HYDROSEDIMENTOLOGIC DISTURBANCE INDEX APPLIED TO WATERSHEDS OF MINAS GERAIS STATE

Índice de perturbação hidrossedimentológica aplicado a bacias hidrográficas do estado de Minas Gerais

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ABSTRACT

Ecological indicators have become important tools for assessment and monitoring of natural resources, being the understanding of the relationship between antropic activities and the environmental response essential for their structuring. Although the development of potential indicators may prove sensitive to many variables, they must demonstrate their ability to take the surrounding conditions, from those relatively preserved to those highly disturbed. Based on this premise, the development of the Hydrossedimentological DisturbanceIndex (HSDI) for environmental assessment at watersheds in Minas Gerais state, emerges as a potential tool to support decisions which should be focused on the improvement of natural resources management. A HSDI proposal was developed from the hydrological, climate and water quality database available in Minas Gerais state, highlighting sediment transport (ST), hydrological stress (HS), groundwater recharge (Rec) and current soil erosion potential (SEP), working with a robust tool for determining the weights of factors with appropriate scientific background and subsequent development of map for analyzing its distribution, having Paraopeba river watershed as study case.

Index terms: Environmental indicators, water resource, soil erosion, sediment transport.

RESUMO

Indicadores ecológicos têm se tornado importantes ferramentas para avaliação e monitoramento dos recursos naturais, onde a compreensão da relação entre as ações antrópicas e a resposta do meio ambiente é fundamental para a estruturação dos mesmos. Embora o desenvolvimento de potenciais indicadores pode se mostrar sensível a diversas variáveis, estes devem demonstrar sua capacidade em retratar as condições do meio, desde aqueles relativamente preservados até aos altamente perturbados. Com base nessa premissa, o desenvolvimento do Índice de Perturbação Hidrossedimentológica (IPHS) para avaliação ambiental de bacias hidrográficas, no Estado de Minas Gerais, surge como ferramenta potencial para subsidiar tomadas de decisão que sejam equilibradas e voltadas para melhorar a gestão dos recursos naturais. Uma proposta de IPHS pode ser desenvolvida a partir da base de dados hidrológica, climática e de qualidade de água disponível no estado de Minas Gerais, destacando o transporte de sedimentos, estresse hidrológico, recarga subterrânea e potencial atual de erosão do solo, trabalhando com ferramentas robustas para a determinação de pesos com a devida base científica e o posterior desenvolvimento de mapas que permitam analisar espacialmente a distribuição do IPHS, tendo a bacia do rio Paraopeba como estudo de caso.

Termos para indexação: Indicadores ambientais, recursos hídricos, erosão do solo, transporte de sedimentos.

INTRODUCTION

The land use in watersheds without technical organization provokes damage, leading to environmental unbalance, with significant consequences for soil conservation and for the hydrological regime, decreasing farmland and impoverishing the soils. The assessment of their condition, according to Dai, Lorenzato and Rocke (2004), involves the consideration of many issues and factors, which vary on different spatial scales, anthropogenic influence and management.

Various algorithms to support decision-making have been developed since the 1980s and according to Trindade-Filho and Loyola (2010), the algorithms currently used in systematic conservation planning can be divided into two large families: heuristic and meta-heuristic. The heuristic reach a solution to a predetermined conservation target, incorporating the principle of complementarity (maximum representation at the lowest possible cost). The meta-heuristic simulates various sets of the "quasi-optimal", overlapping them in order to find a consensus solution, and therefore possibly optimal in terms of formal quality (Margules; Sarkar, 2007). Thus, the process involving the application of these techniques with the aid of algorithms, is called systematic planning, and aims to ensure the allocation of scarce resources for conservation (Margules; Pressey, 2000).

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The process of selecting favorable areas for conservation, according to Humphries, Bourgeron and Reynolds (2008), should not only consider the delineation of areas with land units appropriate to represent the characteristics of interest, but also rather consider the suitability of such units for the purpose of land conservation. Thus, these authors developed an explicit suitability classification for these units through functions based on fuzzy logic in a knowledge base for the ecological features and socioeconomic attributes for a basin of the Columbia River in the United States.

Dai, Lorenzato and Rocke (2004) developed the WAS model ("Watershed Assessment for Sediment"), enabling various experts to contribute to an integrated assessment of watersheds in the U.S. state of California, as a decision support tool, and providing resources to assist in land use policy and regulatory decisions.

In this context and having the hydrological, climate and water quality databases readily available in Minas Gerais state, it becomes plausible to develop an index to quantify the degree of hydrossedimentological disturbance in watersheds of the state, based on a weighted sum structured by a logic of environmental variables associated with soil and water resources, in an inference system to support the environmental management.

MATERIAL AND METHODS

Decision support system (DSS)

The relative importance of each variable in the assessment of impacts on water resources should be made by associating weights to the analysis criteria of each topic, using multi-criteria analysis methods.

One of the main multi-criteria decision analysis methods is the AHP (Analytic Hierarchy Process). The AHP method aims to promote overcoming the cognitive limitations of decision makers, being applied to synthesize a variety of decision problems in different knowledge contexts. It is a simple and robust method, with the ability to assess qualitative and quantitative factors (Shiau et al.,2002) and provide the decision maker with a better evaluation and understanding of the problem (Gomes; Araya; Carignano, 2004).

The AHP structures decision models based on a hierarchy of criteria and sub-criteria, where the weights in a set of sub-criteria are derived as a solution of a vector to an array of pairs of comparisons of relative importance among the sub-criteria, having as a reference, its importance to the main criterion.

Characterization of weights: the *Criterium Decision Plus (CDP* tool)

The CDP program uses the AHP to compare various impacts, being a DSS directed toward the choice of alternatives according to the degree of influence or priority of the attributes identified and selected to compose the analysis. These attributes are organized in a hierarchical decision, once this manner allows translating for empirical knowledge into data which is understandable to the mathematical treatment performed by SSD.

This program provides two basic interfaces to the user, the first known as "Brainstorm" and the second as "Decision Hierarchy". The first elects the criteria, usually based on the opinion of experts, decision makers and, or, local stakeholders and the CDP allows this environment to facilitate the construction of the hierarchical diagram automatically. The second interface is the hierarchical decision diagram, where the first block is the goal and the last, the alternative. Figure 1 represents a diagram drawn in the CDP for the development of an HSDI for Minas Gerais state. The number to the left of the Goal represents the sum of the weights of contribution which is always 1. The values of the criteria boxes ("Level 2") are results of the paired comparison between them. The sub-criteria ("Level 3") present their priorities based on the value of the criterion in which they group.

This review process allows the scientist to use the AHP technique in two ways: "full pairwise" and "abbreviated pairwise". The first performs pairwise comparison between all sub-criteria of a specific criterion, and the second performs the comparison according to the position of the element in the decision diagram drawn.

After structuring the model, it has the criteria relative weight determination stage. One of the more applied alternatives is the "direct", which requires only subjective judgments or intuition to determine the importance of one criterion over another. These values vary on a numeric scale (0-1) for each criterion. After this process, the program calculates the weights for the criteria and sub-criteria considered in the analysis.

After the sub-criteria weights estimation, it is necessary to verify their validity, which is accomplished by examining if the empirical knowledge about the sub-criteria determination is compatible with the selected criteria. As shown by Antoun Netto et al. (2011), the CDP program uses a sensitivity analysis, purposing to improve the structure of the model for the interpretation of the criteria and criteria revaluation.

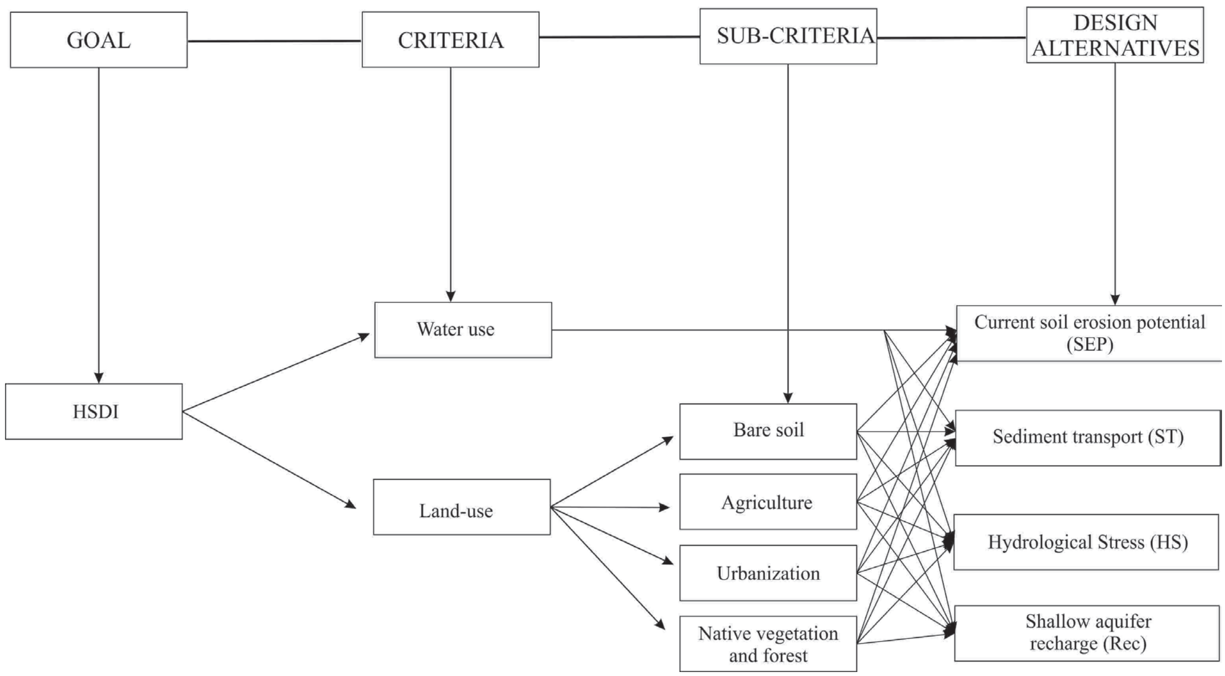

Figure 1 – Hierarchical decision diagram for prioritization of criteria for analysis of hydrossedimentological disturbance in watersheds of Minas Gerais state (Adapted from the CDP program).

This step is done by interpreting a chart prepared by the program for each criterion that indicates how changes in the criteria weights would affect the decision. For this purpose, the program calculates a value called "crossover percentage", which is the proximity of the point at which there is no change in the priority order of the alternatives. Low values indicate higher criteria sensitivity to changes in the weights, thus, the making of small alterations causes large variations in the decision values, indicating that another alternative comes to be studied. The sensitivity threshold is usually considered 10% (Auntoun Netto et al., 2011).

Finally, the weights calculated and validated in the CDP are used to construct the Hydrossedimentological Disturbance Index by ArcGis program (ESRI, 2004), using "raster calculator tool", where the first step to implement the analysis is to develop thematic maps of factors thatwill compound the HSDI and that will assist in understanding and analysis of alterations in the environment.

Factors considered for HSDI development and its applicability to Paraopeba river watershed

Taking as a reference the data availability for Minas Gerais state, it is possible to develop an HSDI for watersheds, considering the land and water uses as criteria and as analysis factors ("Design Alternatives"), those related to the hydrology and land use in the watershed, such as sediment transport (ST), current soil erosion potential (SEP), hydrological stress (HS) and groundwater recharge potential (Rec).

The ST factor can be obtained based on data series measuring total suspended sediment and their flows, adjusting discharge curves (TS = f(Q)) for sub-watersheds located in the watershed. These data sets are monitored by the Minas Gerais Water Management Institute (IGAM) and are available in its website.

The current soil water erosion potential (SEP) is an important factor by adding information related to land use in the watershed as well as its natural vulnerability to the accelerated erosion process. For this application, a simpler model whose necessary data base is widely known and available in the literature, was used. Within these criteria, the best alternative is the RUSLE model ("Revised Universal Soil Loss Equation"), which allows the preparation of maps that qualitatively reflect the water erosion behavior on a watershed scale (Beskow et al., 2009).

The hydrological stress (HS) consists of the analysis of the relationship between the volumes officially granted and minimum availability of flow in the watershed. The first data can be accessed in water resources management agencies (IGAM for state and ANA for federal rivers) and the minimum flow availability associated to the reference flow to grant ($Q_{90\%}$or$Q_{7,10}$), calculated based on historical series of flows. The latter data sets are also available in the "Hidroweb" system which is managed by the National Water Agency (ANA). The work of Durães, Mello and Naghettini (2011) is one of the pioneers in the processing and application of the hydrological stress concept in the Minas Gerais state, whose original concept was developed by Gordon et al. (2004). In this work, it was considered as reference to hydrological stress the $Q_{90\%}$ discharge value.

The groundwater recharge potential (Rec) in watersheds can also be studied based on the historical flow series, consisting of an analysis of the base flow throughout of representative hydrological year (Durães; Mello, 2013). The calculation should be performed working with Barnes's method, which is the most used and recommended for this type of study.

To generate HSDI it is necessary that the factors are integrated and some technique is necessary to normalize the data so that they remain between 0 and 1, given that each one is obtained in a distinct technical unit. The following equation suggested by Vieira and Studart (2009), may be recommended.

$$Xi_{normalized} = \frac{(X_i - X_{min})}{(X_{max} - X_{min})} \quad (1)$$

in which X_i is the measured value, X_{min} is the lowest value of the variable to be standardized and X_{max} is the highest value of the variable to be normalized.

From the normalization and identification of the factor weights, HSDI can be calculated by:

$$HSDI = \sum (w_1 \cdot ST + w_2 \cdot SEP + w_3 \cdot HS + w_4 \cdot Rec) \quad (2)$$

In which w_i represents the factors weight obtained by CDP.

Once equation 2 is calibrated, it can be applied to evaluate different scenarios, identifying the most impacted areas, assist in planning and allocation of natural resources and compare different sub-watersheds in terms of their environmental quality.

Based on the scientific characterization of the factors and their classifications defined by the scientific community, we stipulated a six-level classification key for the HSDI, as shown in table 1.

Table 1 – Levels for HSDI characterization in watersheds for Minas Gerais state.

Class	Context (%)
VeryLow	0 – 15
Low	15 – 25
Average	25 – 45
Averageto High	45 – 60
High	60 – 75
Very High	>75

RESULTS AND DISCUSSION

After analyzing the main criteria and the weights of characterized factors, there are two additional features of CDP, a sensitivity analysis, which provides diagnostics of the robustness of the model, and a "trade-off" analysis that describes how changes in the attribute values can affect their interaction to improve the priority score (Reynolds et al., 2009). In this context, it was observed that sediment transport was the factor with the highest weight in the final CDP analysis for Paraopeba river watershed (0.327), while groundwater recharge was the most sensitive, however, with a crossover higher than 10%, and with the lowest weight (0.098). These results proved adequate because these factors are presented as a function of the characteristics of climate and the erosion process as a whole, i.e., a junction of soil erosion caused by water with the hydrological behavior of the watershed, including the hydraulic characteristics of channels that comprise the drainage network and human interventions in land use what increase the sediment transport capacity. The current soil erosion potential (SEP) had the second highest weight (0.291), followed by hydrological stress (0.284), due to economic and social pressures arising from the demands of users, generating significant disturbance. Based on this finding, in terms of the practical application of HSDI, we can conclude that criteria for regulation and better technologies for water uptake and its management at Paraopeba river watershed may reduce this pressure and the index could even spatially capture the more disturbed sub-watersheds.

Antoun Netto et al. (2011) used the CDP to demonstrate the feasibility of using computational tools acting as decision support in the choice of linguistic variables for selection of a cartographic projection. Through sensitivity analysis, the authors found that even if a variable was the most sensitive to changes in its weight, its amount of "crossover", compared to the reference value, was much higher, which demonstrated the ability to explain the behavior of the proposed index based on the factors considered. After the validation of the model factors, the step of obtaining the weights of each factor is undertaken.

Although the judgments made for the construction of the proposed HSDI are based on perceptions of specific factors associated with the land and water uses, the role of the index is to assist, ensuring quality, organization and documentation of the decision analysis process, making the value judgments explicit and analyzing conflicting goals.

Maps of each factor can be obtained in matrix form, with their values normalizedon a scale from 0 to 1. Figure 2 presents normalized maps of factors ST (a), SEP (b), HS (c) and Rec (d), respectively, for Paraopeba river watershed.

Some considerations can be drawn from figure 2.It's possible to observe that the factors considered in HSDI showed, in general, lower values in the headwater region of watershed (south), while in the lower part (north), they tended to be higher. Another highlight is that in the case of this particular watershed, it was possible to work at a level of 5 sub-watersheds. This condition may not be possible for another watershed, due to the spatial quality of the available data, especially sediment transport, since it depends on analyzes that require higher resources, and at the same time the need for fluviometric stations in the same location of the measurements. This is therefore a major challenge when proposing the development of an HSDI, that is, a suitably refined database, both in space and in time.

The HSDI map obtained to Paraopeba river watershed is presented in figure 3. It is observed that the level of the index ranged from "Average" to "Average to High". Areas classified with level "High" were found especially in areas with bare soils, which have a high SEP value, combined with high hydrological stress (high water demand) and low groundwater recharge (Figure 2). This behavior describes the ability of the index to depict the characteristics of the watershed and its applicability as an indicator of its environmental situation, as well as the targeting of actions associated with the natural resources management contained in it.

The headwater region (south) of this watershed is characterized by pastures and native vegetation, with low hydrossedimentological disturbance due to its lower HS levels and low ST and moderate SEP. Urbanized areas tend to present an "average to high" HSDI. Although the urban area contributes significantly to sediment transport, in regard to its erosion potential this factor becomes practically zero, since the RUSLE value simulated by the model will be close to zero. Thus, for urbanized areas, the factors with the greatest response to the HSDI will be ST, HS and Rec. The first two factors tend to be high due to the characteristics of urbanization process, with increased runoff velocity (increasing the sediment transport capacity) and increased water demand (especially water supply and industrial activities with impact in water quality). On the other hand, it will present low groundwater recharge potential due to the soil sealing. The HSDI proposed here demonstrated to have the ability and sensitivity to capture these situations.

It is important to note that other factors could be aggregated and, or, better structured, however, it is essential that there is the same database for all watersheds under study. Thus, for example, the availability of in scale, high precision hydrogeological data, could be combined to factor Rec or constitute a specific factor associated with groundwater. However, such information, although existing, is in a rough scale for watershed studies.

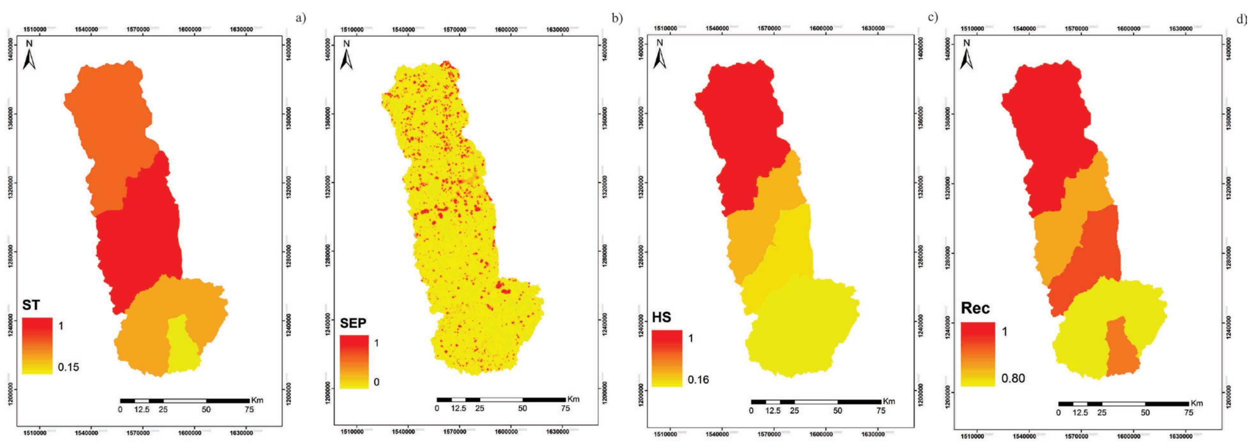

Figure 2 – Raster maps normalized for factors considered in structuring an HSDI for Paraopeba river watershed.

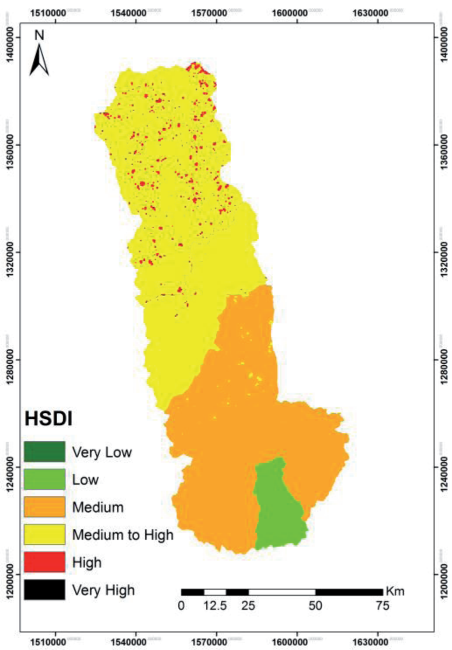

Figure 3 – HSDI map for Paraopeba river watershed, Minas Gerais state developed from land and water use factors.

A final observation is relevant. To compare the degree of hydrossedimentological disturbance among different watersheds it is necessary to group the factors for subsequent normalization, since for this (Equation 1), the maximum and minimum values will depend on each watershed. This means that a given normalized value for a particular watershed will have a different value when grouped with those of another watershed. This allows the relative comparison of the different degrees of disturbance between two or more distinct watersheds.

CONCLUSIONS

The multi-criteria analysis is a unique tool for environmental analysis in watersheds, allowing building an index robust enough to quantify the impacts of activities that can promote negative impacts regarding land and water uses.

The HSDI structured similarly to that presented in this work, assists in the evaluation and differentiation of sub-watersheds regarding the degree of disturbance associated to land and water uses, which enables the precise allocation of resources for conservation.

It is noteworthy that the proposed HSDI shows potentially suitable for employment in other watersheds in Minas Gerais state, provided there is a satisfactory database both in space and time, allowing the characterization scientifically based on the factors associated with the land and water uses.

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