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Research article

Evaluation of climate change, urbanization, and low-impact development practices on urban flooding

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ABSTRACT

The Personal Computer Storm Water Management Model was used in this study to evaluate the potential impacts of climate change, urbanization, and low-impact developments (LIDs) on urban flooding in Robe town, Ethiopia. To achieve the objective, four scenarios were developed in order to simulate changes in peak runoff, inundated volume, and the performance of existing drainage systems. The findings revealed that as urbanization increased from 10% to 70%, the inundated volume of nodes and peak runoff increased from 35,418 to 52,118 $\times$ 10^3 m^3 and 89.4–111.96 m^3/s, respectively. Furthermore, the peak runoff in response to climate change is increased by 46.9%, 34.8%, and 37.5%, respectively, as a result of the Rossby Centre Regional Climate Model version 4 (RCA4), Regional Atmospheric Climate Model (RACMO22T), and the hydrostatic version of the regional model (REMO2009). Overall, the findings showed that existing drainage systems were unable to collect and convey the amplified inundation from different simulated scenarios, and the Welmel sub-city to roundabout was threatened by increased flooding, causing significant damage to properties and infrastructure. The implemented LIDs are capable of reducing the expected peak runoff, flooding magnitude, and flooded junctions in climate change and urbanization scenarios; however, combining both mitigation measures can further reduce the study area. The implementation of a mitigation strategy with adequate drainage systems will be required to mitigate the flooding risks in Robe town.

1. Introduction

In recent years, urban flooding has been identified as a natural disaster that can have a negative impact on the environment, particularly in urban areas around the world, while also threatening human property and life. The factors that caused urban flooding were rapid urban growth, variation in rainfall intensity due to climate change, and inadequately designed drainage systems [1–4]. Studies have also noted that the variation in rainfall intensity and urban development in cities affects urban catchment through flooding problems [5-7]. According to Zang et al. [8] and Wang et al. [9]; urban development activities that increase imperviousness have an impact on the urban hydrological process, which increases flood risk and reduces hydrologic response time. Urbanization reduces infiltration rates while increasing surface runoff and flooding volume [10]. The change of urban catchment from natural surface cover to impervious areas such as residential, commercial, road, and other paved areas increased runoff and flooding in towns/cities all over the world [11,12].

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Furthermore, previous studies used different global climate models (GCM) in different areas to investigate the impact of climate change on the efficiency of stormwater drainage systems. They concluded that the variation in intensity of rainfall caused by climate change is another challenge to increasing urban flooding risks [13,14]; Hassan et al., 2017; [15]. In addition, Balistrocchi and Grossi [16] and Kumar et al. [17] noted that the stormwater drainage system failed due to insufficient/overflowing capacity to accommodate the increased flooding volume caused by climate change.

Although urbanization and climate change may have an impact on the magnitude and frequency of floods, the extent of flooding affects the economy, livelihoods, and daily activities of the inhabitants are not similar in each factor as previously studied by researchers. For example, Hu et al. [18] studied how increased impervious surface area alters urban hydrological processes and causes flooding-related problems in urban areas due to insufficient drainage networks. Similarly, Weesakul et al. [19], Xiong et al. [20], and Padulano et al. [21] used different global climate models to evaluate the potential impacts of future extreme rainfalls on urban hydrological processes. According to their findings, stormwater management infrastructures are unable to accommodate the expected peak runoff, resulting in increased flooding hazards in urban catchments. Few studies, including Akter et al. [22], Gammoh and Shamseldin [23], and Takele [24]; found that stormwater management systems failed under a combined urbanization and climate change scenario, resulting in frequent inundation. The drainage system of developing countries' towns/cities is severely affected by flooding problems because it is based on historical conditions without a detailed analysis of future projected conditions.

As a result, flood recurrence times and associated property loss have increased in many cities around the world [25]. Earlier studies have shown that many Ethiopian cities such as Dodola [26], Robe [27], Dire Dawa [28], and Adama [29] are frequently flooded as a result of dynamic land-use change and a lack of adequate drainage systems. The infrastructures as well as daily socioeconomic activities in these cities are frequently impacted and cause community complaints. This problem was common in Robe town. The existing drainage systems were built without a detailed hydrological process that takes into account both urban development and climate change, which is required for any design of stormwater management systems. The main asphalt road frequently overflowed during the rainy season. Furthermore, the aesthetics of urban areas are spoiled by flood-related problems such as mud on the road and roadside, as well as solid waste disposal. The effects of the floods have disrupted people's daily activities and the town's economy, as well as damaged the homes of several inhabitants. As evidenced by the problems observed on August 3/2022, recent flooding issues have

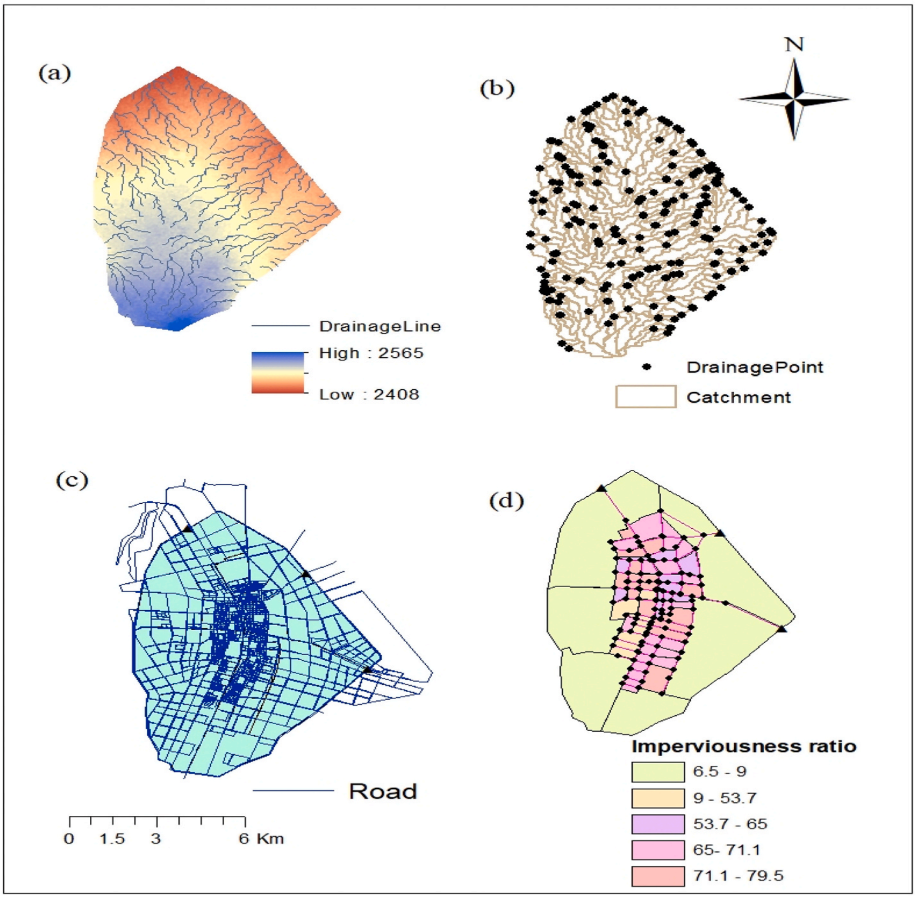

Fig. 1. Study area map (a) elevation and drainage line, (b) discretized sub-catchments based DEM and drainage point, (c) the further discretized and manually adjusted based on the road network, and (d) imperviousness ratio of sub-catchment based on the baseline condition.

caused traffic congestion. As a result, mitigation strategies are required to control increased flooding while preserving existing urban drainage infrastructures functional. As a result, mitigation strategies such as structural and non-structural strategies are useful techniques for mitigating flooding risks in urban areas. Low impact developments are one of the structure flood mitigating techniques used at the local and watershed scales [30-32]. Hence, an adaptation of selected flood reduction strategies in the inundated area of the town is important to alleviate the regularly observed problems, because it is simple, cost-effective, eco-friendly, and sustainable, as suggested by Goncalves et al. [33] and Sohn et al. [34]. The effects of urbanization and climate change on hydrological response and drainage system efficiency were evaluated using PCSWMM in order to design adequate management networks in Robe town, Ethiopia. As a result, the study's objectives were to (1) quantify the effect of climate change of three RCMs (RACMO22T, RCA4, and REMO2009) on urban flooding, (2) evaluate the potential impacts of urbanization on urban hydrological processes by increasing the urbanization rate by 10%–70%, and (3) assess the benefits of LIDs in alleviating the amplified urban flooding.

2. Materials and methods

2.1. Study area

Robe town is situated in southeastern Ethiopia, in the Oromia regional state (Fig.1). The town covers longitudes from $39^0 56'00''$ E to $40^0 6'40''$ E and latitudes from $7^0 5'20''$ N to $7^0 10'40''$ N. It is located in the Welmal catchment in the upper Genale Dawa River watershed. The maximum elevation of the study area is 2565 m above mean sea level and its vicinity is estimated at 6680 ha. The surface runoff generated from this study area flows into the Shaya River used for drinking purposes for the downstream community of Bale zone, near Robe town. The mean annual maximum and minimum rainfall values of the study area are 651 mm and 1309 mm respectively, according to analyzed from the observed rainfall data (1989–2020) of Robe station.

2.2. Data sources and properties

In the present study, both temporal and spatial data used were obtained from a variety of sources, including government organizations and websites. In this study, two daily rainfall datasets were used for peak runoff and flooding volume simulation: historically recorded rainfall data and future year projected rainfall data. Thirty years of daily recorded rainfall data (1980–2020) were obtained from the National Meteorological Agency of Ethiopia. However, after signing up for the CORDEX research, fine resolution ($0.44^\circ \times 0.44^\circ$) future projected rainfall data of the global climate models: EC-EARTH, MPI-ES-LR, CanESM2, HadGEM2-ES, and CNRM-CM5 were downloaded [35,36]. The daily rainfall data from each GCM was downscaled for the study area using the RACMO22T, REMO2009, RCA4, and RACMO22T RCMs for the Representative Concentration Pathway of RCP 4.5 and RCP 8.5.

Different spatial data are used: digital elevation model (DEM); satellite images; master plan data, and soil map dataset. To delineate the town and determine the weighted slope for each divided sub-catchment, an ALOS PALSAR 12.5 m spatial resolution downloaded

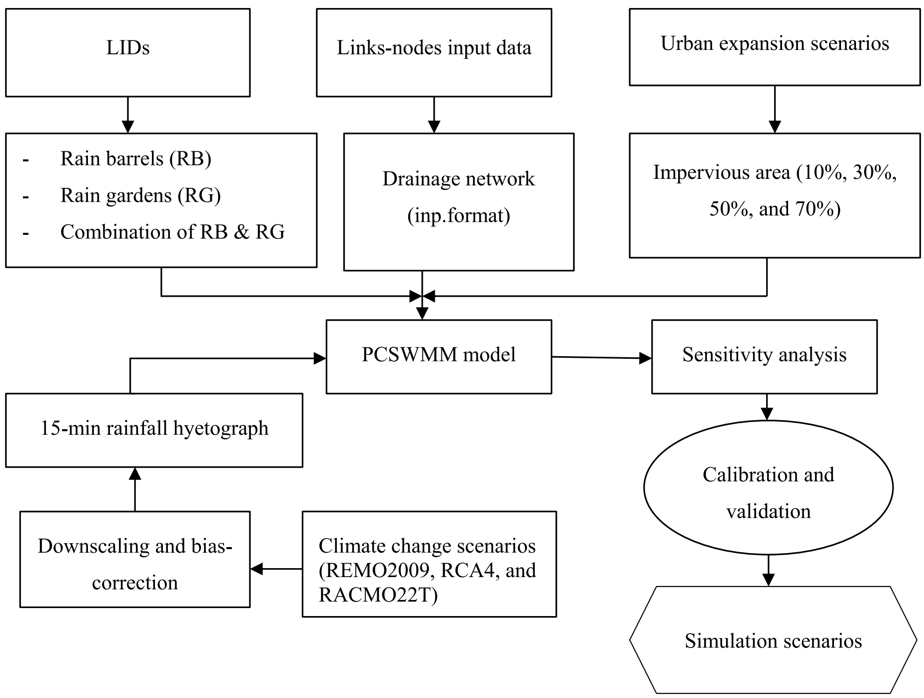

Fig. 2. Schematic representation of the simulation procedures.

from the Alaska Satellite Facility was used. In this study, researchers have taken masterplan data in CAD format from the municipal city office of Robe town and used its planned land-use, road layout, and drainage network. In addition, soil shapefile data obtained from the Ministry of Water and Energy was extracted and projected for the study area in Arc GIS using geographic and projected coordinate systems (WGS 1984 UTM Zone 37°N).

2.3. Methodology

The study methods could be divided into four main stages: estimation of model parameters, sensitivity analysis, hydrological processes analysis as a response to urbanization as well as under climate change scenarios, and evaluation of various LIDs in the PCSWMM model under different urbanization and rain storms. Fig. 2 shows the flow chart of the overall methods in this study. First, the adequacy of drainage systems was evaluated based on the current situation of Robe town, using 2020 land-use and the estimated design storms from observed rainfall data (1990–2019). Then, the peak stormwater and flooding volume were simulated based on urbanization and climate change. Finally, the selected LIDs were implemented to evaluate the reduced percentage of urban flooding.

2.3.1. Rainfall intensity analysis

The relationship between rainfall intensity, duration, and frequency (IDF) is one of the most widely used tools for hydrological applications, specifically in flood management systems studies according to the suggestion of Bezak et al. [37] and Gebreigziabher [38]. The PCSWMM model requires short-duration design rainfall intensity to simulate urban flooding under historical and future periods due to climate change. A short-term design storm is required to assess the effects of extreme precipitation on urban flooding. However, rainfall is measured daily at many rainfall stations, particularly in developing countries such as Ethiopia, and shorter-duration data are not available due to instrument limitations. Due to both observed and projected rainfall were limited to a daily time resolution, estimating short-term rainfall from daily data is difficult. Several researchers developed different equations for different regions of the world to overcome these challenges, such as the Ethiopian Road Authority (ERA) method, Modified Indian Meteorological Department (MCIMD), and Indian Meteorological Department (IMD) equation [39–41]. An IMD equation was previously developed for the Indian rainfall pattern, but it is suggested by Galoie et al. [40] and Nwaogazie et al. [41] as simple and widely used in other parts of the world. As a result, the IMD equation (Eq. (1)) was used to estimate hourly and sub-hourly rainfall from maximum daily rainfall data.

$$P_{td} = P_{24}\, x \sqrt[3]{\frac{td}{24}} \tag{1}$$

where: P24 is the maximum annual daily rainfall (mm), P_{td} is the rainfall depth for the duration of td-hour (mm), and td is the time duration (in hrs) for the required rainfall value.

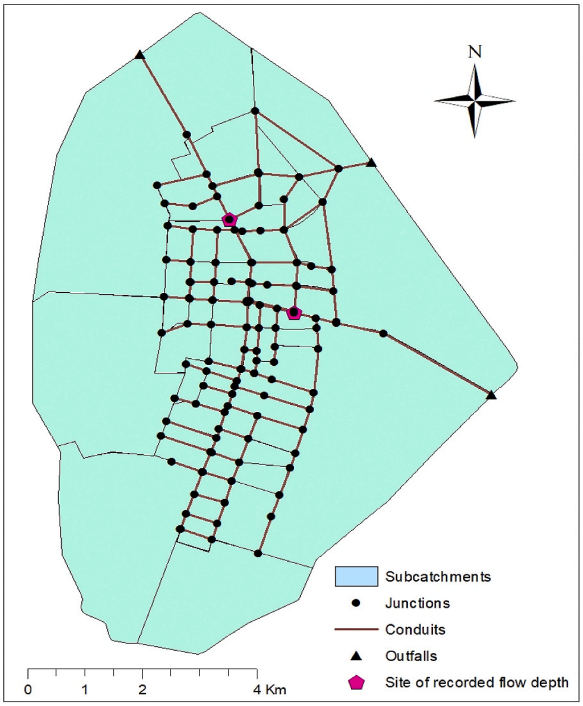

Fig. 3. The layout of the stormwater drainage systems shows the nodes, links, and site of observed runoff depth.

Table 1
The inputted parameters of the PCSWMM model.

Type	PCSWMM parameters	Datasets
Sub-catchment	Area, width, average slope	12.5 m × 15.5 m resolution DEM
	Percentage of impervious, depression storage, and roughness coefficient for pervious and impervious surfaces	Landuse data
	Green-Ampt parameters	Soil data
Junction	Spatial location, Invert elevation, max. depth	Field measurements
Conduit	Inlet and outlet node, length, shape	Field survey
Outfall	Spatial location, invert elevation	Planned stormwater drainage network
LIDs control	Parameters for a rain barrel and rain garden	From literature

To estimate the required quantiles and intensity of rainfall at the T-year return period, different probability distribution methods were first compared using statistical goodness-of-fit tests such as Kolmogorov-Smirnov, Anderson-Darling, and Chi-Square [42,43]. The Generalized Pareto is the best-fitted distribution method for Robe's rainfall data and is used to calculate T-year rainfall depth (PT), which is the return period shown in Eq. (2). The rainfall intensity (in mm/hr) for different time durations (td) is calculated using P_T/t_d.

$$P_T = \xi + \frac{\alpha}{k}\left[(\lambda T)^{-K}\right] \tag{2}$$

where: ξ, α, and k are the location, scale, and shape parameters of the Generalized Pareto distribution.

2.3.2. PCSWMM setup

The PCSWMM model was used to evaluate the effects of urbanization, climate change, and low-impact development techniques on urban flooding. This model was selected to simulate urban flooding in this study because it is a dynamic hydrologic-hydraulic model that can simulate peak runoff and flooding volume in response to different future scenarios. Furthermore, the PCSWMM can select sensitive parameters, calibrate, and validate itself using a sensitivity-based radio tuning calibration (SRTC) tool, and it is also suitable for urban catchments with an area of less than 10,000 ha [27,44,45].

Based on the topography and road layout, the study area could be discretized into 53 sub-catchments, as shown in Figs. 1 and 3. Sub-catchments were first delineated based on the DEM using the Arc-Hydro tool in ArcMap 10.3, by creating a depression-less DEM (filling analysis), defining the flow direction, calculating the flow accumulation, and then creating the outfall of the drainage lines (Fig. 1a and b). According to Kong et al. [46] and Li et al. [47]; the sub-catchment was further subdivided in accordance with the master plan and then manually adjusted based on on-site observations of runoff flow direction after consulting with the local community (Fig. 1c). The surface runoff from each sub-catchment drained through the drainage system which consists of 118 junctions, 120 conduits, and 3 outfalls (Fig. 1d).

The dynamic flood routing method was chosen from three types of hydraulic routing methods in this study because it is best suitable for large drainage networks and accounts for the theory of unsteady flow in an open channel. One of the earliest physical infiltration models developed (the Green-Ampt equation) was used to predict the infiltration rate because it is based on Darcy's Law and requires homogeneous characteristics of the town's soil types.

2.3.3. Determination of model parameters

The model required various input parameters for hydrology (sub-catchments, rain gages, and LID controls) and hydraulics (nodes and links) [44,45]. The required inputted parameters for sub-catchments, such as area, width, and slope, were estimated using DEM; however, other parameters, such as percentage of imperviousness, depression storage, and the Manning coefficient for impervious and

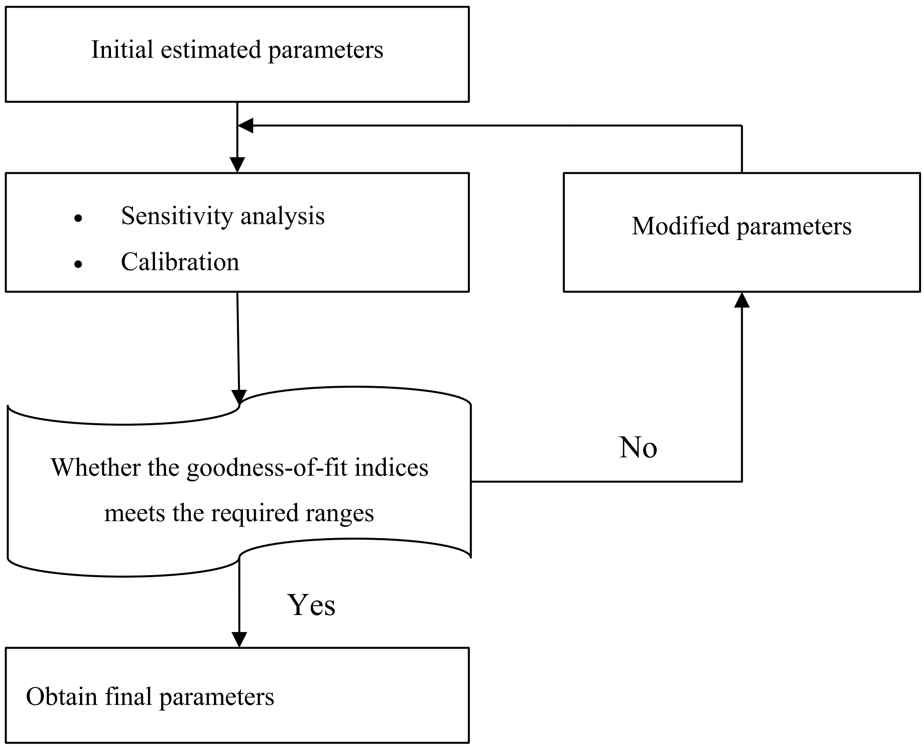

Fig. 4. Schematic illustration of calibration process using SRTC in PCSWMM.

pervious surface, were estimated using land-use data [48]. The Green-Ampt infiltration parameters (suction head of the soil, hydraulic conductivity, and initial moisture deficit) are another sub-catchment inputted parameters that were calculated based on extracted soil types, as presented in Table 1 [49]. Design storms of selected return periods estimated from IDF curves and separately entered into the PCSWMM model [50].

Based on the existing drainage systems, a field investigation was conducted to collect node properties such as X and Y coordinates, invert elevation of nodes, as well as link properties such as inlet and outlet junction of conduit, maximum depth, and length of the conduit. According to Lee et al. [51], the drainage network data were converted into a shapefile using Arc GIS 10.3 and then imported into PCSWMM. The LIDs control parameters, such as barrel height for rain barrels and berm height, vegetation volume fraction, surface roughness, and surface slope for rain gardens, were derived from the literature and PCSWMM manual [52-54].

2.3.4. Calibration and validation

The influence of the input parameters on the model output is evaluated using sensitivity analysis. This was accomplished by varying parameter input values to determine the weight effects of various model parameters on model outputs [55]. The model was run with the initial parameter values, and then the sensitive parameter values were systematically adjusted between their ranges using the sensitivity-based Radio Tuning Calibration (SRTC) tool [56]. The Morris Sieve method was used to change the initial value of one parameter at a time, while the other parameters remained constant [57]. After the uncertainty values of model parameters were assigned, the values of observed and simulated were compared on the graph, and model performance was evaluated using the root mean square error to standard deviation ratio (RSR), Nash-Sutcliffe efficiency (NSE), and the Coefficient of determination (R^2) [55]. As several studies have suggested, it is difficult to get sufficient data in Ethiopian cities to perform robust calibration. However, many earlier studies manually and automatically tested stormwater models using short-term observed data. In this study, we followed the suggestions of Yim et al. [58,59], Perin et al. [60], and Takele [24]. As a result, from the 10th of June to the 15th of September 2021, the researchers collected runoff depth in the conduit along with the corresponding rainfall events at the field. As shown in Fig. 3, runoff depth was measured every 5 min at two stations near the outfall1 (X: 610,474, Y: 788,610) and outfall2 (X: 611,589, Y: 786,817).

Fig.4 shows the calibration and validation process. The initial parameter values in this study were estimated from various spatial data and assumed from recommended literature. The SRTC tool calibrated the final values of each parameter based on the fixed range.

2.3.5. Design of simulation scenarios

Four different simulation scenarios (Table 2) were developed in this study to evaluate the potential impacts of separate and combined climate change and urban growth on stormwater drainage systems in managing inundation. The simulation scenarios were: S1, the baseline scenario (current condition); S2, the urbanization scenario; S3, a 2020 land-use with climate change; and S4, an implementation of LIDs in alleviating flooding. These scenarios were investigated according to the urban development, the future rainfall pattern, and the constructed stormwater management systems (see Table 3).

1) Baseline scenario (S1)

S1 represents the current land-use and observed rainfall conditions. The existing land-use in 2020 was analyzed, and the impervious ratio was estimated and inputted directly into the model as an input parameter. In this scenario, the design storm was estimated using the Chicago method from developed IDF curves of observed rainfall data. The existing drainage systems that followed the main asphalt were designed in 2013 to provide a function for 15 years, without taking future period rainfall conditions or different return periods extreme rainfall into account.

2) Urbanization scenario (S2)

Due to urbanization, the percentage of impervious surface cover in each sub-catchment is changing over time. According to Robe town's actual land use in 2020, the weighted impervious surface cover from all sub-catchments is 68.5%, which contributes to runoff. This imperviousness, however, is changing over time as the study area's urban development changes. The study area is facing urban expansion, which includes the conversion of pervious surface area into residential areas, commercial centers, and other paved surfaces. As a result, an increase in urban flooding and a decrease in infiltration rate beyond urban growth will be expected to occur over time, but the rate is not exactly specified because urbanization takes place in irregular forms. In Scenario 2 (S2), the effects of urban development on the hydrological responses were investigated using four urbanization (U1–U4) cases increasing the imperviousness of

Table 2
Simulation scenarios developed in this study.

Types of scenarios	Case	Description	Land-use data	Rainfall data
S1	Past scenario	Baseline scenarios	2020	Observed from NMAE (1989–2020)
S2	U1–U4	Varied urbanization (10%–70%)	2020	1989–2020
S3	C1–C3	Varied climate scenario (REMO2009, RCA4, and RACMO22T)	2020	Projected rainfall from climate models
S4	L1	Rain barrels only		
	L2	Rain gardens only	2020	
	L3	Both LID		

Table 3
PCSWMM parameters, Min-max ranges, and calibrated value.

S.No	Parameter (units)	Ranges	Sources	Calibrated value
1	Imperv (%)	16.4–84.6	Estimated from land-use data, Bedan and Clausen [72]	25% Imp
2	Width (m)	65.9–699.2	Calculated by Area/longest flow path	60% Initial value
3	Slope (%)	3.7–11.2	Calculated from DEM	30% Initial value
4	N-Impervious surface area	0.01–0.033	McCuen et al. [73] and Bedan and Clausen [72]	50% Initial value
5	N-Pervious surface area	0.24–0.8	McCuen et al. [73] and Rossman [52]	65% Initial value
6	D_{Store}-Impervious surface area (mm)	1.27–2.54	ASCE [74] and Bedan and Clausen [72]	1.35
7	D_{Store}-Pervious surface area (mm)	2.54–7.62	ASCE [74] and Bedan and Clausen [72]	3.8
8	Suction head	240.03	Rawls et al. [75]	Initial value
9	K	0.508	Rawls et al. [75]	$K_{Initial}$

sub-catchments by 10%, 30%, 50%, and 70% at constant rainfall intensity (historical IDF).

3) Climate change scenario (S3)

Climate change-induced variations in design rainfall may render stormwater infrastructures designed to collect peak runoff insufficient. According to Hou et al. [61], a slight change in storm design can result in severe flooding and stress on stormwater management systems. The outputs of REMO2009, RCA4, and RACMO22T (cases C1 to C3) were used to develop IDF curves for mid-future periods (2020–2050) after five RCMs were compared using the availability of future period rainfall data and model output validity [15]. Furthermore, statistical fit tests such as percentage of bias, coefficient of variation, and root mean squared error were used to evaluate the model outputs. However, when compared to observed data, the projected rainfall data contain significant biases, Climate Model for Hydrologic Modelling tool was used to downscale and bias-correct the RCMs rainfall data [62,63]. As a result, in scenario 3 (S3), a design storm estimated from observed and projected rainfall was inputted into the model to compare simulation results under climate change to baseline conditions [64].

4) Urbanization and climate change with LIDs scenario (S4)

The urban catchment has been severely impacted by urbanization and climate change, but implementing LID practices can effectively reduce the risk of flooding. LIDs were then implemented in the most flooded sub-catchment to reduce flood volume and decrease the number of flooded nodes [65,66]. As a result, after knowing the flooding quantity and the location of flooding nodes, from widely available LIDs, only rain gardens, rain barrels, and a combination of both mitigation techniques (in scenario 4) were used in this study because of their simplicity and efficiency. The simulation results with and without LIDs were compared under urbanization and climate change scenarios to calculate the percentage reduction in the magnitude of flooding by mitigating techniques [67]. A field survey was conducted in order to select their applicability. Rain barrels were placed in densely populated residential areas such as near Welmal Sub-city, around roundabouts, near Siko Mando International Hotel, and near Madda Walabu University based on land space and suitability. Residential areas, open spaces between buildings, and condominium areas, on the other hand, were found to be suitable for rain gardens. In sub-catchments prone to flooding, it was proposed that 16.4 ha, 17.8 ha, and 20.2 ha of land be used for rain barrels, green gardens, and combined LIDs, respectively.

3. Results

3.1. Sensitivity analysis, calibration, and validation

A sensitivity analysis was performed after assigning the user-defined uncertainty values (or ranks) to check the extent to which varying parameters were influencing the model and its results. In this study, the most sensitive parameters were screened and systematically adjusted by changing the values of one inputted parameter at a time and then estimating the values of goodness-of-fit statistics: NSE, RSR, and R^2. However, all insensitive parameters were left at their initial values. The adjustment process is completed when the difference between measured and simulated results is closely matched and the model efficiency is within acceptable ranges.

At the last iteration, the results showed that the N-Imperv and D_{Store}-Imperv were very sensitive to peak runoff. This result correlated with the conclusions of many other studies that have always found that variations in imperviousness and N have always had the greatest effect on the PCSWMM outputs. Khodashenas and Tajbakhsh [68] conducted in their study of East Eghbal, Iran, found that the impervious area, manning's roughness coefficient, and width of sub-catchment to be most sensitive that affected peak runoff from the SWMM simulation. Moreover, Luan et al. [30] studied in low-lying urban areas of China and their study showed that the increased impervious ratio by 30% had the greatest influence on peak flow, similar to this study result. When the estimated slope and width from the DEM by GIS were varied by 25% and 50%, and the goodness-fit test values were within acceptable ranges, as highlighted in previous studies by Ahiablame and Shakya [65] and Akhter and Hewa [44,45]. These parameters positively affected the results of the model. According to previous studies Niazi et al. [55] and Neupane et al. [69], PCSWMM achieved acceptance accuracy for flooding simulation in the study area due to NSE $>$ 0.5, PSR $\leq$ 0.7, and R2 $>$ 0.5 for both calibration and validation. Furthermore, Yim et al. [58, 59] noted that PCSWMM is a useful tool for evaluating the hydrological and hydraulic performance of the sewer system with different rainfall design storms in Phnom Penh, Cambodia [70]. In support of this, Takele et al. [27] concluded that the PCSWMM was capable of assessing the impacts of urbanization and climate changes on hydrological responses and stormwater management system performance in Robe town, Ethiopia. Similarly, the findings of Azawi and Sachit [71] study confirmed that PCSWMM is capable of investigating the effectiveness of LIDs in Baghdad.

3.2. Comparison of the peak stormwater under four scenarios

The PCSWMM simulated the hydrological responses in the study area under the separate and combined effects of land-use and climate change on peak flow and flooding magnitudes. The simulated results revealed significant differences among the four examined scenarios.

The peak runoff and runoff coefficients in scenario S1 were 41.6 m^3/s and 0.657, respectively, and the majority of the rainfall (54.7%) infiltrated directly to the surface. However, if the town's urbanization were to change (S2), the hydrological responses would be drastically altered. Peak stormwater increased from 45.13 to 111.96 m^3/s when the impervious ratio of sub-catchments was increased from 10% to 70%. Peak stormwater occurred at 1.35, 2.15, 2.45, and 2.85 h simulation time earlier than in the baseline simulation scenario for 10%, 30%, 50%, and 70% Urbanization, respectively. This meant that a reduction in the pervious surface due to urbanization would result in an increase in imperviousness and a sharp decline in infiltration rate, thereby dramatically increasing the peak runoff, runoff coefficient, and peak runoff time when compared to S1. The findings show that with climate change, severe floods will be expected by heavy rainfall, and the frequency of study area floods will become flashier, which means that their magnitude will be amplified in a shorter time. Furthermore, because the expected extreme rainfall varies, the magnitude of the simulation results will not be the same for all rainfall duration and return periods. Changes in the intensity and frequency of design rainfall caused by climate change have the greatest impact on peak stormwater and flooding risks. For example, the simulation results under S3 show that future projected extreme events in the near future increased peak flow by 34.8%, 37.5%, and 46.9%, respectively, over the baseline scenario (S1) in RACMO22T, REMO2009, and RCA4 (Fig. 5). The design storm and simulation results, such as peak flow and volume of flooding, are high in RCA4 because the projected rainfall data in this model is higher than in RACMO22T and REMO2009.

Peak runoff and runoff coefficient results show increasing trends in all simulated scenarios, which can result in flooding. The implemented LID techniques (S4) can reduce these higher results; however, the effectiveness of LIDs varies greatly, as shown in Fig. 6. In comparison to without LIDs, a rain garden and a rain barrel can reduce stormwater by 26.5%–32.8% and 17.6%–36.8%, respectively. However, both LID practices (rain garden and rain barrel) can reduce peak runoff even further. The implemented LIDs can be reduced the total flooding by up to 43.6%. Besides, when the effectiveness of LIDs has been evaluated under urbanization scenarios of 10%, 30%, 50%, and 70%, the adopted LIDs reduced peak stormwater by 14.6–26.5%, 19.5–31.2%, 21.6–32.8%, and 24.13–35.4%, respectively. This finding indicated that mitigation techniques can reduce the expected runoff in the town; however, adequate drainage systems with LIDs can manage the future scenario runoff that causes urban flooding.

3.3. Comparison of urban flooding under four scenarios

The effects of urbanization on the stormwater drainage system in Robe town were investigated using PCSWMM by increasing the urbanization area by 10%–70%, and the results are shown in Table 4. According to simulations under climate change scenarios, the

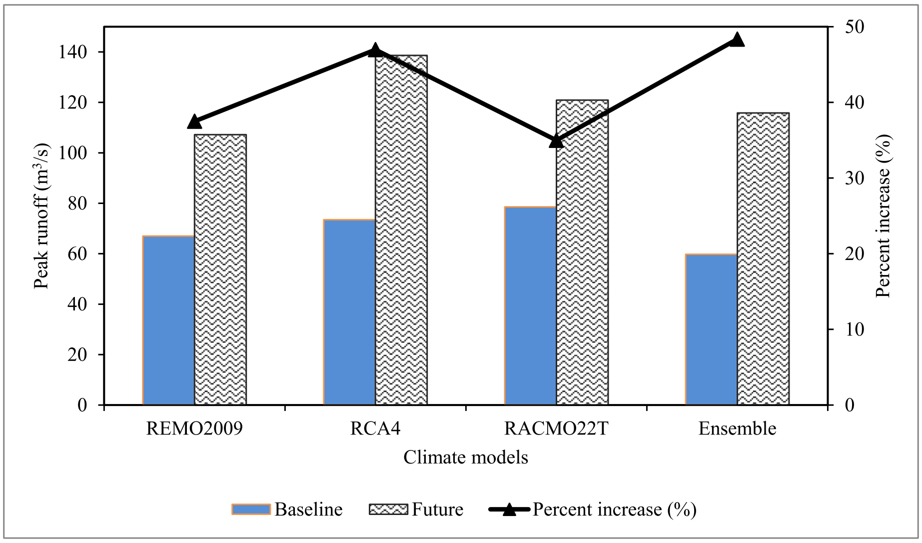

Fig. 5. Comparison of peak runoff during climate change scenarios.

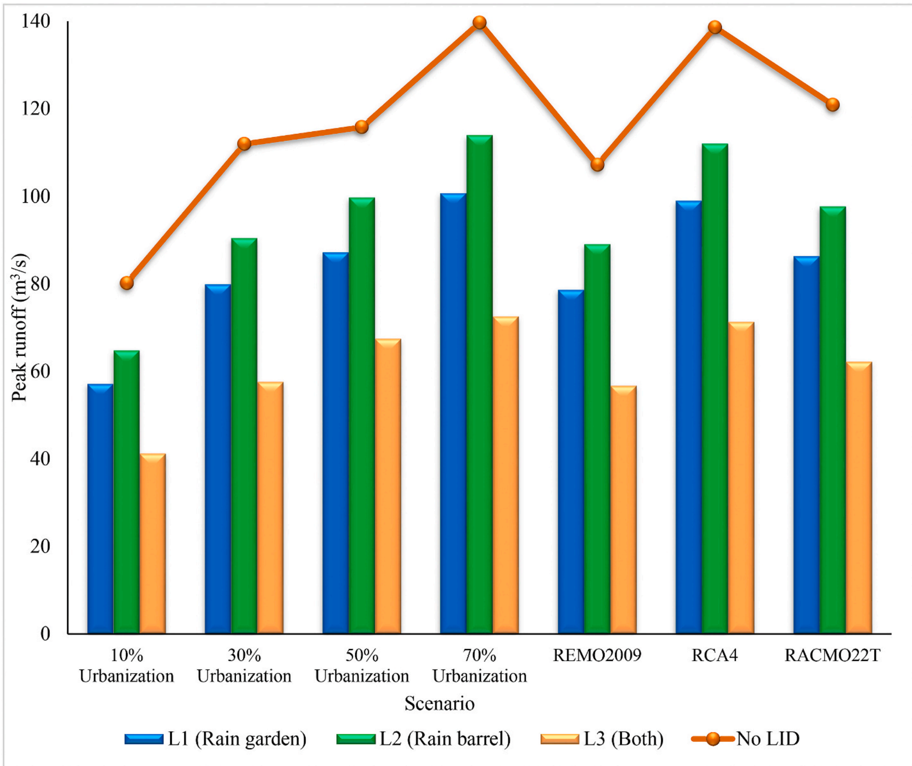

Fig. 6. Comparison of peak runoff with and without implementation of LIDs scenarios.

flooding volume increased approximately from 26,014 × 10^6 L to 44,385 × 10^6 L due to RCA4, but the response differs for the other two climate models. The IPCC report and earlier study findings support this result, as different climate models' projected rainfall events can result in different simulation results [76,77]. This finding indicated that existing drainage systems were inadequate under climate change scenarios. The effects of climate change are greater in this study than the effects of urbanization, but the combined impact of urban growth and climate change has the greatest impact on urban flooding than any other separate scenario. According to the climate change scenarios REMO2009, RCA4, and RACMO22T, 51 (43.2%), 73 (61.8%), and 56 (47.5%) of total junctions were flooded, respectively.

Furthermore, ensemble climate model simulation results revealed that 74.4% of total junctions flooded. This study found that Robe Town's drainage systems, which were designed based on historical rainfall intensity-duration-frequency relationships, are no longer valid under climate change conditions, increasing flood severity and risks in the town. Hou et al. [61] previously assessed the effects of climate for two time periods (the 2030s and 2070s) by comparing the baseline period (1976–2005) in Beijing, China. According to their findings, the number of inundated nodes and volume of inundation is expected to increase by 19.3%–44.8% and 171%–716%, respectively, in future periods due to 20-year rainfall events caused by climate change. This demonstrates how changes in rainfall patterns caused by climate change can affect urban hydrological processes, resulting in sewer flooding. Similarly, Huong and Pathirana [5] used SWMM to study the effects of climate change and urbanization on urban flooding in Can Tho, Vietnam and noted that understanding the impacts of these factors on urban flooding is necessary to reduce the risks to humans and society.

The model response to rapid urbanization also indicated a 47.15% increase in total flooding as urbanization increased from 10% to 70%. The total volume of the system in the current condition, scenario S1, is 280,716 × 10^6 L, the maximum flooded junction volume is 73.4 × 10^6 L, and the number of flooded junctions is 6 (Table 4). In comparison to the baseline scenario, urbanization increased total

Table 4
The effects of urbanization on the drainage system.

Percentage of impervious	The total volume (×10^6 L)	Maximum node inundated volume (×10^6 L)	Total inundation volume (×10^6 L)	Number of flooded manholes
Baseline Scenario	280,716	73.4 (J81)[a]	26,014	6
10%	341,087	86.3 (J81)[a]	35,418	28
30%	451,842	104.6 (J81)[a]	41,872	63
50%	516,876	198.2 (J81)[a]	43,371	74
70%	584,513	214.6 (J81)[a]	52,118	89

[a] Junction name.

flooding from 35,418 to 52,118 × 10^6 Ltr, representing an increase in flooded junctions of 23.7%, 53.4%, 62.7%, and 75.4%, and the time of peak flow shifted earlier by 1.35, 2.15, 2.45, and 2.85 h for U1, U2, U3, and U4, respectively. These findings confirm that the loss of pervious surfaces due to urbanization will most likely have an impact on flow characteristics in drainage networks, increasing the risk of urban flooding. Furthermore, the PCSWMM is used to identify the types of flooding based on the node flooding rate. Fig. 7(a) and (b) indicate flooding locations in town, the number of flooded junctions, and the type of flooding with impervious areas of 10 and 70%, respectively.

Many areas in the town were inundated; for example, the flooded area near the town's roundabout is depicted in Fig. 8 as evidence. Hu et al. [18] found that urbanization increased surface runoff and inundation risks in Beijing's central area, which is similar to this study. This flooding problem has serious social consequences for communities and residents, including property damage, loss of life, and economic disruptions. However, to mitigate the risks of urban flooding, the effectiveness of LIDs (S4) in urban flooding reduction was simulated. When the rain barrel was considered, the flooding volume of scenarios S2 and S3 decreased by up to 35.4% and 43.6%, respectively, when compared to S1. According to simulation results with 10% and 70% imperviousness ratios, flooded junctions in S3 decreased by 41.4% and 16.5%, respectively. As a result, simulation results show that LID techniques will significantly reduce the risk of flooding. LIDs, on the other hand, may be less effective at reducing flooding and peak runoff time during combined scenarios (urbanization and climate change).

4. Discussions

Flooding has become more severe in most parts of the world as a result of rapid urbanization and increased rainfall intensity caused by climate change. The robe is one of the Ethiopian towns most prone to flooding. Understanding the effects of urbanization and rainfall pattern change, as well as implementing effective mitigation techniques at a local scale, is essential for managing the significantly increased urban flooding. The present study considered different scenarios to evaluate the urban development, climate change, and LIDs on urban flooding. In this study, the four cases of urbanization were considered by increasing the percentage of current imperviousness in the future urban growth condition by 10%, 30%, 50%, and 70%, respectively, due to the rapid unplanned urban expansion that takes place in the Robe town. Furthermore, climate change can affect IDF relationships and cause floods; thus, the effects of three RCMs on existing drainage infrastructures are evaluated in this study.

With urbanization, increased flooding volume is to be expected in the future. According to the results, a 10% increase in the impervious surface from the town's current land-use condition will result in a 17.6% increase in flooding volume. In contrast, the assumption of 70% future urbanization from baseline resulted in the highest peak flow (111.96 m^3/s), flooding volume (214.6 × 10^6 L), an increase of 75.4% of flooded junctions, and a very early peak time at the system's junctions and outfalls. These findings were confirmed because many areas in the study area were inundated (especially the Welmal sub-city to Robe Square's main asphalt, which has been observed to have heavy flooding problems). The most frequently flooded junction is J22, which is located near the town's roundabout and is immensely inundated before 1:30 h of the simulation period. Similarly, in order to demonstrate the effects of urbanization on urban flooding, Shanableh et al. [78] revealed that rapid urbanization has flooded 60% of total junctions in the last ten years. Likewise, Kong et al. [46] used SWMM to evaluate the impact of urbanization on stormwater drainage systems and found that urbanization increased peak runoff by 31.7% and shifted peak runoff time by 35 min. As noted by Hassan et al. [1], when 91% of the total area of New Cairo is covered by impervious surfaces, the values of surface runoff are amplified by 135% in 30 years. The trend of

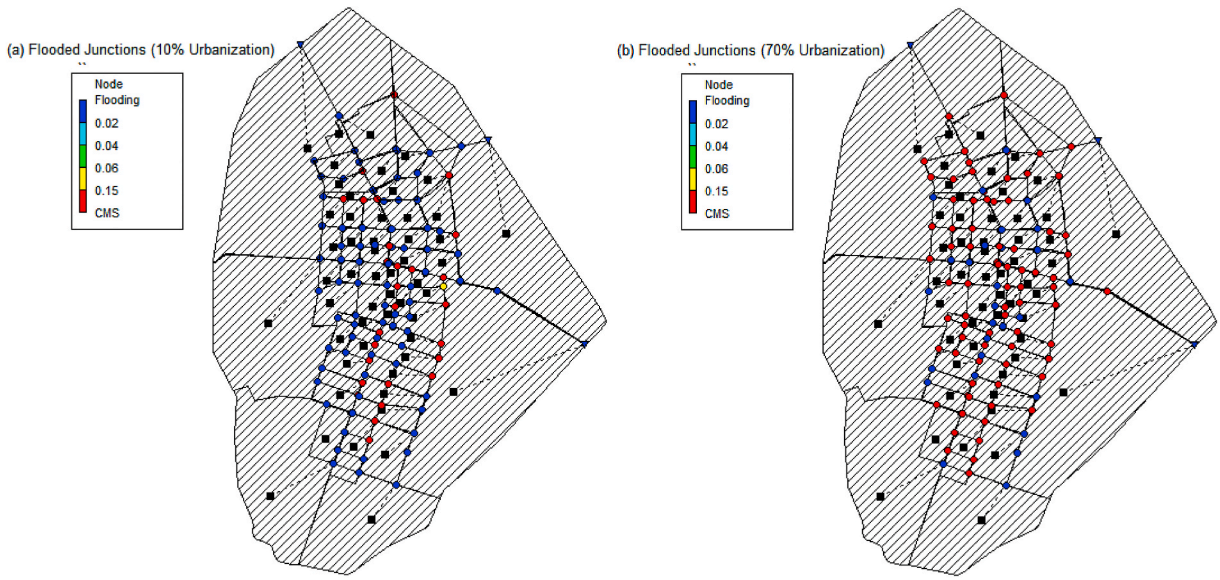

Fig. 7. The expected nodes inundation under (a) 10% urbanization, (b) 70% Urbanization.

Fig. 8. The inundated near Robe town square (*Source:* photo captured by researchers on July 31 and August 3, 2022).

flooding volume and infiltration rate is expected to increase and decrease in all four urbanization cases, which is consistent with the findings of Marhaento et al. [79] and Takele [24]. The urban growth was caused by major land-use changes (residential and public facilities), and these land-use changes increased flooding volume, which was too much for the existing drainage systems, resulting in flooding in the urban center. This was caused by existing drainage systems that were designed without considering future urban growth. Even in the baseline scenario, the simulation results showed that the area near the roundabout is frequently affected by inundation: transportation is disrupted for hours, and the daily activities of the communities are also impacted.

Climate change is expected to affect urban hydrological processes and one result is that peak stormwater and flooding volume is widely expected to increase through the 21st century [2,3,80–82]. Climate change scenarios show that in the near-future period, stormwater management systems in the built environment will be insufficient to meet performance expectations under climatic conditions that differ from historical data. Similarly, Zahmatkesh et al. [83], Rosenberger et al. [84], and Takele [24] simulated the effects of climate change and found that as rainfall intensity increased, drainage networks failed. This worsens urban flooding and increases flooded junctions in selected RCMs when compared to the baseline condition (1990–2020), which is consistent with Takele [24] previous study. According to the simulation results in RCA4, RACMO22T, and REMO2009, 62.7%, 48.1%, and 43.7% of the systems are flooded, indicating that the systems cannot accommodate the expected runoff due to climate change. Similarly, Mohammed et al. [82] quantified the effects of climate change on the sanitary sewage system in Samawah, Iraq using SWMM and found that extreme floods are likely in the future period. As a result, in the case of climate change, stormwater management systems failed to convey peak runoff that exceeded the design capacity. Changes in the frequency and intensity of rainfall events may affect the magnitude and frequency of urban flooding, as reported by Hassan et al. [95] and Hossain et al. [85]; the volume of flooding increased by 47% due to climate change.

To manage the flooding problem in a specific area, the simulation results of PCSWMM were used to identify the locations and types of flooding in junctions under different scenarios based on the nodes' flooding. When the imperviousness was increased by 10%, 28 (23.73% of a total of 118) junctions were flooded. According to Hassan et al. Hassan et al. (2017), under a 10% urbanization simulation, 19.2%, 28.9%, 32.6%, and 19.3% of nodes were inundated as very light-flooded, medium-flooded, highly flooded, and very highly flooded, respectively. In comparison to the baseline, climate change is expected to flood from 23.5% to 74.4% of total junctions. Overall, the simulation findings revealed that the existing drainage network cannot safely carry the expected peak flow as a result of urbanization and climate change. Community activities will be disrupted, and resident infrastructures in Robe Town will be damaged more than in the baseline scenario, necessitating immediate mitigation measures. However, as previously highlighted by McSweeney et al. [86]; Shahabul Alam and Elshorbagy [87]; and DeGaetano and Castellano [88]; the efficiency of drainage systems are not similar in each simulation scenario, indicating that it is dependent on the climate model used and the urbanization rate. Flooding problems are expected to be more severe in the combined scenario (urbanization and climate change) due to higher flooding volume than in other scenarios. As a result, the implementation of LIDs with adequate drainage systems can reduce future flooding problems that impede community activity and cause infrastructure damage.

Similarly, Thakali et al. [13,14] and Binesh et al. [89] have noted, the use of LIDs techniques can help to reduce flooding. It was found that combined LIDs reduced a high percentage of inundation volume, therefore, implying that more LID types will be required to alleviate floods in heavily flooded areas. These findings are consistent with those presented previously in the Zhu and Chen [32], Luan et al. [90], and Fiori and Volpi [91]. However, only resilient systems such as LIDs without adequate drainage systems cannot mitigate inundation; therefore, the system must be redesigned to account for the effects of urbanization and climate change. For evidence, Kirshen et al. [92], and Dudula and Randhir [93]; and Jenkins et al. [94] found that flooding was amplified even with LIDs and affected residents of houses and properties. These studies, in particular, highlighted that the expected peak flow with urban development and climate change will not reduce only considering LID techniques. Hence, the present study suggested that, in order to reduce flooding-related problems in the future due to urban growth and climate change, Rob town should implement selected mitigation strategies. Furthermore, the researchers recommended that drainage systems in developing-country cities such as Robe be designed to account for future urbanization and rainfall patterns to avoid unexpected flooding events.

5. Conclusions

Using PCSWMM, this study attempted to evaluate the performance of Robe town stormwater drainage systems under the impacts of urbanization and climate change. In addition, the benefits of three types of LIDs in flood mitigation were evaluated in this study. For this study, the estimated design storm of RCA4, RACMO22T, and REMO2009, as well as urbanization (from 10% to 70%), were incorporated into the model. As urban development in the Robe town increased from 10% to 70%, the total inundation volume and the number of inundated nodes increased from $35{,}418 \times 10^6$ L to $52{,}118 \times 10^6$ L and 28 to 89, respectively. The increasing trend in flooding volume, peak runoff, and the inundated nodes due to increasing impervious surface cover are investigated in comparison to the baseline scenario. Similarly, due to rainfall intensity variation in the REMO2009, RCA4, RACMO22T, and Ensemble climate models, the flooded junctions of the systems increased to 51, 73, 56, and 88, respectively. These findings indicated that the urban hydrological process can be altered and that increased flooding volume, as well as flooding problems in the town, are to be expected as a result of climate change. Moreover, climate change had a greater negative impact on the stormwater drainage system than urbanization. In all simulation scenarios, the results show that existing drainage systems are unable to convey the peak flow, implying that the system failed before its design period. The study area was frequently inundated by rainfall-runoff during the rainy season, but the severity is worsen due to urban expansion and a lack of adequate drainage systems. The area near the town roundabout was particularly affected by flooding, which hampered people's movement. Mapping technically the location of current floods in the town based on the flooding rate in the nodes, as well as identifying the types and location of inundation in both baseline and future scenarios, can be used to implement effective mitigation strategies. As a result, this study is expected to provide management practices for decision-makers to identify urban flooding problems and evaluate proposed solutions. Three low-impact development practices (cases L1–L3) were implemented in more flooded areas near urban centers to mitigate flooding problems caused by rapid urbanization and climate change. The combination of the two LIDs outperformed the others when compared to no LIDs, and rain barrels are more effective than rain gardens in reducing urban flooding. Overall, an adequate drainage system should be designed to mitigate the effects of flooding in the study area, taking into account urban development and future projected rainfall.

Author contribution statement

Takele Sambeto Bibi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Kefale Gonfa Kara: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Data will be made available on request.

Declaration of interest's statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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