



Assessment of impacts on ecosystem services provided by geodiversity in highly urbanised areas: A case study of the Taubaté Basin, Brazil

Fernanda Coyado Reverte^{a,b,*}, Maria da Glória Motta Garcia^a, José Brilha^b, Alan Uchoa Pellejero^c

^a Institute of Geosciences, University of São Paulo, São Paulo, Brazil

^b Institute of Earth Sciences, University of Minho, Gualtar Campus, Braga, Portugal

^c Institute of Mathematical and Computer Sciences, University of São Paulo, São Paulo Brazil

ARTICLE INFO

Keywords:

Ecosystem services
Geodiversity
Taubaté Basin
Urban expansion

ABSTRACT

This work presents a method to identify, to evaluate and to quantify the losses of the offer of ecosystem services provided by geodiversity, using as a case study the Taubaté Basin region, a highly urbanized portion of southeastern São Paulo State, Brazil. Our method considers not only the qualitative analysis of the abiotic aspects, but also the historical and cultural context, in which the geodiversity elements are crucial for local economy development. The method is based on: i) Qualitative evaluation and definition of six Essential Geodiversity Variables (EGVs), used as the basis for the identification of 53 ecosystem services distributed into four functions: regulating, supporting, provisioning, and cultural; ii) Definition of land use categories based on two land use maps elaborated in order to compare the transformation occurred in the region between 1986 and 2016; iii) Quantification and evaluation of the impacts on the offer of ecosystem services caused by land use transformations occurred in region in a 30-year gap. The results showed that anthropogenic action is the main factor that alter the availability of local services, with emphasis on the supply of water, soils and mineral resources, and its potentially influence on the quality of life of certain species. We reinforce the view that public policies on land management and planning should consider the ecosystem assessment, as it provides evidence to propose actions to mitigate impacts and for environmental compensation, favoring the sustainable use of resources by society.

1. Introduction

The concept of ecosystem was coined by Tansley (1935) to identify a set of communities composed by biotic and abiotic elements, which occupy a place and interact with each other and with the environment, to create a stable and balanced system. The dynamics of a self-sufficient ecosystem influences the supply of natural resources that live beings benefit from. However, the growing transformation of the urban environment by society has increasingly demanded the use of natural resources, influencing these dynamics. Anthropogenic activities, such as inappropriate land use, emission of pollutants and deforestation, generate negative impacts to ecosystems, affecting the flow of environment services that are fundamental to sustain life on Earth.

Since the 1960s, when King (1966) and Helliwell (1969) introduced the concept of natural benefits, the scientific community has been increasingly interested in understanding and describing how the ecosystems work and how they influence the well-being of the population

(Ehrlich and Mooney, 1983; De Groot et al., 2002; MEA, 2005). In the mid-1990s, this concept also started to have an economic bias, referred to as natural capital (Costanza and Daly, 1992; Gómez-Baggethun et al., 2010; Bennett et al., 2014), and which corresponds to the stock of natural resources that generate a flow of tangible and intangible benefits, directly or indirectly useful to humans. These benefits are known as ecosystem services (Costanza et al., 1997).

Many authors have suggested different classifications for the ecosystem services (Costanza et al., 1997; De Groot et al., 2002; Daily and Farley, 2004; Boyd and Banzhaf, 2007; Brown et al., 2007; Fisher et al., 2009; Teeb, 2010; Farley, 2012). However, only after the Millennium Ecosystem Assessment (MEA) — considered the first major international effort to explore the relationship between human welfare and services — did these concepts become more prominent, especially in the scientific and political spheres (Pandeya et al., 2016). The definition proposed by the MEA in 2005 is the most-widely used and groups the services into four functions: provisioning, regulating, supporting and

* Corresponding author at: Institute of Geosciences, University of São Paulo, São Paulo, Brazil.

E-mail addresses: fernanda.reverte@alumni.usp.br (F.C. Reverte), mngmgarcia@usp.br (M.d.G.M. Garcia), jbrilha@det.uminho.pt (J. Brilha), alan.pellejero@usp.br (A.U. Pellejero).

<https://doi.org/10.1016/j.envsci.2020.05.015>

Received 4 December 2019; Received in revised form 3 May 2020; Accepted 19 May 2020

Available online 20 June 2020

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cultural.

Although intensely discussed in recent decades, the existing classifications for ecosystem services often neglect the relevance of the geodiversity elements for the service flows. Geodiversity comprises all abiotic resources that make up nature (e.g. minerals, rocks, soils, rivers and landforms, as well as geological phenomena such as weathering and vulcanism) and whose products are fundamental for the generation and maintenance of natural resources (Gray, 2013). It is worth noting its importance in the context of knowledge, since it allows us to understand the history of Earth, the many geological events that happened throughout the evolution of the planet, and which are recorded in rocks and sediments.

Due to the importance of geodiversity elements in the provision of natural resources, some authors have included the geological aspects in the classification of ecosystem services (Gray, 2011, 2013, 2018a; Gordon et al., 2012). By emphasizing the intrinsic value of geodiversity, Gray (2013) adapted the definition proposed by MEA (2005) and included a fifth category called “Knowledge Services”, which refers to the use of geodiversity elements for research, teaching and spreading geosciences. The author has maintained this proposition in recent papers (Gray, 2018b, 2019), in which these ecosystem services are referred as Geosystem Services.

Brilha et al. (2018) brought a different proposal of classification to the benefits provided by geodiversity, focusing on the sustainable use of natural resources within an ecosystem approach described in consolidated proposals (MEA, 2005; Teeb, 2010; Haines-Young and Potschin, 2018). For each service — regulating, supporting, provisioning and cultural — the authors defined a set of goods and processes with 17 parameters. The “Knowledge Services” (Gray, 2013) is considered as a sub-item in the “Cultural Services” group. All these parameters attempt to illustrate the relationship between nature, geodiversity and society, and emphasize their importance in the provision of resources as a determining factor in the quality of life in the region.

In this context, Schrodt et al. (2019) proposed a list of variables to describe the resources and processes that occur on the Earth's surface, called Essential Geodiversity Variables (EGVs), classified in geology, geomorphology, soils and hydrology. According to the authors, these categories can underpin public policy proposals for geoconservation, balancing economic, social and environmental aspects in promoting sustainable development.

The Taubaté Basin is located in the southeastern region of São Paulo State, between the Mar and Mantiqueira mountains, which are true strongholds of Brazilian biodiversity. The region has a dense hydrographic network, represented by the Paraíba do Sul river and its tributaries, which supply important industrial centers and a large part of the local population. However, this geodiversity has been threatened by the effects of weathering and especially by anthropogenic activities, interfering with the flow of services.

Given the above, this study aims to identify, evaluate and quantify the ecosystem services provided by geodiversity in the Taubaté Basin region, so as to establish the importance of natural goods in the socioeconomic and environmental development of the region. Thus, it is intended to foster the interest of the government in the management of these resources, allowing the creation of necessary measures to mitigate human impacts, which strongly affect geodiversity elements and interfere in the provision of local ecosystem services.

2. Study area: Location and geological context

Located in southeastern Brazil, in the southeastern portion of the state of São Paulo, Taubaté Basin comprises eleven municipalities in the Paraíba Valley and covers an area of just over 2300 km² (Fig. 1). The region has lately been under transformation due to the high density of population and to the urbanization, which requires infrastructure improvements to meet this growing demand. In addition, the area is crossed by major highways that link two of the Brazil's most important

commercial and industrial hubs: São Paulo and Rio de Janeiro.

Geologically, the Taubaté Basin is part of a set of basins that form the Continental Rift of Southeastern Brazil (CRSB), a regional Cenozoic tectonic feature formed by a narrow and depressed 900 km-long strip, (Riccomini, 1989). Taubaté basin is the largest tectonic depression of the rift, with about 850 m-thick, 170 km-long and 25 km-wide (Riccomini, 1989; Fernandes and Chang, 2003; Vidal et al., 2004).

The geological events related to the evolution of CRSB are associated with the final stage of fragmentation of the supercontinent Gondwana, which were responsible for the formation of the South Atlantic Ocean. These events have generated rocks that represent part of the geodiversity of the Paraíba Valley, whose geological wealth is gradually vanishing due to the extreme vulnerability and fragility of its evidences.

3. Materials and methods

This work was carried out in five stages:

- (i) References research: to identify and describe the abiotic resources used for the qualitative assessment of geodiversity and ecosystem services.
- (ii) Identification of the Essential Geodiversity Variables (EGVs) – based in Schrodt et al. (2019): six EGVs were identified in the study area: i) rocks and structures; ii) mineral resources; iii) fossils; iv) landforms; v) water resources; and vi) soils.
- (iii) Identification of ecosystem services provided by geodiversity elements: these services were characterized based on the qualitative evaluation of the EGVs defined in the previous step, and also on Brilha et al. (2018).
- (iv) Land use mapping: based on Google Earth® images land-use maps were produced (1986 and 2016, both in December). Through the interpretation of both maps and using the Quantum Gis® software package, six polygons were delimited referring to the identified areas, called “Land Use Categories”: native vegetation, mineral extraction, urban occupation, forestry and farming (Table 1). These data allowed us to assess the increase of impacts caused by urban development due anthropogenic activities and were the basis for the quantification of services.
- (v) Quantification of ecosystem services provided by geodiversity elements: a three-stage method for the services quantification is proposed (adapted from Longo and Rodrigues, 2017):

➤ Firstly, the Significance (σ) of the natural environment change caused by the “Land Use Categories” was defined based on the parameters described in Table 2. For each parameter — Coverage, Magnitude and Reversal Factor — is given a value ranging from one to three, except coverage which varies from one to two, Local and Regional, respectively, due the size of the area of study.

The Significance (σ) is the sum of the values given to each parameter, as shown below (Fig. 2):

From the statistical point of view, the division of the Significance (σ) in three parts (low, medium or high) permits to identify how representative these parameters are in the quantification context. The choice of whole positive values for the classification results from the fact that the data are ordinal qualitative (or categories) (James et al., 2013), consistent with the respective descriptions made in the Table 2. In order to avoid biased results we did not consider any of the parameters equal to zero since its calculation depends of some product operations.

The numerical data for the quantification of ecosystem services are arranged in tables, containing inline and column information to be associated. For this reason, the following mathematical description will use matrix notation. Therefore, we will consider the matrix $A_{m \times n}$ such that $A = (a_{ij})$, and:

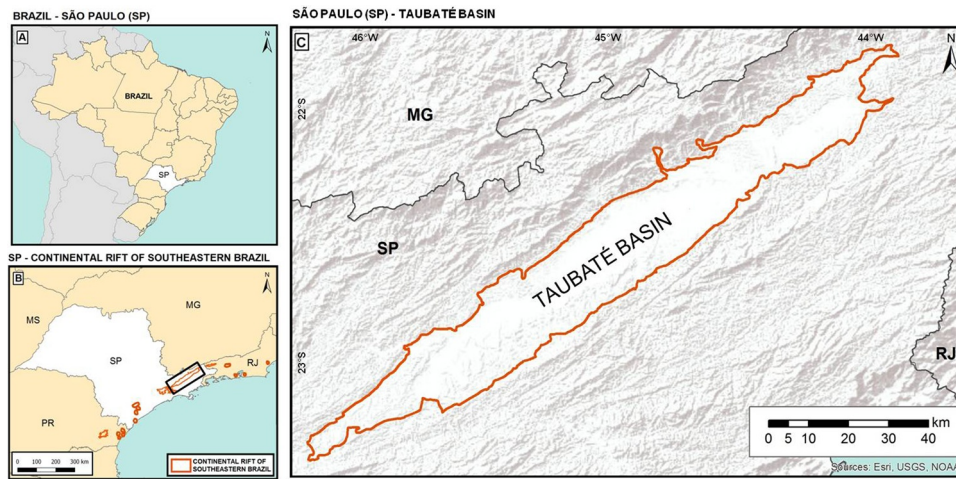


Fig. 1. Location of the study area showing the Continental Rift of Southeastern Brazil.

- (i) $A_{m \times n}$: the rectangular matrix consisting of “m” rows and “n” columns; and
- (ii) $a_{i,j}$: the element of the array A that occupies the i – th row and j – th column.

Associating the data of Table 2 to the significance rating it was possible to create the matrix A (corresponding to Table 7, described in the topic “results” below) to obtain the significance value.

The quantification in Table 7 allowed us to calculate the *Significance* (σ), given by: $\sigma = \sum_{j=1}^3 a_{i,j}$, with $1 \leq i \leq 5$. In the case study, the maximum value for the *Significance* (σ) occurs when $i = 3$; that is, in the “Urban Occupation” category. Thus, $\max \{\sigma\} = 8$.

➤ Secondly, we quantified the relationship between the “Land Use Categories” and the ecosystem services described in Brilha et al. (2018) (Table 3), which allowed the construction of matrix B (corresponding to Table 8, described in the topic “results” below).

In matrix B, formed by numerical data from Table 8, it is observed that the maximum value for an element $b_{i,j}$ of matrix B, with $1 \leq i \leq 18$ and $1 \leq j \leq 5$, is such that $\max \{b_{i,j}\} = 3$, which is the occurrence of a direct relationship between the “Land Use Categories” and the ecosystem services.

➤ Finally, based on matrices A and B (Tables 7 and 8, respectively), matrix C was obtained (Table 9), whose elements $c_{i,j}$ of C, with $1 \leq i \leq 18$ and $1 \leq j \leq 5$, are such that: $c_{i,j} = b_{i,j} \times \sigma = b_{i,j} \times \sum_{r=1}^3 a_{j,r}$. The set of data obtained from the matrix C allowed us to calculate the *Relative Significance* (σ_{rel}) per ecosystem service, which enabled the quantification of the loss of ecosystem services.

The *Relative Significance of the ecosystem services group* (σ_{group}) was calculated using the simple arithmetic mean of the values of *Relative Significance* (σ_{rel}) of each service.

4. Results

4.1. Essential geodiversity variables (EGVs)

For the Taubaté Basin, six EGVs were defined as the basis for the identification of ecosystem services, showing the importance of abiotic resources in local socio-environmental development. These EGVs represent the physical aspects identified in the qualitative assessment of the basin area. The consolidated results of this description are presented in Table 4.

4.2. Ecosystem services provided by geodiversity

4.2.1. Regulating services

These services refer to the benefits obtained through ecosystem processes, such as water cycle regulation, water purification and erosion control, and their influence on the natural management of atmospheric and terrestrial processes as much as the quantity and quality of natural resources.

Among all atmospheric processes, the hydrological cycle is a major factor for life maintenance. In the study region, it is associated to the Paraíba river and its tributaries and is responsible for supporting the refill flow provided by groundwater, providing water to the bodies that converge to the river basin. Other important regulating functions can be associated with the Paraíba do Sul wetlands. Both riparian zones, such as the forest systems located on the banks of watercourses, as the existing river islands in some stretches of the river (Fig. 3A), provide a number of ecosystem services: maintenance of the microclimate and the quality of water, and reduction in erosion rates, sedimentation and runoff (Castro et al., 2013; Hepp and Gonçalves-Junior, 2015).

In relation to terrestrial processes, the rock cycle controls the content of carbon in the atmosphere, released through weathering processes that influence climate throughout the geological time (Fig. 3B). Soils also play an important regulating role, since they have the greatest carbon stock in terrestrial ecosystems, thus helping balance the concentration of the gas in the atmosphere (Bruce et al., 1999).

4.2.2. Supporting services

Geodiversity elements are a form of support for the development of activities of live beings, be it the use of these resources as a habitat, such as caves, or as a substrate for construction of developments. They also comprise places that are used for storage — such as landfills or natural water or oil reservoirs — and burials (human or animal), in addition to the development of soil profiles as support for biodiversity and other economic activities related to agriculture (Gray, 2013; Brilha et al., 2018).

Soils have always played key roles in the economy of the region, serving as the basis for the development of numerous farming activities that have modified ecosystems aiming at optimizing the production to meet the demands of the national and international market.

In the early nineteenth century, it was in this place that coffee became the main Brazilian export product, reaching its peak in 1850, when 37% of farming production and 80% of all coffee in the state of São Paulo came from the Paraíba Valley (Devide, 2015) (Fig. 4A). The culture of coffee, initially produced by slave labor, brought great economic prosperity and political influence to local coffee farmers

Table 1

Classes and interpretation for the elaboration of land use.

CLASS OF USE	DESCRIPTION	EXAMPLES OF THE IMAGES ANALYZED
Mineral Extraction	Areas where mineral extraction occurs on riverbanks and rocks	 
Farming	Areas where agriculture (plant growing) and livestock (animal growing) activities take place	 
Native Vegetation	Atlantic Forest (appears in the image heterogeneously and without continuity)	 
Forestry	Monoculture of Eucalyptus (it presents homogeneity in the image, following a planting pattern with spacing between trees, or following the local land level curves)	 
Urban Occupation	Cluster of buildings for residential, commercial, service or second home use (rest/leisure)	 

Table 2Criteria used to classify the Significance (σ) of alteration of natural environment in the Taubaté Basin.

Parameter		Classification		
Name	Description	Class	Value	Description
Coverage	Size of the impacted area	Local	1	Local and limited changes
		Regional	2	Widespread changes
Magnitude	Intensity of changes	Low	1	Minor changes
		Medium	2	Significant changes
		High	3	Very significant changes
Reversal factor	Capacity of restoration	Fully reversible	1	The initial conditions can be fully restored
		Partially reversible	2	The changes can be ceased avoiding further damages
		Irreversible	3	Not possible to cease changes or to restore initial conditions

Significance (σ)					
Low		Medium		High	
3	4	5	6	7	8

Fig. 2. Significance rating.**Table 3**

Ecosystem Services (Brilha et al., 2018).

ECOSYSTEM SERVICES	DIVISION
REGULATING Conditions that allow the existence of life and modern society	R1. Atmosphere R2. Geosphere R3. Hydrosphere
SUPPORTING Of life conditions and social development	S1. Soil S2. Water S3. Surface rocks and landforms S4. Underground rocks and landforms
PROVISIONING Of renewable and non-renewable resources which are fundamental to life and society	P1. Nutrients P2. Food and drink P3. Water P4. Construction materials P5. Industrial and metallic minerals P6. Energy resources P7. Ornamental products
CULTURAL Contribution of the physical environment to the development of cultural activities	C1. Wellness and health C2. Recreation C3. Human history C4. Knowledge

(Sobrinho, 1978).

The area is currently important due to its flood rice production. This technique requires intense availability of water resources, and its development directly depends on the Paraíba do Sul river. It should be noted that agriculture also corresponds to a provision service, in the case of food, as we will see below.

Regarding the use of geodiversity for storage, there are six landfills in the region that function as large complexes for processing industrial, commercial, hospital and domestic waste. Such facilities contribute to reducing the potential risk of soil and water contamination derived from anthropogenic activities.

There are also archaeological remains, such as burial coffins used by the indigenous people who inhabited the area in the pre-colonial period, as well as other lithic artifacts, dated from the 12th century (Caldarelli, 2003) (Fig. 4B). Although archaeological sites are part of cultural services, in this case we are referring to the use of the subsoil for burial of these peoples, which is a support service.

4.2.3. Provisioning services

These are the services provided by ecosystems for the benefit of species that inhabits the region, especially the human being. They are often associated with monetary value, as it occurs with mineral resources, which helps to be recognized by the society.

Among the provisioning services offered by local geodiversity elements, the Taubaté Aquifer and the Paraíba do Sul river Basin play crucial roles as water sources, in the development of the economy and of the quality of life of the population that lives in the cities within the basin area and also in its surroundings (Fig. 5A).

The existence of this reservoir is directly related to sediments of Resende and Tremembé Formation. This aquifer is recharged by direct rainfall over the basin, and natural discharges into the Paraíba do Sul river. The aquifer, which covers an area of approximately 2340 km², has higher productivity in wells located in sandy sediments, whose flow rates may exceed 120 m³/h (Durigan and Simões, 2015). On the other hand, the Paraíba do Sul river Basin supplies water to more than two million inhabitants in the state of São Paulo alone.

Another significant provisioning service refers to the supply of mineral resources, especially sand and clay. According to the National Department of Mineral Production (DNPM, 2016), 60% of the total mining concessions in the entire region correspond to sand exploitation, most of which targets the construction market (Fig. 5B). Clay deposits are associated with the Tremembé Formation shales, consisting of clay minerals which are marketed under the name of “bentonite” after undergoing chemical processes. Bentonite is used for soil sealing, clumping of smelting sand, oil processing in the production of biodiesel, fertilizers, pesticides, among other applications.

Although clay and sand correspond to the main mineral resources provided by the geodiversity elements in the region (Fig. 6), other materials are also extracted for economic purposes (Table 5).

4.2.4. Cultural services

They refer to the intangible benefits obtained from ecosystems and that may favor the economic and social development of a region, contributing to the well-being of society through spiritual and cultural enrichment, reflection on natural processes, leisure, ecotourism and recreation (Gray, 2013; Brilha et al., 2018). It also covers scientific knowledge, that is, the use of geodiversity elements to promote the teaching and dissemination of geosciences (Reverte et al., 2019).

The variety of geodiversity elements in the basin makes it possible to use them in many ways. In tourism, for example, numerous lookouts supported by rocks of the Proterozoic basement are frequently visited by people who seek adventure sports, leisure and contemplation of nature. Marins's Peak and the geosite Itapeva's Peak (Garcia et al., 2018; Reverte et al., 2019) are good examples of such places. Geodiversity also provides leisure and recreation through nature trails, waterfalls where people swim and practice radical sports, like rappelling and climbing. Additionally, the tributaries of the Paraíba do Sul river are commonly visited for the practice of kitesurfing (Fig. 7A).

Table 4
Description of the six EGVs used in the classification of local geodiversity.

EGVs	BRIEF DESCRIPTION	REFERENCES
ROCKS AND STRUCTURES	Faults and structures related with different stages of the tectonic evolution of the basin; Granite and gneiss rocks of the Precambrian basement; and Sedimentary rocks different depositional contexts: Taubaté Group (Resende, Tremembé and São Paulo Formations), and Pindamonhangaba and Itaquaquecetuba Formations.	Riccomini (1989); Fernandes and Chang (2003); Vidal et al. (2004).
MINERAL RESOURCES	Industrial minerals: sand and clay minerals; Energy minerals (peat); Quartzite and granite rocks (mined for gravel, stonework, cladding or ornamental purposes).	Cabral Junior et al. (2001); DNPM (2016).
FOSSILS	High diversity, quantity and quality of the fossil record, namely angiosperm leaves and trunks, sponge spicules, crustaceans, worm tubes, gastropods, fish, birds, reptiles and mammals.	Mezzalana (1989); Garcia and Saad (1996) Bernardes de-Oliveira et al. (2002)
LANDFORMS	The basin is part of the Paulista Atlantic Plateau, which is included in a mountain range that is the most prominent orogenic feature of the South American Atlantic coast; and The dissected slopes of the Atlantic Plateau, where there are 600 to 700m-high hills with convex tops, floodplains, and the Paraíba do Sul river fluvial plain.	Almeida (1964); Almeida and Carneiro (1998); Ab'Saber (2003);
WATER RESOURCES	Surface	ANA (2002); Coltrinari (2003); Coelho (2012); CEIVAP (2016).
	Groundwater	ANA (2002); Vidal and Chang (2002); Iritani and Ezaki (2009).
SOILS	The soils of the region fall into four major categories: Argisols, Cambisols, Gleysols and Latosols.	Oliveira et al. (1999); EMBRAPA (2013).

Geodiversity elements are also connected with cultural aspects through historical reports, folk tales and religious issues. Among the historical accounts, in addition to the coffee cycle records, artifacts in ceramic, glass and lithic material — chipped stones, spears tips and hand axes — have been found. They are related to the indigenous people who inhabited the region in the sixteenth century (Lopes, 2014). As an example of folk history, the myth of the “Sleeping Giant” tells the legend of an indigenous that saved his people from the explorers in the 16th century and, after the heroic act, lay between the trees in an eternal sleep, turning into a large rock (Fig. 7B). Regarding religious aspects, the municipality of Aparecida is known as the “Mariana Capital of Faith” and is annually visited by more than eleven million people, hence being considered the largest center of religious pilgrimage in Latin America. As a source of artistic inspiration, the French painter Jean Baptiste Debret portrayed the landscape of the Paraíba Valley when he was in the region in 1827, illustrating numerous watercolors that were published in 1843 in his work entitled “Voyage pittoresque et historique au Brésil” (Fig. 7C).

The region also encompasses a relevant geological heritage represented by fossils, which can be used for teaching geosciences, exemplifying the way of life of currently extinct species. In Brazil, fossils are used only for research and exhibition in museums, since their commercialization is a crime. In this sense, it is important highlighting the Natural Museum of History of Taubaté (NMHT), which has an extensive collection of rocks, minerals, fossils and replicas of animals that inhabited the region - *ex situ* geological heritage -, including a fossil skeleton of *Paraphysornis brasiliensis*, a 2.40 m-tall carnivorous bird that inhabited the Paraíba Valley 23 Ma ago, is another example of cultural services. His nearly complete skeleton was found in the city of Tremembé in the decade of 1970 and can be seen in the permanent exhibition of the NMHT (Fig. 7D).

Regarding the dissemination of geosciences, the Taubaté Basin is

considered an open-air school, with potential for the development of research in many fields of knowledge, such as the understanding of geological and geomorphological processes that are responsible for the current landscape. Its strategic location, close to renowned educational institutions in the country — such as the University of São Paulo (USP) — makes it a choice for field work, as well as for activities aimed at teaching, research and extension (Fig. 7E). In the field of geotourism, in addition to visiting the NMHT, only two geosites with geomorphological interests have infrastructure and security and can be explored for tourist visits (Reverte et al., 2019).

The Table 6 summarizes the 53 ecosystem services provided by the geodiversity elements in the Taubaté Basin, distributed among the regulating, supporting, provisioning and cultural categories.

4.3. Land use assessment

For a proper management of natural resources in a certain area, it is important to have a good knowledge of its physical characteristics, land use patterns, and statistical analysis of the local population. Hence, making maps is an effective way to assess eventual environmental impacts (Reverte et al., 2019). Moreover, maps can help in the planning of the territory and in the definition of priority areas for conservation (Pereira et al., 2013). In Santos et al. (2017), geodiversity and urban development maps were used to assess the impacts of urbanization in a tourist zone of the state of Rio de Janeiro, Brazil.

The production of land use maps of the Taubaté Basin, allowed us to quantify urban growth and have provided an accurate assessment of the impacts caused to natural resources, between the years of 1986 and 2016 (Fig. 8A and B).

When maps are compared, it is possible to observe a significant increase in urban occupation and mineral extraction along the Paraíba do Sul river. Other parameters considered in the analysis also varied, as

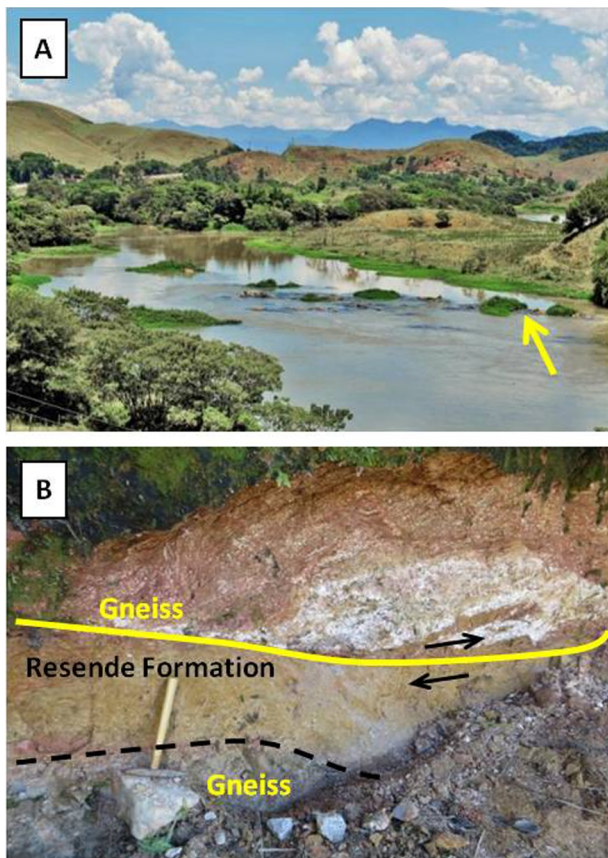


Fig. 3. Regulating services provided by the Taubaté Basin geodiversity. A) Paraíba do Sul river, which is responsible for many regulating ecosystem services, with Fluvial Islands (important in flood control), indicated by the yellow arrow; B) An example of chemical weathering, relevant in the cycle of carbon, in a local geosite (Reverte et al., 2019).

shown in Fig. 9.

In this figure we can observe decreases in native vegetation and agricultural areas, possibly due to urban expansion, whose anthropogenic activities directly affect the offer of regulation, supporting and provisioning services. In this sense, the agricultural activity is exercised in the region, the farming activity is mainly carried out by small farmers, who combine agriculture and livestock, which are the basis for many agricultural business supply chains. Rice production, which occurs mainly on the banks of the Paraíba do Sul river, and cattle ranching focused on milk production, currently stand out (Fagundes, 2019).

In relation to the areas of mineral extraction, the chart shows even more significant growth. In a period of 30 years there was an increase of 573.65% in mining areas, mainly those located along the Paraíba do Sul riverbanks, since the area of mineral extraction in 1986 was 12.94 km² (bar in blue) and in 2016 was 87.17 km² (bar in gray). This fact justifies the increase of forestry in this period, since a considerable number of mining companies usually plant eucalyptus as a form of environmental compensation. In this context, although eucalyptus plantations contribute to atmospheric regulation services, mineral extraction in a predatory manner may lead to the depletion of natural resources, damaging the elements of geodiversity and its supply as a supply service.

Regarding urban occupation, the region encompasses eleven major cities that are economically relevant due to jobs, education and quality of life they offer, like Guaratinguetá, Lorena and Taubaté. This influences the population's increase, whose growth reached almost 70% between 1986 and 2016 and has occurred in an unplanned manner, damaging the supply of environmental services made available by geodiversity. Reverte et al. (2019) describe how the damage resulting



Fig. 4. Supporting services provided by the geodiversity of the Taubaté Basin. A) Slaves working with coffee in a farm in the city of Lorena. Photo: Moreira Salles Institute collection (1882); B) Funeral urn at an archaeological site of Caçapava, containing bone fragments and lithic materials from the 12th century. Left jaw in the detail. Source: Caldarelli (2003).

from anthropogenic activities has affected both the geological heritage and the natural resources of the region, proposing mitigation measures for the impacts identified.

4.4. Quantification of ecosystem services

As described in methods, the Table 7 results from the association between the data in Table 2 and the values of the significance rating (Fig. 2), indicating the *Significance (σ)* values for each land use category, illustrated in the last column of matrix A.

The values 1, 2 and 3 were determined in according to an evaluation of each parameter considering the area in study. Hence, they were filled in by the authors based on prior knowledge of the field of study. For example, for the category "Mineral Extraction", the authors considered the "Coverage" as "Regional" (2), since the mining areas are distributed throughout the basin; the "Magnitude" of impact caused by mining in the region was considered to be "Large" (3), since it occurs in a poorly planned manner and has caused environmental damage; and the mining activity can be "Partially reversible" (2), since these activities can be planned so as not to further harm the environment. The sum $2 + 3 + 2 = 7$ represents the *Significance (σ)* value for the category in question.

The Table 8 represents the matrix B, created from the correlation between divisions of ecosystem services described in Brilha et al. (2018) — totaling 18 services distributed in four ecosystem functions — and the "Land Use Categories". Three values were established: 1 — when the ecosystem service has no relevant relationship with the assessed category; 2 — when there is an indirect relationship; and 3 — when there is a direct relationship. The filling of matrix B is also subjective

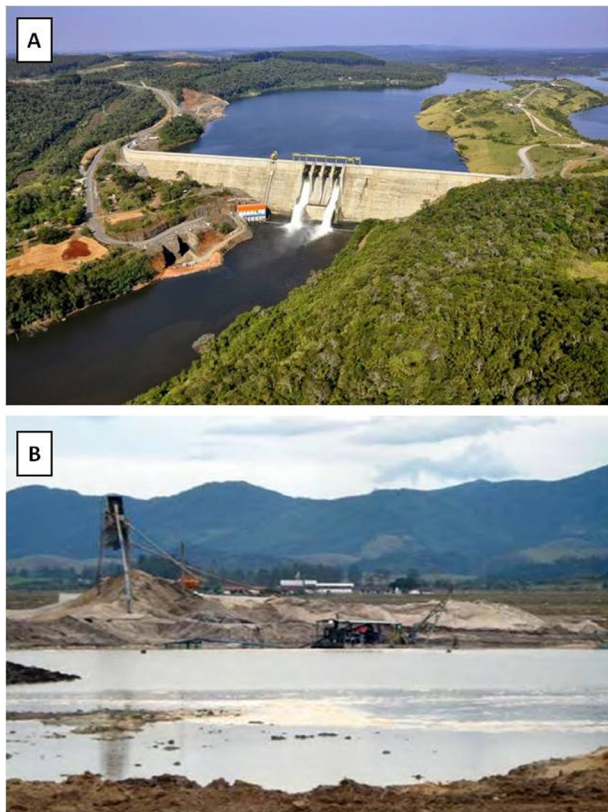


Fig. 5. Provisioning services provided by the geodiversity in the Taubaté Basin. A) Santa Branca Hydroelectric Power Plant. The 500m-long dam was built in the Paraíba do Sul river in the region of São José dos Campos. Source: opetroleo.com.br; B) Active sand mining pit in the municipality of Tremembé. Image: Helio Diniz.

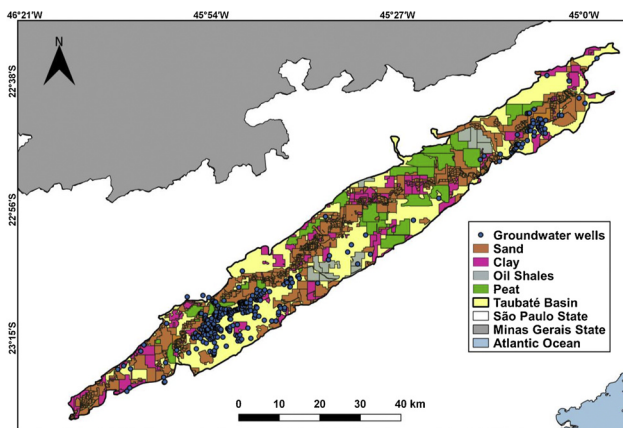


Fig. 6. Location of the areas of extraction of the main mineral resources of the basin (DNPM, 2016) and of the 338 capture wells in the Taubaté Aquifer (CPRM, 2019).

and should be done based on prior knowledge of the area assessed.

From the values obtained in matrices A and B it was possible to calculate the *Relative Significance* (σ_{Rel}) values by ecosystem service and the *Significance of the group* (σ_{Group}) of ecosystem services. The results are expressed in matrix C (Table 9).

As an example of the application of the method, consider the set of ecosystem services. The *sum* S relating to each service s_e is: $S(s_e) = \sum_{j=1}^5 c_{i,j}$, $1 \leq i \leq 18$. For example, in order to calculate the *sum* S relating to the ecosystem service s_2 (Water) consider $i = 5$. Thus, $S(s_2) = \sum_{j=1}^5 c_{5,j} = c_{5,1} + c_{5,2} + c_{5,3} + c_{5,4} + c_{5,5}$
 $= 15 + 14 + 24 + 18 + 12 = 83$

The *Relative Significance* (σ_{Rel}) by ecosystem service is $\sigma_{Relse} = \frac{S(s_e)}{5 \max\{\sigma\} \max\{b_{i,j}\}} = \frac{S(s_e)}{120}$, since $\max\{\sigma\} = 8$ and $\max\{b_{i,j}\} = 3$. For example, if $S = s_2$, then $\sigma_{Rel s_2} = \frac{S(s_2)}{120} = \frac{83}{120} = 69,2$

The diagram on Fig. 10 synthesizes the steps used in the achievement of the values in the proposed method.

5. Discussion

5.1. The importance of the definition of EGVs

The qualitative survey of the geodiversity of the Taubaté Basin region allowed the identification of local ecosystem services, illustrating their importance as a substrate for both the development of economic activities and the subsistence of the living beings that inhabit the area. These services were presented according to their interdependence with the six EGVs defined for the area — rocks and structures, mineral resources, fossils, landforms, water resources and soils —, which represent the elements of local geodiversity, and that should be considered in environmental conservation planning.

From a socioeconomic and environmental perspective, the potential use and fragility of natural resources must be considered when it comes to urban planning. For this, it is crucial to know the geodiversity of a given location to promote a correct land use without interfering with the availability of ecosystem services to the species that inhabit the place. This can be carried out by means of inventories of soils, relief, rocks and minerals, climate, flora and fauna, which practical application is to evaluate the potential use of these resources as life support, considering the fragility of nature, so as not to compromise the intrinsic functionality between physical and biotic components (Ross, 1993).

In this context, some research has been recently done in Brazil considering the ecosystem services of geodiversity as a way to promote more quality of life for the population through the sustainable use of natural resources (Santos, 2018; Silva, 2018; Garcia et al., 2019). However, although these studies indicate the potential use of geodiversity elements by the population, it is necessary to advance in both qualitative and quantitative analyses using well-defined variables in order to propose appropriate management mechanisms adapted to each context.

The EGVs correspond to the variables that describe the resources and processes that occur on the Earth's surface, such as soils and geomorphology (Schrodt et al., 2019). Therefore, the application of this concept on ecosystem services investigations can favor a proper categorization of abiotic resources and direct systematic evaluations of a specific area. In our study, the definition of EGVs as bases for the identification of ecosystem services in the Taubaté Basin region was crucial to detect the potential use of geodiversity elements, whether direct or indirect, as well as to recognize potential threats, creating the scenario for the establishment of concrete proposals on public policies for geoconservation that can contribute to local sustainable development.

5.2. Impacts of anthropogenic activity

The current society has required the use of natural resources in such a scale that it undermines its full renovation. Thus, many environmental problems are caused by predatory practice, which only aim at the exploitation of natural goods and neglect the consequences of such activities. Examples include increased levels of deforestation, contamination of soil and water, air pollution, among other impacts that may alter, irreversibly at times, the natural dynamic of a territory. Such changes are observed in the Taubaté Basin, which has been affected by intense urban change over the last years (Reverte et al., 2019).

The low cost of exploitation and the proximity to large consumer centers make the extraction of sand and clay, an activity started in the 1970s, a very attractive business in the whole area of the basin. This

Table 5
Main mineral goods present in the Taubaté Basin, by municipality (DNPM, 2016).

RAW MATERIALS	LOCATION	USE
Sand	Caçapava, Guararema, Lorena, Jacareí and Tremembé	Aggregate in construction industry
Common clays	São José dos Campos, Jacareí, Taubaté, Pindamonhangaba and Tremembé	Agriculture, pulp and paper industry
Refractory and plastic clays	Pindamonhangaba, Caçapava, Taubaté and Jacareí	Chemical Industry, Foundry, Red Ceramics
Limestone and dolomite	Taubaté	Cement Production, Construction industry
Oil shales	Tremembé	Varied industries and energy purposes
Granite, gneiss and related	São José dos Campos	Cladding, ornamentation, gravel
Lignite	Caçapava	Varied industries and energy purposes
Peat	São José dos Campos, Caçapava and Jacareí	Agricultural fertilizer and energy purposes

represents a serious risk factor both to the environment and to the geodiversity, as it can cause irreversible environmental impacts.

Established by the Forest Code of 1989, the Law No. 7803 (BRAZIL, 1989) classified the floodplains of Brazilian rivers as Permanent Protection Areas (PPA). Nonetheless, many mining pits — some still active — are located in these areas (Fig. 11A), representing a permanent threat to the Paraíba river. In order to lessen the visual impact that such pits could possibly cause to the users of the Presidente Dutra highway, mining companies in the region conceal them by planting eucalyptus, covering up the environmental damage caused by mining activities (Fig. 11B).

In this context, according to Lima (2011), extensive eucalyptus planting in the Paraíba Valley is causing serious environmental damage. Water resources, animals and people are being contaminated by

pesticides. According to the author, the problem is not only the monoculture of eucalyptus, but also its intensive exploitation, which occupies extensive areas, without control and without guarantees of maintenance of the soil and water of these areas for other kind of use.

Countless industries settled and cities grew along the course of the Paraíba do Sul river, dumping waste into its waters, often without any treatment (CEIVAP, 2016). According to Coelho (2012), one billion liters of domestic sewage are discharged daily into the rivers of the region and about 90% of the municipalities do not have a sewage treatment plant. Of the polluting load, approximately 86% comes from domestic effluents, a reflection of the high population concentration that grew in a disorderly manner.

This urban growth also demands infrastructure work, which is made without planning, causing significant damage to the natural resources



Fig. 7. Cultural services provided by the geodiversity in the Taubaté Basin: A) Use of geodiversity for leisure in the Buffalo Waterfall. Image: Ligia Antoniazzi; B) Reference to the legend of the Sleeping Giant, indicated by the yellow arrow. Image: Celso Galvão; C) Jean – Baptiste Debret's watercolor illustrating the city of Guaratinguetá, with the Mantiqueira Mountains in the background; D) Replica of *Paraphysornis brasiliensis* exhibited at the Museum of Natural History of Taubaté; E) Knowledge Service: Taubaté Basin Geosite used for teaching purposes.

Table 6

Summary of the main ecosystem services provided by the geodiversity in the Taubaté Basin region.

EGVs	ECOSYSTEM SERVICES			
	REGULATION	SUPPORTING	PROVISIONING	CULTURAL
ROCKS AND STRUCTURES	<ul style="list-style-type: none"> - Chemical weathering influences the carbon cycle control over time; - Flood control, with water table feeding; - Porous rocks act as a natural filter; - Quality of water. 	<ul style="list-style-type: none"> - Substrate for human construction. 	<ul style="list-style-type: none"> - Natural freshwater reservoirs and filters; - Mineral resources. 	<ul style="list-style-type: none"> - Lookouts; - Climbing; - Adventure sports; - Lithic materials; - Knowledge (Earth History; Tectonics; Stratigraphy; Sedimentation).
MINERAL RESOURCES	<ul style="list-style-type: none"> - Aquifer recharge; - Carbon sequestration from the atmosphere (peat). 	<ul style="list-style-type: none"> - Absent. 	<ul style="list-style-type: none"> - Materials for construction; - Ornamental stones; - Fuel. 	<ul style="list-style-type: none"> - History of mining; - Archaeological remains; - Knowledge (monitoring and environmental quality; mineral prospecting).
FOSSILS	<ul style="list-style-type: none"> - Absent. 	<ul style="list-style-type: none"> - Absent. 	<ul style="list-style-type: none"> - Fossils. 	<ul style="list-style-type: none"> - Museum of Natural History of Taubaté; - Knowledge (Evolution of species; climate change; history of the Earth).
FORMS OF RELIEF	<ul style="list-style-type: none"> - Erosive processes that shape and modify the landscape by interfering with climate over time. 	<ul style="list-style-type: none"> - Habitat and maintenance of biodiversity; - Erosive processes that act in soil formation. 	<ul style="list-style-type: none"> - Absent. 	<ul style="list-style-type: none"> - Artistic inspiration; - Leisure and tourism; - Aesthetic and folkloric values; - Knowledge (evolution of relief; weathering agents).
WATER RESOURCES	<ul style="list-style-type: none"> - Participation in the hydrological cycle and maintenance of the groundwater recharge flow. 	<ul style="list-style-type: none"> - Habitat and maintenance of biodiversity; - Soil formation; - Transport. 	<ul style="list-style-type: none"> - Fresh water supply; - Food production; - Power generation; - Transport. 	<ul style="list-style-type: none"> - Leisure and tourism; - Aesthetic, intellectual and spiritual values; - Knowledge (hydrological dynamics).
SOILS	<ul style="list-style-type: none"> - Climate regulation through carbon sequestration; - Erosion control. 	<ul style="list-style-type: none"> - Nutrient cycling; - Maintenance of biodiversity; - Soil formation. 	<ul style="list-style-type: none"> - Water reservoir; - Energetic (peat); - Agricultural production; - Pharmaceuticals. 	<ul style="list-style-type: none"> - Education; - Historical context; - Knowledge (origin and morphology of soils; geotechnics; management for use and occupation).

(Fig. 12). Environmental impacts that harm the fauna, the flora and the supply of such resources are common in some projects, such as the construction of Aerovale, the airport of the region, which was embargoed for environmental reasons in 2015.

Mining activity also causes serious environmental damage. In 2016 a dam broke in the city of Jacareí – SP and released its tailings in the Paraíba do Sul river (Fig. 13A). To aggravate the situation, many mining companies end their activities without promoting the land recovery that had been proposed and approved before the operating license, leaving extremely degraded areas, which interfere directly in the provision of ecosystem services (Fig. 13B).

Given the above, it is evident that the main effects observed in the region represent direct consequences of anthropogenic actions, such as mining and urban growth. Regarding the latter, Ruppert and Duncan (2017) confirm that human intervention represents the largest negative impact factor in the ecosystem service flow, and its evaluation is fundamental to propose ways to minimize such impacts. Thus, considering the proper management of natural resources, it is important that the ecosystem services of a region should be evaluated and quantified based on the context in which they operate, and be valued and integrated in public policies for regional sustainable development.

In this context, this study demonstrates that the main cause of environmental impacts derives from anthropogenic activities, which can lead to irreversible damage to the environment and depletion of resources, in the case of mining, if there are not adequate management policies for the area. Therefore, it is important to create partnerships between the scientific community, managers, public and private institutions in order to propose ways to minimize environmental impacts allied to the needs of urban growth.

5.3. Analysis of ecosystem services based on quantification

The quantification of ecosystem services provided by the geodiversity elements of the Taubaté Basin presents a *Relative Significance* (σ_{Rel}) assigned to each service group, that is, it shows how each category can interfere in the ecosystem dynamics and, therefore, with providing these services. The values, expressed in percentage, may vary from 0 to 100, and the closer to 100, the greater the potential for interference in the ecosystem service supply, as noted in Matrix C (Table 9). The *Relative Significance* (σ_{Rel}) would be 100% if the sum reached 120, since $5 \max\{\sigma\} \max\{b_{i,j}\} = 120$, with $\max\{\sigma\} = 8$ and $\max\{b_{i,j}\} = 3$.

Based on the values obtained for the *Significance for the ecosystem services group* (σ_{Group}), the highest value, 61.7%, was attributed to the regulating service. The result is consistent with the impacts on the abiotic resources of the basin, especially regarding the water resources provided by the Paraíba do Sul river, being the provisioning of this service the most affected in the region due to anthropogenic activities.

The *Relative Significance of the group* (σ_{Group}) related to supporting services is 60%, the second highest value. Although the *Relative Significance* (σ_{Rel}) of some parameters reached high values (such as soil and water supply, 75.0% and 69.2%, respectively), the final group average was lower because it had a higher number of parameters. The high values for these parameters reflect the impacts on the “Land Use Categories”, considering that there was a significant increase in urban settlement, in mining and in forestry and a decrease of vegetation and farming areas.

The provisioning service was the least affected by the categories. The lowest *Relative Significance* (σ_{Rel}) = 25.0 was assigned to the class of metal and industrial minerals, since the region does not have metallic

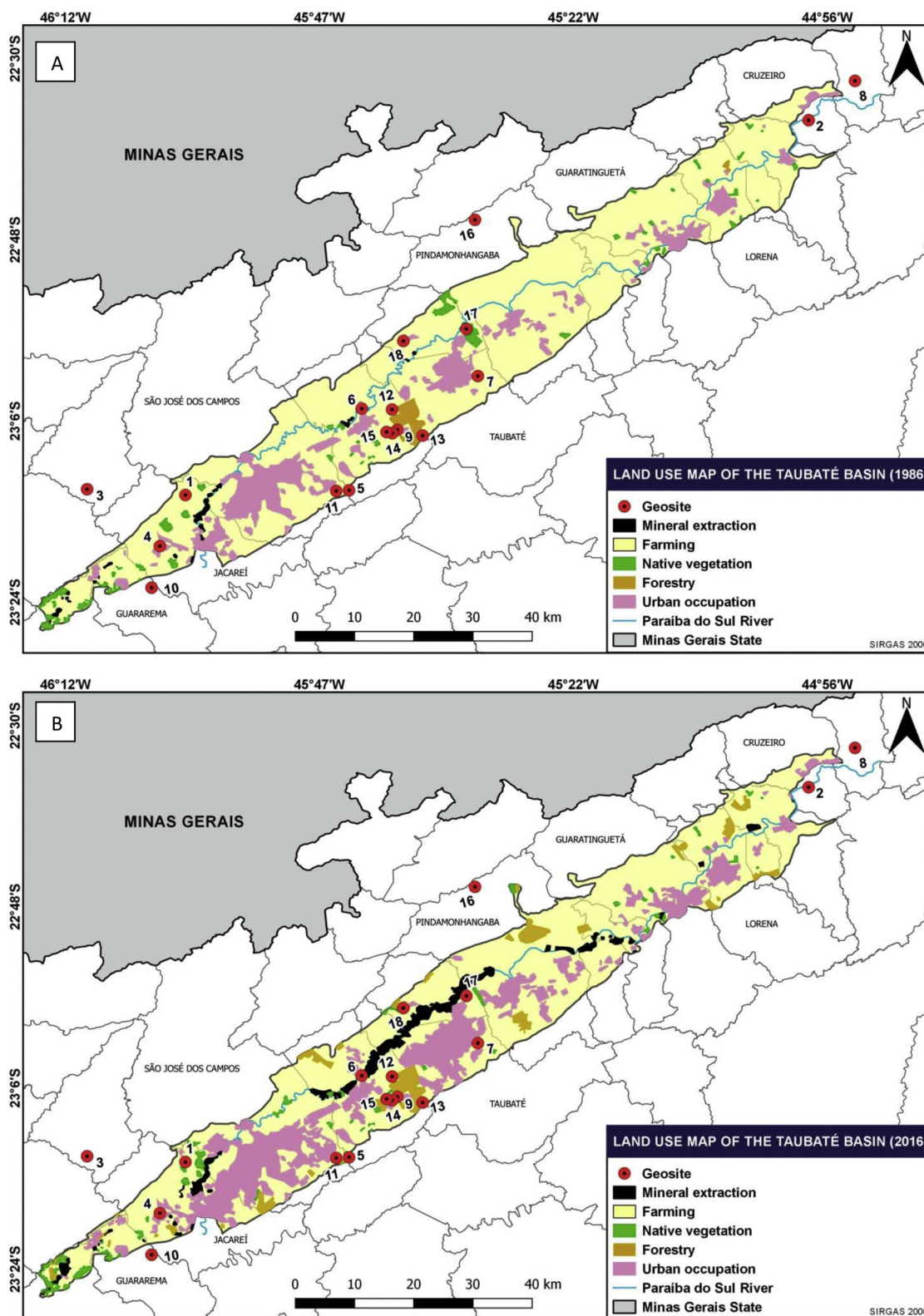


Fig. 8. Land use map in the Taubaté Basin. A) Year of 1986; B) Year of 2016.

minerals, only a small portion of the extracted clay minerals have industrial use, and their main use is in construction. Although other parameters, such as the provision of food, water and building materials, obtained high *Relative Significance* (σ_{Rel}) values, the *Relative Significance of the group* (σ_{Group}) was low, summing up 45.4%, as the group has a higher quantity of parameters.

Regarding the group of cultural services — which includes parameters of well-being and health, leisure, human history and scientific knowledge — the value of *Relative Significance* (σ_{Group}) group was 50%. Although it is higher when compared to the previous group, it has fewer parameters, which decreases its average. The class represented by well-being and health obtained the highest point value within the

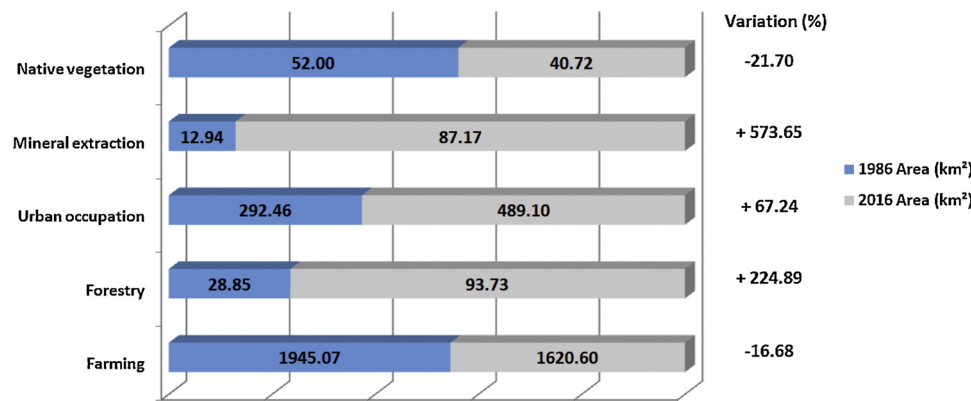


Fig. 9. Variation in area of land use in the Taubaté Basin between 1986 and 2016.

Table 7

Matrix A of significance classification. The signs “+” and “-” correspond to increase and loss, respectively.

LAND USE CATEGORIES	COVERAGE		MAGNITUDE			REVERSAL FACTOR	SIGNIFICANCE (σ)		
	Local (1)	Regional (2)	Small (1)	Medium (2)	Large (3)		Low (3–4)	Medium (5–6)	High (7–8)
(-) Native vegetation	1		2			2		5	
(+) Mineral Extraction	2		3			2		7	
(+) Urban occupation	2		3			3		8	
(+) Forestry	2		3			1		6	
(-) Farming	2		1			1		4	

group (62.5%), due to the increase of disordered urban occupation, which reflects in the quality of life of the local population and the availability of natural resources.

6. Final Considerations

The qualitative assessment of the six EGVs established for the Taubate Basin region identified 53 ecosystem services distributed in four functions. This shows that the geodiversity was and is essential in promoting the local economic development, given the fact that the increase in exploitation of mineral resources fosters the growth of job offers, resulting in urban sprawl and, consequently, increasing the environmental impacts in the region.

The categorization of geodiversity elements according to specific variables was essential to direct both qualitative and quantitative assessment on the ecosystem services in the area. This brings positive perspectives on the use of these criteria on the adequate mapping of geodiversity elements using cartographic tools that can be of practical use in socio-environmental planning and policies.

The method of quantification proposed in this work allowed us to identify the relationships existing between human activities and ecosystems, highlighting which aspects interfere with the supply of these goods through the calculation of significance for loss of services. The values obtained for *Relative Significance* (σ_{Rel}) showed that the impacts caused by “Land Use Categories” mainly interfere in the provision of regulating and supporting services. It is consistent with the changes that

Table 8

Matrix B of the connection between categories and ecosystem services. 1 = not a relevant relationship.

ECOSYSTEM SERVICES		LAND USE CATEGORIES				
		(-) Native Vegetation	(+) Mineral Extraction	(+) Urban Occupation	(+) Forestry	(-) Farming
REGULATION	R1. Atmosphere	3	2	3	3	2
	R2. Geosphere	1	3	3	1	2
	R3. Hydrosphere	3	2	3	3	2
SUPPORTING	S1. Soil	3	3	3	3	3
	S2. Water	3	2	3	3	3
	S3. Surface rocks and landforms	2	3	2	2	3
	S4. Underground rocks and landforms	1	3	1	1	1
PROVISIONING	P1. Nutrients	3	2	1	3	3
	P2. Food and drink	3	2	2	2	3
	P3. Water	2	2	1	2	1
	P4. Construction materials	3	3	1	2	2
	P5. Industrial and metallic minerals	1	1	1	1	1
	P6. Energy resources	2	3	1	2	2
	P7. Ornamental products	1	3	1	1	1
CULTURAL	C1. Wellness and health	3	2	2	3	3
	C2. Recreation	2	1	2	2	1
	C3. Human history	1	2	2	1	2
	C4. Knowledge	2	3	2	2	2

² = indirect relationship; 3 = direct relationship. The signs “+” and “-” correspond to increase and loss, respectively.

Table 9
Matrix C of Relative Significance of the land use categories linked to the provision of ecosystem services provided by the geodiversity in the region.

ECOSYSTEM SERVICES	LAND USE CATEGORIES					SUM (\$)	Relative Significance per ecosystem service (σ_{REL}) (%)	Relative Significance per ecosystem services group (σ_{Group}) (%)	
	<i>Classification of the Significance (σ) of the natural environment change by elements associated to land use (Table 6)</i>								
	(-) Native vegetation	(+) Mineral Extraction	(+) Urban Occupation	(+) Forestry	(-) Farming				
	5	7	8	6	4				
REGULATION	R1. Atmosphere	15	14	24	18	8	79	65,8	61,7
	R2. Geosphere	5	21	24	6	8	64	53,3	
	R3. Hydrosphere	15	14	24	18	8	79	65,8	
	S1. Soil	15	21	24	18	12	90	75,0	
SUPPORTING	S2. Water	15	14	24	18	12	83	69,2	600
	S3. Surface rocks and landforms	10	21	16	12	12	71	59,2	
	S4. Underground rocks and landforms	5	21	8	6	4	44	36,7	
	P1. Nutrients	15	14	8	18	12	67	55,8	
PROVISIONING	P2. Food and drink	15	14	16	12	12	69	57,5	45,4
	P3. Water	10	14	8	12	4	48	40,0	
	P4. Construction materials	15	21	8	12	8	64	53,3	
	P5. Industrial and metallic minerals	5	7	8	6	4	30	25,0	
	P6. Energy resources	10	21	8	12	8	59	49,2	
CULTURAL	P7. Ornamental products	5	21	8	6	4	44	36,7	50,0
	C1. Wellness and health	15	14	16	18	12	75	62,5	
	C2. Recreation	10	7	16	12	4	49	40,8	
	C3. Human history	5	14	16	6	8	49	40,8	
	C4. Knowledge	10	21	16	12	8	67	55,8	

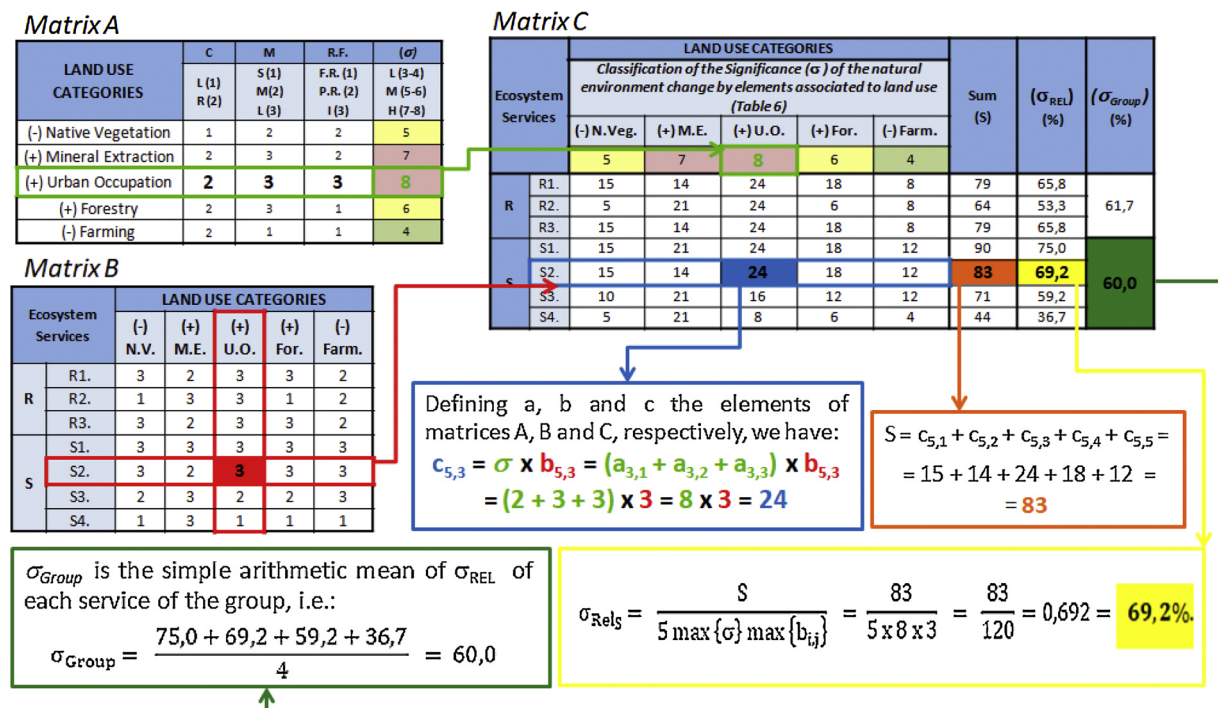


Fig. 10. Schematic flowchart illustrating the steps used for quantification. The land use category "Urban Occupation" and the service "S2 - Water" (Supporting function) are used as references.



Fig. 11. Sand mining areas in the Taubaté Basin region. A) Sand extraction pit invading a protected area, destroying riparian forest near the Paraíba do Sul river; B) Hydraulic dismantling in Jacareí, on the shores of Rodovia Dutra. Note the eucalyptus barrier planted along the highway to hide the pits. Source: <http://www.quimicosjc.org.br/pdfs/especiais/Cavas-de-areia-2012.pdf> (Accessed: 14 Feb. 2019).

have affected the region over the 30 years and were evaluated in the maps.

It is noteworthy that the calculation of the significance of the loss of services can be applied in other contexts, adapting the parameters to be investigated. However, for the best use of this tool, a detailed inventory of the region to be assessed should be made, considering possible environmental impacts and analyzing the demand for ecosystem services, through the identification and description of the goods and beneficiaries.

The obtained values of significance have a great potential to contribute to the monetary valuation of the ecosystem services. Thus, the method can be used to perform other environmental assessments, serving as a subsidy for the business sector and other institution, helping incorporate the natural capital into decision making.

It is necessary to reconcile the sustainable use of resources and the process of urbanization, in order to less interfere in the availability of services when promoting spatial planning. To achieve that, it is important that the private institutions and the public administration work together and encompass human activities in an approach that enables full socioeconomic development while minimizing potential impacts on the supply of ecosystem services, through the proper management of natural resources.

Funding acquisition

CAPES - Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Government agency): - Regular research scholarship (to PhD) - Academic Mobility Program PDSE Scholarship Process Nr. 88,881.135227 / 2016-01 (for seven months)

CRedit authorship contribution statement

Fernanda Coyado Reverte: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing - review & editing. **Maria da Glória Motta Garcia:** Conceptualization, Investigation, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration.



Fig. 12. Impacts caused by anthropogenic activities: Construction of the Aerovale airport. Source: www.aerovalce-cea.com.br.



Fig. 13. Impacts caused by anthropogenic activities: A) Breakage of a dam of mining pond in Jacaref. Source: www.veja.abril.com.br; B) Environmental degradation generated by mining in Guararema. Photo: Cícero Oliveira.

José Brilha: Conceptualization, Investigation, Resources, Writing - original draft, Writing - review & editing, Supervision. **Alan Uchoa Pellejero:** Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank CAPES for the Academic Mobility Program PDSE Scholarship / Process Nr. 88,881.135227 / 2016–01 and for the PhD research scholarship in Brazil awarded to the first author.

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