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Using geospatial computation intelligence for mapping temporal evolution of urban built-up in selected areas of the Ekurhuleni Municipality, South Africa

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ABSTRACT

Rapid urbanization in Ekurhuleni Metropolitan Municipality has transformed local landscapes, impacting stormwater management, rainfall, and temperature patterns. This study introduces a novel approach by integrating Google Earth Engine (GEE) with Geographical Information Systems (GIS) to analyze urban growth trends over multiple decades, highlighting both the spatial extent and the rate of expansion. Using geospatial analysis of remotely sensed data, this preliminary study mapped urban growth from 1990 to 2030, in the suburbs of Alberton, Boksburg, Brakpan and Kempton Park. The results demonstrated how readily available maps can be used to depict the rapid urban growth in the area of interest. Additionally, this study found substantial increases in impervious surfaces, which suggests increased runoff and reduced water infiltration into the soil, with adverse consequences on stormwater systems. Furthermore, such maps could be useful for urban planning and sustainable water resource management, with particular attention to monitoring built-up areas.

Keywords: geo-spatial intelligence, remote sensing, urban expansion sustainable urban planning.

INTRODUCTION

Urban expansion within the Ekurhuleni Metropolitan Municipality has accelerated over recent decades, particularly in Ekurhuleni. This growth, marked by increases in impervious surfaces, reflects broader patterns of urbanization that reshape local landscapes and impact natural water pathways, climate patterns, and stormwater infrastructure. This study focuses on Alberton, Boksburg, Brakpan, and Kempton Park due to their distinct urban growth patterns and proximity to critical industrial and transport hubs and the cumulative effects of urban growth on water resource management and environmental resilience. In an urbanized setting, natural infiltration often declines as permeable land is replaced by infrastructure, roads, and buildings, leading to increased surface runoff. This shift poses risks for stormwater systems, especially during peak rainfall periods, as they become increasingly strained under urbanization. Given these challenges, there is a growing need for accessible tools that can effectively monitor urban expansion and its environmental impacts. This study leverages GEE's cloud computing capabilities, coupled with GIS, to analyse and map spatio-temporal urban growth, providing real-time tracking advantages over conventional methodologies. The rest of the study is organised as follows: the impact of impervious surfaces on stormwater runoff is covered in Section 2, followed by Section 3, which discusses the use of cloud computing and remote sensing for built-up monitoring. The Methodology is presented in Section 4, with results and discussion in Section 5. Finally, Section 6 summarises the findings of the study and suggests direction for future research.

IMPERVIOUS AREA AND RUNOFF

Impervious surfaces influence runoff in urban areas, particularly within the context of low impact developments [1]. The analysis of the different types of residential areas and urban growth scenarios, shed light on the complexities of urbanization and its impact on surface runoff [2]. These authors found that low-density settlements harbor more vegetation, resulting in less surface runoff, whereas high-density settlements exhibit greater impervious coverage, reduced vegetation, and increased runoff.

GOOGLE EARTH ENGINE AND REMOTE SENSING FOR URBANIZATION MONITORING

The use of geospatial tools like (GEE) has revolutionized urban monitoring by enabling efficient analysis of large-scale remotely sensed data. GEE and Sentinel-2 spectral indices, such as the Band Ratio for Built-up Area (BRBA) and Normalized Difference Vegetation Index (NDVI), were employed to assess urbanization in Istanbul, achieving high accuracy in detecting built-up areas and vegetation cover [3]. Similarly, GEE's capability to map urban flooding using Synthetic Aperture Radar (SAR) imagery was demonstrated, providing practical applications for disaster management [4].

Advanced geospatial tools to analyze land use and land cover changes was used [5], revealing significant urban expansion and corresponding vegetation loss over time. Their findings align with those of [6], who highlighted GEE's utility in monitoring urban growth patterns and informing sustainable planning decisions. The integration of GEE and GIS offers robust frameworks for mapping urbanization, analyzing land cover changes, and assessing environmental impacts.

9Urbanization disrupts natural hydrological cycles, increasing runoff and flooding risks while placing additional demands on stormwater infrastructure. Integrating Blue-Green Infrastructure (BGI) was proposed to mitigate these impacts, emphasizing the importance of natural systems in urban planning [7]. Similarly, Global Earth Observation Data was used to assess land use efficiency [8], offering actionable insights for sustainable resource management.

DATA AND METHODS

Study area

The study focuses on four selected suburban areas within the Ekurhuleni Metropolitan Municipality in the Gauteng Province, South Africa. These suburban areas, Alberton, Boksburg, Brakpan and Kempton Park, these areas were chosen based on their diverse land uses, offering varied insights into urbanization patterns and its impacts. Each suburb represents a different aspect of development—residential, industrial, commercial, or mixed-use—providing a more comprehensive understanding of built-up surface expansion. The municipality experiences hot, rainy summers and cooler, drier winters. It receives an average annual precipitation of approximately 713 mm, with most rainfall occurring between October and March. Average temperatures range from 16°C in winter to 26°C in summer.

The locality map of Ekurhuleni and the respective study areas are depicted in Figure 1 and Table 1 showing the approximate geographical coordinates and elevations of each of the studied suburban areas.

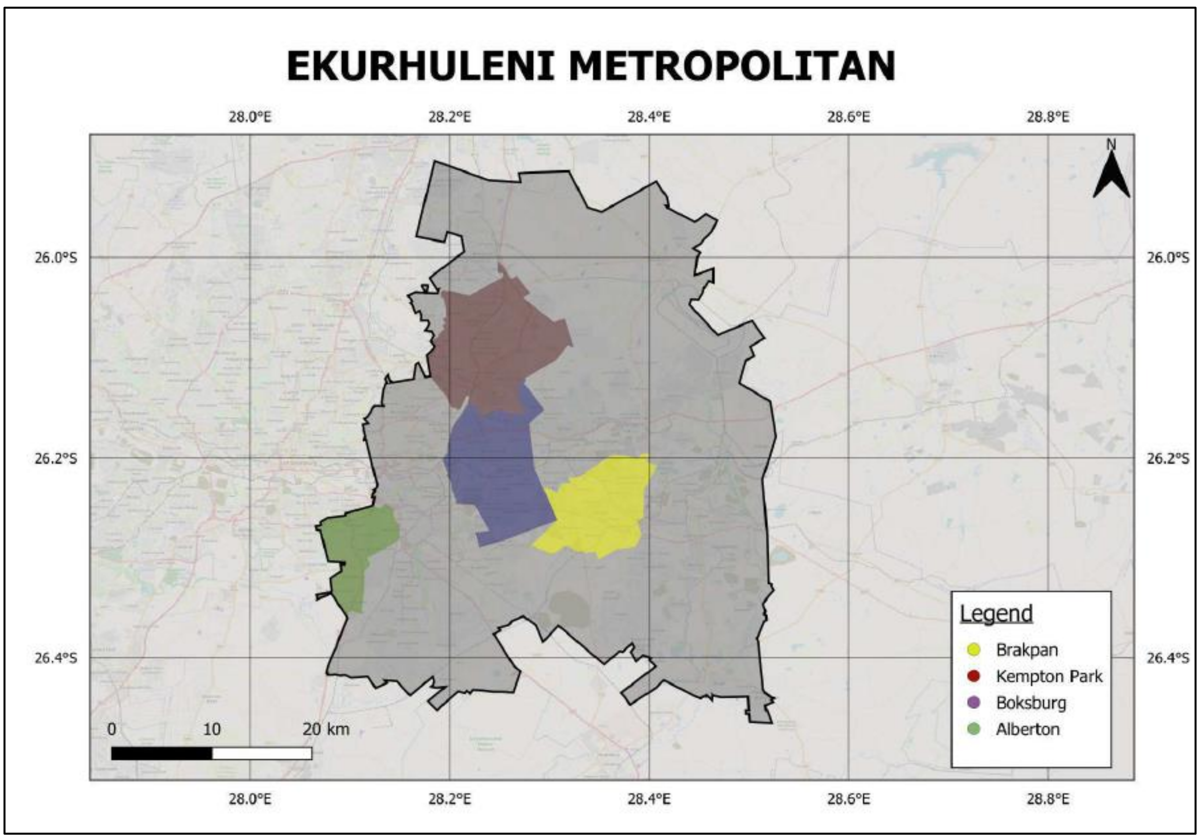

Figure 1: Location of Ekurhuleni Metropolitan Municipality

Table 1: Approximate coordinates and elevations for each studied suburban area

Suburb	Co-ordinates	Elevation
Alberton	26°18’22.71”S and 28°06’16.22”E	1610 m
Boksburg	26°12’42.98”S and 28°14’56.44”E	1633 m
Brakpan	26°15’16.82”S and 28°20’46.00”E	1659 m
Kempton Park	26°06’17.40”S and 28°13’14.60”E	1662 m

Ekurhuleni is a significantly industrial and commercial hub within Gauteng. The selected suburban areas contribute to various sectors:

Alberton: Primarily residential with growing commercial zones, including retail centres and small industries.
Boksburg: Known for manufacturing and mining industries, with a mix of residential and commercial developments.
Brakpan: Historically, a mining town, now featuring industrial activities and residential areas.
Kempton Park: Hosts the O.R. Tambo International Airport, making it a key area for logistics, aviation, and related industries.

Data used

Satellite imagery from Sentinel-2 and Landsat was used to evaluate built-up area expansion and land cover changes. High-resolution imagery was analyzed at five-year intervals (1990, 1995, 2000, 2005, 2010, 2015, 2020) with projections for 2025 and 2030. The Global Human Settlement Layer (GHSL) built-up surface raster dataset (GHS-BUILT-S R2023A) served as the primary data source, derived from multi-temporal imagery using spectral and textural analysis at a 100-meter resolution. This dataset effectively identified built-up surfaces by distinguishing between residential and non-residential areas based on pixel classification techniques. Boundary files for suburban areas were obtained from Ekurhuleni GIS and Google Earth Pro to ensure accurate spatial delineation of built-up areas. The platform is routinely updated to reflect zoning changes, providing valuable insights into land-use patterns and urban development trends over time.

Methods

Boundary definition and map generation

Suburban areas’ boundary files were obtained from Ekurhuleni GIS and Google Earth Pro. GEE was used to process satellite images and map built-up areas for each suburban area. A separate coding script was created for each suburban area to ensure clarity and avoid processing errors. These scripts utilized the GHSL: Global built-up surface 1975-2030 (P2023A) dataset, a global dataset designed for analysing built-up surface expansion. The GHSL dataset uses a specific data band that highlights built-up surfaces by identifying their unique reflectance values. Built-up areas reflect light differently from natural surfaces due to their material composition, such as concrete and asphalt. This distinct reflectance from the satellite images was isolated in the dataset, producing white pixels that represent built-up surfaces. These white pixels can be extracted from the software and classified during processing, enabling precise identification of urbanized areas in each satellite image. Tag Image File Format (TIFF) files were generated for each suburban area at 100-meter resolution, representing total built-up areas for each five-year interval (1990, 1995, 2000, 2005, 2010, 2015, 2020) and projections for 2025 and 2030. These TIFF files, which serve as visual representations of built-up area distribution for specific years, can be exported for map generation. The images were subsequently imported into QGIS to create detailed maps illustrating changes in urbanization over time. This process ensures a robust and accurate depiction of built-up area growth across the selected suburbs. The coding approach used in this study was adapted from Amirhossein Ahrari - Create 00022_urban_built_up.

Data band utilization

The GHS-Built-up surface data highlights urban pixels by isolating their distinct reflectance values, distinguishing them from natural surfaces. By isolating white pixels in the data band, urban surfaces were identified and quantified across intervals. This approach allowed for pixel-based calculations of urban growth, offering both visual and numerical outputs. The generated TIFF files were then overlaid in QGIS to produce finalized maps for each suburban area, showing built-up surface changes across time intervals.

Future projections

Spatial interpolation techniques within GEE were used to project built-up area expansion for 2030 based on historical growth trends. These projections provide insights into potential future increases in impervious surfaces and their impacts on local hydrology.

Rainfall and temperature trend analysis

Data preparation

SAWS data required reformatting for input into the MAKESENS 1.0 template. Monthly cumulative rainfall, average temperature, and maximum temperature were calculated for each month from 1990 to 2023. Missing data points were interpolated to maintain continuity across the dataset, ensuring temporal consistency. To address inconsistencies in the dataset, a spatial-temporal interpolation technique was used to estimate missing values across both space and time, ensuring a more continuous and accurate trend detection process.

Trend analysis

Using MAKESENS 1.0, this study applied the Mann-Kendall test to identify trends in monthly rainfall and average temperature data. The Mann-Kendall test, a nonparametric method, evaluates trends without requiring assumptions about data distribution, while Sen's Slope estimates the rate of change over time, providing a measure of both positive and negative variations in climate parameters over a specific period.

RESULTS AND DISCUSSION

The results of urban built-up analysis were executed using GEE code and are presented in Table 2, Figures 2 and 3 (Appendix), providing a comprehensive view of the urban growth patterns for each suburban area. Figures 2 and 3 illustrate the total rate of change in built-up surfaces from 1990 to 2030 and the rate of change every five years, respectively. These trends reveal that the urban sprawl in Brakpan and Kempton Park were the most prominent, likely due to their proximity to industrial and transportation zones.

The GEE analysis revealed significant urban expansion across all four suburban areas, with notable increases in built-up areas such as roads, buildings, and impervious infrastructure, from 1990 to 2030.

These expanded built-up areas could reduce natural water infiltration, leading to increased surface runoff and thereby impacting stormwater management directly. The GEE-generated maps illustrate clear spikes in urban growth, particularly after 2000, as shown in Table 2, suggesting accelerated expansion linked to residential and industrial development. As impervious surfaces continue to expand, the resulting impacts on stormwater systems become more evident. This growth in built-up areas can intensify runoff volumes and peak flows during rainfall events, potentially overwhelming existing drainage infrastructure (Kaur et al., 2022). The rise in impervious surfaces underscores the need for enhanced stormwater infrastructure to mitigate flood risks and manage increased runoff associated with urban sprawl.
The following observations were made.

Total change in built-up surface
Alberton exhibited moderate urban growth, with a 28% increase in built-up area from 11.6 km² in 1990 to 14.1 km² by 2030. The most noticeable expansion occurred from 1990 to 2000 with the built-up area increasing by over 5% each year, from 11.6 km² to 12.8 km². This change is visualized in the GEE-generated maps (Figures 4a and 4b), which display the gradual intensification of urban surfaces, particularly in the western region of this suburban area.

Boksburg experienced a steady 37.8% increase in built-up area, from 20.9 km² in 1990 to 26.7 km² by 2030. The most significant growth occurred between 1990 to 2000, with a rise from 20.9 km² to 23.5 km², which is an increase of 6.7% each year. This is largely driven by industrial developments. This growth is represented in Figures 5a and 5b, showing substantial expansion, particularly near industrial zones and along transport corridors like the N12 highway. Brakpan has experienced the largest urban expansion of 45.5% from 8.4 km² in 1990 to 11.0 km² by 2030. The results show a rapid boom in urban built-up surfaces prior to 1990 and then the rate decreased slightly but had a steady increase in expansion thereafter. This shift is depicted in Figures 6a and 6b, showing expansion from the southern and western regions toward northern areas. Kempton Park also exhibited a high increase in built-up area, growing by 43.8% from 22.8 km² in 1990 to 30.2 km² by 2030. This significant expansion is visible in Figures 7a and 7b, with the eastern region showing marked growth in recent years.

Interpretation of GEE maps
For Alberton, the GEE maps illustrate an evolution from sparsely clustered pixels in 1990 (Figure 4a) to a denser accumulation by 2030 (Figure 4b), indicating steady residential development. This densification of pixels, particularly in western Alberton, suggests ongoing urban expansion due to commercial and residential demand, rather than solely industrial growth. For Boksburg, the GEE maps illustrate densification in the southern areas, with new development expanding outward from central industrial hubs. This growth pattern suggests significant increases in impervious surfaces, amplifying potential stormwater management issues due to increased runoff volumes. The proximity of urban growth to transport routes and industrial zones has also facilitated rapid expansion. The GEE maps in Kempton Park display high-density urbanization near industrial hubs and along major routes, particularly near O.R. Tambo International Airport and the R21 highway. This increasing trend of impervious surfaces in proximity to large infrastructure emphasizes the need for sustainable stormwater infrastructure to mitigate the hydrological impacts of rapid urbanization and has likely exacerbated stormwater issues, as such areas typically generate more runoff due to limited natural ground cover.

The GEE-generated maps reveal a dispersed urban growth pattern in Brakpan, with densification occurring across the suburban area, specifically in the southern and western regions. This spatial spread presents unique challenges for stormwater infrastructure, as widely distributed impervious surfaces generate runoff across a broader area, necessitating extensive drainage networks and sufficient stormwater management strategies.

Rainfall analysis

Annual rainfall trends
Figure 8 presents the total annual rainfall from 1990 to 2023, showing a steady decline in precipitation over the period. The trend line indicates an annual reduction in rainfall, underscored by notable high-rainfall years, such as 2000 (1088.5 mm), and low-rainfall years, such as 2023 (442.6 mm). Seasonal patterns reveal January and February as the wettest months, with peaks recorded in January 2010 and February 1996. Conversely, extended periods of drought, particularly in 2015 and 2023,

highlight heightened aridity, with some months recording no rainfall.

Monthly rainfall trends

The MAKESENSE 1.0 analysis identified statistically significant declines in rainfall for March and August, as detailed in Table 3 (Appendix). March exhibited a 90% confidence level decline (Z = -1.75), with an annual reduction of 4.01 mm, while August showed a 95% confidence level decline (Z = -2.25) with an annual reduction of 0.40 mm.

Cumulative rainfall decreased from 101.15 mm in 1990 to 52.48 mm in 2023 for the month of March. Residuals from the regression analysis indicate sharp deviations, with notable declines in recent years (e.g., -51.45 mm in 2022 and -26.88 mm in 2023). This reduction could exacerbate surface runoff risks during peak rainfall events in highly urbanized areas such as Brakpan and Kempton Park.

In August rainfall dropped from 2.60 mm in 1990 to 0.32 mm in 2023, signalling drier conditions leading into spring. These conditions reduce soil infiltration and may amplify runoff during subsequent rains, increasing strain on stormwater systems.

Temperature analysis

Monthly average temperature data revealed a significant warming trend between 1990 and 2023, particularly in May, June, and July. This trend aligns with the expansion of impervious surfaces in urbanized areas like Brakpan and Kempton Park. A comparison of average monthly temperatures (Figure 9) shows statistically significant warming trends for May, June, July, August, and November, confirmed by Mann-Kendall Z scores and Sen's slope estimates (Table 4). May and June recorded the highest warming trends. May exhibited temperature increasing from 10.96°C in 1990 to 14.39°C in 2023. June followed closely (Z = 3.91), rising from 9.02°C to 12.47°C. March exhibited variability, with average temperatures increasing from 17.43°C in 1990 to 19.54°C in 2023, and notable anomalies in 1998 and 2007.

These findings underscore the impact of urbanization on local climate dynamics in Ekurhuleni. Rising temperatures, particularly in May and June, highlight the potential influence of expanded impervious surfaces and reduced vegetation cover. This warming effect could exacerbate stormwater management challenges by reducing water availability and increasing the demand for resilient infrastructure to cope with urban heat effects and hydrological changes.

Implications

The findings from rainfall and temperature analyses underscore the compounded challenges of urbanization in Ekurhuleni. Decreased rainfall in March and August, alongside rising temperatures in May, June, and other months, highlights the complex interplay between urban growth and climate variability. Reduced rainfall, combined with increased surface runoff and drying soils, places greater strain on stormwater systems. These findings align with research by [9], emphasizing the need for targeted infrastructure upgrades and adaptive planning to mitigate these risks. This study explored the complex relationship between urban built-up surfaces, rainfall trends and temperature patterns in Ekurhuleni Municipality, focusing on Alberton, Boksburg, Brakpan, and Kempton Park. Using GEE and GIS tools, detailed maps were created to show built-up surface changes from 1990 to 2030. The analysis revealed significant increases in built-up areas, especially in Kempton Park and Brakpan, driven by residential, industrial, and infrastructural developments, this urban growth reduces natural infiltration, increases surface runoff, and heightens flood risks, particularly in high-growth areas. The combined effects of urbanization and climatic variability underscore the urgency for adaptive stormwater management strategies and sustainable urban planning.

CONCLUSION

Using GEE and GIS tools, detailed maps were created to show built-up surface changes from 1990 to 2030. The analysis revealed significant increases in built-up areas, especially in Kempton Park and Brakpan, driven by residential, industrial, and infrastructural developments. By identifying high-risk areas for increased surface runoff and flood vulnerability, this study provides actionable insights for urban planners and policymakers. Without improved stormwater infrastructure, the risk of flooding could increase. In contrast, Alberton and Boksburg display continuous, albeit less intense, urban growth, posing unique challenges due to their lower-density areas and open spaces. The findings also indicate a decrease in rainfall during specific months, such as March and August, alongside rising temperatures throughout the year. These climatic trends emphasize the importance of climate-resilient urban planning, including permeable surfaces, green infrastructure, and stormwater retention solutions. As urban growth continues, it is recommended that Ekurhuleni incorporate sustainable urban planning measures, such as permeable surfaces, green infrastructure, and stormwater retention solutions, to effectively manage long-term flood risks.

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APPENDIX

Table 2: Built-up area (km²) from 1990 to 2030 for the studied suburban areas

Year	Alberton	Boksburg	Brakpan	Kempton Park
1990	11.568	20.931	8.401	22.757
1995	12.171	22.179	8.789	24.281
2000	12.816	23.504	9.217	25.973
2005	13.062	23.889	9.412	26.677
2010	13.322	24.307	9.62	27.477
2015	13.594	24.871	9.889	28.355
2020	13.851	25.934	10.408	29.226
2025	14.025	26.342	10.755	29.799
2030	14.09	26.658	10.984	30.155

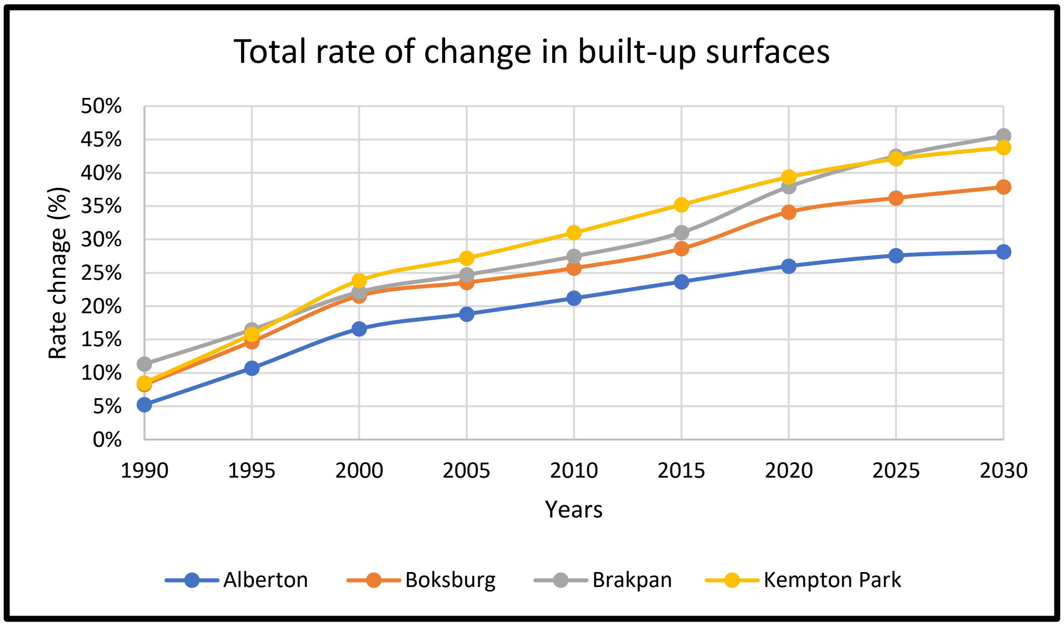


Figure 2: Total rate of change in built-up surface from 1990 to 2030

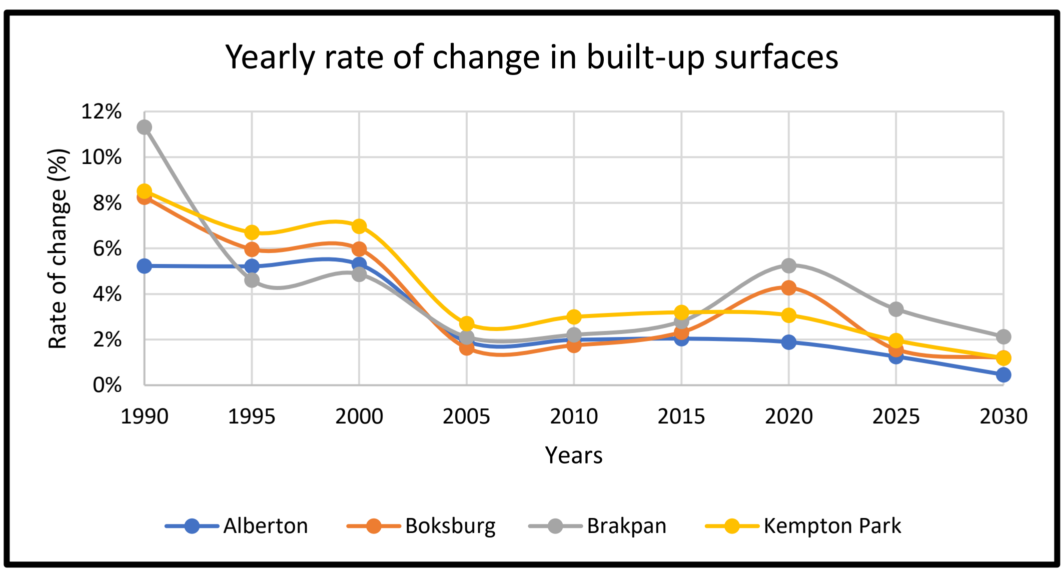
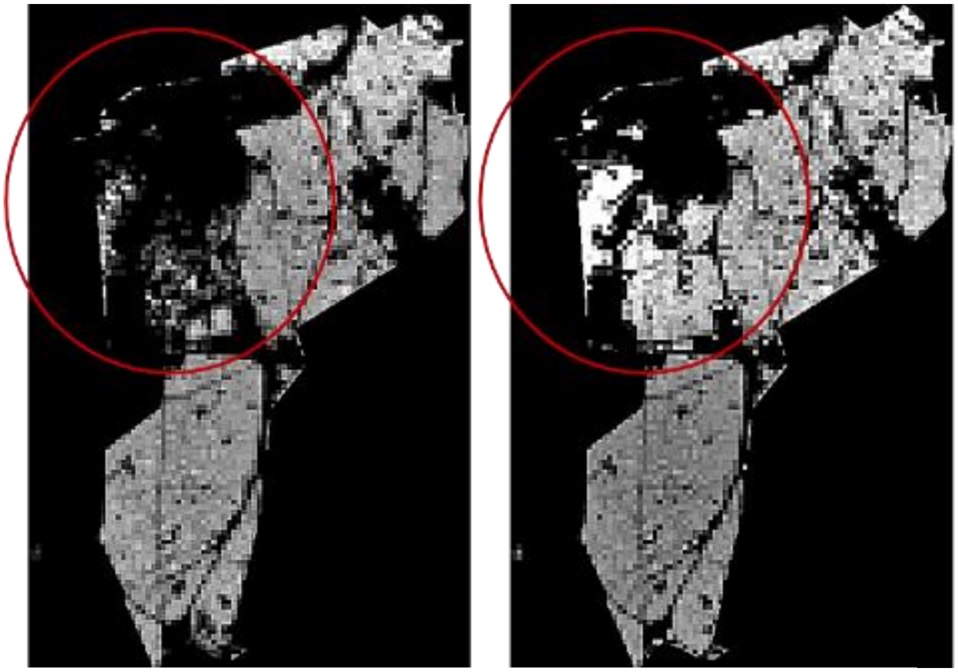


Figure 3: Yearly change in built-up surface from 1990 to 2030



a **b**

Figure 4a and 4b: Built-up Surface in Alberton (1990 to 2030)

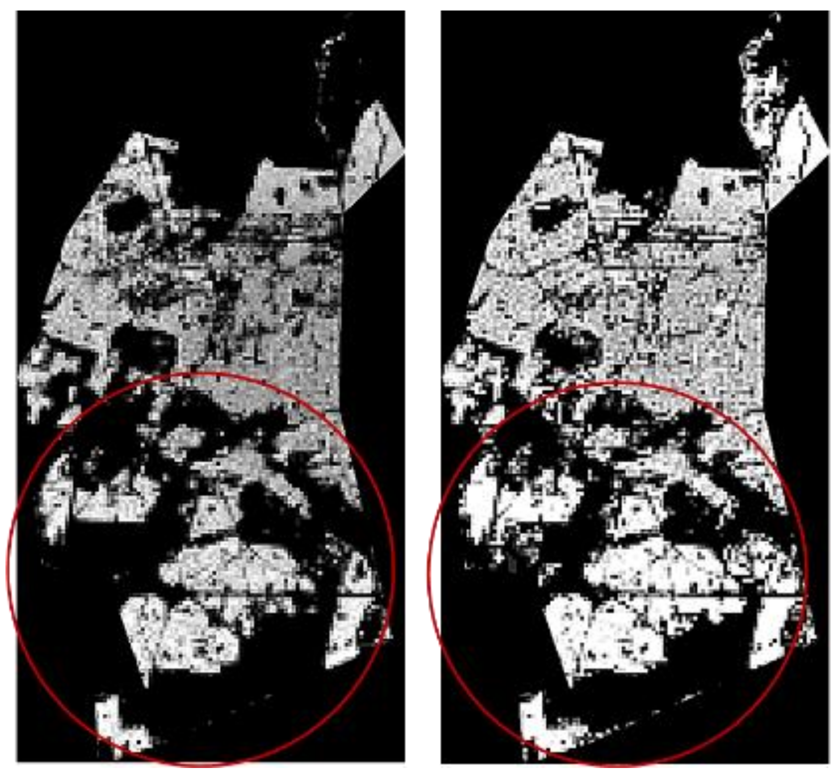


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Figure 5a and 5b: Built-up Surface in Boksburg (1990 to 2030)

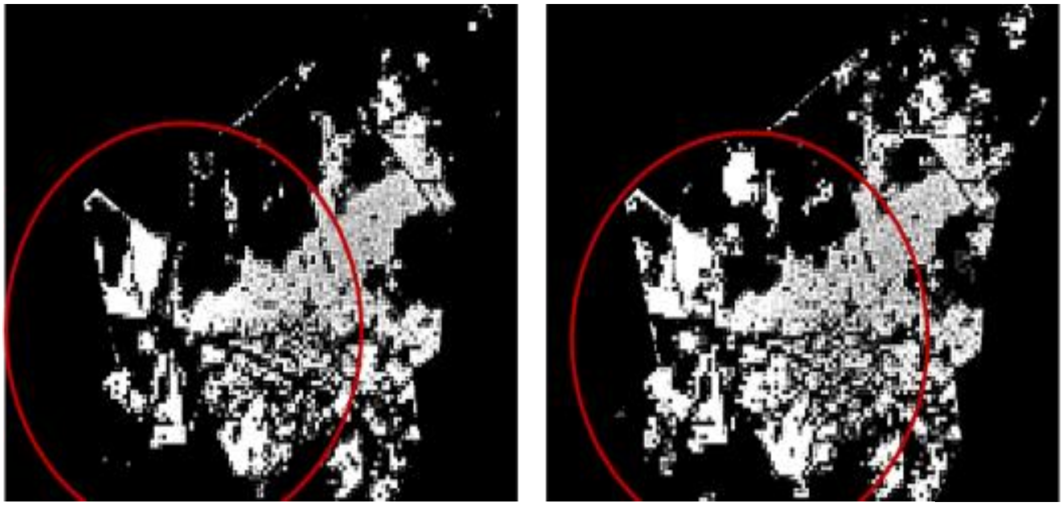

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Figure 6a and 6b: Built-up surface in Brakpan (1990 to 2030)

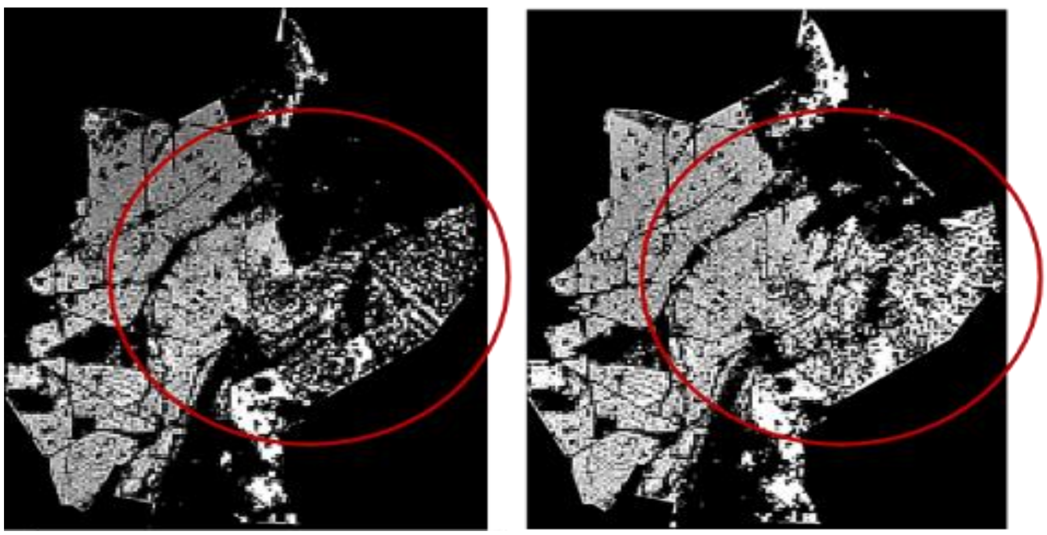

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Figure 7a and 7b: Built-up surface in Kempton Park (1990 to 2030)

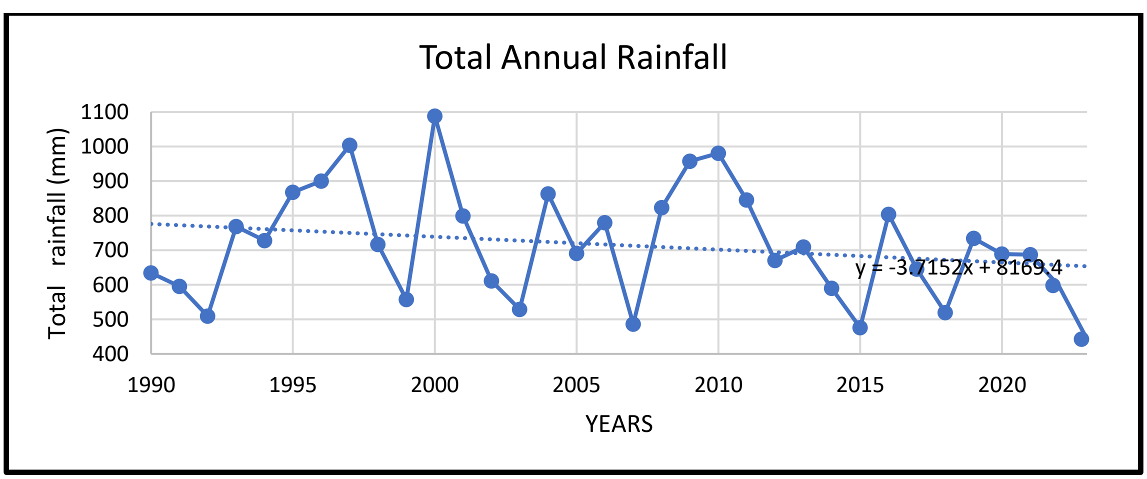

Figure 8: Total recorded annual rainfall in Ekurhuleni from 1990 to 2023.

Table 3: MAKESENSE 1.0 Monthly rainfall trend analysis. Symbols indicate the significance level of trends: + represents significance at the 90% confidence level, and * represents significance at the 95% confidence level.

				Mann-Kendall trend			Sen's slope estimate	
Time series	**First year**	**Last Year**	**n**	**Test Z**		**Signific.**	**Q**	**B**
January	1990	2023	34	-0.53		-0.63	-2.87	179.66
February	1990	2023	34	-0.06		-0.03	-3.32	151.67
March	1990	2023	34	-1.75	+	-1.48	-4.01	153.94
April	1990	2023	34	1.04		0.51	-0.95	49.68
May	1990	2023	34	0.06		0.00	-0.73	22.59
June	1990	2023	34	-0.03		0.00	-0.19	6.36
July	1990	2023	34	0.36		0.00	0.00	0.00
August	1990	2023	34	-2.25	*	-0.07	-0.40	11.15
September	1990	2023	34	-0.74		-0.10	-0.72	22.39
October	1990	2023	34	-1.30		-1.16	-3.05	125.93
November	1990	2023	34	1.32		1.03	-1.28	120.83
December	1990	2023	34	-0.56		-0.55	-3.37	187.58

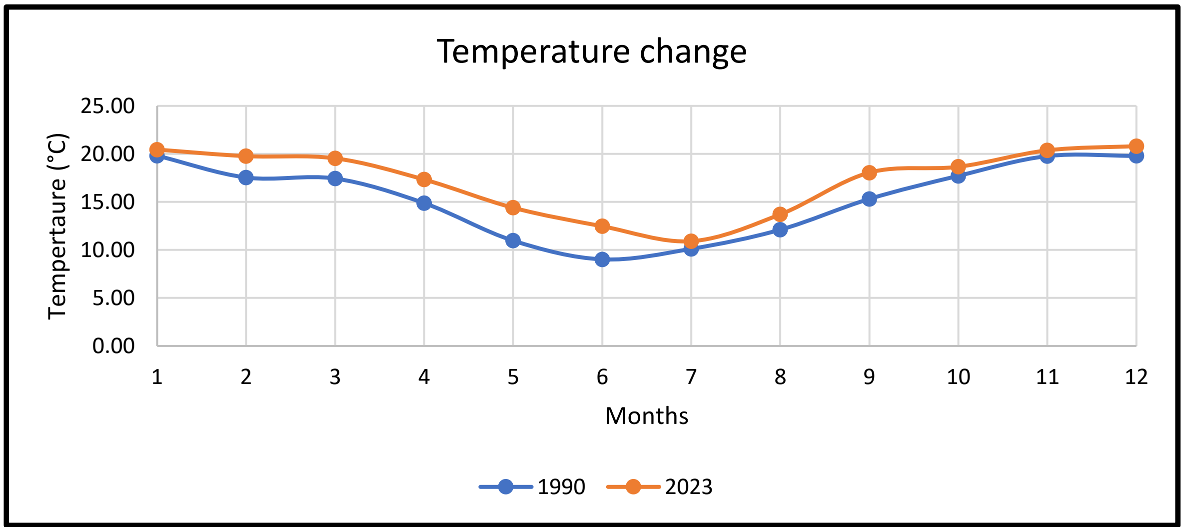

Figure 9: Comparison of monthly average temperatures in 1990 and 2023

Table 4: MAKESENSE 1.0 monthly average temperature trend analysis. Symbols indicate the significance level of trends: + represents significance at the 90% confidence level, and * represents significance at the 95% confidence level.

				Mann-Kendall trend			Sen's slope estimate	
Time series	**First year**	**Last Year**	**n**	**Test Z**		**Signific.**	**Q**	**B**
January	1990	2023	34	1.48		0.03	-0.02	20.40
February	1990	2023	34	1.36		0.02	-0.03	20.58
March	1990	2023	34	2.40	*	0.04	-0.01	18.79
April	1990	2023	34	1.78	+	0.04	-0.01	16.08
May	1990	2023	34	3.62	***	0.06	0.02	13.19
June	1990	2023	34	3.91	***	0.06	0.02	10.13
July	1990	2023	34	2.85	**	0.05	0.01	10.46
August	1990	2023	34	3.05	**	0.07	0.01	12.95
September	1990	2023	34	2.37	*	0.06	-0.01	17.17
October	1990	2023	34	2.13	*	0.05	-0.01	18.41
November	1990	2023	34	2.70	**	0.05	0.00	18.80
December	1990	2023	34	1.75	+	0.03	-0.01	19.95