Environmental Earth Sciences (2023) 82:461
https://doi.org/10.1007/s12665-023-11126-4

TOPICAL COLLECTION

Limpopo National Park (Mozambico): groundwater assessment as a tool for a sustainable management of the area

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Received: 26 January 2019 / Accepted: 31 July 2023 / Published online: 12 September 2023

Abstract
This paper deals with updated results coming from hydrogeological studies carried on the framework of the SECOSUD Phase II, called "Conservation and equitable use of biological diversity in the SADC region (Southern African Development Community), a project supported by the Italian Ministry of Foreign Affairs in the SADC, whose focus area includes South Africa Development Countries. The main goal of the SECOSUD Phase II Project is the definition and implementation of scenarios for sustainable development, aimed at an equitable conservation of biodiversity resources and, as a consequence of this target, the hydrogeological characterization, with the groundwater recharge assessment, of this area and its buffer zone. Limpopo National Park is one of the jewels in the crown of Mozambique's protected areas. As a matter of fact, sustaining the conservation of biodiversity, due to its complexity and multiple drivers, which stress it, is on first a matter of water environment assessment, as most ecosystems are highly dependent on the hydrological cycle and groundwater availability. After gathering regional and local geological data, which let us set up a detailed geological map of the area under study, pointing out the main outcropping geological units, with their main hydrogeological properties, the methodological approach adopted has been to assess the potential infiltration, applying the Inverse Hydrogeological Budget Technique, performed for the focus area. Because of the lack of meteorological data referred to Limpopo National Park, it has been applied a spatial distribution of precipitation measurements, collected in many gauge stations, located in the Kruger National Park during the last 54 years, which represent an interesting rainfall historical series. The target of the study has been to assess a trend of meteorological data with the aim of understanding how precipitations could affect groundwater recharge, and their influence on groundwater availability. The estimation of groundwater recharge is the tool for suggesting better water management in the area, aimed to preserve as much biodiversity as people living in the buffer zone.

Keywords Mozambico · Limpopo National Park · Biodiversity · Inverse Hydrogeological Budget · Groundwater recharge · GIS environment

Introduction

The Convention on Biological Diversity (CBD) gives this formal definition of biodiversity: "the variability among living organisms from all sources including, among others, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems". Regarding this definition, Limpopo National Park, one of the jewels in the crown of Mozambique's protected areas, is, with its buffer zone, the area under study, and it is, exceptionally, rich from a biodiversity point of view and, as a matter of fact, it has a wide variety of genes, species and ecosystems. Many and updated studies refer to the strong linkage between groundwater management

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This article is a part of the Topical Collection in Environmental Earth Sciences on "Groundwater Resources and Sustainability" guest edited by Nam C. Woo, Xiaosi Su, Kangjoo Kim and Yu-Chul Park.

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and biodiversity conservation, and it is well known as this important linkage is affected by climate changes. Managing groundwater supplies, sustainably, is critical to the challenge of simultaneously sustaining biodiversity. The management of human and environmental water needs is therefore challenging and calls for an integrative view of ecosystem services. On the other hand, much of the world's biological diversity exists outside a formal protected and reserved areas network. Very often, many biological diversity examples outcome on land, that is managed for some forms of agricultural production and the maintenance of rural livelihoods. Effective biodiversity conservation will therefore require innovative ways to merge the needs of farmers and rural communities with the need to conserve globally significant biodiversity. Unfortunately, many areas in the Southern African Development Community are data-poor and poorly accessible (Barbieri et al. 2019) referring to meteorological and groundwater information, and it makes quite difficult to give any support in better managing groundwater with the aim of protecting biological diversity outcrops. On the contrary, in South Africa, significant progress has been made by the government in reshaping water governance, since the end of apartheid in the early 1990s. The role of government in water governance and water politics has thus been emphasized to a large degree (Meissner and Ramasar 2015). On the other side, all the sub-Saharan region is characterized by a high economic dependence on local natural resources in the form of agriculture (frequently subsistence) and pastoralism, in which the variability of climate and the availability of water to a large extent determine production. This fact, coupled with its relatively low development status, makes the economies and social character of Southern Africa particularly vulnerable to climate changes, especially related to the availability of water over space or time. Such changes may be defined in terms of the total amount of precipitation received, its frequency of occurrence, the persistence of wet or dry day combinations or the onset and duration of the rainy season (Schulze et al. 2001) or in terms of the quality of the available resource (Beekman et al. 2015). Both surface waters and groundwater of southern Africa and, specifically, South Africa ones are increasingly under pressure due to the constant growth in the population as well as increased climate variability. It is important to note that more than half of the country's WMAs (Water Management Areas) are in a water deficit, after the allocation of enough water for rivers and environmental flow requirements despite significant water transfers into the country from other systems to assist in meeting water requirements (du Plessis 2019).

In view of this, an important first phase in developing the conservation of biodiversity requires reliable groundwater characterization and protection, especially where groundwater is fundamental for nature and people life support, as it happens in Mozambico Limpopo National Park area and its buffer zone, as many studies refer to (FAO 2004a, b).

Study site

The Limpopo National Park spreads on a surface of about 11.433156 km^2 in the Mozambican part of the Limpopo River basin, situated in the East of Southern Africa, between about 20° and 26° S and 25° and 35° E. The Mozambique portion of the Limpopo basin consists of gently undulating terrain, between ranges of hills and mountains, with numerous small tributary streams.

The rich biodiversity of the Limpopo basin can be attributed to its biogeographical location and to its variety of topographical features. It is an important agricultural area, with extraordinary mineral resource reserves, where rural settlements are predominating. In these rural areas, water point sources include shallow wells with hand pumps, handy dug wells with access from hand pump, natural springs without fencing protection, and shallow alluvial aquifers with highly mineralized water. The lack of management of groundwater resources is also evident in community water supplies and, as a consequence of it, there is an inadequate water resources information system. Women and children spend their time collecting water.

The exact location of the Limpopo National Park (LNP), which, borders the Kruger Park, is the west of Gaza Province, near the South Africa border and South of the Zimbabwe border (Fig. 1).

The Limpopo National Park area, inside Mozambico, is surrounded by its buffer zone, which is the area peripheral to the protected area, set up with the aim of not having a sharp division between the area under protection and the rest of the region.

On the whole, a buffer zone has been created to enhance the protection of a specific conservation area. UNESCO defines a buffer zone as "an area that should ensure an additional level of protection to areas recognized as World Heritage sites", with an emphasis on the importance of these areas in the proper management of protected areas.

Unfortunately, the buffer zone of Limpopo National Park is still poorly defined and characterized, as several drivers stress the resilience of these areas and make groundwater resources very sensitive to any change and, as a matter of fact, very vulnerable.

The Shingwedzi River flows through the core zone of Limpopo National Park, ensuring that it is populated with a wide range of wildlife. The park takes up the river catchment and borders both the Limpopo and Olifants rivers for long stretches.

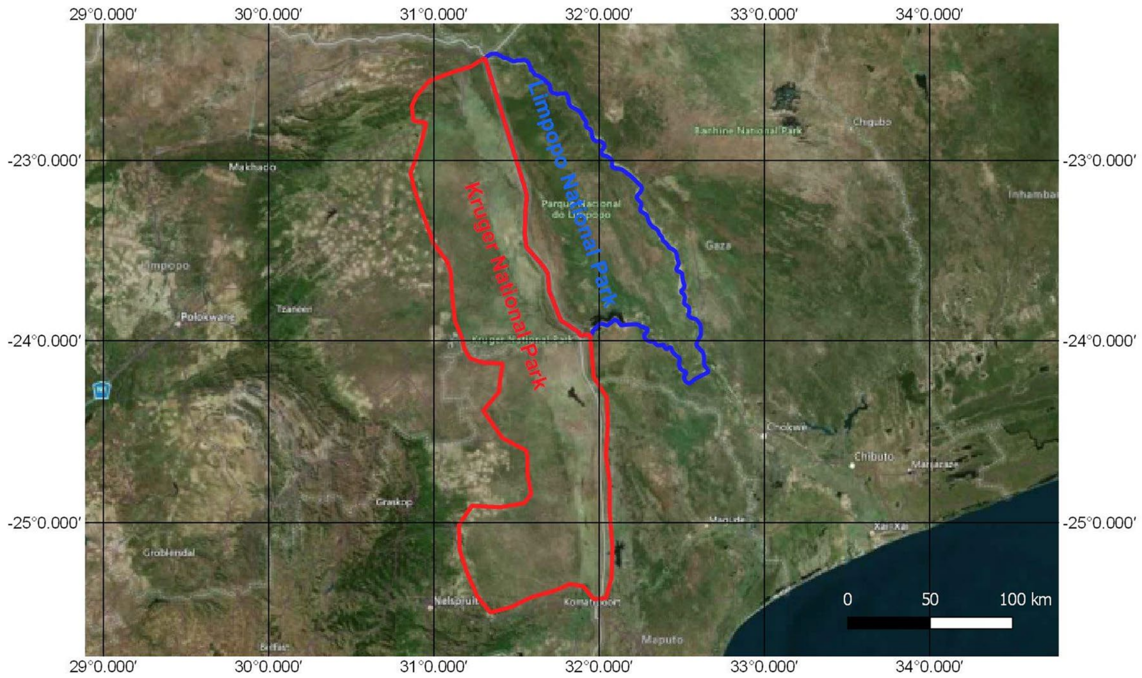


Fig. 1 Map of the Limpopo National Park buffer zone

Fig. 2 Groundwater extraction in one of the village of the buffer zone of Limpopo National Park

Many rural villages rely entirely on groundwater abstraction for farming, irrigation and drinking water supply, domestic uses (Fig. 2), but groundwater supplies are increasingly threatened by contamination by various sources, and their overexploitation makes it, sometimes, to be not enough available, as for human demand as for biological diversity conservation. Moreover, climate change is a growing up factor of pressure on groundwater resources availability and water quality protection.

Due to the complexity of geological and hydrogeological framework within the SADC region, as Mozambique is too, groundwater quality varies considerably depending on different climatic regions and on aquifer geological and lithological features and thickness.

That is why, the priority is to make sure that their water resources, especially groundwater, are managed in a sound and equitable manner as for people supporting as for biodiversity conservation.

Geological and hydrogeological setting

The African continent is made of a mosaic of old, stable, mostly crystalline, crustal blocks, called cratons, surrounded by a network of younger orogenic belts including deformed metamorphic rocks and granites, called mobile belts. This scenario comes from the geological evolution of the ancient geological continent, named Gondwana (European Union and GTZ 2009).

The geographic position of Mozambique, in the framework of Gondwana, makes this country a geological important framework, particularly because inside it there are boundaries between cratons and mobile belt terrains. The crystalline basement of Mozambique belongs to three larger ‘building blocks’ or terrains: East, West and South Gondwana. These blocks collided and amalgamated during the Pan-African orogeny to form the Gondwana Supercontinent (European Union and GTZ 2009). In the southern and middle Mozambique area, the Phanerozoic outcropping rocks can be divided into the Karoo Supergroup (Permian-Jurassic) followed by a succession of Cretaceous and younger sedimentary formations, partly associated with the development of the East Africa Rift System Phanerozoic sedimentary rocks of the Mozambique basin occupy vast areas in southern Mozambique.

Geological properties and features of Southern Mozambique are poorly known, due to the lack of more detailed studies and maps. The Limpopo basin is floored by Jurassic volcanic rocks and filled by Early to Middle Cretaceous and younger sedimentary ones. Mapai formation, occurring in the western part of the Gaza Province in the southern part of Mozambique, is divided into 6 parts, that are characterized by calcareous siltstones, calcareous sandstones and calcareous conglomerates, locally calcified and oxidized. The Mapai rock formations, typically, have been deposited from both continental and coastal sedimentation environments, and are locally largely outcropping in the river bed of the Limpopo, dos Elefantes and Singuédzi Rivers. In the west, the lowermost limestone of the Mapai Formation overlies volcanic rocks of the Karoo age.

The Limpopo Belt of Southern Africa is a high-grade metamorphic province, which includes Archean and Paleoproterozoic lithologic components, and is bounded by the Zimbabwe and Kaapvaal Craton. The geological features of this area is mostly made of basic mafic and ultramafic intrusive rocks, accompanied by extensive areas of acidic and intermediate intrusive rocks. The lower part of the Limpopo basin is characterized by extensive erosion plains, gently dipping coastward. The coastal belt is characterized by a dune area with an average width of 30 km, but reaching 100 km in some places. The lower Limpopo basin consists largely of unconsolidated and consolidated sedimentary rocks with granitic intrusions, exposed as erosion rests in the landscape.

The hydrogeology of the basin is dominated by the Limpopo Mobile Belt, a metamorphic zone of high grade, that lies in the collision zone between the Kaap Vaal craton and the Zimbabwe one, two Archean continental shield areas. Due to the metamorphism process, these rocks have very low primary porosity or permeability and the groundwater occurrence is largely restricted to secondary features such as fault zones, joints, lithological contact zones (Owen and Madari 2010).

The Karoo volcanic rocks of the Limpopo basin in Mozambique are, from the hydrogeological point of view, quite similar to crystalline ones, everywhere else in the Limpopo basin, where primary and secondary fractures are the most important water-bearing features (Boroto 2001). The water-bearing formations of the Basement complex are low productive and discontinuous. The groundwater occurrence is associated with geologically weak zones. The aquifers are divided into separate lenticular units and are found in the deep alteration zone of the rocky substratum; contact zones between rocks of different types; faulted, fractured or crushed zones.

The main hydrogeological units correspond to geological ones and are, as in the followings: aquifers related to the crystalline basement complex, aquifers occurring in Karoo formations and aquifers related to post-Karoo formations (Ferro 1987). The aquifers are divided into different lenticular units and are found in the deep alteration zone of the rocky substratum; contact zones between rocks of different types; faulted, fractured or crushed zones. In the crystalline complex formations aquifers have only local size (Ferro 1987). They provide low unit yields, rarely more than 2 l/s. Dug wells generally take advantage of a suspended aquifer on the top of a lateritic layer.

The aquifers in the lower parts of the Limpopo basin in Mozambique are of poor water quality, due to the high salinization, coming from the high mineralization (Mineral Resource Centre 2009). Old alluvial plains (bordering the dune area) and erosion plains and erosion valleys (shallow eluvial cover of sandy clays over the entire inland area) have highly mineralized groundwater. However, some of the alluvial aquifers do have good water quality such as recent coastal dunes, alluvial deposits along the Limpopo River and erosional plains along rivulets, all of which are regularly recharged (FAO 2004a, b).

Materials and methods

In the aim of contributing to the baseline knowledge of aquifers recharge and to identify which phenomena such as climate change, drought cycles or someone else, can be connected to it, the hydrogeological inverse budget (Civita et al. 1999) was applied in order to estimate the groundwater recharge, referred to the area under study in different rainfall scenarios, due to climate change effects. In the aim of better understand meteorological trends referred to Limpopo National Park, authors have been considered, on the first, the existing meteorological station network inside and in surroundings of Limpopo National Park area and its buffer zone, which is very poor, as it is reported in Table 1, and represented in Fig. 3. Unfortunately, the Limpopo National Park hasn't a sufficient coverage of rainfall records for his scale basin wide. Operational rainfall stations are mostly located on the East Southern part of Mozambique (Vitale et al. 2017a; b).

In the framework of SECOSUD Phase II activities to improve climate characterization of the area under study, authors have designed a network of meteorological stations, reported in Table 2, some of which have been already installed, and data have been going to be registered starting from June 2018.

Table 1 Current rainfall monitoring network (after INAM 2016)

Meteorological stations	Period of observations		Functionality
Massangena	1960	2015	Operative
Chicualacuala	1961	2003	Inoperative
Chigubo	1961	1978	Inoperative
Mabalane	No data	No data	Operative
Massingir	1961	2014	Operative
Funhalouro	1951/2003	1980/2007	Inoperative
Chibuto	1965	2014	Inoperative
Bilene-Macie	1965	2014	Operative
Xai-Xai	1951	2016	Operative
Panda	1951	2016	Operative
Massinga	1951/2003	1980/2016	Operative
Ndindiza	2006	2016	Operative

Unfortunately, up today, data coming from all these meteorological stations are not enough to make a historical series of rainfalls, which could be statistically representative of climate evolution in the area under study. This is the reason why they have been considered data coming from the large meteorological station's network of Kruger National Park, which is made of 21 stations, covering the whole area of the Park and referring to 54 years of measurements, as it is represented in Fig. 4 and summarized in Table 3 (Sappa et al. 2018).

The groundwater recharge, referred to the area under study, has been assessed by the application of the inverse hydrogeological water balance, which is a spatial spread data method for the evaluation of aquifer recharge (Fig. 5). The inverse hydrogeological water balance (Civita et al. 1999) was applied to estimate the average annual active recharge (i.e. the effective infiltration—I) for the Limpopo National Park area, by a GIS support, referring to different range of years. This procedure, for groundwater recharge evaluation, has the advantage of not needing any information on runoff, which aren't available in the area under study. The application of this method involves a series of steps, which are presented in the flowsheet of Fig. 5 (Civita and Maio 2001).

Steps of inverse hydrogeological water balance are the followings:

1. Discretization of the study area into a grid of finite square elements (FSE).
2. Selection of rainfall data for sufficiently long periods (20 years).
3. Georeferencing the positions of the existing pluviometric gauging stations inside or immediately outside the study area.
4. Calculation of the monthly and annual average of the pluviometric data for each gauging station.
5. Calculation of the rainfall-elevation [$P = f(q)$] function. This function described above, valid for the whole study area, are used to compute the hydrogeological water balance within each elementary cell.
6. Calculation of the mean elevation (q) of each FSE.
7. Calculation of the specific rainfall (P), on the basis of points 4 and 5.
8. Identification of the potential infiltration coefficients, (χ_s) on the basis of the surface lithology.
9. Calculation of the specific active recharge (I) on the basis of points 7 and 8.
10. Calculation of the active recharge.

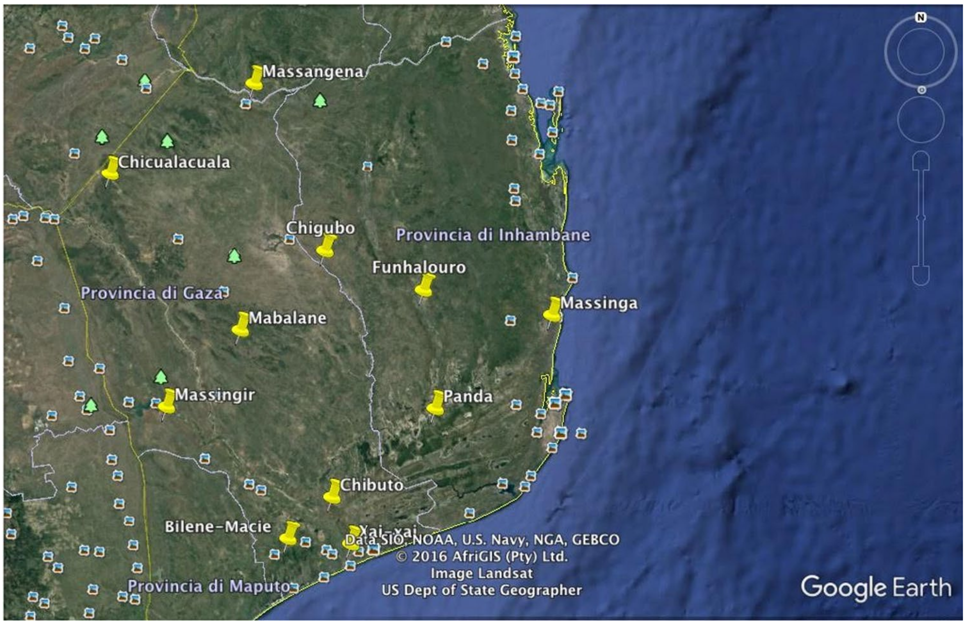


Fig. 3 Map of Mozambique rainfall monitoring stations

Table 2 Designed meteorological stations network inside the Limpopo National Park area and its buffer zone

Meteorological stations	Geographical coordinates	
Mapai	22°51′ 7.01″ S	31°58′1.99″ E
Mapulanguene	24°29′25.89″ S	32° 4′55.47″ E
Komatipoort	25°25′37.96″ S	31°57′7.00″ E
Pafuri	22°27′0.10″ S	31°19′16.50″ E
Letaba	23°51′22.72″ S	31°34′37.63″ E
Combomune	23°28′8.98″ S	32°27′14.55″ E
Devende	23°20′30.34″ S	32°20′53.30″ E
Nyando	22°47′46.28″ S	31°25′33.94″ E
Giriyondo	23°35′2.09″ S	31°39′36.08″ E
Massingir	23°55′15.68″ S	32° 9′43.05″ E
Phalaborwa	23°56′51.53″ S	31° 8′18.11″ E
Mabalane	23°25′21.05″ S	32°48′30.42″ E
Chicualacuala	22° 5′4.29″ S	31°40′46.70″ E

As a matter of fact, starting from a digital elevation model (DEM), built by registering one point any 90 m^2 of surveying, all over Kruger and Limpopo National Park area, and coming from the elaboration of data, obtained from CGIAR-CSI (http://srtm.csi.cgiar.org/), the area under study has had been divided finite square elements of 1 km^2, and it is has been obtained the discretization of the area of Limpopo National Park, as asked by the applied method and represented in Fig. 6.

Mozambico Limpopo National Park and its buffer zone, inside Limpopo River basin, covers an area of about 11.433156 km^2 [4] and this is the reason why, for this study, it has been chosen 1 × 1 km finite square element (Fig. 6), as this is the dimension considered as the smallest one to give a reliable representation of morphological features of the area under study. Any finite square element (FSE) has been the reference basic unit, on which, it has been carried on the hydrogeological inverse budget. For any further elaboration, especially meteorological ones, any FSE has been represented by an altitude value, coming from the application of a special script, included in QuantumGis software. Geological information, considered for the hydrogeological characterization of the area, have been gathered from the Soil and Terrain SOTER database (ISRIC 1991) which gave, for the Limpopo National Park area, a detailed database, that includes the outcropping rock formations reported in Table 6. These pieces of information are useful for the potential infiltration estimation of any finite square element (Table 4).

As a consequence of it, to match information coming from the geological map with other data, referred to the area under study, it has been elaborated a digital geological map of it, using open source software Quantum Gis, taking into account the lithostratigraphic units, obtained from the Soil and Terrain database (SOTER) for Southern Africa, occurring in the area of concern, giving for it a

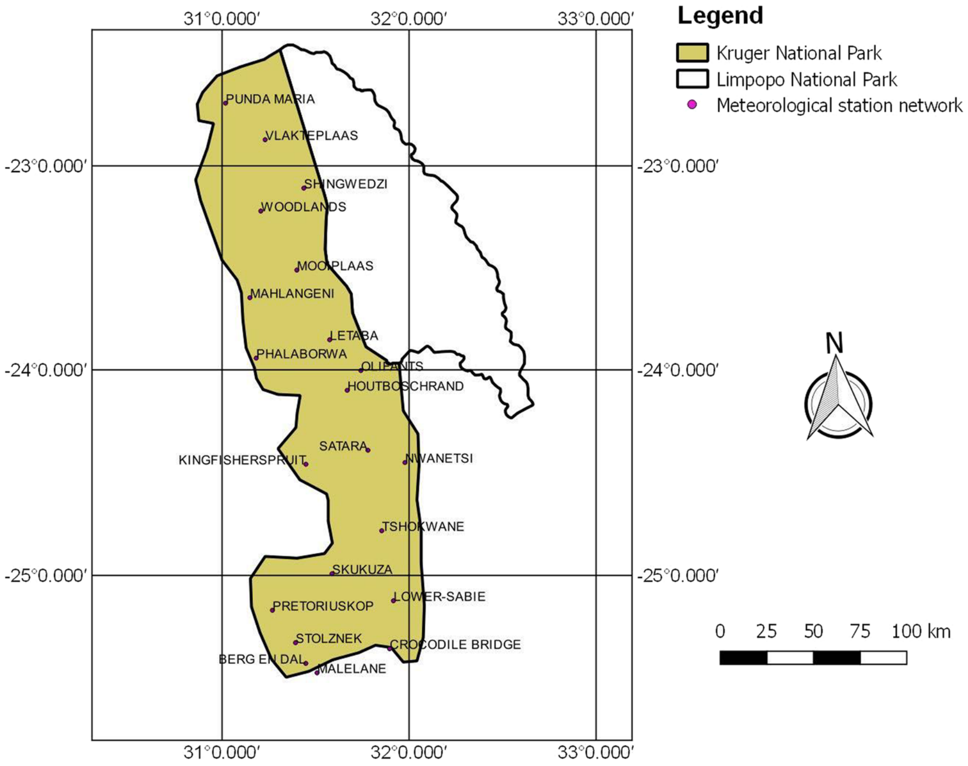


Fig. 4 Meteorological station network inside Kruger National Park area

Table 3 The 21 stations of the Kruger National Park area

Meteorological stations	Abbreviation	UTM		Altitude (m a.s.l.)	Year rain
		East (*X*)	North (*Y*)		
Crocodile Bridge	KRO	388,865.049	7,195,400.074	166	1956–2014
Houtboschrand	HOU	364,730.525	7,334,147.063	242	
Kingfisherspruit	KFI	342,729.090	7,294,024.974	418	1956–2014
Letaba	LET	354,918.906	7,361,395.020	230	1956–2018
Lower-Sabie	OSA	390,750.923	7,221,110.698	180	
Phalaborwa	PHA	315,016.729	7,351,013.311	415	1956–2018
Pretoriuskop	PRE	325,558.058	7,215,312.511	587	1956–2014
Punda Maria	PUN	296,444.252	7,489,385.095	460	1956–2018
Satara	SAT	376,276.456	7,301,914.212	267	1956–2014
Shingwedzi	SHI	339,947.651	7,443,580.099	272	1956–2018
Skukuza	SKZ	357,467.637	7,235,290.841	280	1956–2014
Tshokwane	TSH	384,111.931	7,258,634.317	252	1956–2014
Berg En Dal		343,900.461	7,187,099.476	350	
Mahlangeni	MAH	311,159.387	7,383,696.289	300	1956–2018
Malelane	MAL	349,981.920	7,182,128.550	320	1956–2014
Mooiplaas	MOP	336,609.402	7,398,989.116	368	1956–2018
Nwanetsi	NWA	396,395.644	7,295,454.522	180	
Olifants	OLI	372,035.176	7,344,901.345	220	
Stolznek	STO	338,224.922	7,198,110.34	480	
Vlakteplaas	VLA	318,436.002	7,469,727.302	341	
Woodlands	WOO	316,521.346	7,430,839.311	337	

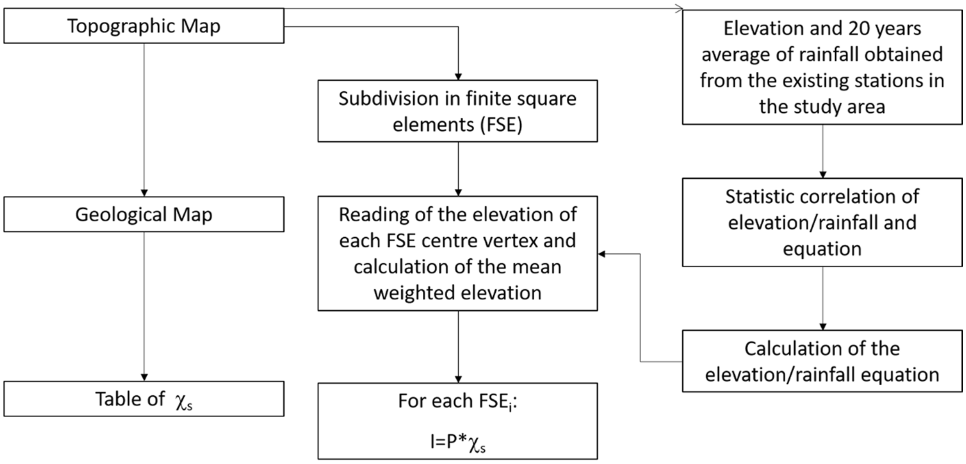


Fig. 5 Flow-chart of the inverse hydrogeological water balance

simplified interpretation aimed to emphasize hydrogeological features of them, as it has been represented in Fig. 7.

In the aim of well considering any effects on the area under study, due to climate change factors, the key step of the hydrogeological inverse budget (Civita and Maio 2001) has been the set up of a relationship between rainfalls and altitude inside the Limpopo National Park area, in spite of our not having any statistic significant historical series, coming from rainfall stations inside this area. This is the reason why they have been considered precipitation data coming from the meteorological stations network, existing in the area of Kruger National Park.

In consideration of this, in the present study, for the evaluation of the Limpopo National Park groundwater recharge, they have been considered the available precipitations data coming from 58 years of measurements, collected in 6 meteorological stations located in the Kruger National Park, inside the boundary of the park area (Fig. 8). Among the all meteorological stations available for Kruger National Park area, they have been chosen, for our elaborations, some

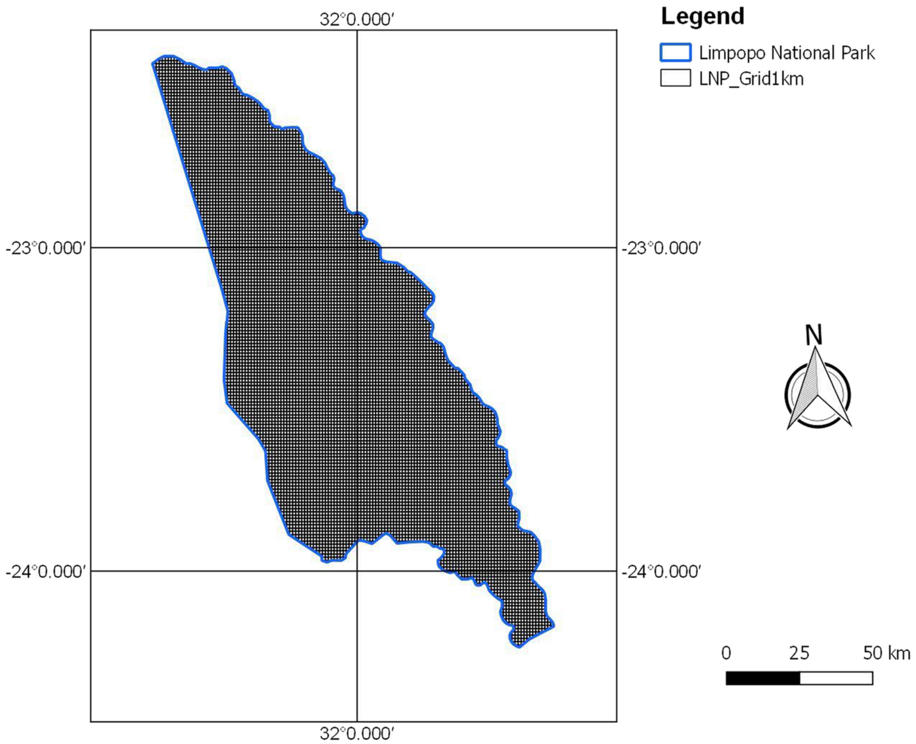


Fig. 6 Discretization of the Limpopo National Park in FSE (1 × 1 km)

Table 4 Lithological description of Limpopo National Park (as SOTERSAF)

Major class	Group	Type
Unconsolidated	UF	Fluvial: sediments generally consisting of gravel and sand or silt and clay
	UC	Colluvial: massive to moderately well-stratified unsorted to poorly sorted sediments
	UE	Eolian: sediments consisting of medium to fine sand and coarse silt particle sizes
Basic igneous rock	IB2	Basalt
Clastic sediments	SC2	Sandstone, greywacke, arkose
	SO2	Marl and other mixtures

of which, placed about at the same latitude of Limpopo National Park area, and better representing the altitude distribution inside the Limpopo National Park area.

On the first, annual average precipitation (AAP) was calculated for each rainfall station, referred to the historical series 1956–2018 of the six, represented in Fig. 8, which, unfortunately, is not strictly continuous. For them, they are known also altitude information (Q) and a rainfall–altitude relationship, the linear interpolation, shown in Fig. 9, has been built.

The elaboration of precipitation measurements, referred to the stations existing inside the Kruger National Park, has been the first step to assess the effective infiltration action on the basis of the outcropping lithologies. As a matter of fact, according to this relationship, it has been possible to set up the following expression, which allows to have a rainfall value for any altitude:

$$\text{AAP (mm)} = 0.344 * Q(m) + 375.46,$$

where: AAP is the average annual precipitation, given in mm and Q is the altitude, given in m a.s.l.

This elaboration drove to have an estimation of precipitations distribution, all over the area under study, as it is represented in Fig. 10, which highlights that inside the Limpopo National Park area, the Average Annual Precipitation, between 1956 and 2018, has a maximum value of about 600 mm, in North West zone of the investigated area and a minimum value of about 400 mm in the Southern East part of it. It is interesting to notice, as a validation of the applied extrapolation of meteorological data from Kruger National Park area to Limpopo National Park one, that previous studies carried on the same area, using meteorological data referred to all over Mozambique, gave very similar values (Vitale et al. 2017a, b).

Fig. 7 Simplified geological map of Mozambique and Limpopo National Park

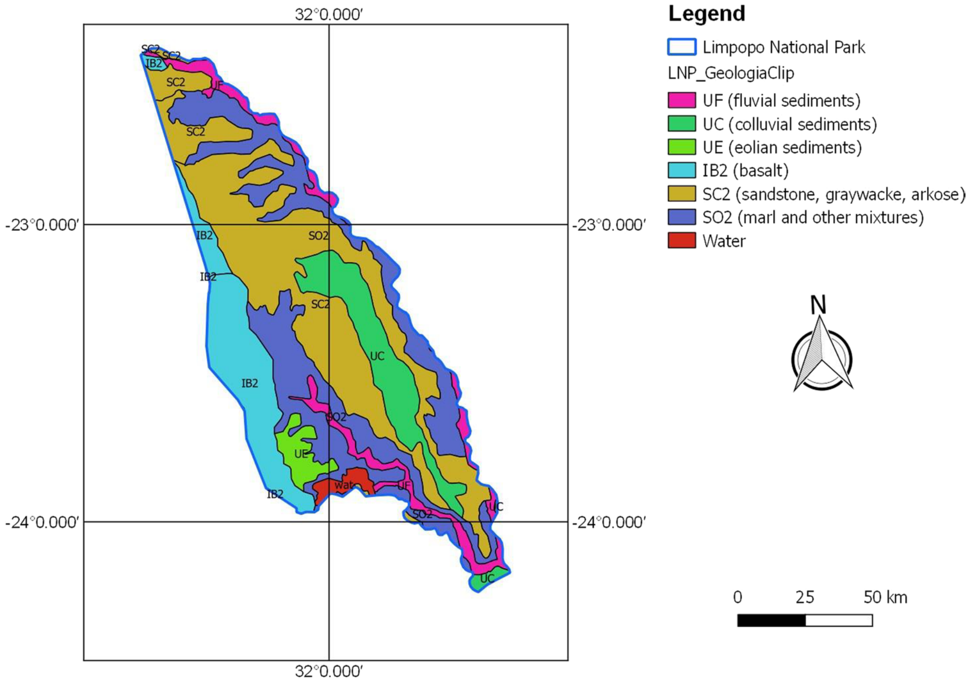
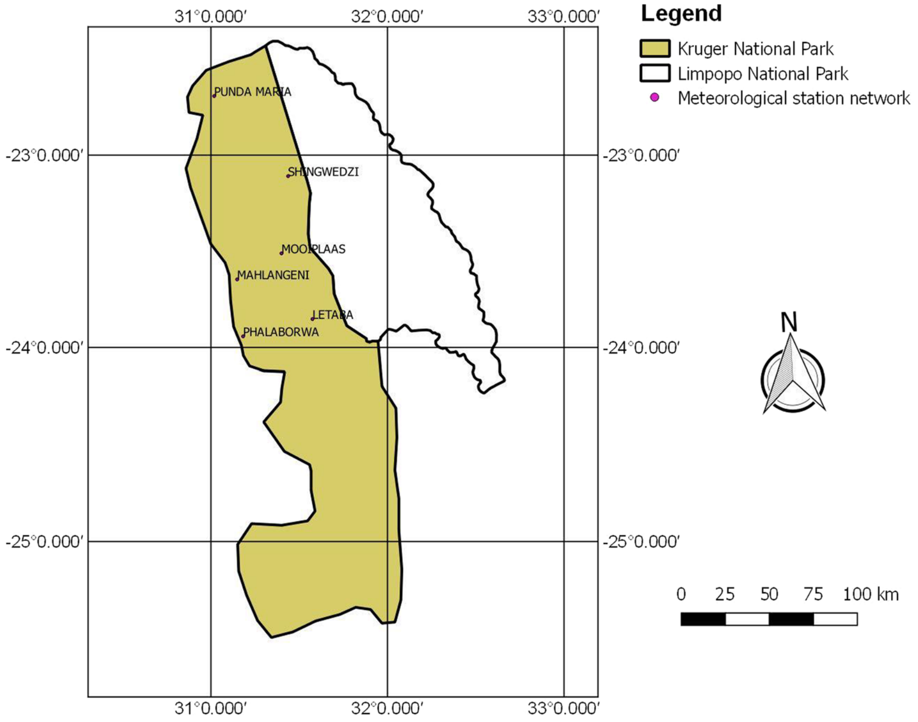


Fig. 8 Meteorological stations of Kruger National Park considered in present study



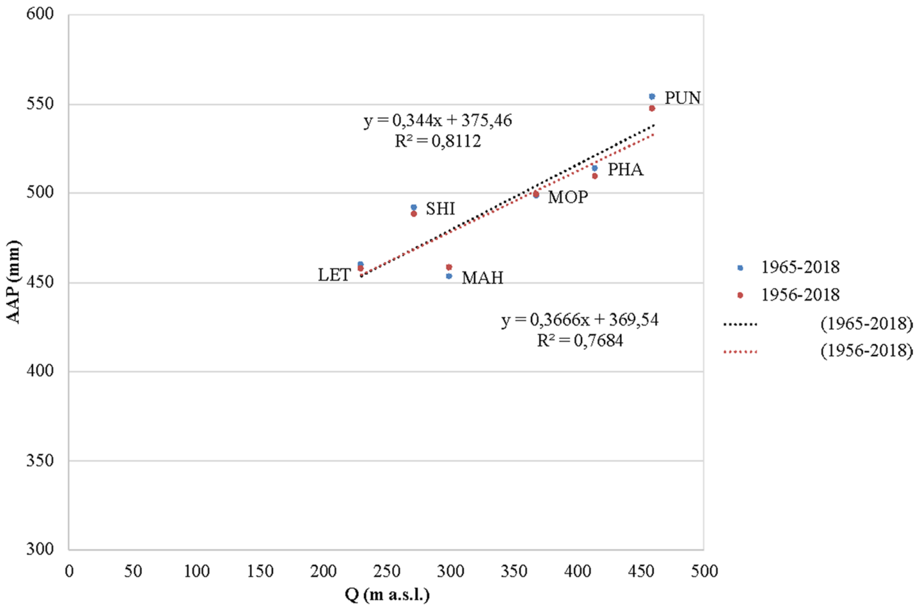
In the aim of estimating climate change effects on precipitations and, consequently, on groundwater recharge, they have been considered different range of years, included in the historical series, going from 1965 to 2018, as this range of years takes to a very similar evaluation of rainfalls distribution of the 1956–2018 one, and it has the advantage of being continuous, as it represented in the equation reported on Fig. 9, which is:

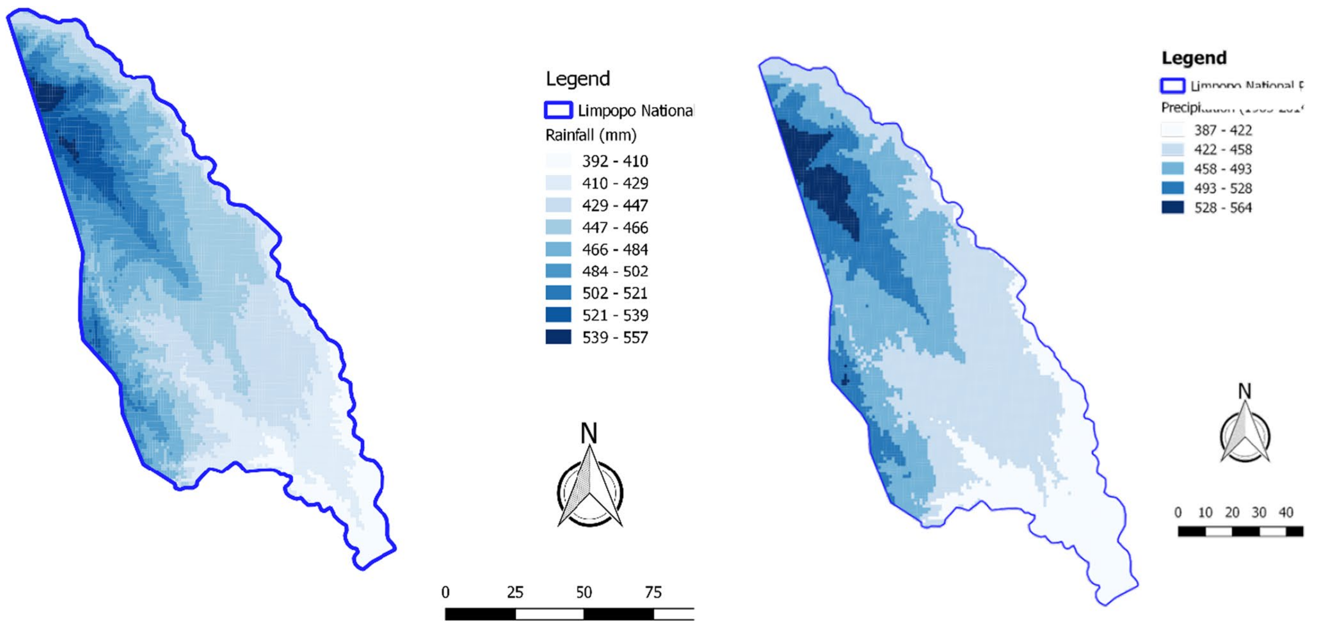
$$\mathrm{AAP\ (mm)} = 0.367 * Q(m) + 369.54,$$

where: AAP is the average annual precipitation, given in mm and Q is the altitude, given in m a.s.l.

Starting from these about fifty years, whose spatial distribution of precipitations, is represented in Fig. 10, due to the data availability, they have been considered

Fig. 9 Linear regression line rainfall–altitude (1956–2018) and (1965–2018)





(1956-2018) (1965-2018)

Fig. 10 Map of the rainfall in the Limpopo National Park

meteorological stations included in Table 5 to set up relationships altitude-AAP, for any considered station.

Afterwards, the range of time from 1965 to 2015 has been divided into decades and also, the last three years 2015–2018 have been considered. Then the method has been applied for the evaluation of rainfall spatial distribution, referred to the decades represented in Table 6, where they have also represented the relationships that come out between rainfalls and altitude.

In Fig. 11, they have represented the spatial distribution of rainfall, referred to the considered decades.

It is interesting to outline that there is no evidence of rainfall homogeneous evolution in this range of time, which let us suppose that we are under a regular climate change trend. It is possible to say, on the other side, that they have been decades characterized by rainfall decreasing, except for one, going from 1995 to 2004. Out of this decade, whose behavior is quite peculiar, from the other

Table 5 Meteorological stations considered for rainfall characterization between 1965 and 2014

Meteorological stations	Abbreviation	UTM		Altitude (m a.s.l.)	$AAP_{1965–2014}$ (mm)
		East (*X*)	North (*Y*)		
Letaba	LET	354,918.906	7,361,395.02	230	459
Phalaborwa	PHA	315,016.729	7,351,013.311	415	513
Punda Maria	PUN	296,444.252	7,489,385.095	460	553
Shingwedzi	SHI	339,947.651	7,443,580.099	272	491
Mahlangeni	MAH	311,159.387	7,383,696.289	300	452
Mooiplaas	MOP	336,609.402	7,398,989.116	368	498

Table 6 Evolution of relationships between rainfalls and altitude from 1965 to 2018

Decade	Altitude–rainfall relationship
1965–1974	AAP (mm) = 0.355*$Q(m)$ + 379.09
1975–1984	AAP (mm) = 0.591*$Q(m)$ + 350.71
1985–1994	AAP (mm) = 0.408*$Q(m)$ + 272.83
1994–2004	AAP (mm) = 0.423*$Q(m)$ + 431.37
2005–2014	AAP (mm) = 0.364*$Q(m)$ + 340.65
2015–2018	AAP (mm) = 0.3789*$Q(m)$ + 229.24

ones it comes out that rainfall have sensitively decreased from 1965 to 1974 decade to 2005–2014 one (Table 7). As a matter of fact, the lowest rainfall estimated value in the first decade, which is 1965–1974, was 396 mm/year, while the minimum one referred to the last decade, going from 2005 to 2014, has been 258 mm/year. The same comparison made between maximum values, referred to the same two decades, gives the largest value of rainfall, estimated for the decade 1965–1975, to be 567 mm/year, and the same one, estimated for 2005–2014 decade, is 433 mm/year. It means that between these two decades, in the range of about 50 years, they have lost about 30% of rainfalls, referred to the area under study. This trend seems to be confirmed in the last three considered years. For better analyzing these data, in Table 9, they are presented minimum and maximum values of rainfall, referred to any considered range of years, with the aim of let us appreciate climate change effects on rainfalls, in the area under study.

The next step of carried on elaborations, has been made by the match between rainfall estimation and outcropping rock masses hydrogeological properties, in the area under study, with the aim of gathering an estimation of infiltration and as a consequence of it, an estimation of groundwater recharge in Limpopo National Park area and in its buffer zone.

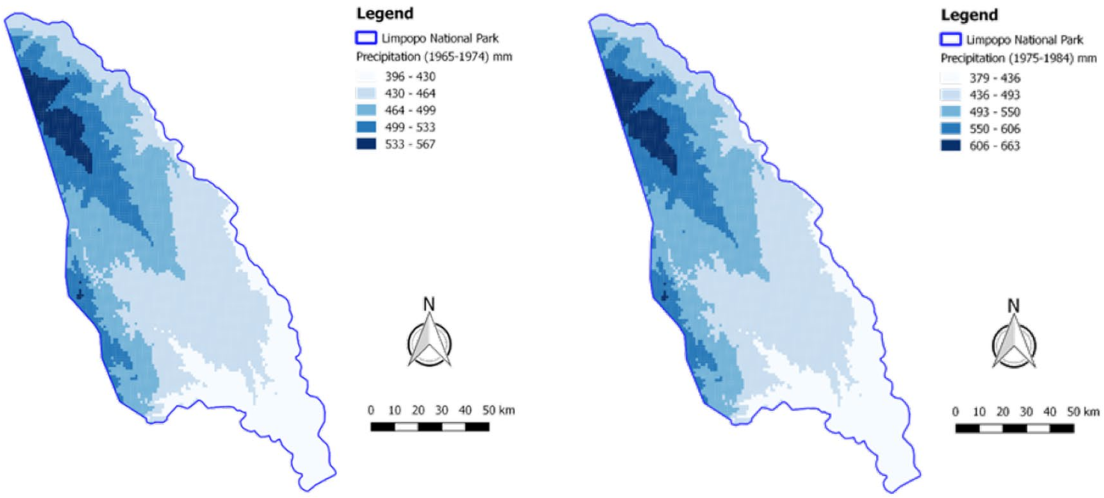
It has been carried out the assessment of the effective infiltration action, starting from the estimation of a potential infiltration factor (χ_s), set up taking into account properties of outcropping rock masses standing on information, gathered from the Soil and Terrain database (SOTER) for Southern Africa (Meissner and Ramasar 2015) as the target of the study is to evaluate the groundwater recharge and how it is sensitive to climate change. The choice of χ_s has been made taking into account the specific guideline offered by the method authors as the experience carried out by the authors in previous studies (Sappa et al. 2015). According to the outcropping lithology of the SOTER database, the Limpopo National Park outcropping rocks include the following formations (Table 8), which have been assigned an average χ_s value as represented in Table 8.

The value of the effective infiltration to assign to each cell is a linear function of the rainfall, whose distribution of the average annual pluviometric modulus has been calculated, applying the previously described function, related to altitude data. As a matter of fact, the effective infiltration (I) has been calculated starting from rainfall (P) values and potential infiltration factor (χ_s) using the formula:

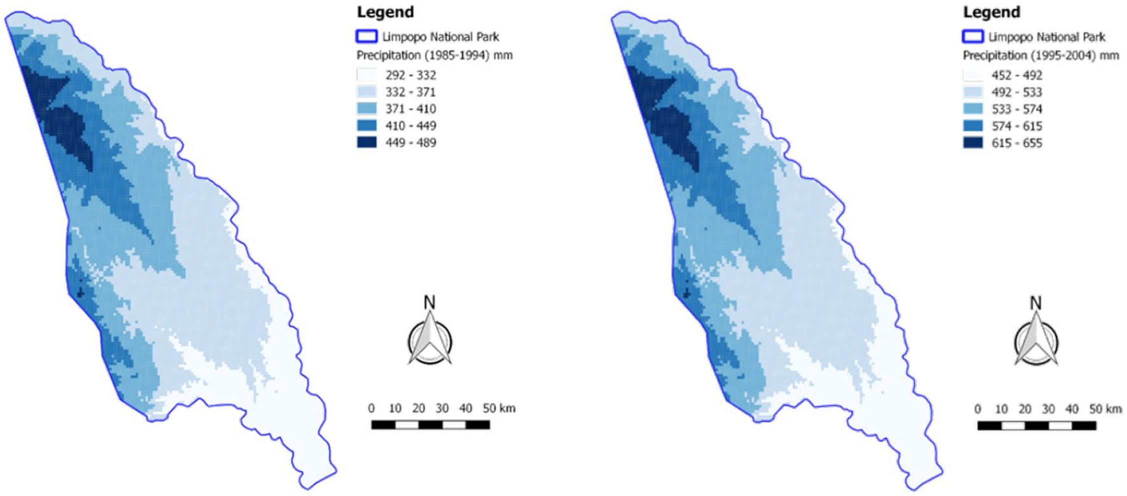
$$I_{\text{eff}} = P * \chi_s.$$

The applied methodology leaded to the determination of the average annual infiltration rate, given in millimetres, for each FSE of the discretization grid in the study area. The Effective Infiltration has been assessed by the hydrological balance performed for the study area, taking into consideration the mean precipitation data, referred to different periods, starting from years 1956–2014 and performing any range of years, as it has been done for the evaluation of rainfall evolution in inside this period, taking in account the outcropping lithology (Sappa et al. 2015) coming from the Soil and Terrain database (SOTER) for Southern Africa referring to the Limpopo National Park. At the end of these elaborations, which drove to have a spatial distribution map of infiltration for any considered range of years, they have been set up seven maps, like ones, represented in the following Figs. 12 and 13.

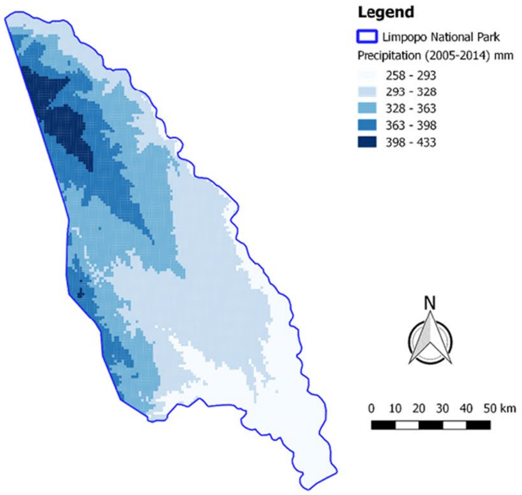
For a better evaluation of infiltration distribution all over the area under study, in Table 9, they are reported results referring to the maximum and minimum values of infiltration gathered for any considered range of years.



(a) 1965-1974 (b) 1975-1984



(c) 1985-1994 (d) 1995-2004



(e) 2005-2014

Fig. 11 Map of the rainfall in the Limpopo National Park in the considered range of years

Table 7 Summary of maximum and minimum values of rainfall in the considered range of years

Range of years	Max (mm/year)	Min (mm/year)
1965–1974	567	396
1975–1984	663	379
1985–1994	489	292
1995–2004	655	492
2005–2014	433	255
2015–2018	430	247

In this case, as the minimum calculated value is always zero, it has been preferred to report, as a representative minimum value, the maximum value of the lowest class of infiltration, considered in the map.

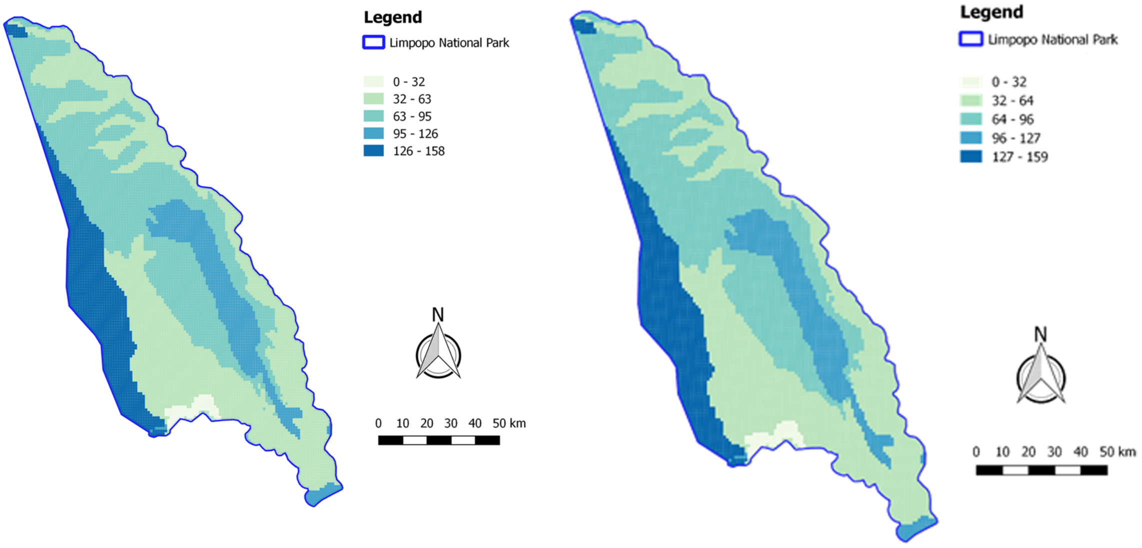
It is interesting to highlight two aspects of these calculation results. The first one is the very little part of precipitations, which becomes infiltration, in the area under study. This is due to the very low hydraulic conductivity of outcropping rock masses in the area under study. On the second, as it has been noticed for rainfall evolution within the considered range of years, there is no regular trend of decrease in infiltration, but, in this case, it is very evident that in the last considered years, from 2005 to 2018, it has been output a sensitive decreasing of infiltration, as in comparison with the previous decade, from 1995 to 2004, as with the whole considered period, from 1965 to 2018.

Results

At the end of its application, the hydrogeological inverse budget leads to an evaluation of groundwater recharge, expressed, not only as infiltration values of mm, referred to any singular finite square element (FSE), but also by the multiplication of any single FSE infiltration value by the value of its area it is possible to obtain the infiltration value in terms of annual volume. The addition of every value, referred to each FSE of the grid, provided the estimation of the aquifer annual average recharge as average annual volume:

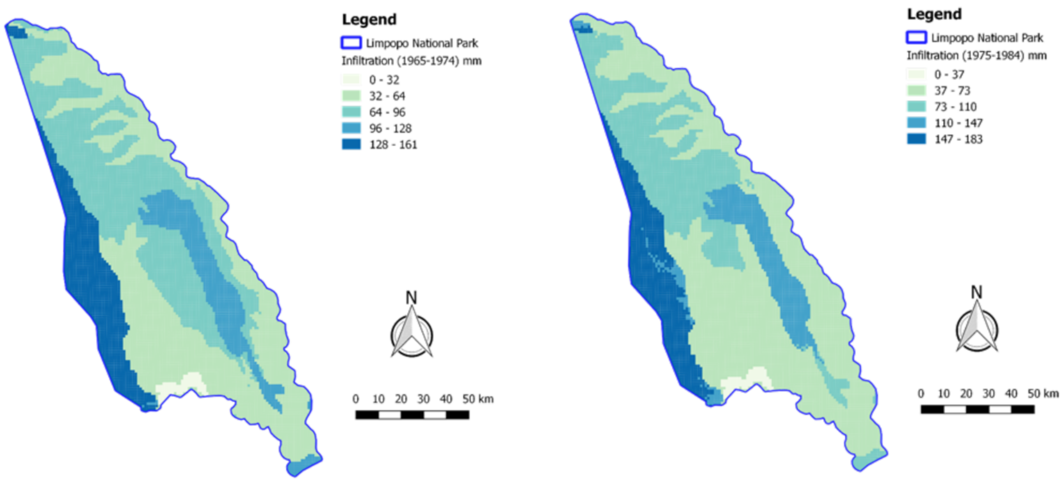
Table 8 Lithological description of Limpopo National Park (as SOTERSAF)

Group	Type	χ_s
UF	Fluvial: sediments generally consisting of gravel and sand or silt and clay	0.1
UC	Colluvial: massive to moderately well-stratified unsorted to poorly sorted sediments	0.25
UE	Eolian: sediments consisting of medium to fine sand and coarse silt particle sizes	0.1
IB2	Basalt	0.3
SC2	Sandstone, greywacke, arkose	0.15
SO2	Marl and other mixtures	0.1

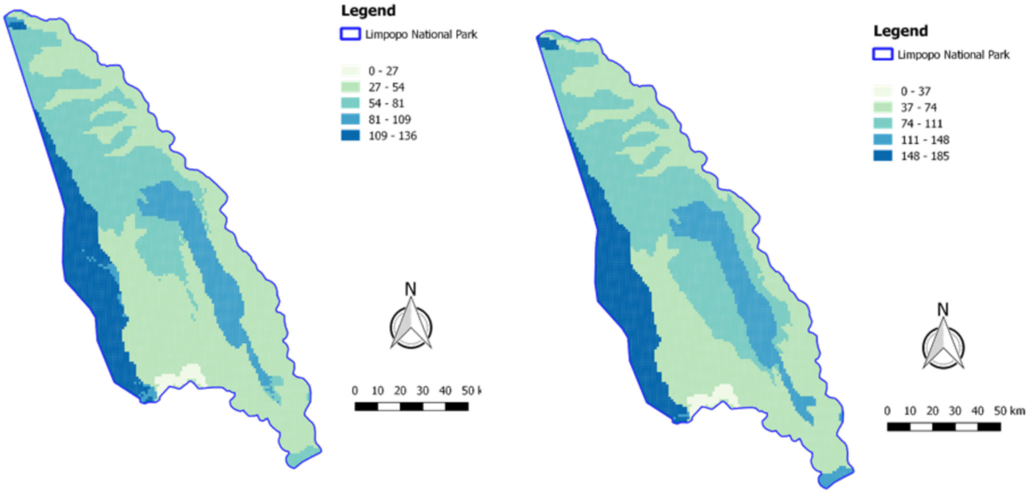


(1956-2018) (1965-2018)

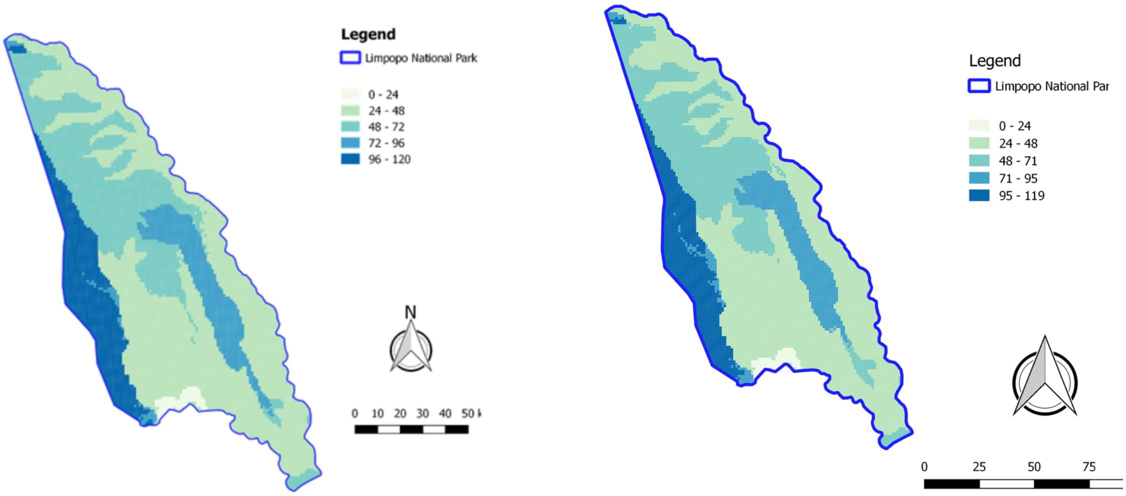
Fig. 12 Map of the infiltration in the Limpopo National Park



(a) 1965-1974 (b) 1975-1984



(c) 1985-1994 (d) 1995-2004



(e) 2004-2015 (f) 2015-2018

Fig. 13 Map of the infiltration in the Limpopo National Park in the considered range of years

Table 9 Summary of maximum and minimum values of infiltration in the considered range of years

Range of years	Max (mm/year)	Min (mm/year)
1965–1974	161	32
1975–1984	183	37
1985–1994	136	27
1995–2004	185	37
2005–2014	120	24
2015–2018	119	22

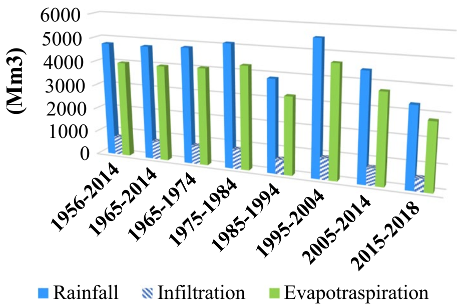


Fig. 14 Distribution of precipitation, infiltration and evapotranspiration in different ranges of years

$$\text{A.R.}\left(\frac{\text{m}^3}{\text{year}}\right) = \left(\sum_{i=1}^{N} I_{\text{EFQ}_i}\right) \times A_{\text{EFQ}_i},$$

where:

- A.R. is the annual active recharge;
- $I_{\text{EFQ}i}$ is the effective infiltration of the i-th FSE;
- $A_{\text{EFQ}i}$ is the area of the i-th FSE.

In this case, results coming from the calculation of groundwater recharge in the Mozambico Limpopo National Park area, referred to different ranges of years are represented in Fig. 14, and they confirm what already noticed for the elaboration of data referred to precipitations and infiltration rate, referred to the last 50 years and, specifically, the sensitive decrease registered in the last decade. There is no evidence of a decreasing trend in groundwater recharge, referred to the considered range of time. On the other side, there is a very remarkable difference among groundwater recharge estimation, referred to different considered decades, as it is also reported in Table 10, which highlights, moreover, that in the last decade, going from 2005 to 2014, it has been registered a very hard loss in groundwater recharge, which, is probably, a consequence, of climate change effect on this area. This fact coupled with the very low percentage, represented by infiltration, in comparison with precipitation calculated for the last 50 years (Fig. 15), make this area very sensitive to climate change effects on groundwater availability.

Table 10 Respect to (1965–2018)

Range of years	ΔI (%)
1965–1974	1
1975–1984	7
1985–1994	−27
1995–2004	35
2005–2014	−45
2015–2018	−30

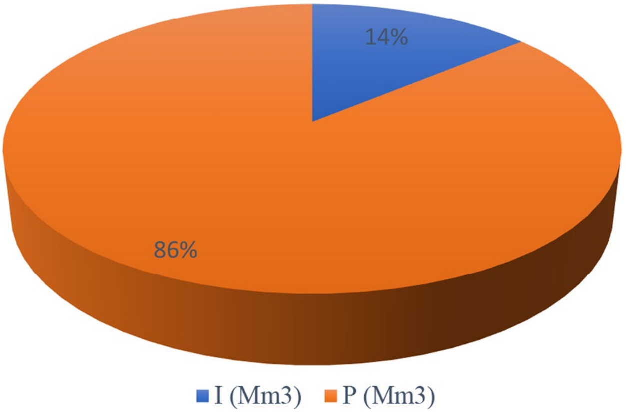


Fig. 15 Distribution of Infiltration and Precipitations in the last 50 years

Standing on these data, represented in Fig. 15, in the area under study, the rate of infiltration related to rainfall is very low and is, on the whole, related to the last observed period, about 14%, and it has been put in comparison with the rate of infiltration, coming out the direct elaboration of evapotranspiration, by Turc equation, referred to the same range of years. According to these elaborations, which considered an average temperature of 17.8 °C, referred to the rainfall months in the Kruger Park Area, results reported in Fig. 16 came out.

Looking at these results the rate between infiltration and rainfalls is about 11%, which is lower than one coming from the application of the hydrogeological inverse budget method, but it is comparable to it, taking into account that, usually, the application of the Turc equation for the evapotranspiration estimation gives an overestimation of this parameter in wet seasons (Diouf et al. 2016), as it seems to come out also in this case.

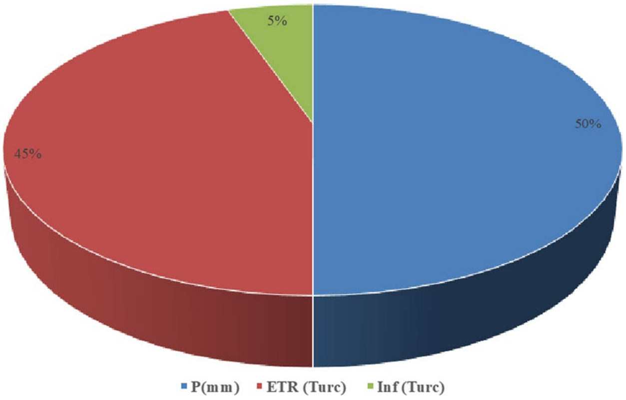


Fig. 16 Distribution of Precipitations, Evspotraspiration and Infiltration in the last 50 years coming from the direct elaboration of evapotraspiration

Conclusions

This paper has presented the results of the application of the Hydrogeological Inverse Budget to the Limpopo National Park area, by sharing meteorological data coming from historical series collected in the Kruger National Park, which is close to the area under study. This study, carried on in the framework of SECOSUD Phase II, called "Conservation and equitable use of biological diversity in the SADC region (Southern African Development Community), a project supported by the Italian Ministry of Foreign Affairs in the SADC, is aimed to evaluate groundwater recharge in the Limpopo National Park area, as for biodiversity conservation as for people supporting, in the buffer zone of it, because of the effects of climate change on the same area. In the whole, results, coming from the carried out elaborations, are quite interesting at least for two aspects, which are both very important as for biodiversity conservation as for people, living in the village, which are still present in the buffer zone of the Limpopo National Park area. As a matter of fact, it comes out, from the abovementioned elaborations that, in the last considered decade and, also, in the last fifteen years, we are facing a sensitive climate change, as in the area under study, as all over the world. It means that precipitations are sensitively decreasing, with a consequent decrease also in groundwater availability. This is more meaningful in the area under study, as results, coming from present elaborations, highlight, but also previous ones, carried out by the authors, that infiltration rate of precipitations is very poor, due to the low hydraulic conductivity of rock masses outcropping in the area under study. These results, referred to infiltration, coming from the application of the Hydrogeological Inverse Budget, have been compared with ones, obtained by the application of Turc equation to evapotranspiration estimation, and they seem to be validated. The authors are aware of having worked with very poor data, but they seem to be enough to highlight that people living in this area and biodiversity conservation in it, suffer, more sensitively, of climate change effects and it is necessary to go on with more detailed studies about water supply in this area. It could be suggested, due to this situation, to improve surface water management in this area. As a matter of fact, the Limpopo National Park area is very close to Massingir lake, made by the construction of a very important dam, built along the Oliphant River, aimed to store millions of cube meters of water. Part of this large volume could be managed, by the construction of adequate water network or channels for feeding people living in the buffer zone, and for a sound conservation of biodiversity in the Limpopo National Park area.

Funding Open access funding provided by Università degli Studi di Roma La Sapienza within the CRUI-CARE Agreement. The Funding was provided by Secosud Phase II.

Data availability Not applicable.

Declarations

Conflict of interest The authors have not disclosed any competing interests.

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