W²DVI - A WATERSHED INDEX BASED ON GIS AND SATELLITE IMAGE DATA

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Abstract:

Indexes reflecting vulnerability to pollution of watersheds have been developed and used by environmental agencies. The indices are based on Theory of Multiple Atributtes and used in decision analysis and watershed planning. A watershed index is formed by addition of information about indirect water quality parameters, translating it in a single index. Water quality parameters are integrated in a linear sum of functions, to produces a single index of watershed as a whole. The quantities of parameters depending on temporal and spatial dimensions and reflecting environmental factors influencing on water quality of the watershed. Numerous problems have been highlighted concerning some characteristics of this type of index, like delimitation of spatial and temporal units, choice of weights and use of subjective indices. In sense to minimize the above cited limitations of some watershed indicators, we present in this paper a new watershed index based on GIS and satellite image data: the Watershed Water Degradation Vulnerability Index – W²DVI.

The W²DVI uses as database the following watershed parameters: urbanization coefficient (UBC), vegetation index (VGI) and topographic index (TPI). The UBC coefficient reflects constructed and impervious areas density existing in the watershed. The VGI index indicates green biomass over watershed terrain, and identifies the relative infiltration capacity and erosion suitability of watershed. The VGI index is calculated applying the NDVI vegetation index algorithm in TM-Landsat 7 satellite images. The UBC index is obtained by digital classification of land use of color composite images. The TPI index is related to the flood risk, soil loss and potential energy of watersheds, and uses the following watershed morphometric data: first order stream density, relief ratio and circularity index of watersheds

The indexes values are equalized on a scale of common values, with intervals between 0 and 1 interval. The scale of values of the three indices are used to construct a three-dimensional space of data in a cubic format, representing the W²DVI index. This cube is divided in eight blocks, each related to a category of watershed degradation vulnerability. The watershed are classified according to the block to they correspond, depending on the UBC, VGI and TPI values. The W²DVI index methodology was applied in Sao Francisco watershed, located in the northeast region of Brazil, and is associated to a water quality monitoring program in semi-arid areas, supported by National Water Agency of Brazil.

Key terms – *watershed index; GIS, vulnerability to pollution; water quality; satellite image, Brazil*

1 INTRODUCTION

The recent proliferation of watershed committees in Brazil demonstrates that Brazilian citizens are anxious to participate in decision-making and policy formation regarding planning and sustainable management of water resources. Decision-making activities at the level of watersheds have been guided by the use of indicators related to the impact resulting from the land use, including increases in DBO, salinity, frequency of flooding, and soil erosion.

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This procedure has been adopted most frequently by the U.S. Environmental Protection Agency (EPA), mainly in relation to the Clean Water Act (US EPA, 1997). In this act, the EPA used the Index of Watershed Indicators (IWI) to classify environmental conditions and the vulnerability of the watersheds to pollution, and to inform the community and planners regarding which watersheds needed environmental protection and changes in land use (Spooner & Lehmann, 1998).

Although it has been widely used in the U.S. and Europe, the methodology employed by the EPA reflects geographical contexts and land use that is quite different from the Brazilian case. For this reason, we believe that this approach should not be adopted as a whole. Iit is necessary to develop an index that is adapted to the context of tropical regions, with land use practices and socioeconomic profiles similar to those of Brazil.

The object of this study was to develop an index of ecological risk (IER) to classify the watersheds according to their degree of degradation of the natural conditions, integrated with hydrological, land use, and morphometric parameters and TM-Landsat 7 satellite images, into a geographical information system.

2 STUDY AREA FOR TESTING THE INDEX

The area used to apply the methodology was a set of 35 watersheds located in the region of the Sub-Médio Rio São Francisco (Figure 1). This area was chosen because the Brazilian Agricultural Research Institute (Empresa Brasileira de Pesquisa Agropecuária - Embrapa), with which this study is associated, is conducting a project to monitor water quality in this location, and would be able to provide assistance in the use of watershed indicators.

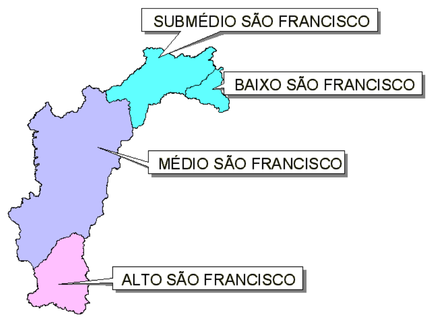

Figure 1 – Study area location in Brazil and South America.

The study area is located between 7º - 11º latitude S and 37º and 43º longitude W, with a surface area of approximately 126,700 km2 , including more than 80 municipalities. It is an area that is relevant because of its potential to generate electricity, as well as its capacity to irrigate crop land in this dry region of northeastern Brazil.

3 WATERSHED INDICATORS

The indices used to diagnose the vulnerability of watersheds to environmental alternations is based, primarily, on the Theory of Multiple Attributes. This theory defines algorithms to aggregate multiple indicators (hydrological, land use, and morphometric, among others) into a single, integrated index which makes it possible to classify watersheds according to the ecological risk to which they are exposed (Schultz, 2001).

Due to the spatial complexity of this type of indicator, the large quantity of maps needed, and the temporal variability of the attributes used to calculate an index of susceptibility for the watersheds, methodologies based on geographical information systems and orbital remote sensing data are needed (He, et al, 2000).

In the last decade, there has been a trend, in agencies responsible for environmental protection and water quality management in developed countries, toward using ecological risk indices to evaluate and monitor water quality in watersheds. The application of this kind of indicator in the context of watersheds has broadened the reach and improved the quality of environmental monitoring and the data available for decision-making (Serveiss, 2002).

Spatial units that are defined by their hydrological characteristics, such as watersheds, aggregate environmental variables from different categories, such as geomorphology, hydrology, land use, water chemistry, and ecology, among others. In this sense, some studies have been concerned with developing indices that integrate indicators from different levels of environmental information for use in watershed management. Some indices have been suggested as a solution to aggregate information about water quality parameters on a temporal and spatial scale, and convert them into a single indicator representing the time and space considered for the evaluation of the conditions of alteration of a watershed (Schultz, 2001).

An example of this approach is the work of He, et al. (2000), who provided a model for the integration of hydrological and biological indicators to evaluate the altered conditions of watersheds, called an integrated ecological indicator. According to the authors, this type of indicator can reveal the spatial and temporal distribution of the modifications in the hydrological and biological systems resulting from the land use. This integrated ecological index, the authors state, can assist water management agencies to detect and evaluate the environmental conditions of watersheds.

In the work of Ravichandran, et al., (1996), geological, geomorphological, and morphometric attributes of vegetation, climate, and land use were integrated using principal component analysis and cluster analysis to form eco-regions. Physical-chemical water samples from rivers located in each of the units were analyzed, and it was concluded that the eco-regions were appropriate for describing the spatial variations of the water quality parameters.

Modelling alterations in water quality caused by land use was the principal objective of studies developed by Mattikalli & Richards (1996) and Mattikalli et al. (1996), in watersheds located in eastern England. They used TM-Landsat and HRV-Spot satellite images, associated with spatial analysis methods within an Arc-Info geographical information system, to develop a model to estimate solutes exported by the watersheds.

Pollution of watersheds located in rural areas was modelled using spatial analysis methods in geographical information systems by Ha et al. (1998). They integrated digital land use maps with digital elevation models (DEM) in a GRID geographical information system using spatial analysis operations to construct maps of the potential for water to purify itself in watersheds located in South Korea.

Wang et al. (2001) used SIG Arc Info to analyze the effects of the spatial pattern of urban land use on fish communities and fluvial habitats of small watersheds in Wisconsin, U.S.A The researchers developed various biotic and abiotic indices for urbanized watersheds and applied them to estimate the water quality of watersheds located in urban areas.

4 THE WATERSHED WATER DEGRADATION VULNERABILITY INDEX (W^2DVI)

We developed the Watershed Water Degradation Vulnerability Index (W2DVI) for application in the Brazilian context. The following parameters were used as a database: coefficient of urbanization (UBC), vegetation index (VGI), and the topographic index (TPI) of the watershed.

4.1 Coefficient of Urbanization

The Coefficient of Urbanization of the watershed is calculated using the ratio of urbanized area A_{ub} to surface area of the watershed A_b, using the following equation:

$$IUB = (A_{ub}/A_b)\ 100$$

The values of A_{ub} are obtained using TM-Landsat 7 images, and to obtain the value of A_b, topographical maps with a scale of 1:100,000 were used.

4.2 Vegetation Index

This index reflects the density of the vegetation cover in the watershed and reveals the capacity to retain surface run-off, biodiversity, and stability of ecosystems in the watershed. It is calculated using the algorithm of the perpendicular vegetation index which is available on the SIG Idrisi32, from TM-Landsat 7 images. The final value of this attribute is standardized by the area of the watershed, expressing the number of pixels of vegetation per unit of area.

4.3 Calculating the W^2DVI

The values of the UBC, VGI, and TPI indices are equalized based on a scale of common values, with intervals between 0 and 1. The scale of values of the three indices are used to construct a three-dimensional space of data in a cubic format, representing the space of the W^2DVI index. This cube is divided into eight blocks, each related to a category of watershed degradation vulnerability. The watersheds are classified according to the block to which they correspond, depending on the UBC, VGI, and TPI values (Table 1)

Table 1 – Intervals of UBC, TPI and VGI values for each block, respective W^2DVI order and correspondent watershed vulnerability zones.

Block #	UBC	TPI	VGI	W^2DVI class	Watersheds Zones
1	≤ 0.50	≤ 0.50	> 0.50	I	I
2	≤ 0.50	> 0.50	> 0.50	II	Low Vulnerability
3	≤ 0.50	≤ 0.50	≤ 0.50	III	
4	≤ 0.50	> 0.50	≤ 0.50	IV	II
5	> 0.50	≤ 0.50	> 0.50	V	Medium Vulnerability
6	> 0.50	> 0.50	> 0.50	VI	III

7	> 0.50	≤ 0.50	≤ 0.50	VII	High Vulnerability
8	> 0.50	> 0.50	≤ 0.50	VIII	

5 RESULTS

Table 2 presents the UBC, VGI, and TPI values for the 35 watersheds analyzed. The Figure 2 shows the map of vulnerability degradation water watershed, classified in three different vulnerability zones: low, medium and high.

5.1 Zone 1 - Low vulnerability

This unit includes watersheds concentrated in the extreme southwest and northeast regions of the Sub-Medio São Francisco, defining a continuous zone composed of the following watersheds:7, 9, 10, 11, 12, 13, 25, 26, 27 and 32.

Long-term preventive measures are recommended for this region with respect to the regeneration and preservation of the original vegetation cover, regulation of rural occupation on the steeper slopes, and programs to monitor the quality of the water.

It is a zone that is appropriate for the implantation of conservation units (areas of environmental protection) associated with environmental education programs directed to the local population.

5.2 Zone II - Medium Vulnerability

This is a zone that is located mostly downstream from the sub-media São Francisco, in the central sector of the area. It is composed of the following watersheds:1, 3, 4, 8, 14, 15, 16, 17, 18, 19, 20, 22, 23, 24, 28, 33 and 34. For this region, the implantation of medium-range measures to mitigate impacts that can threaten the water quality is urgently recommended, such as: water treatment plants for household wastewater, re-planting of the riparian forest, measure to contain sheet erosion, and environmental education programs.

Because it is located in a transitional area between high and low-risk zones, this unit acts as a buffer zone, preventing the watersheds located in Zone I from suffering the impact of those watersheds that are in more critical condition due to urban expansion or occupation of the slopes, which are not recommended.

Table 2 - Values of the parameters UBC, VGI, TPI, and final values of the W2DVI for the 35 basins of the Sub-Medio Rio São Francisco valley, Brazil.

Code	Name of River	UBC	VGI	TPI	W^2DVI class	Vulnerability
1	R. da Brígida	0.249	0.041	0.581	IV	Medium
2	R.Paredão	0.754	0.286	0.535	VIII	High
3	R.Terra Nova	0.455	0.064	0.707	IV	Medium
4	R. S.Cristóvão	0.335	0.161	1.000	IV	Medium
5	Médio Alto Pajeu	0.632	0.112	0.669	VIII	High
6	Alto Pajeu	1.000	0.210	0.745	VIII	High
7	R. Pau de Fumo	0.000	0.507	0.811	II	Low
8	R. Moxotó	0.109	0.064	0.526	IV	Medium
9	R. do Navio	0.020	0.148	0.488	III	Low
10	R. S. Domingos	0.167	1.000	0.527	II	Low
11	R. da Posse	0.210	0.806	0.608	II	Low
12	Médio Baixo Pajeu	0.367	0.417	0.489	III	Low
13	Baixo Pajeu	0.095	0.870	0.517	II	Low
14	Riacho Ipueira	0.000	0.286	0.767	IV	Medium
15	Riacho Barreira	0.185	0.072	0.817	IV	Medium
16	Alto Itaparica	0.099	0.080	0.717	IV	Medium
17	Riacho da Vargem	0.000	0.103	0.670	IV	Medium
18	Riacho das Graças	0.074	0.054	0.752	IV	Medium
19	Riacho do Tourão	0.147	0.056	0.562	IV	Medium
20	Riacho Dormente	0.025	0.039	0.822	IV	Medium
21	Riacho Jardim	0.689	0.582	0.579	VI	High
22	Riacho do Mocó	0.076	0.182	0.828	IV	Medium
23	Riacho Grande	0.017	0.098	0.610	IV	Medium
24	R. Tanque Real	0.000	0.447	0.574	IV	Medium
25	Rio Jibóia	0.000	0.628	0.575	II	Low
26	Alto Sobradinho	0.000	0.951	0.518	II	Low
27	Alto Jibóia	0.005	0.695	0.541	II	Low
28	Rio Bazuá	0.091	0.109	0.796	IV	Medium
29	M. B. Sobradinho	0.856	0.328	0.625	VIII	High
30	Baixo Sobradinho	0.655	0.575	0.632	VI	High
31	Baixo Salitre	0.000	0.867	0.577	II	Low
32	Rio Pacui	0.151	0.900	0.441	I	Low
33	Riacho Jardim	0.161	0.224	0.523	IV	Medium
34	Alto Salitre	0.086	0.281	0.555	IV	Medium
35	Vereda da Caatinga	0.579	0.061	0.509	VIII	High

5.3 Zona III - High Vulnerability

This zone includes the watersheds located mainly in the southwest and northeast downstream from the sub-médio São Francisco. The watersheds included in this zone are:2, 5, 6, 21, 29, 30 and 35.

The adoption of public policies is urgently recommended for this zone, which is at high risk of water degradation, with the aim of correcting the effects of urbanization, soil erosion, intensive use and occupation of the land, and the dumping of urban industrial waste in water springs.

Other urgent measures which are recommended include the implantation of systems to monitor the water quality, adoption of public health and sanitation policies, and environmental education programs. These measures should be undertaken in a global context of land management, involving diverse actors and partners, international organizations, non-governmental organizations, and federal governmental organizations related to health, housing, and the environment.

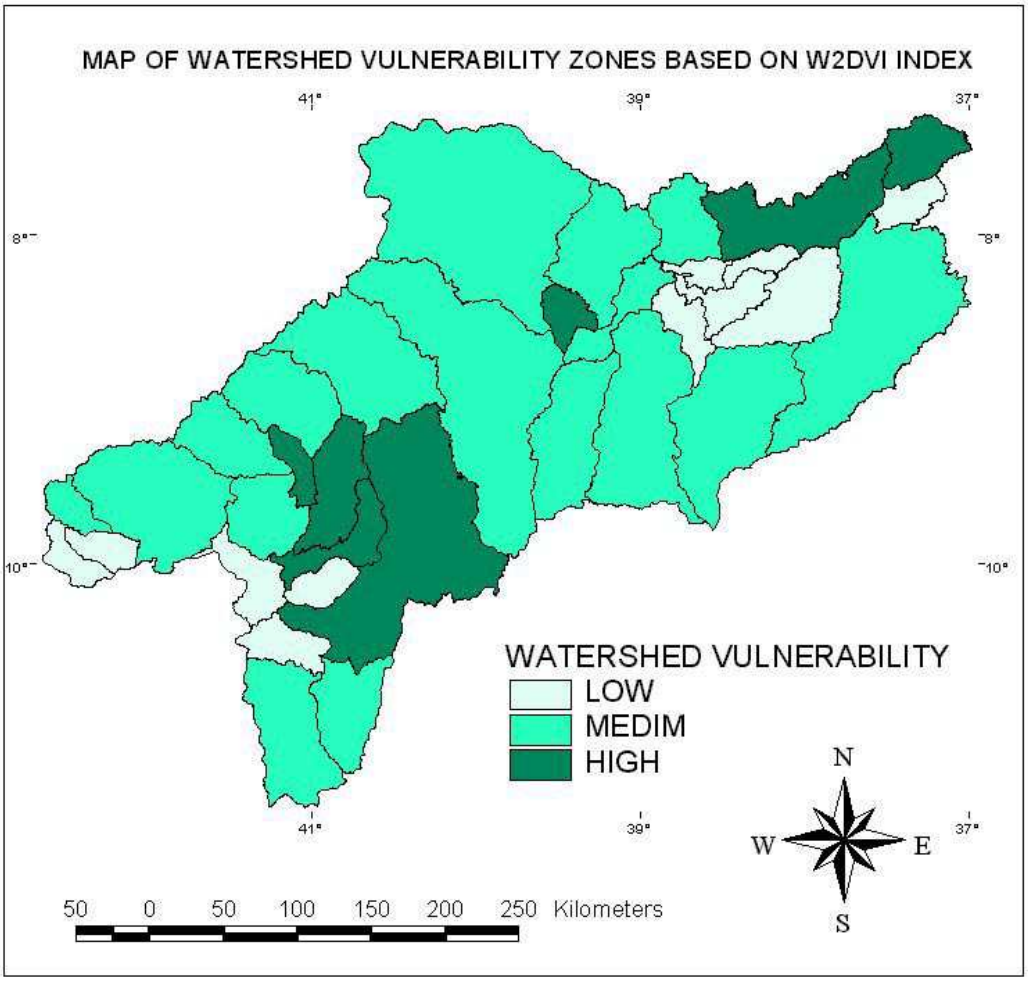

Figure 2 – Map of watershed water degradation vulnerability zones based on W^{2}DVI index

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