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Monitoring Impervious Surface Area Dynamics to Assess Urbanisation of a Catchment: Msimbazi River Valley Dar es Salaam, 1989 - 2015

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Abstract

This work examined the effects of land use and cover change on the impervious surface as a measure of urbanisation together with its driving factors such as population growth and economic development. The spatial and temporal variations of the impervious surface area were extracted from the Landsat images of the years 1989, 1995, 2005, and 2015. Data analyses involved the selection of the endmember through Minimum Noise Fraction (MNF) and Linear Spectral Mixed Analysis (LSMA) on the images. Four dominant land cover types were mapped as results, which are forest, non-forest vegetation, bare-land, and built-up area. The non-forest vegetation and bare land were dominant cover classes in the catchment in 1989, occupying over 80% of the land use and cover. The built-up environment increased from 11% in 1989 to 53% in 2015, encroaching other covers. This correlates with the growth of population and gross domestic product as measures of economic development and driving forces for the growth.

Keywords: Land use; Impervious Surface Area; Urbanisation; Msimbazi River; Minimum Noise Fraction

Introduction

Urbanisation is the process of change in land use that continuously transforms land valuable for surface runoff infiltration to an impervious surface (Hamdi 2011). Globally, it is estimated that 2% of the global surface area has been altered to develop urban areas (Meyer et al. 1994). Amongst the contributing factors is the population increase in urban areas, whereby currently half of the global population is living in urban areas (Kunzig 2011). United Nations estimated the increase of population by up to 60% in 2030 (Kunzig 2011). Developing countries are expected to have more of this growth as they transform into the shared socioeconomic pathways (Jiang and O'Neill 2017). Land use and cover changes tend to be pervasive, a small change into built-up amplifies to an urban area. The change of bare land and vegetation land covers into impervious surfaces reduces urban sustainability. In a water catchment, an increase in the impervious surface area alters the watershed hydrological conditions and is associated with an increase in flood events (Nirupama and Simonovic 2007). This is a result of increased surface runoff volume, peak discharge and decreased groundwater recharge.

For a larger area, estimating coverage and change in impervious surface area as a measure of urbanisation can be a challenge. However, advancement in remote sensing technology has improved the process of estimating the rate of urbanisation and effectiveness in detecting the land-use change in relation to the changing area of the impervious surface (Weng 2012, Wu and Murray 2003). Therefore, an accurate estimation of the impervious surface area (ISA) as an indicator and measure of urbanisation is a prerequisite in understanding and addressing the problem of reduced area for surface runoff infiltration (Shahtahmassebi et al. 2016). Furthermore, the growth and expansion of the urban areas are always associated with environmental challenges, particularly when the planning and designing of the urban cities are not well strategized.

Tanzania is among the developing countries whose cities are trending in urbanisation. This may be because of its favourable geographical location, industrialisation and rapid population growth (Kebede and Nicholls 2012). Dar es Salaam, the business capital of Tanzania, was upgraded into city status early in 1940, and by then it had one-third of the country population (Armstrong 1987). Despite its rapid urbanisation (Sawio 2008), it lacked a growth plan from the onset in the 1940s (Armstrong 1987), which is still the case to date (Augustijn-Beckers et al. 2011).

Msimbazi River catchment is an urban basin of Msimbazi River within Dar es Salaam, stretching from Pugu Hills to the Indian Ocean through the city centre. It is one of the urbanised areas with the high informal settlements, population density and lack of necessary flood control infrastructures (Augustijn-Beckers et al. 2011). To date, the catchment is one of those areas that regularly flood in Dar es Salaam.

Several urban flood studies of vulnerability assessment, coping strategies and perception of indigenous knowledge on flood management have been done in Tanzania (Kebede and Nicholls 2012, Sakijege et al. 2012). The study by Sakijege et al. (2012) on Msimbazi catchment in Dar es Salaam found that the risk of flooding was high in unplanned settlements. The coping strategies at the household level included raising doorsteps to prevent water from getting indoors. Mutayoba et al. (2018) studied land-use change from bushlands to agricultural land in sub-catchment of the Great Ruaha River in south-central Tanzania and found that it has contributed to reduced surface runoff by 4% to 9%. Limited research has been done on progressive land-use change into impervious surfaces as a causal factor in the urban catchments of Tanzania. This underpins the objective of this study, which is to study the land-use change and cover to impermeable surface area (ISA) in an urban water catchment to establish the trajectory of urbanisation in the Msimbazi watershed catchment and the major drivers for the change.

It is of interest to understand the urban river catchment transformations into impervious surface areas in developing countries, where urban planning commonly lags behind population and economic growth. The study is relevant to policymakers and planners in developing settlement policies that consider environmental initiatives of sustainable cities integrating the dynamics of impervious surfaces as key precedence in urban growth.

Materials and Methods

Study area

Dar es Salaam is the largest industrial city in Tanzania. It is located in the east of the country, on the coast, that is, along the Indian Ocean (Figure 1). The city grew from the small natural harbour that hosted about 900 people in 1867 to 69,000 in 1948 (Armstrong 1987). The 2012 National Census indicated Dar es Salaam population size of 4.3 million with 5.6% Intercensal Growth Rate (IGR) from 2002 to 2012 (URT 2013). Msimbazi watershed (Figure 2) is the largest watershed in Dar es Salaam with an area coverage of 192 km^2, equivalent to 15% of the regional coverage. The river itself originates in Pugu Hills and flows through the north of Dar es Salaam City centre into the Indian Ocean. Some of its tributaries are the Ng'ombe and Kibangu Rivers. Dar es Salaam has a warm tropical climate throughout the year with an average temperature of 26 °C at about 24 m above sea level. The average annual rainfall in Dar es Salaam Region is 1050 mm experienced in two rainy seasons. One is a short rainy season from October to December with a monthly average of 75 – 100 mm. The longer season is from March to May, averaging 150 to 300 mm (Ndetto and Matzarakis 2015). The vegetation land cover in the region includes coastal shrubs, swamps, and mangroves (Kebede and Nicholls 2012). The watershed covers some of the informal settlements, including Hananasif, Mchikichini, Ilala, and Jangwani. The area was identified as hazardous in the 1979 Dar es Salaam city master plan (Armstrong 1987). Unplanned settlements within the catchment began in the early 1980s and their development peaked in the 1990s (Kombe 2005). In comparison with other water catchments within the Dar es Salaam City; the population is mostly concentrated in the Msimbazi watershed due to its closeness to the city centre giving convenience for socio-economic activities.

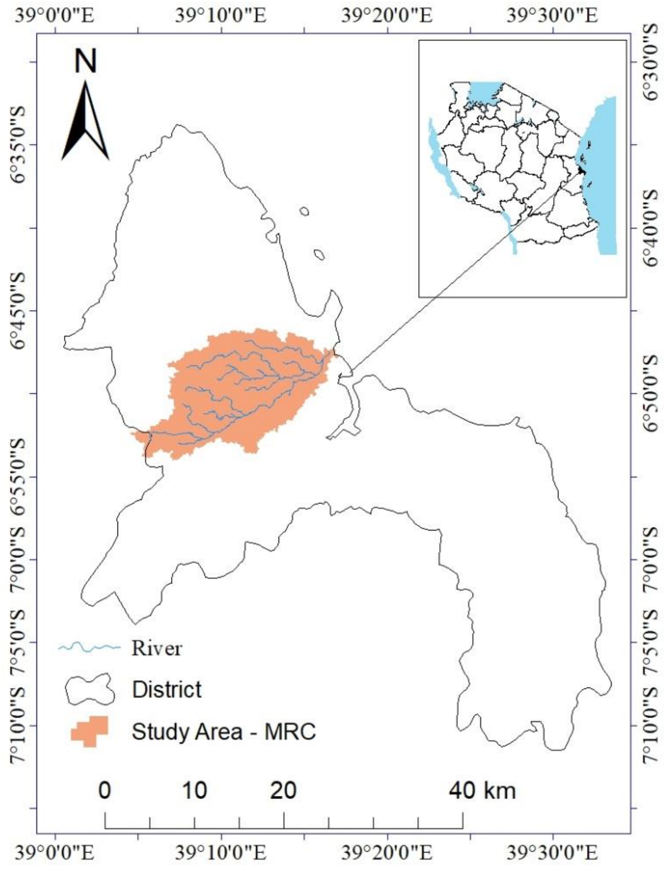

Figure 1: Location of the study area Msimbazi River Catchment within Dar es Salaam Region.

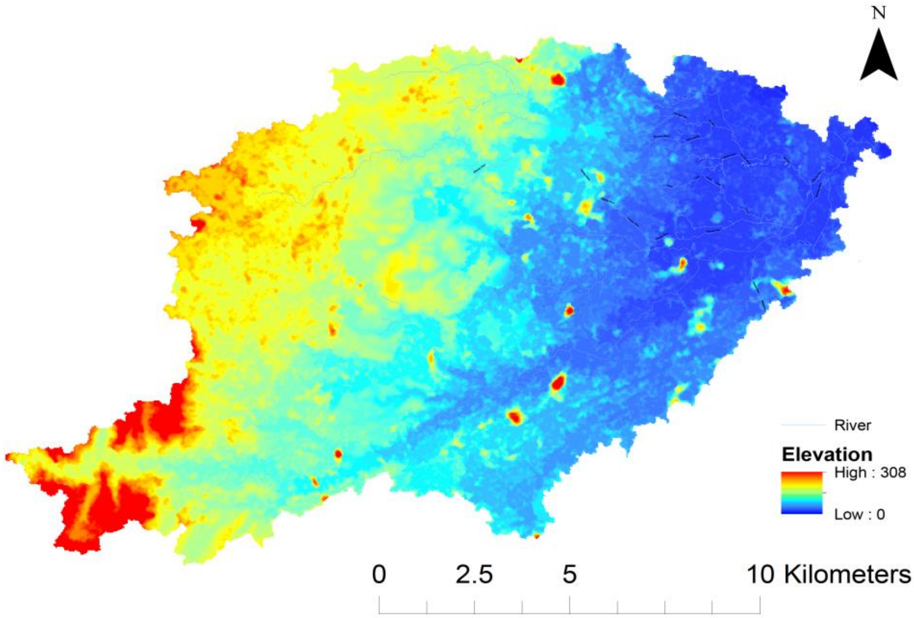

Figure 2: Location of the study area Msimbazi River Catchment displayed from the highest elevation of 308 m Pugu hills to the lowest elevation of 0 m in the Indian Ocean.

Simulations of the past land-use scenarios

The study area was extracted using ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) Global Digital Elevation Model (GDEM) version 2 acquired from the USGS website (https://earthexplorer.usgs.gov/). The Digital Elevation Model (DEM) has a spatial resolution of 30 m, and it was used to delineate the Msimbazi watershed. Meanwhile, Landsat 4 and 5 TM (thematic mapper) and 8 OLI (Operational Land Imager) images acquired from USGS Archive (https://earthexplorer.usgs.gov) were used for land-use change analyses. The Landsats datasets were suitable given their relatively high spatial resolution and repetitive mapping spanning over 30 years. In comparison, other freely available optical remote sensing datasets such as SPOT (Satellite Pour l'Observation de la Terre) and ASTER have a higher spatial resolution but does not offer long term images suitable for the case study objectives. Table 1 describes the details of the Landsat images acquired in the dry and wet season of 1989, 1995, 2009 and 2015, providing discrete temporal snapshots for 26 years. The images were already georeferenced into the coordinate system of Universal Transverse Mercator (UTM). The Landsat data used in this study lack a sequential time series for acquisition due to cloud and shadow contamination of the study area. To maintain consistency of the images in the tropical varying seasons, images acquired in the peak of green foliage periods were maintained except for that of 2015.

Lastly, the socio-economic variables for urbanisation including population growth and Gross Domestic Products (GDP) (Table 2) were acquired from the Tanzania National Bureau of Statistics (NBS).

Table 1: Detail of Landsat images use for classification and estimation of pervious surface area

Date	Date of acquisition	Spacecraft	Path/Row	Spatial resolution	Cloud cover (%)
1989	1989-12-09	Landsat 4 TM	166/65	30 m	3
1995	1995-06-25	Landsat 5 TM	166/65	30 m	1
2009	2009-07-01	Landsat 5 TM	166/65	30 m	1
2015	2015-08-03	Landsat 8	166/65	30 m	1

Table 2: Population data of Dar es Salaam and Gross Domestic Product of Tanzania 1989, 1995, 2009 and 2015

Description	1989	1995	2009	2015
Population size	1,396,130	1, 651,534	3,040,118	5,166,570
Gross Domestic Products (Billion $)	4.4202	5.2552	28.5738	45.6282

Data source: National Bureau of Statistics (Tanzania)

The pre-processing (Figure 3) was done by radiometrically and atmospherically calibration in image bands of the TM and OLI. Radiometric calibration involved dark object subtraction to remove dark pixels and convent images raw digital numbers (DN) into radiance. Atmospheric correction was carried out using a Fast Line-of-Sight Atmosphere Analysis of Spectral Hypercube (FLAASH) that convent the radiance into normalized exo-atmospheric reflectance according to the method proposed by Markham and Barker (1987). The radiometric correction and calibration of the image bands is an important step for a study that is used to compare time-series events.

The Linear Spectral Mixture Analysis (LMSA) was applied to extract different classes of land-use from images. The use of the spectral mixed analysis requires extraction of the endmember as a salient task in image analysis (Wang and Chang 2006). The endmember selection can be through visual inspection of the image in the pixel that has abundant homogeneous land cover class; however, in order to reduce image classification error, endmember selection was made through Minimum Noise Fraction (MNF) transformation. MNF has the advantage to reduce the inherited dimensional damage in the image by reducing noise (Smith et al. 1985).

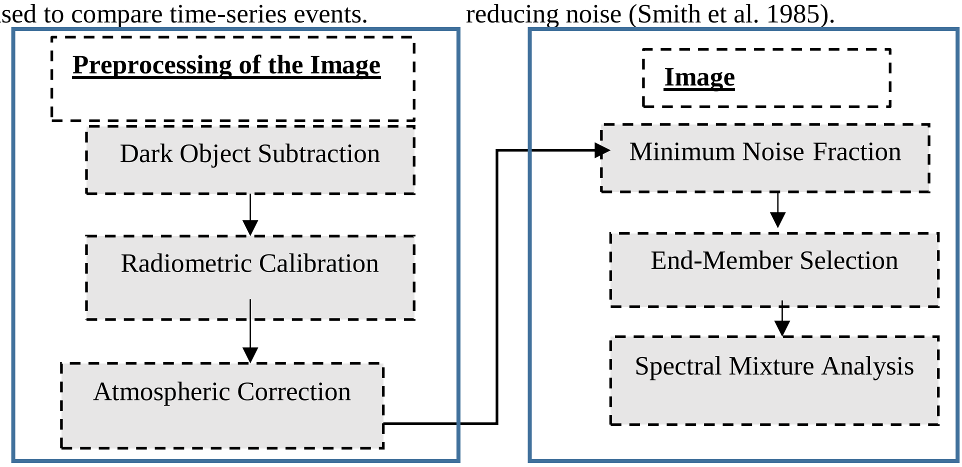

Figure 3: Flow diagram of the land covers pre-processing and processing used in the image analysis of the Landsat data.

Therefore, the Minimum Noise Fraction (MNF) analysis was performed on the seven bands of Landsat images isolate excessive noise content from signals (Smith et al. 1985). It resulted in bands 1, 2, 3, 4, 5, and 7 for Landsat 4 and 5 TM being retained and band 1 to 9 for Landsat 8 OLI being retained after the analysis with the rest of the bands being discarded due to higher noise content. The outputs of the scatterplots (Figure 4) that were generated using a different combination of the MNF bands were used to isolate abundant pixels representing the endmember (Smith et al. 1985). Therefore, based on the land covers available and fieldwork, four endmember representing land use classes were selected from the catchment area.

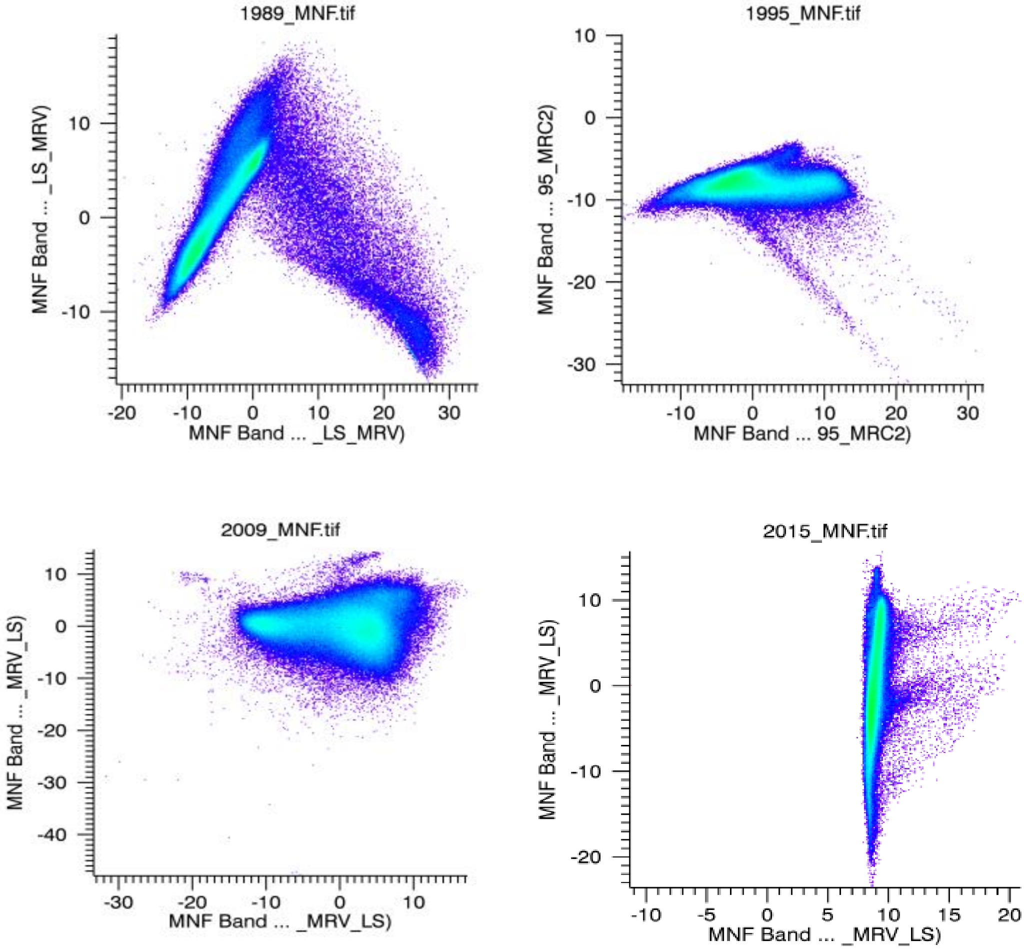

Figure 4: 2-D scatted plots for MNF Endmember extraction plotted against original bands to visualize potential pure pixels of similar land cover for 1989, 1995, 2009 and 2015.

The four selected endmembers were confirmed through the survey conducted in the study area; they represent the forest, vegetation, bare land and built-up. These endmembers were the ones used on Spectral Mixture Analysis (SMA). For an urban catchment that has an informal settlement, it is highly likely to have pixels with mixed land uses of the all built-up, vegetation and bare-land. Hence, a method that involves sub-pixel analysis is more appropriate than traditional land use methodology of supervised and unsupervised classification (Hegde et al. 2014).

The land use classification accuracy was evaluated using overall accuracy assessment and kappa analysis (Congalton 1991). Fieldwork on the study area was carried to collect ground truth data of the identified land cover classes available within Msimbazi watershed. An error evaluation matrix was generated and used to calculate the overall accuracy and kappa coefficient according to the method proposed by Congalton (1991). The overall accuracy was calculated from the ratio of sum of correctly classified pixels to the total number of cells (Table 3). The calculation yielded a value of 89.8%. Kappa analysis, which is the measure of the modal agreement, gave the coefficient value of 85.7%. Both results for accuracy assessment are within the accuracy requirement (Congalton 1991).

Table 3: Land use accuracy assessment of the study area estimate based on the 2015 ground and remote sensing image

Land class	Forest	Vegetation	Bare land	Built-up	Ground Truth Total
Forest	166	45	0	0	211
Vegetation	2	160	0	0	162
Bare land	0	0	35	0	35
Built-up	0	3	7	146	156
Total	168	208	42	146	564

Data analysis

The analysis of the land-use change involves estimation of the proportional changes over a given period. The proportional change is a ratio of the coverage of a specific land class change to all classes in the catchment. The change in land use cover for a certain period was estimated based on their differences. Lastly, is the rate of land-use change which is a change in land-use over a given period (Rawat and Kumar 2015). The growth of impervious surface area from 1989 to 2015 was correlated with socio-economic driving forces of population and growth of the domestic products and statistically analysed by using Pearson’s correlation coefficient.

Results

Land cover and use mapping of the Msimbazi River Catchment flood plains was done using Landsat images of 1989, 1995, 2009 and 2015. The focus was to observe changes of impermeable surface area over a period as an indicator of urbanisation within the catchment. Four land-uses were mapped, characterising the catchment from 1989 to 2015 (Figure 5). These were the forest, vegetation, bare-land and the built-up area (Table 4). The dominant land cover in early 1989 vegetation that has changed into the built-up area in 2015. Water cover could not be identified due to seasonal variations of the Msimbazi river and vegetation cover along the river.

Through mapping, the impervious surface area representing the built-up area was examined within the Msimbazi river catchment from 1989 to 2015 (Figure 5). A graph was plotted (Figure 6) to examine the relationship of the percentage change in the impervious area over time. The coefficient of determination (R^2) was 93% of the variation in annual increase is due to a linear relationship with percentage change impervious area. The impervious area increased from 22 km^2 in 1989 to 101 km^2 in 2015, equivalent to an average rate of 1.7 km^2/year. The highest rate of 2.5 km^2/year was between 2009 and 2015. In 1989 the built-up area within Msimbazi catchment was only 11%, confined within the city centre; by 2015 it increased to 53%. This consecutive increase in the built-up area from 1989 to 2015 indicates a high urbanisation rate within the catchment. The vegetation and bare land area interchangeably vary depending on the season of the image acquisition. Given that land cover and use mapping utilised images of the peak season as a constant, the quantified changes were those of year over year than seasonal changes. Vegetation decreased from 70% of the total area in 1989 to 40% in the year 2015.

The population and impervious surface area of Dar es Salaam increased by a factor of 3.7 and 4.5, respectively from 1989 to 2015. Figure 7 shows an association of the two variables which were later tested by Pearson correlation. The analysis indicates a significant positive correlation at 99% confidence level (R^2 = 0.998, P < 0.001) level (2-Tailed) for population and impervious surface area growth within the catchment. Furthermore, correlation analysis of Tanzania Gross Domestic Product (GDP) and impervious surface area within catchment revealed a significant positive correlation at 99% confidence level (R^2 = 0.9955, P < 0.009).

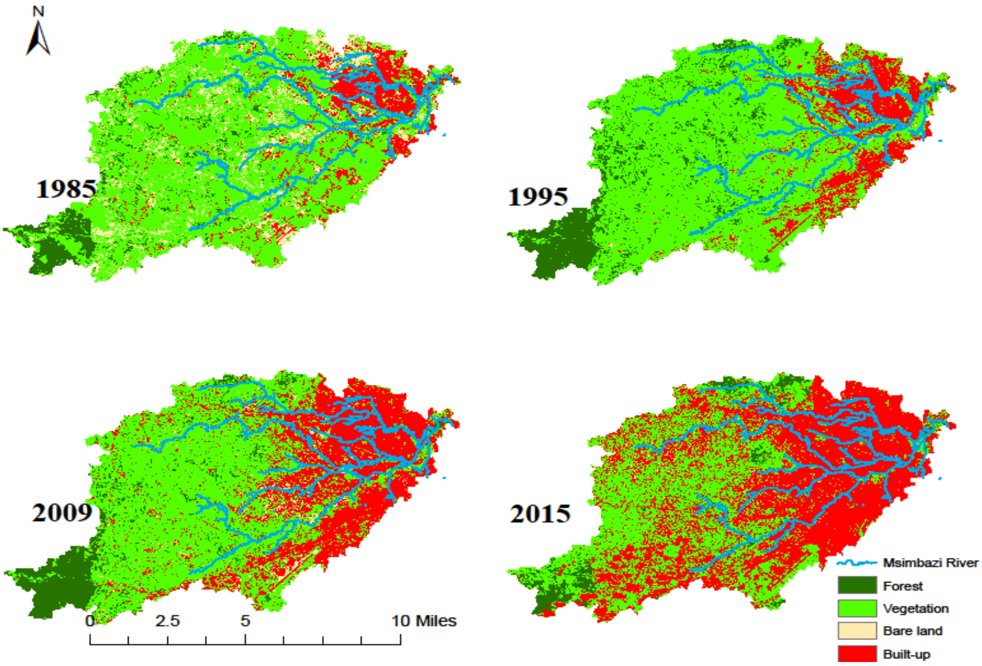

Figure 5: Land use classification of Msimbazi River catchment for 1989, 1995, 2009 and 2015.

Table 4: 1989-2015 land use classification for the Msimbazi River Catchment

	1989		1995		2009		2015	
	%	Km^2	%	Km^2	%	Km^2	%	Km^2
Forest	7.5	15.0	12.9	23.4	9.5	18.0	4.9	9.2
Vegetation	71.6	142.6	71.3	129.1	57.0	108.4	41.4	78.7
Built up	11.2	22.4	15.2	27.6	31.4	59.8	53.0	100.8
Bare Land	9.7	10.2	0.6	10.0	2.1	4.0	0.8	1.5

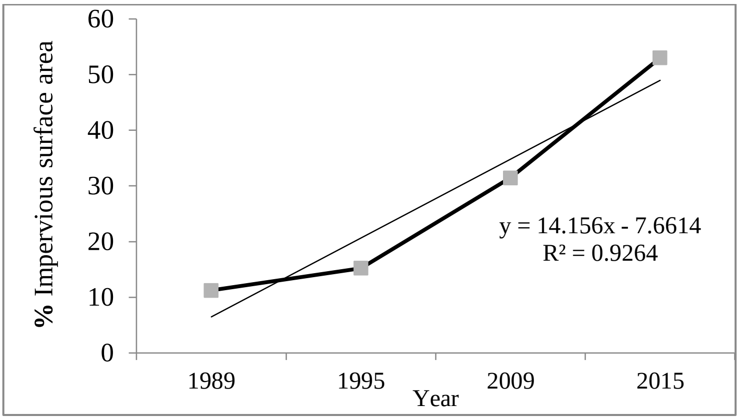

Figure 6: The functional trend of the impervious surface area within the Msimbazi River Catchment, Dar es Salaam.

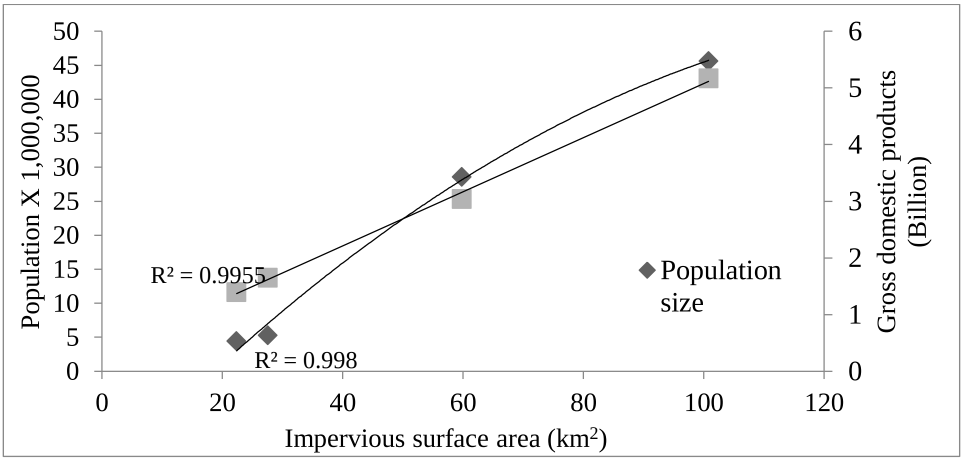

Figure 7: Correlation of the gross domestic product and population for the Msimbazi area against the impervious surface area.

Discussion

The four mapped land cover types could easily be identified by visual inspection of the images, but the mapping methods applied have enhanced the results obtained and further gave more details related to results. The classification has indicated that in the early 1990s the dominant land cover was vegetation, covering over 70% of the area. This was followed by the urban built-up environment, which occupied 11% of the catchment area. However, the most recent snapshot of land cover and use within the catchment in this study shows the built-up area covers over 50%. This could be attributed to progressive urban development from the period around 1995. This is in line with studies done by Kombe (2005) and Lupala (2001). These found out that land use in Dar es Salaam predominantly changed to the built-up environment in the early 1990s due to the rural-urban migration. In addition, uncontrolled land acquisition led to individual ownership and development of small and concentrated land units, which culminated into informal settlements and their densification in the study area. The variations of vegetation and bare land within the catchment are highly influenced by wet and dry seasons of the year. However, the land cover units observed within the catchment appear to transition steadily into the built-up environment. This, therefore, will impact the biogeochemical cycle (Chithra et al. 2015, Haustein 2010) and also lead to the development of urban heat islands in the catchment (Weng 2012).

The analysis of the built-up area indicates the spatial variations within the catchment. In 1989, a larger part of the impervious surface area was found to be distributed from the city centre to the peripherals. The larger impervious surface area in 2009 compared to that of 1995 within the catchment indicates a high rate of urbanisation in the early 2000s. This is linked to an increase in population, which correlates with the increased civil infrastructures to cope with demands. On the other hand, the observed distribution of the settlements from the city centre to the peripheral within the catchment is an indicator of increasing socio-economic activities. However, the distribution of the impervious surface area along the Msimbazi River suggests a strong relationship between human, socio-economic activities, and water resources. The dominant human activities observed in the catchment include settlement, industrial activities and urban agriculture (Leonard et al. 2012). These findings of the progressive growth of impervious surface area in urban areas are similar to those found in the growth of other cities such as Harbin and Beijing (Li et al. 2018, Tian et al. 2014).

The changes in land uses, particularly the increased impervious surface area can be attributed to factors including population growth, economic development, and urban planning as shown by previous studies (Brueckner 2000, Li et al. 2018). The related association of growth in population and impervious surface area is an essential finding in understanding population as a factor in the urbanisation processes. Population growth triggers urban planning and infrastructure development. If not controlled, it promotes the development of unplanned cities and encroachment of water catchments. This is similar to the unplanned settlement observed in the study catchment area (Bartlett and Satterthwaite 2016). Figure 7 also shows that an increase in the impervious area is directly correlated with the increase in GDP, which is an indication of economic growth with respect to infrastructure development (Brueckner 2000, Li et al. 2018).

It is essential to highlight the unfolding impacts of the execution of the policy of the fifth phase Tanzanian government development towards industrialization. It will potentially increase the coverage of the impervious surface area from infrastructure development and other circumstances that underpin the growth of urban spaces. Dar es Salaam is continuing to build upon the diverse industry it already has. Thus, the impervious surface characterising the built-up space will continue to grow as projected in the Msimbazi and other watersheds in the region. This is likely to accelerate environmental challenges such as recurring floods (Kebede and Nicholls 2012, Sakijege et al. 2012) as a result increased surface runoff, which is, in turn, a result of reduced surface area for infiltration.

The limitations of this study include cloud contamination and their shadows in some of the main image datasets that can be used in the analysis. This is a common problem for the optical satellite remote sensing datasets of the tropical regions. This problem is however attenuated by use of two or more images taken repetitively in the same geographical coverage. The Landsat mission, images of which were used in this study, has a good repetitive mapping pedigree, where at least one image covering the same geographical space is available every month. Furthermore, population and GDP data specific to the study area were not available, thus the study utilised more generalised datasets as a workaround.

Conclusion

The analysis of Landsat images for Msimbazi watershed area in the years 1989, 1995, 2005 and 2015 generalises a 26-year land use and cover dynamics trajectory. During the quarter-century, the impervious cover increased substantially, encroaching vegetation and bare land. The growth of impervious surface consumes arable urban vegetation, including forests. The vegetation, including that of the riverine flanking the rivers and streams, is vital for the sustainability of the water bodies. Its degradation deteriorates the urban ecology of the Dar es Salaam. Population growth and economic development showed a linear correlation to urban growth, hence that of the impervious surface area. The observed increase of the impervious surface area can be linked with on-going environmental challenges within the catchment, including floods. Pre-emptive measures should therefore be taken to consolidate other rural and urban catchments to develop sustainable cities.

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