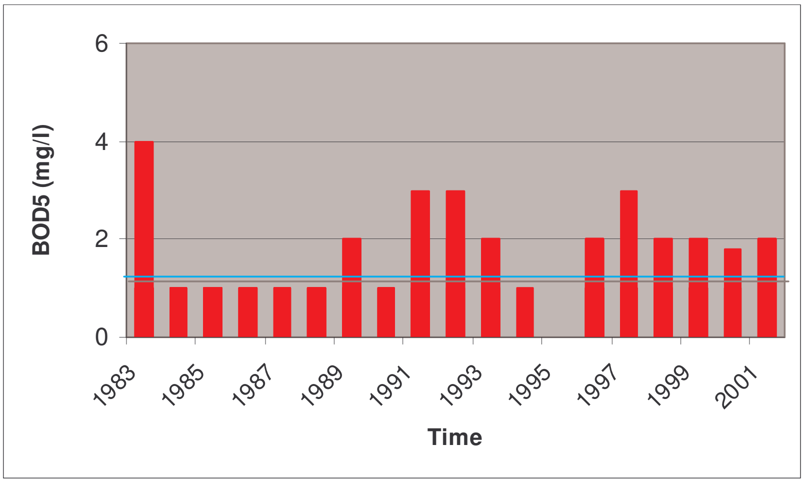

Figure 3. Yearly BOD5 values in the low SF Verdadeiro river, with a long term average of 1.3 mg/l.

The *Response* for the quality sub-indicator resulted in a value of 0.25 (poor improvement in sewage treatment/disposal in the 5 yrs studied). The quality sub-indicator is therefore (0.5+1.0+0.25) / 3 = 0.58.

Hence, the overall Hydrology indicator value is simply the average of the quantity and quality sub-indicators, or (0.75+0.58) / 2 = 0.67.

3.2 Environment Indicator

Similarly to the Hydrology indicator, the *Environment* indicator was computed using its *Pressure, State*, and *Response* parameters. In the case of *Pressure*, the combined basin variation (increase) in agricultural area and urban population in the period studied was 13% and 9%, respectively, yielded an EPI value of (13%+9%)/2 = 11%. This corresponds to an environmental *Pressure* value of 0.25.

In the case of environmental *State*, the basin had 26% of its original vegetation cover in the year 2000, which, according to Table 3, results in a value of 0.75. Remaining natural vegetation cover in a basin could be estimated by remote sensing techniques (e.g., NDVI), or indirectly, through agricultural censuses.

The environmental *Response* (evolution in protected areas and areas with BMPs) was 2% in the basin, resulting, according to Table 4, in a value of 0.75. Therefore, the combined value for the Environment indicator was (0.25+0.75+0.75) / 3 = 0.58.

3.3 Life Indicator

Life *Pressure* in the basin was estimated by the variation in the basin's HDI-Income sub-index in the 5 yr period (1996-2000). In that period, there was an increase in HDI-Inc of 3.4% (UNDP, 2004), resulting, according to Table 3, in a value of 0.75 (Good).

In the case of Life *State*, the basin HDI in the last year of the period studied (2000) was 0.81, resulting in a value of 0.75, according to Table 4. Figure 4 gives the distribution of HDI in the SF Verdadeiro basin in the year 2000. The overall basin HDI was the weighed average of the HDI values of each municipality and its corresponding population.

Life *Response*, i.e., the evolution of the expenditures in WRM in the basin, was 5% in the 5-yr period, resulting in a parameter value of 0.75 (Table 5). Therefore, the combined livelihood value for the basin was (0.75+0.75+0.75) / 3 = 0.75.

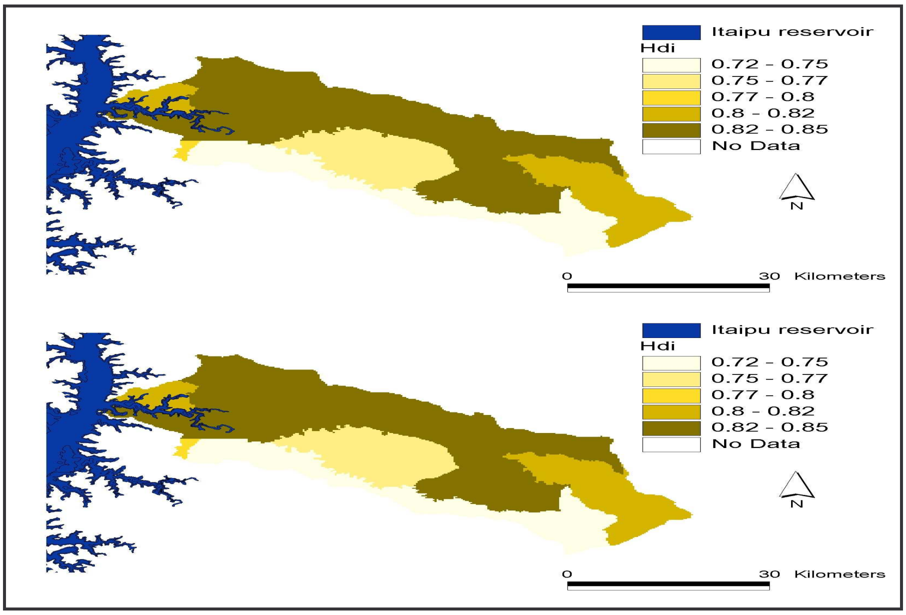

Figure 4. Spatial distribution of the Human Development Index (2000-basis) in the SF Verdadeiro basin.

3.4 Policy Indicator

The policy *Pressure* level (variation in the HDI-Ed in the 5- yr. period) for the basin was +6.3%, resulting in a parameter value of 0.75 (Table 3). This indicates that there was a significant increase in the educational level of the basin, which would help pressure for responses in WRM in the basin.

As for the policy *State* parameter (basin institutional capacity), although there is a legal framework available (federal & state water & environmental laws & regulations), little was accomplished in participatory water resources management in the period studied. The SF Verdadeiro basin still lacks a watershed committee or organization, which is, according to the law, the institution responsible for the water management at the basin level. As a consequence, the basin was ranked poor in this item, with a corresponding parameter level of 0.25.

With regard to policy *Response*, the evolution in the basin expenditures in WRM was +5% in the 5-yr period, yielding a value of 0.75 for this parameter. The overall Policy indicator was the average of the 3 parameters, i.e., (0.75+0.25+0.75) / 3 = 0.58.

3.5 Watershed Sustainability Index

The WSI is simply the global average of the 4 indicators. Applying equation [2], we obtain a WSI value of 0.65 for the SF Verdadeiro basin. Table 5 below presents the levels, values and the overall WSI for the basin.

Table 5. Levels & values for the parameters, and the basin WSI.

	Pressure		***State***		***Response***		*Result*
	Level	**Value**	**Level**	**Value**	**Level**	**Value**	
	4.8%	0.75	33,600	1.00	Medium	0.50	
	4.6%	0.50	1.3	1.00	Poor	0.25	
Hydrology		0.63		1.00		0.38	0.67
Environment	11%	0.25	26%	0.75	2%	0.75	0.58
Life	3.4%	0.75	0.81	0.75	5.1%	0.75	0.75
Policy	6.3%	0.75	Poor	0.25	5%	0.75	0.58
Result		0.59		0.70		0.66	**0.65**

Using a similar classification as the UNDP's HDI (low for HDI <0.5, intermediate for HDI between 0.5 and 0.8, and high for HDI >0.8), the WSI obtained for the SF Verdadeiro basin (0.65) would fall in an intermediary level. According to Table 5, the indicators with the lowest values are *Policy* and *Environment* (0.58), and the highest is *Life* (0.75).

In terms of the Pressure, State, and Response indicators, the lowest value was obtained for Pressure (0.59), and the highest for State (0.70). This indicates that although the present basin conditions (*State*) are good, there are pressures (particularly environmental) which threaten the basin sustainability.

More specifically, the poorest indicator combinations in Table 5 are Environmental *Pressure* (0.25), Policy *State* (0.25), and Hydrology *Response* (0.38). Therefore, in order to improve the global watershed sustainability, stakeholders and decision-makers shall work more effectively in reducing the pressure over the remaining vegetation, enhancing the WRM institutional capacity, and improving sewage treatment in the basin, respectively.

Due to its dynamic characteristics, if applied to different periods of time, the WSI can give an idea of the evolution of the watershed sustainability along the years, helping stakeholders and decision-makers in their planning and decision-making process, providing for an adaptive management tool for the basin's water resources.

4. CONCLUSIONS

Several issues impact the water sustainability of a river basin. Among them are the social, economic, and environmental issues. However, they are often treated separately, and not as an integrated, dynamic process. In order to integrate the hydrologic, environmental, life & policy issues, as well as the existing pressures and policy responses in one quantitative, dynamic, and aggregated indicator, a watershed sustainability index (WSI) was developed for river basins. This index is simple, robust, and uses readily available parameters. Its dynamic characteristics allow for the estimation of human, environmental, and climate-related pressures and responses, which affect basin sustainability.

Applied to the SF Verdadeiro basin in the period between 1996 and 2000, the WSI resulted in a global value of 0.65, which represents an intermediate level of sustainability. Aspects needing attention by decision-makers in that basin are those related to *Environmental Pressure*, *Policy State, and Hydrology Response*..

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