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Geosystem Properties and Services in Global South Cities: Examples of São Paulo and Johannesburg

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Abstract: Geosystem services are increasingly recognized as critical for the sustainable development of rapidly growing cities in the Global South, because of their association with improved public health, reduction in environmental pollution, microclimate effects, and the ecological goods and services that provide benefits to local people. However, maintaining urban green spaces is a particular issue in cities in the Global South, such as São Paulo (Brazil) and Johannesburg (South Africa), where rapid inward migration and poor urban planning result in low environmental quality and the deterioration of geosystem services. This study explores the geosystem (including environmental and ecosystem) services provided in protected green spaces in these two cities, using the specific examples of Parque Estadual da Cantareira (São Paulo) and Melville Koppies (Johannesburg). This study uses an inventory-based approach to list and critically explore the availability and properties of different geosystem services found in these sites, and their wider implications for environmental planning and sustainable urban development. The results show that, although superficially similar, these sites have very different geosystem services, and that a simple inventorizing approach for geodiversity and geosystem service provision as used in many previous studies is highly problematic and over-simplifies site-scale geological and environmental properties, and how these are used and valued by local people. A more integrated approach dealing with the interplay of geosystem, environmental, and ecosystem services can provide a much firmer basis for urban planning and management in the Global South, suitable for achieving the Sustainable Development Goals.

Keywords: environmental services; ecosystem services; geodiversity; geosystems; global south; sustainable development goals; urban landscape

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1. Introduction

The relationship between the properties of the physical landscape (including its geology, topography, and soils) and its environmental services (including ecosystem provisioning services, water, microclimate, and recreation) is a fundamental part of Earth System Science, human–environment relations, and environmental sustainability [1–8]. These issues are particularly important in resource-scarce settings, such as rapidly expanding cities in the Global South, where urban sprawl, poor urban planning, high pollution levels, and the lack of enforcement of environmental codes have meant that different types of ecosystem services found in urban areas have come under pressure (e.g., [9–13]). One key way to promote the sustainability of different types of services provided by green spaces that still exist within urban areas is to better understand the relationships between different

elements of the physical landscape, including its rock, soils, ecosystems, water, and the societal/cultural values of that green space held by local residents and users. Previous studies have explicitly linked landscape geodiversity to the development of certain geosystem properties, and the ecosystem services provided within that landscape (e.g., [7,14–18]). This approach therefore considers that the conservation of geodiversity and biodiversity can be undertaken as part of the same integrated geosystem (e.g., [18–23]). Other studies have also considered how these geosystem properties can be linked to urban planning and environmental decision-making [10,11,13].

Although the relationship between geosystems (geodiversity) and ecosystems (biodiversity) is strongly founded on both field observations and through empirical models [2–4,14–18], there is less understanding of the wider environmental services provided by urban green spaces. In part, this arises because of the multiple direct and indirect ways in which geodiversity affects other landscape elements, such as soils, water, ecosystems, and the operation of geomorphic, biophysical, and biogeochemical processes [3,12,22]. It also arises because of the varied ways in which the physical environment is important to, and impacts upon, human activity both directly and indirectly [4,8,24], especially in an urban context [11,13,17].

Ecosystems and geosystems and their services can be distinguished using Fox et al.'s [5] framework. *Ecosystem services* are those services that are achieved by interactions with biotic elements whereas geosystem services are those with no participation of biodiversity. The concept of *geosystem services* is useful because it emphasizes the role of the physical environment, including geodiversity, in contributing to the provision of ecosystem and environmental services [2,7,8,25–27]. *Environmental services* refer to all services that are provided to people, both directly and indirectly, by biotic and abiotic systems and processes [6]. As such, the concept of environmental services is broader and more inclusive than the related concept of ecosystem services, which has been well-explored with respect to its relationship to geodiversity [2,3,28]. Geosystem services and their links to the physical landscape are of relevance here because these can include microclimate effects, biogeochemical cycles, and fluxes through the landscape (not all of which are captured by ecosystem supporting services). Geosystem services can also encompass the development of mining, archaeological heritage, patterns of historical human occupation in the landscape, contemporary impacts on urban design and management, and aesthetic aspects of the environment (vistas, sounds, experiences, sensations), and these aspects are linked to human health and wellbeing. As such, ecosystem, geosystem, and environmental services provide different conceptual approaches to the same thing—the benefits provided by the physical landscape to other elements of the environment and to people. However, studies of geosystem services have an advantage over other approaches because of the fundamental basis of geology, weathering, soils, and water in shaping subsequent landscape development, including ecosystems [28].

The relationships between different geosystem services noted in the literature are described in Figure 1. These illustrate the complex overlaps and co-relationships between different types of geosystem services that are offered by the physical environment. In addition, each of these major types of services have various elements within them that in turn influence each other. For example, soil processes (supporting services) influence flood control (regulating services) and agricultural production (provisioning services). Urban landscape change can lead to changes in water systems, deforestation, and pollution, and can impact on geosystems. This interplay highlights the complex ways in which geosystem services can interact with the physical landscape and then, in turn, with communities and society.

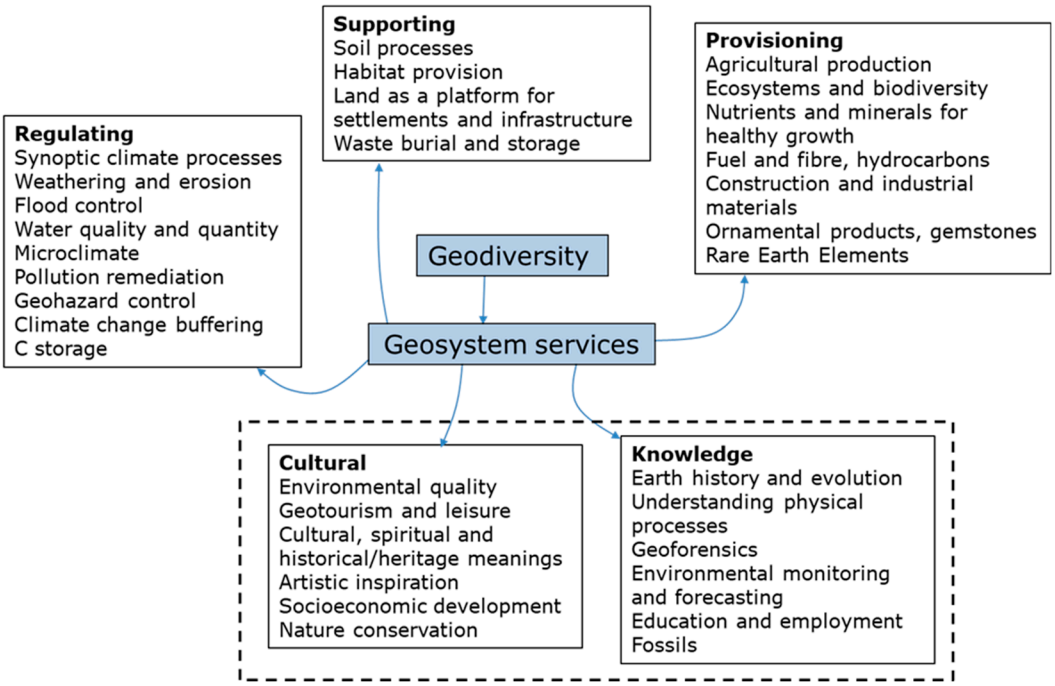


Figure 1. Illustration of the different types of geosystem services (redrawn with many additions from [25]). Cultural and knowledge services were differentiated by Gray [25]; here they are grouped together as cultural geosystem services (dotted box), consistent with the main ecosystem services classification. The different geosystem services listed here are described with respect to the two sites examined in Table 1.

Table 1. Key geosystem services present at the study sites, based on the list provided by Gray [25] (Figure 1). Where particular services are present, the basis for this is identified.

Service Types	Cantareira State Park (São Paulo)	Melville Koppies (Johannesburg)
Provisioning		
Agricultural production	No	No
Ecosystems and biodiversity	Yes, as a State Park and part of a Biosphere Reserve, including the Atlantic forest ecosystem	Yes, as a Nature Reserve and based on the presence of xeric grass species
Nutrients and minerals for healthy growth	Yes, where minerals and nutrients from the underlying bedrock are provided for plant growth	Yes, where minerals from the underlying bedrock give rise to the specific low-nutrient soil and grassland
Fuel and fiber, hydrocarbons	No	Yes, although this is not permitted, local people come into the area and harvest firewood or collect medicinal plants
Construction and industrial materials	No	No
Ornamental products, gemstones	No	No
Rare Earth Elements	No	No
Regulating		
Synoptic climate processes	Yes, by virtue of this being a large, protected forest area and part of a regional network of similar sites	No
Weathering and erosion	Yes, through the presence of vegetation that reduces soil erosion and slope hazards	No
Flood control	Yes, through water management	No

Table 1. *Cont.*

Service Types	Cantareira State Park (São Paulo)	Melville Koppies (Johannesburg)
Water quality and quantity	Yes, through water filtration and management, including engineering	No
Microclimate	Yes, in its role in remediating the urban heat island (UHI) of São Paulo	No
Pollution remediation	Yes, through the role of extensive forestry in reducing air pollution and by water filtration through the soil and river systems	No
Geohazard control	Yes, through water management and landslide reduction in vegetated slopes	No
Climate change buffering	Yes, through its UHI and flood management effects	No
C storage	Yes, through the forest ecosystems	No
Supporting		
Soil processes	Yes, by the weathering of the underlying igneous and metasedimentary rocks	Yes, through the weathering of quartzites to produce a distinctive xeric, low-nutrient soil
Habitat provision	Yes, for both high animal and plant biodiversity	Yes, by providing regionally rare xeric grasslands
Land as a platform for settlements and infrastructure	No	No
Waste burial and storage	Yes, there are sites even within the protected area for urban waste disposal	No
Cultural		
Environmental quality	Yes, but offering green space within São Paulo which has otherwise very limited green space in this area	Yes, as an area of recreation and green space, and as sites for rock climbing
Geotourism and leisure	Yes, through public information boards, a network of trails, parking, and other facilities for visitors	Yes, but limited to local dog-walkers
Cultural, spiritual, and historical/heritage meanings	Yes, but limited to some historic buildings	Yes, a significant cultural site for outdoor religious services, and because of archaeological evidence of past human occupation
Artistic inspiration	No	No
Socioeconomic development	Yes, as a tourist site	No
Nature conservation	Yes, as a State Park and part of a Biosphere Reserve	Yes, as a nature reserve
Knowledge		
Earth history and evolution	No	No
Understanding physical processes	Yes, in the context of ecological processes	Yes, through quartzite strata weathering and the creation of local relief
Geoforensics	No	No
Environmental monitoring and forecasting	Yes, environmental monitoring takes place throughout the site	No
Education and employment	Yes, through staff employed in the park and the provision of educational trails and resources; as an ecological research site	Yes, as an archaeological research site
Fossils	No	No

The availability and quality of these ecosystem functions are directly related to the integrity of the geodiversity at a site [29]. In the Global South, however, the recognition and management of geodiversity and geoheritage is a challenge. In these regions, where governments often struggle to meet the population's basic needs, nature conservation and the sustainable use of natural resources are generally considered less relevant compared to the significant socioeconomic and socio-environmental challenges affecting rapidly growing urban areas. Additionally, the state of constant political unrest or internal conflict in some countries may hinder effective nature conservation and natural resource management [13]. In the case of geoconservation, the methods and practices applied are mostly based on European experiences, which reflect realities that are often very different from those observed in the Global South and are frequently not applicable to the local context.

Based on this context, this study aims to explore and understand the relationships that exist between landscape geodiversity and the provision of ecosystem, geosystem, and environmental services in an urban context in the Global South, using the examples of protected green spaces in the cities of São Paulo (Brazil) and Johannesburg (South Africa). The reason is that landscape geodiversity, and its varied geosystem services, provides the basis for other ecological and environmental services (Figure 1). This is the motivation for focusing on geosystems in the first instance. In addition, these cities are chosen because, over several decades, they have both experienced rapid population growth, expansion of the urban footprint through (in some places unplanned) suburban and periurban sprawl, development of extensive shanty towns or informal settlements, high economic and social inequality, high unemployment and in-migration rates, and associated socioeconomic and environmental issues. These factors include high air, soil, water, and waste pollution; urban heat island effects; decreased green spaces; food and water insecurity; traffic congestion and transport problems; floods and mass movement; and political and governance instability. In addition, their physical environments are also similar as they are both set in low-temperate hilly landscapes, where topography has influenced urban growth patterns; they are both water-stressed cities, where natural water resources (both rivers and groundwater) have come under pressure, and they have specific local areas of high biodiversity and/or heritage or cultural value within the urban area.

For these reasons, identifying and comparing the geosystem services found in these areas can inform sustainable development strategies in the developing world. This can help us understand how geosystems help sustain the different services that are vital for the functioning and sustainability of Global South cities. In detail, this paper (1) considers the geological history and geosystem properties of the two study sites within these cities; (2) inventorizes and describes the varied geosystem services found at these sites, including their cultural and heritage properties that are valued by local communities; and (3) discusses the importance of geosystems in underpinning the sustainability of Global South cities.

2. Methodological Approach

This is a comparative study designed to highlight the entangled and contested relationships between different geosystem properties, resources, and services, using the specific examples of Cantareira State Park (São Paulo) and Melville Koppies (Johannesburg) (Figure 2). These cities were chosen because they are both rapidly-growing cities that are important economic hubs in their countries, and have associated problems of environmental pollution, governance, and ineffective spatial planning (e.g., [30–32]). These specific sites were chosen because they are long-established and well-known sites within their cities. Both sites are also protected as nature reserves mainly for their high ecological and biodiversity values, but they also have rich geodiversity that supports various geosystem (including ecosystem and environmental) processes and services. As such, they can be

considered as comparable with respect to their geosystem services and sociodemographic contexts. This study adopts a case study approach, in which the major properties of the two study areas were systematically inventorized, described, and interrogated, and then qualitatively compared to each other with reference to the typical range of geosystem elements identified in the literature (Figure 1). In detail, systematic field observations were made at both sites by the researchers. This involved qualitative observations of: (1) geology, rock outcrops, topography, and soils; (2) ecosystems and vegetation patterns; (3) water patterns and availability in the landscape; and (4) human activities present within the site, including the ways in which people interact with and move around the site and any associated infrastructure. This qualitative approach has been used in similar previous studies (e.g., [13,16,17]). To inform on these observations, the different geosystem services identified by Gray [25] (Figure 1) were used as an inventory against which the observations could be compared. This better allowed for a standardized comparison between the two sites (Table 1). The field observations were also then contextualized with respect to site management strategies, and with reference to the literature, where available.

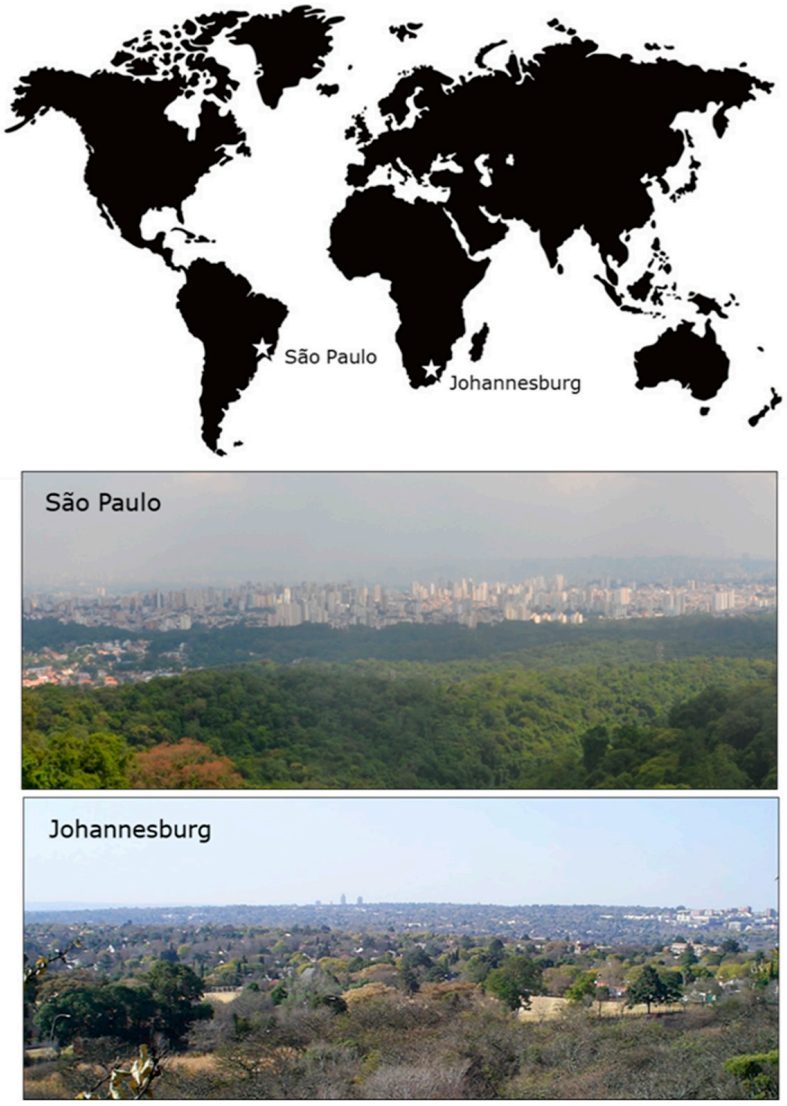


Figure 2. Locations of the cities examined in this study and views over the cityscape from the elevated positions of the study sites (Cantareira State Park in São Paulo and Melville Koppies in Johannesburg).

3. Results: Characteristics of the Study Sites

3.1. Cantareira State Park (São Paulo)

3.1.1. Background and Geology

The Cantareira State Park (São Paulo, Brazil) is a protected area of 79 km^2 at the northern edge of the city (Figure 3). The park comprises an elevated area of interconnected hills and valleys with regenerating Atlantic temperate rainforest. As such, there has been extensive research on plant ecosystems [33], birds [34–36], insects [37], and primates [38].



Figure 3. Examples of the physical landscape and human engagement with the site: Cantareira State Park, São Paulo, Brazil. (**a**–**c**) Visitors on an exposed rock outcrop overlooking the city, (**e**,**f**) details of structural features within the granite, and (**d**,**g**,**h**) information and trails within the forest that are used by different groups of visitors, including tourists and schools.

Geologically, the area of the park is dominated by low-grade, Palaeoproterozoic metavolcano–sedimentary sequences of the São Roque Group with syn- to post-tectonic granitoid intrusions [39]. The main magmatic body is the Neoproterozoic Cantareira

Batholith that extends from the northern part of São Paulo to the neighboring municipalities of Caieiras and Mairiporã. Subsequent erosional processes gradually removed the surrounding rocks, leaving the more resistant granitoid exposed, which today constitutes a significant portion of the Cantareira Mountain Range. Soil geochemical properties reflect in part the underlying geology but also pollutants related to human activity within the park [40]. The highest altitude of the park is 1010 m asl, being represented by the Geosite "Cantareira porphyritic biotite monzogranite of the Pedra Grande", part of the geological heritage of the state of São Paulo [41], and this provides a panoramic view of the city. Annual rainfall in São Paulo is ~1400 mm and the monthly mean temperature varies from 14 °C (winter) to 21 °C (summer). These climatic conditions result in relatively high humidity and air pollution [42,43].

The lands that currently make up Cantareira State Park were acquired by the state through expropriations, primarily aimed at carrying out water collection and distribution projects, with the main objective of supplying the northern zone of the Municipality of São Paulo [44]. For this reason, the park is also important for water supply to the city and significantly moderates the area's microclimate due to the high relief. For example, the growth of São Paulo's urban fabric has been linked to an increase in temperatures in the range of 0.6–0.8 °C/decade in the period 1933–2015, and greater variability of extreme precipitation events [43]. Urban sprawl has also progressively encroached around the protected area, thereby increasing the significance of the park as a green space within the city. The microclimate of the park is influenced by the presence of both forests and water bodies within valleys, and these conditions are important for accessory species, such as some birds [34].

3.1.2. Ecosystems and Species

There is little remaining intact regarding the dense ombrophilous vegetation of the Atlantic Forest in Cantareira State Park, and the area mainly reflects different phases of deforestation and forest regeneration, experienced from the late-19th Century onward [33]. Many studies have examined individual species' patterns, and high biodiversity within the park has been identified [35]. The 866 faunal species (388 vertebrates and 478 invertebrates) include 97 mammal, 233 bird, 28 amphibian, 20 reptile, and 10 fish species [45]. The 678 floral species comprise 650 angiosperm, 27 pteridophyte, and one gymnosperm species [45]. Detailed mapping and inventorizing of different genera within the park have also been performed (e.g., [37,46,47]). These analyses show the close genetic relationships between biodiversity, the physical landscape (slope steepness, soil type, hydrology), and aspects of park management (e.g., intact versus disturbed forest stands).

3.1.3. Human Activity, Management, and Conservation Issues

The entity of Cantareira State Park as recognized today was originally protected as a Forest Reserve in 1899 as the city of São Paulo developed [45]. In 1962, it was designated as a State Park. The area of the park is part of the São Paulo Green Belt Biosphere Reserve, which was recognized by UNESCO in 1994 as an integral part of the Atlantic Forest Biosphere Reserve. However, it was granted a distinct identity due to its unique setting around one of the world's largest metropolitan areas. Beyond São Paulo, the Green Belt Biosphere Reserve includes 77 municipalities that, together, encompass 10% of Brazil's total population. A consultative management council for the park was created in 2003 and the park is managed in an integrated manner through four sectors: Pedra Grande, Cabuçu, Engordador, and Águas Claras. Since 2016, water management within the park has been undertaken by Sabesp, the government-owned water and waste management company in the State of São Paulo and provides ~33,000 L of water/second for 8.8 million

consumers [45]. The Cantareira System serves as the primary water supply for the São Paulo Metropolitan Region, providing water to over eight million residents [48]. Even having its area protected by the State Park, the region experiences limited water availability and a complex hydrological system due to extensive canalization, water diversions, and alterations to river courses. Between 2013 and 2015, the São Paulo Metropolitan Region faced a water crisis, which was triggered by an extreme hydrological and climatological event, exacerbated by unsustainable water resource management [49].

The park lies within several different administrative municipalities and is adjacent to Albert Löfgren State Park located to the south. All these elements demonstrate that there are several competing conservation and management interests at the park at present, and that balancing these issues, especially with respect to conservation priorities, resource exploitation, and public access, requires a complex and integrated management approach. Since 2022, part of the park was leased to a private company, with the aim of improving tourism infrastructure, promoting recreational activities, and generating revenue for its maintenance. However, this measure has been raising concerns about balancing economic exploitation and environmental conservation.

The park is extensively used by local people within the State of São Paulo. Among the thousands of annual visitors, it receives a significant number of students from public and private educational institutions. The park is open for scheduled school groups during the week and to the general public at weekends, being an important location for research activities and education. All the four sectors of the park offer activities designed for the general public, including a network of interpretative trails that showcase various natural elements, being unique attractions and opportunities for education, recreation, and environmental appreciation. There is a ranger service in the park.

The Pedra Grande sector, the most visited, is home to the Pedra Grande Trail, a 3184 m paved route leading to a panoramic viewpoint of São Paulo. The Engordador sector has significant cultural and historical landmarks, including the Casa da Bomba (Pump House), built in 1907 and recognized as a heritage site. The sector's decommissioned reservoir, once vital for São Paulo's water supply, now serves as a scenic attraction, alongside waterfalls accessible via dedicated trails. The Cabuçu sector stands out for its historical importance, featuring Brazil's first reinforced concrete dam, built between 1904 and 1907. Visitors can explore the Cachoeira Trail, offering recreational opportunities with its cascading waterfalls and rock outcrops. The Águas Claras sector, though less frequented, offers the Lago das Carpas, with picnic areas and scenic viewpoints. The Samambaia-Açu Trail, following the Águas Claras stream, provides educational insights into hydrology and water resources.

These activities provide information about park ecosystems and biodiversity, but less so about its geology. Roads within the park provide different levels of access for visitors and park workers, but are also sites for waste disposal and general environmental degradation.

3.2. Melville Koppies (Johannesburg)

3.2.1. Background and Geology

Melville Koppies (Johannesburg, Gauteng Province, South Africa) is an east–west-aligned set of ridges (in total 3.5 km long, 350–400 m wide, <60 m high, 1.6 km^2 in total) located just north of the city center (Figure 4); the local term "koppie" refers to a ridge or hilltop. This ridge set is one of several parallel systems found within Johannesburg that are composed of quartzites of the Witwatersrand Supergroup (Proterozoic) [50]. The stratigraphy of these rocks in the Johannesburg area and their geochemical properties are presented by Guy et al. [51]. These rocks are interbedded with mudstones. The quartzites weather to form a thin and nutrient-poor soil over the ridges, whereas the mudstones weather more quickly, underlie valleys, and sustain wetter edaphic conditions. Melville

Koppies is located on the Kaapvaal craton, formed from 3.5 Ga onward and subject to several later tectonic phases that are marked by faults that cut through earlier synclines [52]. Faults aligned NW–SE demarcate the quartzite ridge of Melville Koppies. Conglomerate, quartzite, shale, and siltstone of the Witwatersrand Supergroup are exposed in Melville Koppies. This includes good outcrop exposures of wave-rippled quartzites. The basal unconformity of the lowest Orange Grove Quartzite unit above the granitoid basement can also be observed in the reserve. These sedimentary units are tectonically tilted with a dip to the south, and this has exerted an impact on the ridge topography, with steeper slopes found on the northern side and shallower slopes (parallel to bedding planes) on the southern side. Weathering of different bedrock types has influenced soil geochemistry [53]. Northern slopes have thicker, reddish soils reflecting the weathering of the granodiorite basement, whereas southern slopes have thin and acidic soils derived by the weathering of quartzites and shales. Altitude in the region is in the range of 1450–1750 m asl, ranging from 1660 m to 1725 m asl in Melville Koppies itself. Annual precipitation in the region is ~700 mm with most falling in the summer, and monthly mean temperatures range from 12 °C (winter) to 21 °C (summer). Small streams drain from and around Melville Koppies, which are the Braamfontein Spruit and Westdene Spruit, the latter of which flows northward through a steep, rocky gorge.

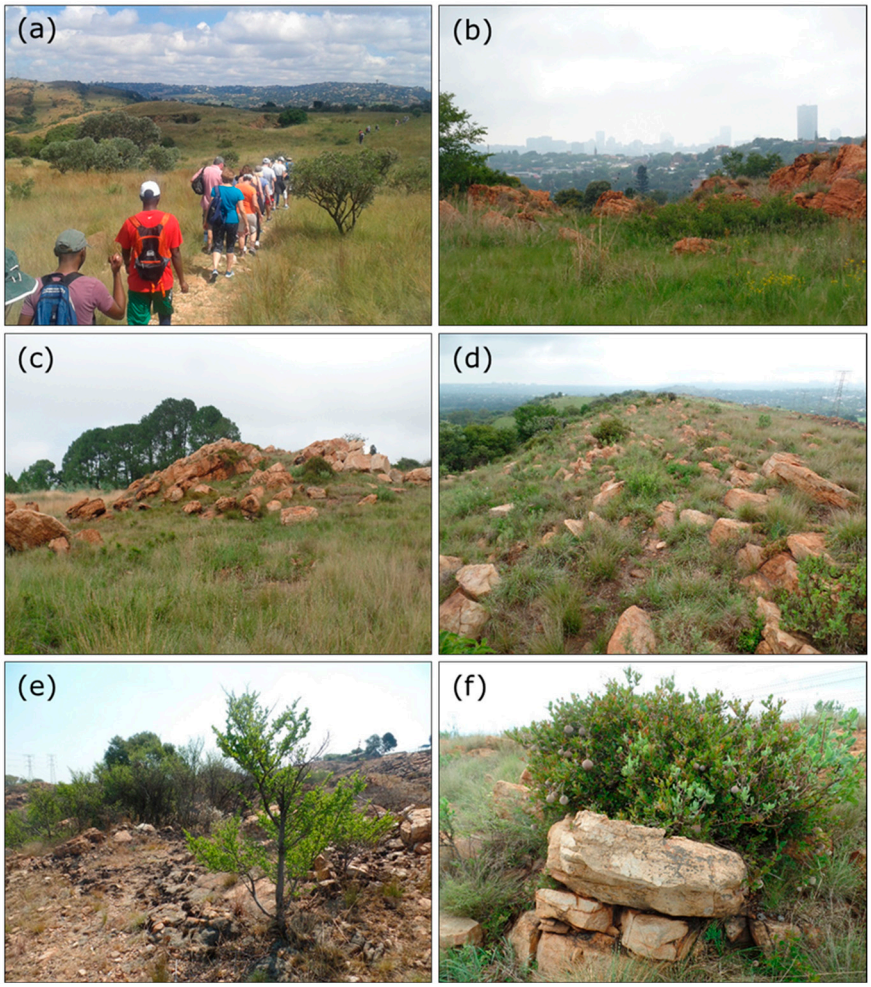


Figure 4. Examples of the physical landscape and human engagement with the site: Melville Kop-pies, Johannesburg, South Africa. (**a**) Guided walks offered to visitors through the site, run by a community conservation group, and following maintained paths; (**b**) physical setting of the site overlooking the city in the distance; (**c**,**d**) quartzite outcrops forming ridges within the site; (**e**,**f**) relationship of bedrock outcrops to plants.

3.2.2. Ecosystems and Species

The presence of the ridges as topographic highs, located some 30 m above the surrounding landscape, provides important sites for xeric Highveld grassland biomes [53,54], with 42% of Red Data List plant species found in the province being recorded here [55]. They are thus grassland-dominated with isolated patches of indigenous trees and bare rock exposures. These ridges are important as they commonly act as refugia for different ecosystems and species whose habitats have been steadily encroached upon by the surrounding urban area. On Melville Koppies, 518 taxa in 298 genera are present, of which 464 taxa from 268 genera are indigenous [56]. Around 10% of taxa are alien. Several different ecological communities are present and these are found in different physical settings [56]. For example, species-rich grassland with *Aristida transvaalensis* (Henrard, 1932)/*Coleochloa setifera* (Ridl., 1943)/*Loudetia simplex* (Nees, 1934) is found on rocky sites with thin, skeletal soils derived from weathered quartzite. *Hyparrhenia hirta* (L. Stapf, 1919)/*Setaria sphacelata* (Schumach. Stapf & C.E.Hubb. ex Moss, 1929) grassland by contrast is found on shallow slopes with deep soils derived by the weathering of diorite and shale. Across the site as a whole, there is a taxon density of 325 taxa/km^2, which is moderately high compared to other sites regionally [56]. Important mammals found in Melville Koppies are the African Civet (*Civettictis civetta* (Schreber, 1776)), Common Genet (*Genetta genetta* (L., 1758)), Slender Mongoose (*Galerella sanguinea* (Rüppell, 1835)), Yellow Mongoose (*Cynictis penicillata* (Cuvier, 1829)), and African Hedgehog (*Atelerix frontalis* (Smith, 1831)). In total, 185 species of bird have been noted in and around the reserve, and there is an active ringing program for bird monitoring in the reserve, run by volunteers. Eleven different species of snake are present, and two species of tortoise.

3.2.3. Human Activity, Management, and Conservation Issues

Melville Koppies is protected as a Nature Reserve and a Johannesburg City Heritage Site because of its archaeological interest [57], including the presence of gold-rich rocks that are the basis of the development of mining in the city in the 1880s. In detail, the site comprises three interlinked, protected sections (named west, central, east) that are defined, historically, by patterns of land ownership. The area that is now protected has its origins as a farmstead of the Geldenhuys family in the mid-19th Century that gradually became encroached by the developing urban area of Johannesburg, following its foundation as a gold-mining town in 1886 [58]. Low-lying areas around the ridge margins developed as suburban areas, and these suburban roads now terminate at the ridge foot (Figure 4).

The central section is the oldest part of the nature reserve, protected in 1959. A number of different church groups also use the west part of the site for open-air services, and this continues the close cultural relationship that many local indigenous people have with such prominent ridge sites. In 1963, an Iron Age (~1800–200 years ago) smelting furnace was discovered and excavated in this part of the site. Stone-walled farm enclosures (kraals) also dating from the Iron Age are present, and these are constructed from local detached boulders and are therefore bedrock-dependent. Settlement sites containing Iron Age lithic flakes are also found here. In total, seven archaeological sites ranging from the Middle Stone Age (broadly 280–22 kyr) to gun emplacements from the Anglo–Boer War (1899–1902) have been identified from Melville Koppies (there are doubtless others that have not been hitherto identified). Limited archaeological investigation took place in the 1960s, but there has been very little more recent work. This means that it is difficult to evaluate the archaeological heritage or the potential record available at Melville Koppies.

The western section of the site (100 ha) was incorporated into the Nature Reserve in 1993 when over 70 squatter camps were cleared from the site and invasive species removed. Lower slopes in this part of the site have been extensively modified by suburban spaces and

sports fields, and are on a long-term lease from the City of Johannesburg. The northeast side of the site adjacent to a boundary road has a steep cliff face developed in quartzite. This has been used for recreational rock climbing, but it also has a cave at the cliff foot from which Late Stone Age (~22–10 kyr) artefacts were recovered. It is on this basis that this cave is recognized as a heritage site. The eastern sector of the reserve is 10 ha and was also incorporated in 1993. Since this time, invasive prickly pear (*Opuntia ficus-indica* (L. Mill, 1768)) and *Lantana camara* (L., 1753) have been removed. Controlled fire is also used as a grassland management strategy.

The initial management framework of the Nature Reserve of Melville Koppies comprised a management committee made up of community volunteers that was concerned with establishing guidelines for on-site use for different purposes and by different groups. The focus was on the research, guided tours, school education, publicity, conservation, volunteer workers, fire management, infrastructure, site security, fund raising, and relations with the Johannesburg Council for Natural History (now a department within the City of Johannesburg Metropolitan Municipality). These have been ongoing activities to date. Nature trails within the site were planned and enacted from the outset, including information panels about the site. At various times, significant management issues have included vandalism to the site, violence/mugging of visitors, squatter camp development (and the removal of squatters), access and use of the site by indigenous church groups, and management of invasive plant species. The western and eastern parts of the sites are open daily for public use. Public access to the central part of the site is by guided tours on Sundays only. The site was declared a National Monument in 1968. Management of such sites today is informed by key legislation, including the National Environmental Management Act, 107 of 1998 (amended 2013), and the National Environmental Management: Protected Areas Act, 57 of 2003 (amended 2009). The latter identifies several different categories of protected areas, which are (1) special nature reserves, national parks, nature reserves, and wilderness areas; (2) World Heritage Sites; (3) marine protected areas; (4) specially protected forest areas, forest nature reserves, and forest wilderness areas; and (5) mountain catchment areas. The National Heritage Resources Act, 25 of 1999, also protects archaeological and paleontological sites [59,60].

3.3. Comparison Between the Geosystem Services at the Two Sites

Both sites investigated in this study show a range of geosystem services that vary according to the particular characteristics of the physical environment and how local communities interact with and value these environments. Table 1 lists the major types of geosystem services observed at these sites, following the list of services identified by Gray [25] (Figure 1). The results of this inventory show that, although these sites are superficially similar because they are both protected green spaces within rapidly growing Global South cities, they are actually quite different (Table 1). For example, the larger siof ze and densely forested cover at Cantareira State Park means that it offers significant regulating services that are completely absent from Melville Koppies. The greater visitor infrastructure present at Cantareira State Park also means that a range of cultural and educational activities can be supported. Both sites are protected areas for their very different types of biodiversity, and both are used for very different types of academic research. In terms of the total number of geosystem services listed by Gray [25] (n = 32), Cantareira State Park appears to offer 22 services (69%) whereas Melville Koppies offers 11 (34%) or half of that number. Although neither Gray [25] nor Table 1, however, represents an exhaustive list and other geosystem services can be included [8,13], it is clear that the meaning and significance of any geosystem service should be critically interrogated. This is discussed below.

4. Discussion

4.1. Critique of Inventories of Geosystem Services

Different geosystem services are present at the two study sites (Table 1), but their presence/absence may not tell the whole story. For example, the bare list of service types themselves does not say anything about the quantity, quality, uses, and values of these services, and this makes it difficult to compare these services when they are found in different contexts. For example, at both sites, bedrock properties and structures control landscape topography and geomorphic character (e.g., Figures 3 and 4), but soil and ecological properties are more strongly climatically controlled and give rise to important ecosystem services. The availability of environmental and ecosystem services is thus linked to geodiversity [3,5]. At both sites, provisioning services are not well-represented (Table 1), and this is largely because of the lack of formal agriculture allowed in these protected areas. This means that provisioning geosystem services are limited, not by their absence in the environment but by management policies that restrict their use.

In addition, other elements of the inventory presented in Table 1 also require greater critical analysis. For example, at Cantareira State Park, microclimate modification due to the large area and canopy height of Atlantic Forest has helped maintain the conditions under which high biodiversity can develop, including by providing different ecological niches according to tree density, slope, and soil properties [35] (Figure 3g,h). By contrast, the low-density scrub and dominance of xeric grassland in Melville Koppies (Figure 4) means that microclimate effects and associated regulating geosystem services are absent (Table 1). Both sites are also protected as Nature Reserves, but the effectiveness of any conservation designation depends on environmental policies, legislation, management structures, personnel, funding, and monitoring [59]. Thus, this fact alone may not reveal any information on site sustainability, or its impacts on geosystem properties, biodiversity, or site users.

Another feature is that the different types of geosystem services present at the two sites do not exist in isolation but exhibit complex interrelationships (Figure 5). This feedback means that different service types affect each other and influence their presence and dynamics. For example, local relief and vegetation type/cover affect the microclimate which in turn impacts on human health and comfort, wellbeing, and quality of life. Vegetation and biodiversity are influenced by climate, soil, and surface processes, such as erosion and mass movements, and in turn influence the ecological properties of the protected area, carbon storage, and pollution remediation. This nuance, which is site-specific, affects the detailed properties of any site and the ways in which local communities interact with and value them. For example, at Cantareira State Park, the maintenance of vegetated slopes reduces slope and flood hazard risks and buffers environmental pollution. At Melville Koppies, scrub clearance, grassland management by seasonal burning, and continued quartzite weathering together increase slope hazard risks. Both sites also provide green spaces for recreation, but the user experience and contribution to quality of life may be limited by site maintenance, infrastructure, and management strategy. At Cantareira State Park, marked trails and controlled parking and access facilitate this user experience, whereas at Melville Koppies these things are absent, giving rise to heightened safety risks to visitors.

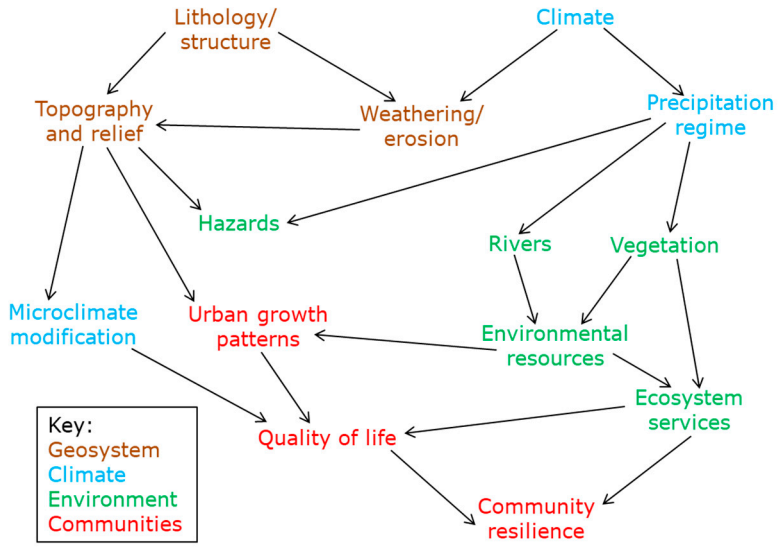


Figure 5. Flow diagram showing the relationships between geosystem and environmental properties as demonstrated at the two study sites, with implications for the sustainable development of these Global South urban green spaces.

4.2. Exploiting Geosystem Services in the Pursuit of Sustainable Development

Close relationships between geodiversity and ecosystem services have been noted in several studies worldwide (e.g., [3,4,14,17]), but, in detail, there are more complex relationships to diverse aspects of human activity, especially in the Global South [17], where sites of high geodiversity and/or ecological or hydrological importance come under developmental pressure [61]. Supporting and provisioning geosystem services in particular are important for sustainable development in rapidly growing Global South cities because of their links to ecosystem services and food/water security [6,62]. The characteristics of these cities also make them sensitive to the availability and exploitation of geosystem services, in particular, given the issues of poor infrastructure, water and waste management, urban agriculture and food production, and urban heat island effects [8,13,17,29,63,64].

At the study sites, because they are protected areas, the direct exploitation of ecosystem services or urban agriculture is limited. However, other green spaces or brownfield (waste) sites within these and similar cities are very commonly exploited for urban agriculture and can also be considered in a geosystem context, even if they are dominated by made ground or with polluted water/soil [8,65]. Natural green spaces within the urban environment are also positively associated with social and environmental indicators, such as public health, mental wellbeing, air quality, temperature regulation, and biodiversity [8]. In the context of UNESCO Global Geoparks, for example, the maintenance of geodiversity and related ecosystems, as well as important sites, is a challenge in highly urbanized areas, but also an opportunity to engage communities [66]. This kind of land use planning has been also related to healthy lifestyles [67].

Therefore, meeting the Sustainable Development Goals (SDGs) whilst also ensuring protected areas are maintained and used to support community development is a key issue in cities in the Global South, requiring strategic and integrated governance and management systems [5,9,12]. Protected areas are the primary defense against ecosystem and ecosystem service loss. In large and rapidly developing cities, protected areas have close links to several SDGs, as they play a crucial role in enhancing quality of life by providing ecological, aesthetic, and recreational benefits while regulating urban climate and serving as carbon sinks [68,69]. Some key links between protected areas and the SDGs were addressed by Dudley et al. [70], many of which were related to ecosystem functioning

and climate change adaptation, which includes the proper management of both biotic and abiotic elements of protected areas, which includes the consideration of geosystem services [7].

The effective management of geosystem, ecosystem, and environmental services in Global South cities requires an effective governance framework that is linked to city planning and resource management, including water, food, waste, and sustainable transport [10,11,71,72]. Climate models predict that, by 2100, for São Paulo, there will be an increase in mean temperatures and an increase in the number of extreme warm events [73], and that there will be an increase in extreme precipitation events as well as longer dry spells [74]. Climate models show similar patterns for Johannesburg, where mean annual temperatures are predicted to increase by 2.3 °C by the mid-century (2056–2065) and by over 4 °C by 2100 [75]. Total annual precipitation is predicted to increase by 18% by the mid-century and by 27% by 2100, but with much less confidence. Geosystems on all scales have to respond to these future climatic conditions, with implications for the availability of other environmental resources, and their properties and services (Figure 5). In this sense, nature-based solutions are increasingly shaping urban development agendas, and being globally discussed, planned, and promoted by the researchers, NGOs, and policymakers as key strategies for urban regeneration and sustainability [62]. In this context, ensuring environmental protection and financial resources for municipalities requires integrating environmental priorities into urban planning [76]. The ways in which these geosystems or protected areas are likely to respond, however, are largely unknown, and this is a significant limitation for future urban development planning in developing world cities.

4.3. Research Limitations and Future Research Directions

This study provides an overview of the geosystem services offered by two protected green spaces of high-biodiversity importance in different Global South cities, based on an inventory of service types identified in the literature (Figure 1). This case study approach, however, may not capture the diversity of different services that may be present in different types of urban green spaces. In addition, the inventorizing approach used here (very similar to the method used for identifying ecosystem services at Ramsar sites, see [77]) is based on a simple presence/absence of certain services, and this may not capture any nuances in the availability or their properties. In addition, some geosystem services may be missed out in the list used, based on the literature (Table 1). The relationships that exist between these different services also need to be considered, where one service type may influence another (Figure 5). These points highlight the importance of field-based site-specific observations, as undertaken in this study.

Future research directions on geosystem service provision in urban green spaces can include quantifying and weighting these services and their characteristics; monitoring of environmental change or human impacts at the sites to evaluate their impacts on service availability; and valuing geosystem services from an economic perspective—following Natural Capital and Willingness to Pay models—that can be used to inform environmental management strategies [78]. In addition, future research should engage with and collect data from site managers and visitors, regarding how green spaces are used and valued from different perspectives, and the applicability of top-down management approaches used for different sites with different geosystem properties. This is particularly important in the context of climate change and developing more resilient urban infrastructure [76].

5. Conclusions

The geosystems resources and services provided by protected green spaces in the Global South cities of São Paulo and Johannesburg are important for local communities

and should be part of the sustainable development strategies of these cities. The examples of Cantareira State Park (São Paulo) and Melville Koppies (Johannesburg) exhibit different types of geosystem services (Table 1), and this is largely dependent on the geological, ecological, and climatic properties of these sites. In addition, the geosystems resources and services found within these protected green spaces can serve as a buffer against climate change impacts, in particular through microclimate modification, water resource management, and by maintaining biodiversity. Thus, the presence of urban green spaces can increase urban environmental and societal resilience to climate change. In rapidly developing Global South cities, urban green spaces can provide a range of geosystem services that can promote environmental sustainability, such as nature tourism and geotourism. Meeting the Sustainable Development Goals in cities in the Global South requires a better understanding of the contribution of geosystem resources and services. This can be achieved by planning for protected areas as urban buffers, enhancing green spaces, and establishing a monitoring framework in partnership with relevant nature agencies and local communities.

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