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REPORT

# Impact of urbanization on groundwater recharge: altered recharge rates and water cycle dynamics for Arusha, Tanzania

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## Abstract
The profound effects of urbanization on groundwater recharge rates are investigated by conducting a comprehensive land use and land cover analysis in Arusha, Tanzania, using the WetSpass model. Between 1995 and 2016, the urban area has expanded from 14 to 45% within the study area. This rapid urbanization has resulted in the conversion of forested areas, agricultural land, shrublands, and bare soil into urban zones. Results indicated that under preurban conditions, groundwater recharge from precipitation was ~116 mm/year, which increased to an average of 148 mm/year by 2016. When accounting for anthropogenic factors such as drinking water leakage and on-site sanitation, recharge further increased to 195 mm/year. These supplementary recharge sources, along with reduced evapotranspiration due to land-use changes, contributed to the increase, despite higher surface runoff. These findings underscore the significance of land use and leakage management in urban areas, as well as the spatial variability in groundwater recharge rates across different urban zones, emphasizing the importance of local factors. This study advances the understanding of the intricate relationship between urbanization and groundwater dynamics, and provides insights for future water resource management in rapidly growing urban regions.

**Keywords** Tanzania · Urban groundwater · Recharge · Groundwater management · Land use change · Hydrogeology

## Introduction

Urbanization, characterized by the rapid growth of cities and the expansion of urban areas, is a dominant global demographic trend of the twenty-first century (La Vigna 2022). As the world's population increasingly gravitates toward urban areas, the environmental consequences of this phenomenon are becoming more pronounced (Howard 2002).

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Rapid urbanization and enhanced global connectivity present unprecedented challenges and environmental risks, as well as potential opportunities (Coaffee and Lee 2016). Among many, one critical aspect of urbanization is its profound impact on groundwater resources and the broader water cycle (Jurado et al. 2012).

Groundwater, a vital component of the Earth's hydrological cycle, serves as a significant source of freshwater for human consumption, agriculture, and various industrial processes (Bierkens and Wada 2019; Moeck et al. 2020). However, the rapid conversion of natural landscapes into urban areas significantly modifies the hydrological dynamics of the affected regions (Lerner and Barrett 1996). One of the most prominent effects of urbanization on groundwater is the alteration of groundwater quantity and quality (Schirmer et al. 2013; Vázquez-Suñé et al. 2005). Urban groundwater creates benefits and problems because it is beneficial as a source of water for different uses but also it is a problem due to the consequences that could result from pollution (Lerner 1997; Moeck et al. 2021)—for example, urban areas tend to experience higher rates of water consumption and wastewater discharge into aquifers, including emerging contaminants

(Sharp 2010; Vystavna et al. 2019; Burri et al. 2019; La Vigna 2022).

Urbanization also affects the entire water cycle (Eshtawi et al. 2016; McGrane 2016; Miller and Hutchins 2017) and urban heat islands generated by the built environment often intensify evapotranspiration rates, which can have cascading effects on local climate and hydrology (Previati et al. 2022). Less vegetation in urban areas can potentially lead to lower evapotranspiration rates compared to forests (Minnig et al. 2018; Vázquez-Suñé et al. 2010). This can be important because urban development often involves the alteration of natural landscapes, including the removal of vegetation, which plays a crucial role controlling groundwater recharge rates (Han et al. 2017). The proliferation of impermeable surfaces such as roads, buildings, and pavements in urban areas reduces the capacity of the area to infiltrate rainfall into the subsurface. Instead, rainwater often becomes surface runoff, swiftly draining into stormwater system and natural water bodies (Weatherl et al. 2021) and can exacerbate flooding during heavy rainfall events (Rubinato et al. 2019). These alterations in the flow pathways of water can potentially lead to changes in groundwater recharge rates, particularly in areas with high urbanization intensity (Eshtwi et al. 2016).

Moreover, the urban water cycle consists of various natural and man-made components (e.g. sewers), which strongly interact with each other (Kuhlemann et al. 2020)—for example, the building of water supply, and sewer networks often leads to an increase in groundwater recharge rates due to leakages (Attard et al. 2016; Held et al. 2006; Minnig et al. 2018; Nguyen et al. 2021).

Water supply and wastewater removal rely on pipe networks, and sewer systems, but the effectiveness of these networks can be compromised by various factors, including aging pipes and improper pipe placement among many other factors. This substantial loss directly contributes to groundwater recharge (D'Aniello et al. 2021). In many densely populated areas, insufficient water supply and infrastructure problems are common (Foster 2001; Gaye and Tindimugaya 2019; Van der Bruggen et al. 2010); however, it is important to note that these processes are complex, and drawing general conclusions can be challenging, as the specific conditions of each city can produce varying and sometimes contradictory results. Urban settings, therefore, are much more difficult to model and monitor than natural areas due to the complex interactions, as well as numerous water flow components and contaminant sources.

Numerous studies (see for example the review by La Vigna 2022 and the references within) have examined the connection between urban expansion and groundwater recharge. Some investigations have documented an increase in urban groundwater recharge as cities expand, attributed to the introduction of supplementary recharge mechanisms, such as leakage, and a decrease in evapotranspiration (Abdelaziz et al. 2020; Appleyard 1995; Locatelli et al. 2017; Minnig et al. 2018; Tubau et al. 2017; Wakode et al. 2018). Conversely, alternative research has demonstrated a decline in urban groundwater recharge as urban areas expand, primarily due to alterations in land cover favouring impermeable surfaces that obstruct direct infiltration (Hardison et al. 2009; Rose and Peters 2001; Siddik et al. 2022). However, it is worth noting the traditional notion that the growth of cities decreases recharge due to an increased proportion of impermeable surfaces has been refuted for many locations worldwide. There is no direct evidence suggesting that the increased runoff necessarily comes at the expense of recharge; it could instead result from reduced evapotranspiration, given the reduced plant cover in urban settings (Lerner 1997). A comparison of groundwater recharge before and after urbanization in different cities worldwide (Howard 2023; Morris et al. 2003) reveals that, in most cases, urbanization results in an overall increase in total groundwater recharge (Appleyard 1995; Locatelli et al. 2017; Minnig et al. 2018; Wakode et al. 2018; Abdelaziz et al. 2020). As an example of this, Minnig et al. (2018) reported an increase between 29 to 67% in groundwater recharge in Dubendorf (Switzerland) compared to preurbanization, while, similarly, Abdelaziz et al. (2020) observed that groundwater recharge in Abidjan (Ivory Coast) increased from 21 to 26% of the total precipitation and Kim et al. (2001) documented a roughly 50% increase in recharge in Seoul, South Korea. These findings are consistent with numerous other studies that have reported significant increases in groundwater recharge across various regions (Howard 2023). In all studies, the impact of impervious surfaces was offset by the substantial volume of water leaking from water and wastewater infrastructure and changes in evapotranspiration rates (Morris et al. 2003). Nevertheless, it is important to note that the change in urban groundwater recharge varies spatially—in areas with impervious surfaces and compacted soil, recharge rates may be low, whereas areas with leaks or permeable surfaces could exhibit higher recharge rates (Sharp 2010).

The processes and changes in the urban water cycle, especially for groundwater recharge, which cannot be measured directly (Berghuijs et al. 2022), are still not fully understood, likely due to the heterogeneous setting of urban areas. A systematic understanding of the process and interaction with the groundwater system are, however, a requirement for sustainable groundwater management in urban areas, necessitating a detailed knowledge of the hydrogeological system and reliable predictions of the amount of groundwater recharge rates (Moeck et al. 2016), especially in cities that are growing fast and are vulnerable due to changing climatic conditions and therefore often dependent on groundwater resources (Lapworth et al. 2017).

This study explores the intricate relationship between urban areas and groundwater, with a particular focus on the changes in groundwater recharge rates and the alterations in other vital components of the water cycle, including surface runoff and evapotranspiration for the fast-growing city of Arusha in Tanzania (East Africa). The spatially distributed WetSpass model (water and energy transfer between soil, plants and atmosphere under quasi-steady state) was used to estimate groundwater recharge from precipitation. Additional recharge sources from leakage of drinking water pipes and onsite sanitation were also estimated to obtain the total groundwater recharge within the study area.

For the same study area (but different spatial extent), Olarinoye et al. (2020) combined satellite imagery, urban growth modelling, groundwater modelling and hydrogeological field investigations to estimate the potential impacts in 2050 of rapid urbanization and climate change on groundwater. The primary distinction between this study and that of Olarinoye et al. (2020) lies in the scope and approach to estimate groundwater recharge. Olarinoye et al. (2020) focused on modelling the impact of urbanization, climate change, and land use planning, considering factors like population growth, water abstraction, and especially climate variability to forecast future availability. In contrast, this study emphasizes historical data to assess the impact of land use and land cover changes on groundwater recharge. The evolution of recharge rates from preurban conditions to recent years was specifically investigated to more effectively isolate and distinguish the influence of urbanization on recharge rates, independent of varying climate data or abstraction rates. Here, the aim was not to exactly replicate each year; instead, the focus was to provide a relative comparison and evaluation of how land use changes and increasing urbanization affected recharge rates. While there are some overlaps in the themes of both studies, it is important to clarify that the findings of this study were derived independently and are not based on the modelling used by Olarinoye et al. (2020). Nonetheless, specific data from Olarinoye et al. (2020) was utilized, particularly concerning drinking water pipe networks from AUWSSA, to identify potential leakage areas within the city and used reported recharge rates served as one of several benchmarks for model validation.

This study aims to provide valuable insight into the changes in groundwater recharge resulting from urbanization in the city of Arusha using information about land use changes over time and scenario modelling. Intricate interactions between urbanization and groundwater were identified, which is crucial for sustainable urban development and effective water resource management. This study examines the effects of urbanization on groundwater recharge rates. Unlike other studies, this research specifically isolated the influence of urban land use changes on recharge rates. This focused analysis was achieved by employing constant climate data, allowing the discernment of the direct effects of urban expansion and land use evolution without the confounding variations in climate. Moreover, a clear before-and-after snapshot of the impact of urbanization is provided. This temporal approach enabled a relative comparison rather than absolute year-to-year changes and highlighted how different urbanization levels influenced groundwater recharge. By enhancing the understanding of how urban areas influence the water cycle, this study contributes towards more resilient and water-efficient urban environments in the face of increasing urbanization and global climate change challenges.

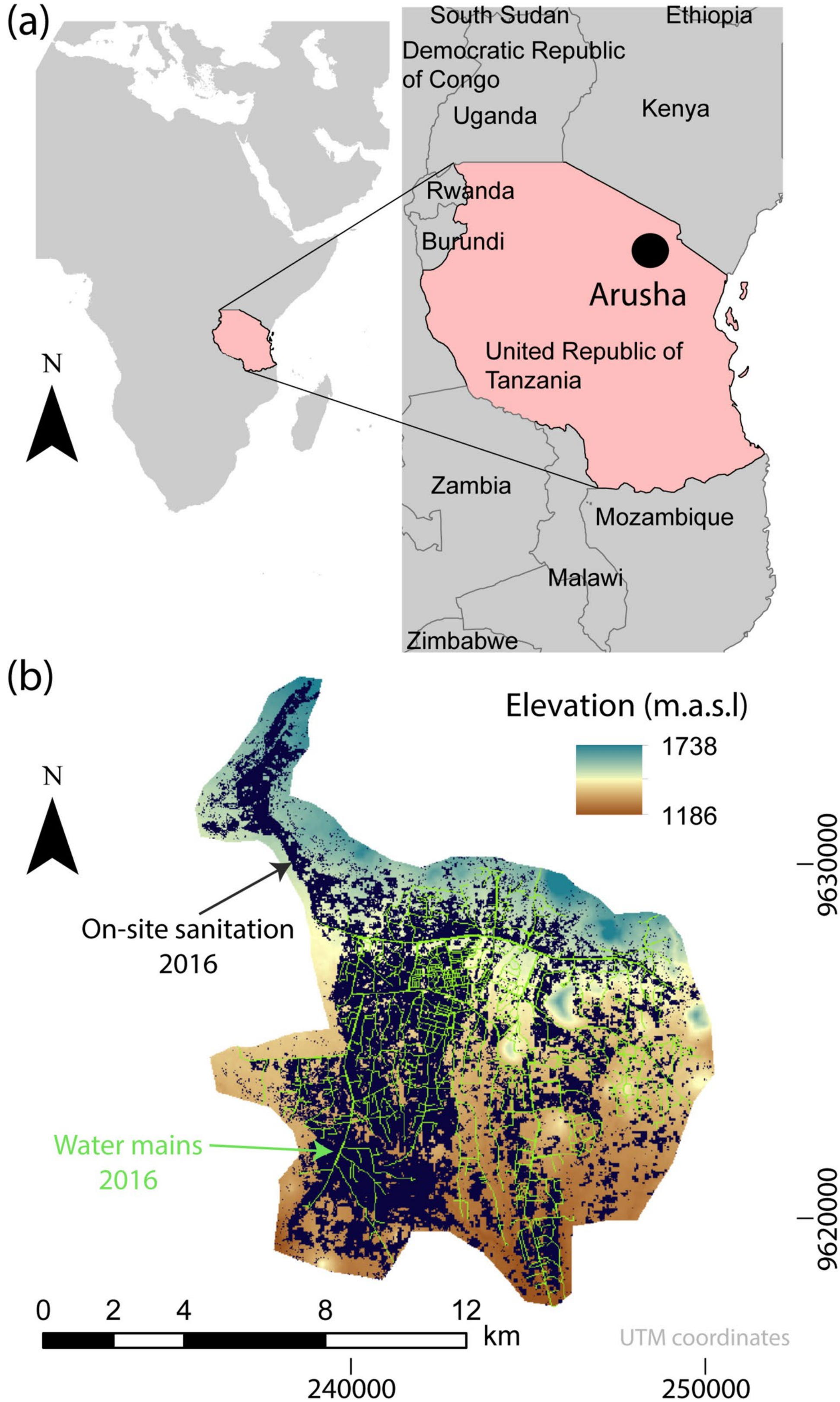
## Study area

Arusha is located in Tanzania, East Africa. It is the third largest city in the country with a total area of 267 km$^2$ and ~519,000 inhabitants (Olarinoye et al. 2020) (Fig. 1). The majority of the occupants have low to average incomes (Olarinoye et al. 2020). The population has been growing fast with 21% of the growth being in the past 10 years (Silva et al. 2020). The city has a semiarid climate with an annual average precipitation of 870 mm/year, average temperature 22 °C and potential evapotranspiration rates of 924 mm/year. It has two rainfall seasons—the short rainfall season lies between November and December and the long rainfall season occurs from March to May (Olarinoye et al. 2023). The intensity of rainfall varies with elevation, with the higher elevation areas such as Mount Meru (4560 m) receiving rainfall of up to 2000 mm/year or more. The warmest month in the city is February, with an average temperature of 25 °C, while the coldest month is July, with a temperature of 13 °C.

The topography of the city is a result of East African Rift processes which gave rise to Mount Meru, a young volcano of Pleistocene origin (Kashaigili 2010). The elevation varies from 1000 m asl in the south to 4560 m at Meru Mountain, where Arusha is located at its base (Fig. 1). Alluvial fan deposits derived from the detritus of Mount Meru, feature a radial drainage pattern and parasitic cones which dominate the topography of the area (Olarinoye et al. 2020). The geology of the area is dominated by igneous rocks, volcanic mudflows, and pyroclastic ashes. In addition, due to the weathering, lower permeability soil types make up the majority of the soil in the area (Silva et al. 2020). The exact extent and boundary of the aquifer has not yet been identified; however, the thickness is assumed to be >150 m (Olarinoye et al. 2020).

The Arusha Urban Water Supply and Sanitation Authority (AUWSSA) is responsible for managing public water supply; however, this network only reaches 40% of the city population (African Development Bank Group 2015) and the drinking water networks are mainly concentrated in the

**Fig. 1** Map showing the location of Arusha (**a**) and the elevation and spatial distribution for on-site sanitation (in black) and water mains (shown in light green) across Arusha for the year 2016



city center serving middle-income households (Silva et al. 2020; Olarinoye et al. 2023). The people who live in the areas without water supply coverage by AUWSSA obtain water from informal water suppliers and private wells (Olarinoye et al. 2020).

## Methodology

The model, input variables and work flow to calculate the WetSpass model outputs, such as groundwater recharge, surface runoff and actual evapotranspiration, are shown in Fig. 2 and are explained in detail in the following.

### WetSpass model

WetSpass is a spatially distributed water-balance model developed by Batelaan and De Smedt (2001). WetSpass estimates the temporal and spatial distribution of surface runoff, actual evapotranspiration, and groundwater recharge using meteorological, hydrogeological and land use model inputs (Fig. 2) based on water balance calculations. This approach is flexible and takes into account the spatial variation of the processes related to recharge (Woldeamlak et al. 2007).

Groundwater recharge is simulated in WetSpass as the residual term of the water balance Eq. (1) (Dams et al. 2007):

$$R = P - S - E - I \tag{1}$$

where $R$ is groundwater recharge [$LT^{-1}$], $P$ is precipitation [$LT^{-1}$], $S$ is runoff over the land surface [$LT^{-1}$], $E$ is evaporation [$LT^{-1}$] and $I$ represents interception of $P$ by vegetation [$LT^{-1}$].

The WetSpass model operates in a spatially distributed manner, providing $R$ outputs at the same resolution as input

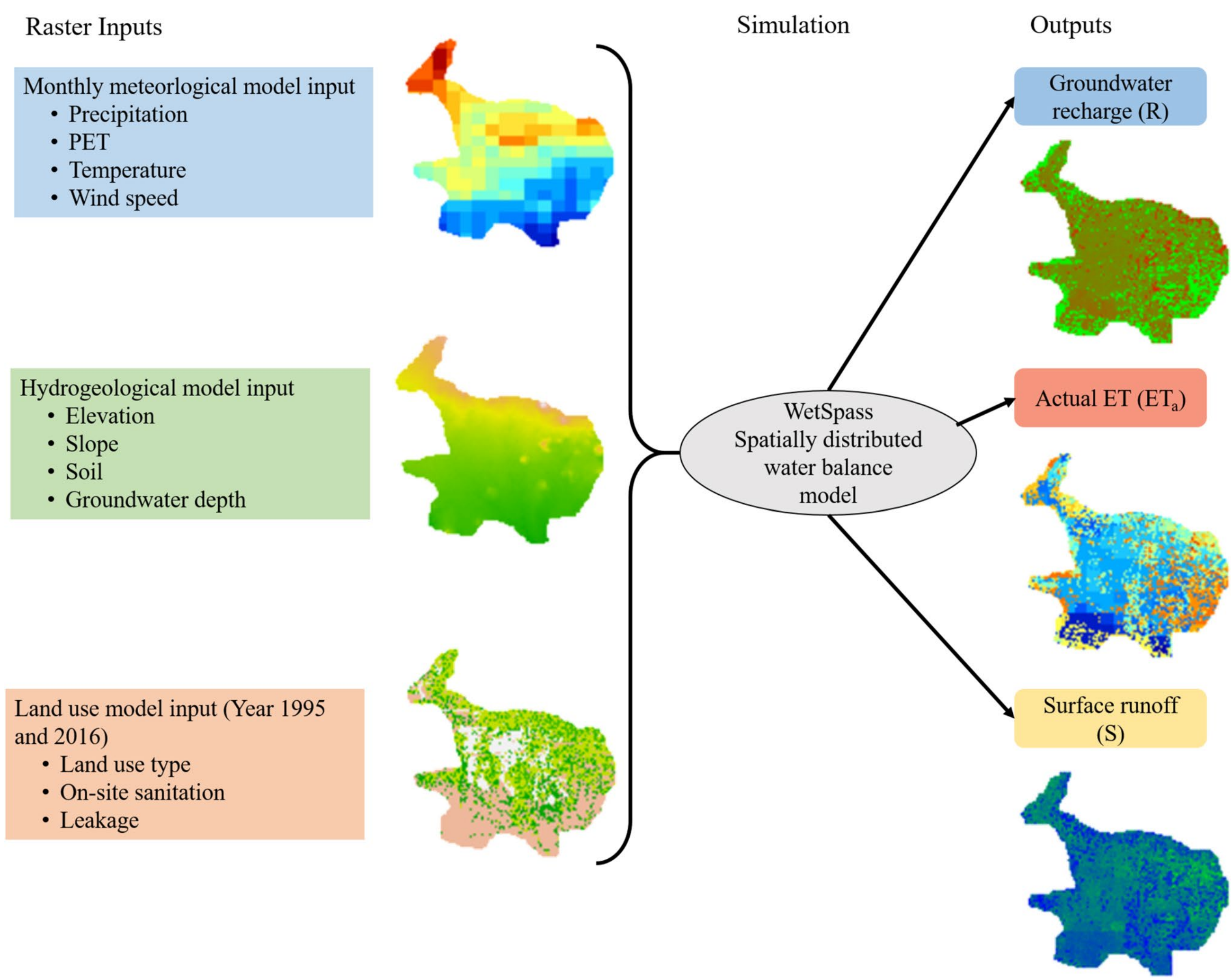



**Fig. 2** Conceptual diagram of the WetSpass model, including raster input and output variables

variables. In this study, the spatial and temporal meteorological, hydrogeological and land-use model inputs have cell sizes between 30 m and 1 km. The use and impact of data of varying resolutions due to data availability will be detailed in section 'Discussion'. The simulations were carried out on monthly time steps in order to capture the temporal dynamics of the study site and climatic conditions. The study area was considered as a regular pattern of raster cells, further subdivided into vegetated, bare soil, open water and impervious surface fractions for which the independent water balances were calculated (Batelaan and De Smedt 2001; Fig. 2). Surface runoff depended on land-use, soil, slope and precipitation intensity in relation to infiltration capacity of the soil. Actual evapotranspiration (Eta) was calculated as the sum of evapotranspiration and interception (César et al. 2014). Simulated monthly spatial output variables are runoff, ETa and groundwater recharge, which were summed yearly to obtain annual rates.

## Input data

Different spatial and temporal model inputs were required for WetSpass which could be grouped into meteorological, hydrogeological and land use inputs (Fig. 2). Monthly meteorological data, including precipitation, potential evapotranspiration, temperature and wind speed were obtained from Worldclim (Fick and Hijmans 2017) with a spatial resolution of 1 km$^2$; the average monthly values for a 30-year period (1970–2000) were used. In order to investigate the change in groundwater recharge induced by urbanization without being influenced by the varying climatic conditions, the climatic data was held constant in estimating groundwater recharge for all the scenarios. To more effectively isolate and distinguish the influence of urbanization on recharge rates independent of varying climate data (e.g., different precipitation rates), the aim was not to replicate each year precisely. Instead, the focus of this study was to provide a relative comparison and evaluation of how land use changes and increasing urbanization affected recharge rates.

The land use changes in the year 1995 and 2016 were the focus for this study due to availability of the required data. Land use/land cover data with a 30-m spatial resolution from a previous study by Olarinoye et al. (2020) was used and reclassification was performed to obtain seven different land use classes that were consistent with the WetSpass model. Artificial surfaces such as roads and urban features were merged into one urban area class. Land use classes used were urban area (including roads and built-up areas), agricultural area, bare soil, shrubland and thicket, mixed forest, coniferous forest, and broad-leaved forest (Fig. 3).

Moreover, this study aimed to recreate and simulate the preurban conditions; however, due to the limited availability of detailed historical data on land use and distribution, constructed scenarios were relied upon to depict plausible situations. The preurban conditions on groundwater recharge were considered by including two different scenarios and were defined as:

- Scenario 1: Agricultural land was converted to coniferous forest and urban area was converted to shrubland and thicket.
- Scenario 2: Agricultural land and urban area was converted to shrubland and thicket.

The elevation was obtained from the USGS (Danielson and Gesch 2011) with a resolution of ~30 m and slope values were subsequently calculated within WetSpass from the available digital elevation model. Depth to the groundwater table was obtained from Fan et al. (2013) with a resolution of 1 km and soil data were from Hengl et al. (2017) with a resolution of 250 m.

Another potential source of groundwater recharge in urban areas was leakage from wastewater and drinking water mains as well as from on-site sanitation (Elisante and Muzuka 2017; Minnig et al. 2018; Olarinoye et al. 2023).

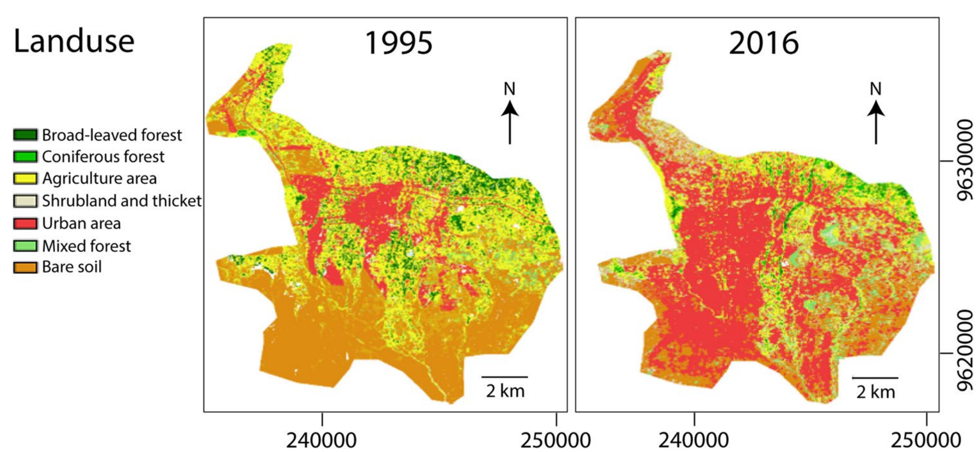



**Fig. 3** Land-use map for 1995 and 2016 with classes: urban (including roads and built-up areas), agriculture, bare soil, shrubland and thicket, mixed forest, coniferous forest, and broad-leaved forest

In Arusha, only 40% of the population has access to a piped drinking water network. The leakage percentage from wastewater and drinking water mains was assumed to be ~20–30% everywhere throughout the study area, based on previous studies (Alexander Saria 2015).

Total leakage from drinking water pipes was estimated by taking 30% of the product of 40% of the total population and average daily water use per person (0.04 $m^3$/day). Data on drinking water pipe networks from AUWSSA was used to identify the possible areas of leakage in the city (Olarinoye et al. 2020). The assumed leakage remained 30% for both years (1996 and 2015). For the calculation of onsite sanitation in Arusha, existing data on return flow as wastewater from Olarinoye et al. (2020) was utilized. The total return flow as wastewater in the city was determined by multiplying the daily wastewater generated per person with the total population and counted as the recharge rate from on-site sanitation. The spatial leakage rates from both onsite sanitation and water mains were computed by assuming that the leakage was distributed throughout the area covered by the piped drinking water network. The calculated groundwater recharge from WetSpass was subsequently combined with leakage rates from both calculated onsite sanitation and water mains.

The use of constant climate data was an intentional decision to focus the analysis on relative changes in recharge rates due soley to urbanization. By maintaining consistent climate variables, any observed differences in recharge rates could be specifically attributed to changes in land use and urban expansion, rather than temporal fluctuations in climate. Here, the differing time spans for the input data were less relevant for the relative comparison. This approach allowed for the identification of the impact of urbanization on recharge rates, independent of other environmental factors. The selection of land use data from 1995 and 2016, despite the time gap, was based on the availability of high-quality datasets that best represented significant land use changes over this period, providing a robust basis for assessing the effects of urbanization.

As there was no calibration of water balance components, the results were instead validated with independent recharge rates obtained from other studies. Unfortunately, recharge cannot be measured directly (apart from lysimeter measurements) (Ghasemizade et al. 2015; MacDonald et al. 2021) and so the recharge estimates were compared with the results from other studies in the vicinity of Arusha.

## Results

### Land use change and leakage

In 1995, bare soil (in the south) and agricultural areas (in northern part of the study area) were the dominant land cover types (Fig. 3). However, in 2016, urban areas showed a significant increase from 14 to 45% at the expense of agriculture, which decreased from 29 to 15% (Fig. 4). Bare soil decreased from 32 to 23%, and broad-leaved forest decreased from 7 to 1% (Fig. 4). Mixed forest and coniferous forest showed a 1% increase, attributed to a reforestation program implemented to control deforestation in the area (Olarinoye et al. 2020). Based on these observations, it was concluded that between 1995 and 2016, a significant level of land use change occurred (Fig. 4).

The leakage rate from drinking water pipes and on-site sanitation in 2016 amounted to 47 mm/year for the entire

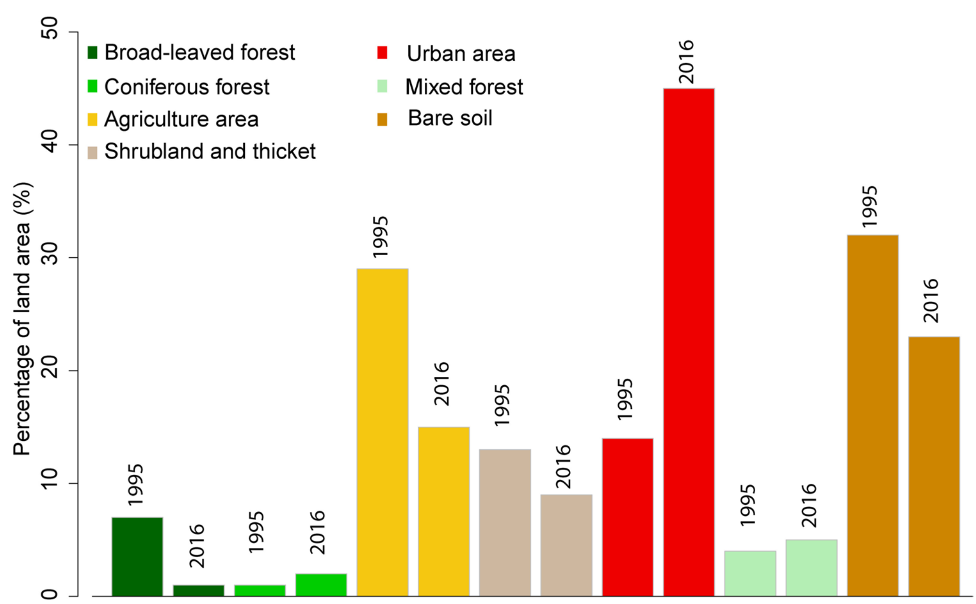



**Fig. 4** Percentage of land area (%) for the seven different land use classes in 1995 and 2016

study area and was higher than 27 mm/year in 1995. This increase was attributed to an increase in population and water demand (Fig. 5); however, the rates at specific locations with leaks or on-site sanitation (indicated by green lines in Fig. 5), may be higher than the overall rates for the entire study area, as the latter includes regions where factors such as water pipe leakage are absent. The values for the entire study area are primarily influenced by on-site sanitation, with leakage contributing to a lesser extent. This is largely because of the uneven distribution of the sewer network and the lower percentage of the population that has access to it.

## Natural groundwater recharge

Recharge rates ranged from 140 to 400 mm/year in the forest, urban and agricultural areas, while bare soil exhibited lower rates ranging between 0 to 150 mm/year (Fig. 6). The highest surface runoff was observed for bare soil areas, likely due to the absence of vegetation cover, leading to small recharge rates, where recharge <1 mm/year was simulated for a negligible number of model cells. Notably, a relatively high recharge rate (>150 mm/year) was observed in the urban areas from precipitation, which was attributed to lower evapotranspiration rates, although surface runoff was relatively high. Higher recharge rates occurred in 2016 compared to 1995 due to land use change and, consequently, changes in runoff and evapotranspiration, with an average annual recharge of 148 mm/year, surpassing the 127 mm/year recharge rate observed in 1995.

## Validation

When comparing the estimated groundwater recharge with previous studies on groundwater recharge rates in Arusha municipality and the surrounding area (Table 1), a similar range of annual recharge rates was obtained, although the methods differ as well as the time period and area considered. It was expected that differences in groundwater recharge rates occurred when using different methods because the methods depend on different concepts and spatiotemporal scales (von Freyberg et al. 2015). The average natural recharge rates of 127 (year 1995) and 148 (year 2016) mm/year and total recharge, which included leakages of 148 mm/year (year 1995) and 195 mm/year (year 2016), aligned well with values reported in the literature.

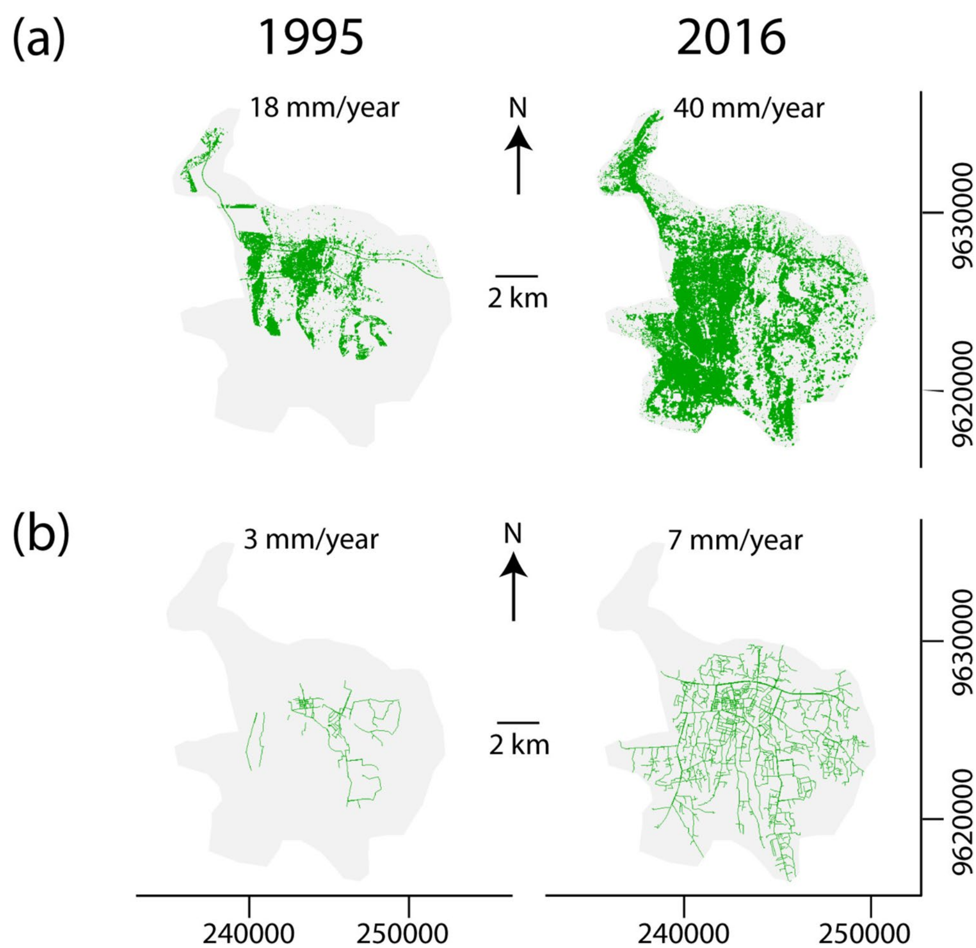



**Fig. 5** Spatial distribution of on-site sanitation (**a**) and water pipe leakage (**b**) rates in mm per year for the years 1995 and 2016 in Arusha

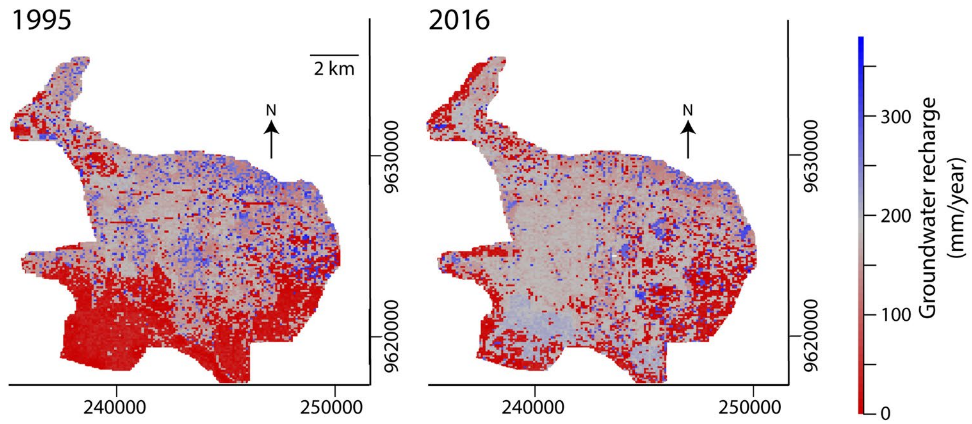



**Fig. 6** Spatial distribution of annual groundwater recharge rates in Arusha for the years 1995 and 2016. The rates provided exclude leakage rates from on-site sanitation and water mains

**Table 1** Comparison of annual groundwater recharge rates in Arusha municipality and surrounding area from this and previous studies using different methods to estimate recharge

| Reference | Groundwater recharge (mm/year) | Method | Location |
|---|---|---|---|
| This study for the year 2016 | 148 | WetSpass | 962,000 S–963,000 S and 240,000 E–250,000 E |
| | 195 | WetSpass + leakage | 962,000 S–963,000 S and 240,000 E–250,000 E |
| Ong'or and Long-Cang (2007) | 145 | DRASTIC method | 9,653,011 S and 242,473 E246217E |
| Olarinoye et al. (2020) | 107 | WetSpass | 960,000 S–966,000 S and 270,000 E–220,000 E |
| Mussa et al. (2021) | 185 | Modified soil moisture balance method coupled with the curve number (CN) | 920,000 N–925,000 N and 450,000 E–550,000 E |
| Lwimbo et al. (2019) | 124–202 | Chloride mass balance (CMB) | 9,645,000 S—9,585,000 S and 315,000 E–360,000 E |
| Ntembeleha (2001) | 256 | Cumulative rainfall departure (CRD) | 9,640,055 S–9,612,397 S and 231,468 E–253,699 E |
| Kashimbiri et al. (2009) | 286 | Cumulative rainfall departure (CRD) | 9,623,893 S–9,634,956 S and 9,634,938 E–9,634,960 E |

## Total recharge and water balance components

Total recharge was defined as the sum of leakage from drinking water pipes, on-site sanitation (Fig. 5), and recharge from precipitation (Fig. 6) obtained from the WetSpass model. Surface runoff increased from 1995 to 2016 by 23 mm/year (Fig. 7), which was expected due to the expansion of urban areas in 2016 due to the decrease in actual evapotranspiration, which was less in 2016 than in 1995, and the increase in impervious areas. An average decrease of 44 mm/year was calculated for evapotranspiration. The bare soil land cover fraction typically showed high evaporation rates, decreased in area between 1995 and 2016. A significant portion of this land cover was converted to urban area in 2016 and therefore, actual evaporation in 2016 decreased. Moreover, forest and agricultural areas in 1995, which also had high actual evapotranspiration rates due to a large proportion of vegetation, were converted to urban areas, thus leading to less evapotranspiration and ultimately to an increase in recharge.

With a modest increase in surface runoff from 230 to 253 mm/year and a more substantial decrease in actual evapotranspiration from 521 to 477 mm/year, natural recharge rates increased from 127 to 148 mm/year between 1995 and 2016 (an increase of 21 mm/year, or 16.5%). This increase in recharge, combined with additional leakage from both on-site sanitation and water pipes, led to a total recharge of 148 mm/year in 1995 and 195 mm/year in 2016, representing a 31.8% increase.

## Preurban versus urban areas

Although an increase in groundwater recharge from 1995 to 2016 as a result of urbanization was observed (Fig. 7), preurban conditions were also considered to systematically assess the impact on groundwater recharge. As stated in section 'Methodology', natural conditions were unknown; therefore, two realistic scenarios were developed. In scenario 1 (S1) agricultural land was converted to coniferous forest and urban area was converted to shrubland and thicket. In

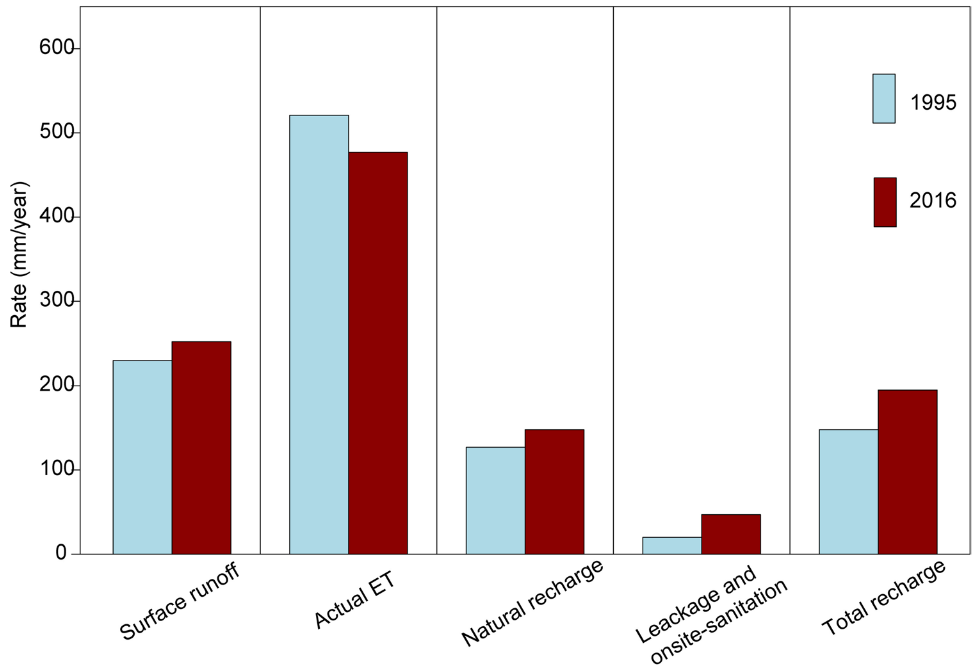



**Fig. 7** Average annual water balance components for the years 1995 and 2016

scenario 2 (S2) both agricultural land and urban area were converted to shrubland and thicket. The average values for the preurban conditions, in the case of both scenarios, were around 120 mm/year (Fig. 8). An increase from these preurban scenarios to 1995 and 2016 could be observed for both natural recharge from precipitation and total recharge, which included human-induced leakage rates. Although land use change (e.g. bare soils to urban areas) lead to an increase in recharge, the strongest impact on recharge rates was leakage from on-site sanitation and water pipes—for instance, recharge rates in S1 were 116 mm/year and increased to 148 mm/year for 2016 without leakage, which was an increase of 32 mm. When recharge from leakage was also considered, there was a difference of 79 mm and a total recharge of 195 mm/year, thus illustrating the critical role of leakage in recharge dynamics for urban areas.

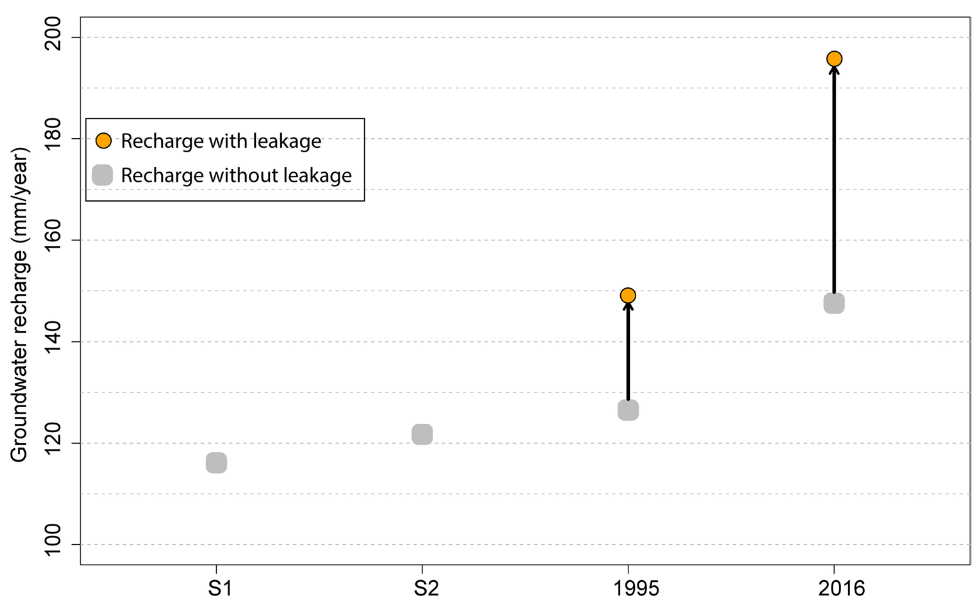



**Fig. 8** Annual groundwater recharge rates for Arusha for the two preurban scenarios (S1 and S2) and the years 1995 and 2016. The comparison of groundwater recharge from natural sources and recharge with the addition of leakage from urban leakage are shown for 1995 and 2016. Note that there is no leakage in the preurban scenarios

## Discussion

The land use/land cover analysis of 1995 and 2016 showed that the urban area expanded from 14 to 45% at the expense of forest, agricultural land, shrubland, thicket and bare soil. Similarly, there was a fast population growth, which resulted in an increase in water demand and wastewater disposal. The simulated recharge, combining natural recharge from precipitation and recharge from leakage and on-site sanitation indicated an increase due to urbanization.

The observed increase in recharge in 2016 can be primarily attributed to the transformation of a larger area of bare soil from 1995 to 2016. The bare soils typically had lower recharge rates compared to urban areas due to lower infiltration capacity relative to soils covered with vegetation due to a more compacted subsurface with reduced porosity (Zomlot et al. 2015). It is important to note that recharge does not occur on completely sealed surfaces in urban areas; however, urban areas are inherently heterogeneous, allowing for preferential infiltration in certain areas despite the presence of impervious surfaces.

In many urban areas, including Arusha, a significant portion still retains vegetation, unsealed surfaces and some infiltration capacity. Only roughly <40% of the urban area could be assumed to be completely impervious based on observations from satellite imagery and aerial photography. Additionally, the combination of pipe networks, sewer systems and the low effectiveness of these networks results in water losses. In the study area, leakage of wastewater and drinking water mains was estimated to be ~20–30%, a value that is consistent with previous studies (Alexander Saria 2015; Olarinoye et al. 2023). This loss directly contributed to groundwater recharge, aligning with findings from other studies (e.g., Attard et al. 2016; Held et al. 2006; Minnig et al. 2018; Nguyen et al. 2021) among many others).

Urbanization was observed to impact the entire water cycle, with impervious surfaces elevating surface runoff volumes (Rubinato et al. 2019); however, as also shown in this study, there was no direct evidence suggesting that the increased runoff necessarily was at the expense of recharge (Lerner 1997). The proliferation of impermeable surfaces, such as roads, buildings, and pavements in urban areas, reduced the capacity of the area to infiltrate rainfall into the subsurface. This caused a greater proportion of precipitation to be partitioned into surface runoff, which rapidly drained into stormwater systems and natural water bodies (Weatherl et al. 2021). This effect was certainly important for urban areas but also for the bare soil land cover class in the study area. It is speculated that bare soils were more susceptible to erosion and surface sealing, which reduced their capacity for water infiltration. In terms of soil characteristics, bare soils may have reduced the capacity to infiltrate water during strong rainfall events, leading to higher surface runoff. In Arusha, two rainfall seasons exist—the short rainfall season is from November to December, while the long rainfall season spans from March to May (Olarinoye et al. 2023). Thus, a large volume of precipitation is expected within these time periods leading to a larger amount of surface runoff relative to the remainder of the year, which could potentially lead to riverbank infiltration and groundwater/surface-water interaction (Cuthbert et al. 2016; MacDonald et al. 2021), possibly promoting groundwater recharge indirectly, but not necessarily within the city boundaries considered in this study. Overall, the transformation of natural landscapes into urban areas has led to an increase in groundwater recharge rates due to the leakage from mains water and leakage from on-site sanitation as well as the increase in surface runoff which have both compensated for the reduction of evapotranspiration.

The results of this study align with previous work that reported an increase in urban groundwater recharge as cities expand (Abdelaziz et al. 2020; Appleyard 1995; Locatelli et al. 2017; Minnig et al. 2018; Tubau et al. 2017; Wakode et al. 2018; Vázquez-Suñé et al. 2010; Howard 2023, among many others). However, it is important to note that the change in urban groundwater recharge varies spatially. In areas with impervious surfaces and compacted soil, recharge rates may have been low, whereas areas with leakage from mains water and on-site sanitation, or permeable surfaces could exhibit higher recharge rates (Sharp 2010).

Although WetSpass is a valuable and robust tool for simulating the complex processes involved in groundwater recharge, including infiltration, evapotranspiration, percolation, and subsurface flow across different land use and various geographical settings, it is important to acknowledge its limitations. The model relies on certain simplifications in process representation and uncertainties associated in the input data, which may affect the accuracy of model predictions.

The applied model was sensitive to inputs such as land use cover, leakage rate assumptions, and model parameters (Abdollahi et al. 2017; Armanuos and Negm 2016); therefore, the accuracy of these inputs was critical for reliable estimation of groundwater recharge, although the model typically performs well as shown in other studies (e.g. Batelaan and De Smedt 2001; César et al. 2014; Dams et al. 2007; Salem et al. 2023; Yenehun et al. 2022; Zomlot et al. 2015). The use of data with varying resolutions can influence WetSpass recharge estimates. Higher spatial resolution data could provide more detailed spatial information, which could result in more accurate model outputs, especially in terms of runoff distribution. In this study, data of varying resolutions were used due to data availability; however, it is acknowledged that using data of the same resolution could have improved the modeling results by reducing errors associated with data integration and interpolation. Although the data resolutions used in this study ranged between 30 m and 1 km, this was considered to be generally suitable for a data-scarce region. Additionally, WetSpass employs a lumped modeling approach and does not numerically solve, for example, the Richards' equation, meaning it is not fully physically based. In addition, input data was utilized from different time periods and with varying temporal resolutions, a necessity due to data availability that could introduce inconsistencies in the modeling results. Higher-resolution temporal data could provide more detailed information and potentially more accurate outputs; furthermore, the Land Use and Land Cover (LULC) data used in this study was obtained for the years 1995 and 2016 also due to data availability; however, a wider range of years could offer a more comprehensive understanding of land use changes over time. The limited temporal scope may overlook significant changes that occurred between or beyond these years. Although the model validation showed that the simulated recharge rates align well with other studies in the same area, it is acknowledged that direct calibration and validation of the model were not feasible with the data that were available, adding another layer of uncertainty. Future research should consider using uniform high-resolution data and a more extensive temporal range for LULC data, alongside developing methods for more rigorous calibration and validation of model outputs.

Despite the limitations of the model developed in this study and its inputs, the simulation results aligned well with the range of values reported in the literature for the area, providing a form of indirect validation. However, variations in groundwater recharge rates were anticipated due to the different methodologies used for estimating recharge and the inherent discrepancies between field experiments and modeling efforts, as noted by von Freyberg et al. (2015). Overall, despite the loss of forest and agricultural land due to the expansion of urban areas, the impact on groundwater recharge suggested a groundwater recharge surplus, which can potentially compensate for the increasing water demand in some cities. In Arusha, groundwater contributes ~80% of the water supply (Lugodisha et al. 2020). However, while recharge rates are simulated to increase within the considered area, the water demand appears to exceed recharge, which has led to continuous abstraction of groundwater from aquifers in Arusha, resulting in a decline in groundwater levels (Chacha et al. 2018). Additionally, it is important to note that groundwater quality may potentially decline due to urban growth, especially where some of the increased recharge is derived from onsite sanitation leakage.

## Conclusion

The ongoing global demographic trend of urban population growth has led to significant expansion of urban areas. In this context, this study delves into the profound impact of urbanization on groundwater recharge rates, employing a comprehensive land use and land cover analysis in Arusha, Tanzania, along with simulations of various water balance components using the WetSpass model. This study, as demonstrated in the city of Arusha, provides general insight into changes in groundwater recharge resulting from urbanization.

From 1995 to 2016, urban areas within the study area expanded from 14 to 45%. This rapid urbanization prompted the transformation of forested areas, agricultural land, shrublands, and bare soil into urban zones. It was found that during preurban conditions, recharge from precipitation was ~116 mm/year, increasing to an average of 148 mm/year by 2016. When additional recharge inputs from drinking water and sewer system leakage, total recharge reached 195 mm/year in 2016. These anthropogenic sources of groundwater recharge contributed to 14 and 24% of the total groundwater recharge in 1995 and 2016, respectively. Beyond these human-induced supplementary recharge mechanisms, reduced evapotranspiration resulting from land use changes further contributed to the recharge increase, even as surface runoff increased. Overall, increased urbanization has led to higher recharge rates in Arusha; however, urban areas are inherently heterogeneous, allowing for preferential infiltration in some locations despite the increased presence of impervious surfaces. The change in urban groundwater recharge varied spatially across the study area. In areas with impervious surfaces and compacted soil, recharge rates may have been low, whereas areas with leaks or permeable surfaces could exhibit higher recharge rates. Thus, this study also brings attention to the role of spatial variability, emphasizing the necessity for localized solutions and monitoring to address potential groundwater quantity and quality issues arising from urban growth.

While this research highlights opportunities for improved water management through increased recharge rates, it also underscores the need for sustainable water management. Although urbanization has led to higher recharge in Arusha, this is unlikely to fully compensate for the observed decline in groundwater levels.

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## Declarations

**Conflict of interest** None.



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