Research Article
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Modeling flood reduction effects of low impact development at a watershed scale: case study of Nekemte town

Abstract

With urbanization, a significant increase in the area of impervious surfaces has been observed, which means that stormwater is no longer an opportunity to infiltrate into the soil. This results in the accumulation of surface runoff and the congestion of the conventional drainage management system. To counteract these changes, implementing low-impact development (LID) practices in conjunction with traditional drainage systems is necessary. This study aimed to identify effective (LID) practices for reducing stormwater runoff and evaluate the performance of this practice for mitigating urban flooding, besides a conventional urban stormwater drainage system. The study results revealed that the maximum peak runoff reduction of 33.2% was achieved with the LID combination scenario, while the minimum reduction of 19.3% occurred in the LID storage scenario. This study highly recommends that using LID practices in urban areas, in addition to the existing conventional drainage conduits, is an effective solution for restoring the natural circulation of water in the environment and reducing flood peaks.

Keywords: conventional drainage, stormwater management model (SWMM), Low Impact Development (LID), Sustainable stormwater management

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Introduction

Urbanization transforms natural land surfaces into impervious infrastructure, such as roads, buildings, and parking lots, disrupting natural infiltration and substantially increasing stormwater runoff.[1,2] This process elevates flood frequency and severity,[3] intensifies nonpoint source pollution,[4] and, when coupled with climate change, poses serious risks to human safety, economic stability, and aquatic ecosystems through urban waterlogging, water pollution, and habitat degradation.[5,6] Conventional drainage systems, designed primarily to regulate runoff quantity, are increasingly inadequate under these pressures, resulting in more frequent urban flooding and deteriorating water quality.[4,7,8]

Low-Impact Development (LID) has emerged as a sustainable alternative that integrates ecological processes into urban design, mitigating the adverse hydrological impacts of urbanization while enhancing urban resilience.[7] LID structures are typically smaller in scale and located near the source of rainfall runoff, aiming not only to reduce peak flows but also to maintain pre-development runoff volumes. Over time, the benefits of LID have expanded to include pollution reduction, protection of downstream water bodies and wildlife habitats, improved aesthetics and property values, and enhanced quality of human life.[9] Consequently, managing urban runoff through LID stormwater control measures (SCMs) has become a preferred approach, representing a multifunctional, nature-based, sustainable blue-green infrastructure capable of significantly reducing urban runoff pollution loads.[7,10,11]

Globally, LID is implemented under different terminologies: Water-Sensitive Urban Design in Australia, “Sponge City” in China, and Sustainable Urban Drainage Systems (SUDS) in the UK. These approaches have been successfully applied in cities such as Portland in the US, Melbourne in Australia, and pilot sponge cities in China.[3] However, adopting sustainable stormwater management practices in developing countries remains challenging due to limited technical expertise in planning and implementation.[12] In Ethiopia, high-magnitude flooding has frequently affected urban areas, with recent events in Dodola, Dire Dawa, and Addis Ababa driven by rapid land-use changes and inadequate drainage infrastructure, causing property damage, infrastructure disruption, and traffic congestion.[13]

Currently, Nekemte Town has suffered from various drainage and drainage-related problems. Urbanization in the town has been associated with the rapid conversion of land from rural to urban uses. Following urbanization, there is also the conversion of land from pervious to impervious and deforestation. This change increases the surface runoff, reduces the infiltration, and results in susceptibility to flooding. In addition to these, an accumulation of wastes in the drainage conduit, structural failure due to the lack of regular inspection and maintenance are some reasons that worsen the performance of the drainage system and creates unintended effects such as water pollution and flooding. During the rainy season in this town, street flooding and overtopping of the drainage system are the major challenges. Consequently, this flooding causes significant damage to infrastructure, and pavement distress, which causes driving problems, and environmental pollution, and hinders the day-to-day activity of people, resulting in heavy economic losses. In this town, local authorities generally prefer traditional drainage management system solutions rather than providing LID practices which is innovative sustainable solutions in urban stormwater management (SWM). Development plans prepared by them have not been capable to identify this modern practice for sustainable stormwater management due to a lack of technological innovations and required standards. Generally, to solve all the above-mentioned problems, this study has great importance: to identify the drainage problems and give a scientific solution to any stormwater drainage and related problems in the area. Therefore, there is a need for an effective decision-support framework to design sustainable stormwater management alternatives for urban areas in this town.

Low Impact Development (LID) practices are structural techniques used to reduce flooding at local and watershed scales. They are simple, cost-effective, eco-friendly, and sustainable, aiming to slow, capture, purify, and infiltrate runoff at its source while maintaining the natural hydrologic regime.[2,13,14] LID practices also enhance groundwater recharge, improve surface water quality, support habitat, and protect downstream water resources.[9,14] Common LID measures include rainwater harvesting systems, bioretention cells, vegetated open channels, downspout disconnection, permeable pavements, green roofs, rain gardens, and infiltration trenches.[4] Studies have shown their effectiveness in flood mitigation: infiltration trenches can reduce runoff from paved roads by up to 90%,[12] while permeable pavements can lower peak flow by 60–75% and allow rainwater reuse.[16] Comparisons with conventional drainage systems indicate that swales, permeable pavements, and green roofs are consistently more effective in reducing urban flood risks.[17]

The Stormwater Management Model (SWMM) is widely used for urban hydrological modeling and is recognized as one of the most accurate and practical tools.[2,19] For example,[6] studied the effect of LID on roof runoff reduction using SWMM, while[18] analyzed the impacts of urbanization and climate change on flood magnitude with SWMM and Low Impact Development (LID) sustainable land-use techniques. Effective urban flood management requires LID practices that are cost-effective, simple, environmentally adaptable, and sustainable, complementing existing drainage infrastructure. Due to their efficiency, climate adaptability, and sustainability, the use of LID practices for urban stormwater management is increasingly in demand worldwide.[19] Specifically, the implementation of four LID stormwater control measures—vegetative swales, bioretention cells, permeable pavements, and infiltration trenches—can reduce flood volume at the basin outlet by at least 20%, demonstrating their effectiveness under varying climate change conditions.[20]

The objective of this study is to identify effective Low Impact Development practices for reducing stormwater runoff and to evaluate the performance of its designs for mitigating urban flooding beside a conventional urban stormwater drainage system. The effect of four different types of LID practice scenarios (i. no application of LID technique, ii. infiltration-based LID technique, iii. water storage-based LID technique, and iv. LID technique based on the combination of water storage and infiltration) is designated to evaluate their peak runoff reduction performance in various land uses by using the SWMM (stormwater management model) model.

Methods and materials

Study area

Nekemte Town, the capital of East Wollega Zone and a separate district (woreda), is located in the Oromia Regional State, approximately 331 km southwest of Addis Ababa and 250 km northwest of Jimma. Situated in southwestern Ethiopia, Nekemte has experienced rapid urban expansion in all directions, largely due to its role as a transportation hub connecting Jimma, Bedelle, Bahir Dar, Asosa, Dambidolo, and Gambela. According to data from the National Meteorology Agency of Ethiopia, the town is among the rainiest in the country, receiving intensive rainfall during the rainy season, with an average annual precipitation of 2,263 mm. The study area covers 176 ha and comprises both pervious and impervious surfaces.

In Nekemte Town, the existing stormwater management system was designed based on the principle of rapid discharge, emphasizing the construction of gray infrastructure (conventional drainage systems). This approach is costly and has struggled to keep pace with the rapid urban expansion and increasing impervious surfaces. Modern international approaches to urban stormwater management, such as Low-Impact Development (LID) and green infrastructure, which focus on controlling runoff near its source, have not been implemented in the study area. The town's drainage network currently spans a total length of 18.56 km Figure 1.

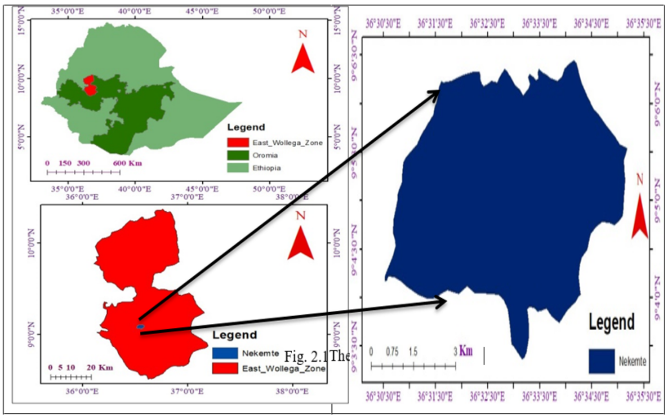

Figure 1 The map of the study area.

The soil type of the study area was obtained from the Harmonized World Soil Database (HWSD) viewer map by uploading the study area's shape file into the map. Humic Nitosols is the dominant soil type in this study area, and the textural class of this soil is clay. Identification of this soil type is essential to determining the relationship between rainfall and runoff or the rate of infiltration.

Hydraulic capacity of an existing conventional stormwater drainage system

To determine the velocity of flow through the existing drainage network, the size of the sewer network needed to be identified. The location, depth, and width of the conduits were identified via field surveys by tape meters and GPS data collection. The slope of each channel was determined separately by dividing the average elevation difference between the inlet and outlet by the length of each channel section. The velocity of flow through the channels was determined by using the Manning equation.

$$V\ (m/s) = {}^{1}\!/_{n} \times R^{2/3} \times S^{1/2} \qquad 2.1$$

Where;

V = velocity of flow (m/s)

R = hydraulic radius (m)

n = manning roughness

S = slope

Design rainfall

The design of rainfall is the basis of urban stormwater management planning. Rainfall data from five stations was obtained from the National Meteorological Agency of Ethiopia. Based on the evaluation results of the difference in average annual rainfall between stations by more than 10%, the normal ratio method was used to fill in the missed data. The quality of the data was checked by using the outlier test to detect data that lies outside the range.[21] The consistency of this rainfall data was checked by using a double mass curve. For this study, design rainfall was determined as recommended in the Ethiopian Road Authority Drainage Design Manual, (2013) by using Normal, Log-normal, Log-Pearson Type-III, and Gumbel Max probability distribution methods. Then the best-fit probability distribution was selected based on the total score from all the goodness-of-fit tests. Based on this result, the Gumbel max probability distribution was chosen for determining the design rainfall in this study. Design rainfall is adequate for the design of storm drains during intensive runoff to safely address the generated runoff.

Intensity- duration – frequency curve (IDF)

The daily 24-hour rainfall is too sparse to develop highly accurate intensity, duration, and frequency curves. It is known that this recorded 24-hour rainfall duration will be greater on average than the rainfall depth that might occur. So, to develop intensity, duration, and frequency curves for each rainfall region, the ratios of the short-duration data available were compared to the 24-hour data. The calculation of the rainfall depth of shorter duration in this study was performed using the formula suggested by the Ethiopian Road Authority (2013), as described in Equation 2.2.

$$I_t = \frac{(b+24)^n \times R_{24}}{24 \times (b+t)^n} \qquad 2.2$$

R_{24} = rainfall depth in 24 hours, t = time (hr).

b and n are coefficients based on regional

b = 0.3 and n = 0.935 were used, and the IDF curves are plotted for return periods of 2, 5, 10, 25, 50, and 100 years. Then IDF will be tabulated for rainfall durations of 10, 20, 30... 180 minutes Figure 2.

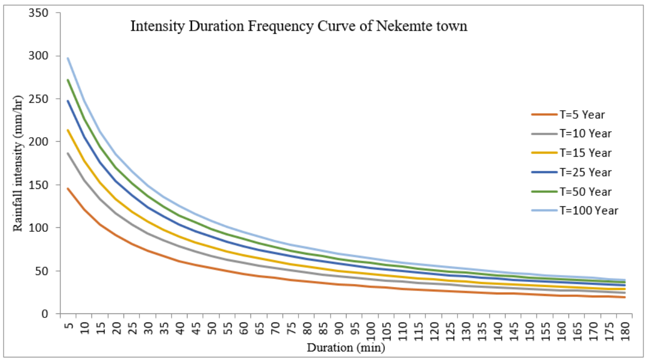

Figure 2 IDF Curve.

The time of concentration is the time that a drop of stormwater runoff takes to arrive at the basin outlet section, starting from the most hydraulically distant point of the basin. This time of concentration is divided into two parts: the time of entry and the time of travel. The time of entry represents the time taken by water drops to arrive on the ground surface and enter the drainage channel. The travel time represents the time taken to convey rainwater through the stormwater drainage channel, which depends on flow velocity, the travel distance (length), the channel slope, and dimensions.

$$T_{ci} = 0.604 \times \left(\frac{L}{3600V}\right) \qquad 2.3$$

Where T_{Ci} is the time of entry (minute), L is the travel length for water in the sub-catchment area (km), **C** is representing the runoff coefficient, and S is the catchment area slope (m/m).

Travel time was calculated by the equation below

$$T_t = \frac{L}{3600V} \qquad 2.4$$

L =length of the drainage channel (m) V = flow velocity in the channel (m/s)

$$T_c = T_{ci} + T_t \qquad 2.5$$

Tc= time of the concentration (hr), Tci = time of entry (hr), Tt= the travel time of channel flow (hr).

The result of time of concentration was used for the determination of the rainfall intensity for each representative subcatchment, which is used for the calculation of peak runoff.

Land use land cover

The computation of land use was an essential parameter to determine the coefficient of runoff. Field observations were carried out to identify the actual land use, the topography, drainage network, and direction of flow. Then the land use was conducted using Google Earth Pro and ArcGIS 10.7.1, after being verified by field observation. Google Earth Pro was used to search and digitize the land use and land covers through all study areas and then save the polygon as kml. ArcGIS 10.7.1 was used to convert the kml into a shapefile. Finally, the runoff coefficient value for each representative land use was determined as recommended in Ethiopian road authority drainage design manual, (2013) by using equation 2.6.

$$C_w = \frac{\sum(c \times A)}{\sum A_T} \qquad 2.6$$

Where A= Area of the individual land use (ha)

A_T = Catchment area (ha)

C= Runoff coefficient for consistent land cover

Stormwater management model

SWMM has been widely used as an urban hydrological model for qualitative and quantitative simulation of runoff in urban areas, and it incorporates the LID module.[5,1] The SWMM module has been upgraded various times, and the newest version has been verified to satisfactorily reflect the actual hydrological performance of each LID practice types.[6] This model accounts for various hydrologic processes, including rainfall, infiltration, snow melting, evapotranspiration, overland flow, interflow between groundwater and drainage systems, and the capture and retention of stormwater runoff from various LID practices.[2] In this model, numerous LID practices are selected based on suitable site factors such as terrain slope, precipitation regime, land use, and environmental characteristics.[1] Several LID practice types components were created within the SWMM model and then added to the corresponding subcatchment by varying input parameters according to the actual site condition.[18] SWMM treats catchments as non-linear reservoirs that get inflows from precipitation and neighboring catchments, generating surface runoff, infiltration, and evaporation.[22] In this study, the SWMM model was used to simulate the forming process of urban stormwater runoff. Infiltration modeling was carried out by using Green-Ampt Method and flow routing of one-dimensional Saint Venant flow equations was solved by using dynamic wave routing. In this SWMM model to resolve surface runoff and conduit flow, Manning's and water balance equations were used.[2] The model required various input parameters for runoff simulation (sub-catchments, rain gages, and LID controls) and hydraulics (nodes and links (channels)). The other input parameters, such as depression storage, percentage of imperviousness, and the Manning coefficient for pervious and impervious surfaces, were estimated using land-use data. The Green-Ampt infiltration sub-catchment input parameters are the suction head (ψs), saturated hydraulic conductivity (Ks), and initial deficit (θmax), which were determined based on extracted soil types. The design storm intensity of selected return periods was estimated from IDF curves and separately entered into the SWMM model. A field investigation was conducted to collect the existing drainage system link properties, such as the inlet and outlet junction of the conduit, the maximum depth and length of the conduit, as well as node properties such as X and Y coordinates and the inverted elevation of nodes.

Calibration and validation

The influence of the input parameters on the SWMM model output is evaluated using sensitivity analysis. This was accomplished by varying parameter input values to determine the weighted effects of various model parameters on model outputs. The model was run with the initial parameter values, and then the sensitive parameter values were systematically adjusted between their ranges. After the uncertainty values of model parameters were assigned, the values of observed and simulated values 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).

$$NSE = 1 - \frac{\sum_{t=1}^{n}\left(Q_{obs} - Q_{sim}\right)^2}{\sqrt{\sum_{=1}^{n}\left(Q_{obs} - Q_{ave..obs}\right)^2}}$$

$$RSR = \frac{\sqrt{\sum_{t=1}^{n}\left(Q_{Obs} - Q_{sim}\right)^2}}{\sqrt{\sum_{t=1}^{n}\left(Q_{obs} - Q_{ave.obs}\right)^2}}$$

$$PBIAS\ (\%) = \frac{\sum_{t=1}^{n}\left(Q_{obs} - Q_{sim}\right)^2}{Q_{obs}}$$

Q_{obs} = observed flow

Q_{sim} = simulated flow

$$R^2 = \frac{Sum\ squared\ regression\,(SSR)}{Total\ sum\ of\ squares\,(SST)}$$

$$= 1 - \frac{\sum\left(Yi - \hat{Y}i\right)^2}{\sum\left(Yi - \overline{Y}i\right)^2}$$

As several studies have suggested, performing robust calibration, it is difficult to get sufficient data in Ethiopian cities. For this reason, many earlier studies manually and automatically tested urban stormwater models using short-term observed data. In this study, we followed the suggestions of,[13,23] As a result, from the 16th of June to the 21st of September 2022, the researchers collected runoff depth in the channel along with the corresponding rainwater events at the field. Runoff depth was measured every 5 minutes at two stations near outfall one (9° 5'36.06" N and 36°32'21.57" E) and outfall two (9° 5'10.09" N and 36°32'23.21" E).

In this study, the initial parameter values were estimated from various spatial data and assumed as recommended in the SWMM manual. The suction head (ψs), saturated hydraulic conductivity (Ks), and initial deficit (θmax) are the infiltration parameters required in the Green Apt method for modeling infiltration by using the SWMM model. The values of all these parameters were used from the SWWM manual[22] based on the soil textural types of the study area used. Hence, the infiltration parameter values determined from this manual were 0.254mm/hr, 320.04mm, 0.475, 0.378, and 0.265 for a suction head, hydraulic conductivity, porosity fraction, field capacity, and Wilting point, respectively. Also, the initial deficit is determined by the difference between soil porosity and field capacity, which is 0.097. Then the performance of the model was determined by comparing the results of the simulated and observed flow data.

Calibration

Model calibration was required to adjust certain parameter values of the model until the simulated runoff results matched acceptably with the observed data. Model calibration was carried out for the model parameter adjustment. The calibration of the SWMM model was mainly for the parameters of catchments such as N-impervious, N-pervious, Dstore-impervious, Dstore-pervious, and Zero-impervious. The parameters used for sensitivity analysis and their allowable range was tabulated in Appendix 1, 2. After being evaluated for NSE, R^2, RSR, and PBIAS, the results were: 0.86, 94%, 0.34, and -4.16%, respectively. These values showed that the simulated runoff and the observed runoff in this study area matched well. Model calibration is considered satisfactory if the NSE and R^2 values are greater than or equal to 0.50.[24] The validation was done after the calibration. The values of NSE, R^2, RSR, and PBIAS were 0.84, 98.49%, 0.27, and -3.6%, respectively. The value of these model evaluation functions indicated that the simulated runoff and the observed runoff in this study area is well matched. Therefore, the SWMM model was accepted for runoff modeling in this study area based on the model evaluation results of both model calibration and validation.

Low impact development

Low-impact development practice type is considered to be a distributed practice that manages stormwater near the source of runoff generation, while conventional drainage system development is referred to as a centralized practice or end-drainage conduit practice.[6] (LID) practices have been considered a promising strategy to control stormwater runoff flooding and non-point source pollution in urban areas. They are an effective and environmentally friendly practice for urban stormwater runoff management.[9] Effective LID practices provide numerous benefits to the community, including protecting people and property from increased flood risk, protecting the quality of groundwater and surface waters from pollution, reducing erosion and flooding, increasing groundwater recharge, and delivering a cost-efficient solution that uses fewer natural resources than conventional drainage management systems.[25] Also, it can provide aesthetic and recreational benefits by creating attractive green spaces within urban areas,[26] improving air and water quality, and decreasing urban heat island effects.[3] A risk-based integrated stormwater management model is to be applied to qualitatively and quantitatively assess the flood risks in urban drainage systems.[27] According to[26] Best Management Practice (BMP) is a sustainable approach to controlling stormwater that seeks to mimic the natural hydrological cycle by using small-scale techniques that can infiltrate, retain, and evaporate the stormwater close to the areas where runoff is generated. There are numerous practices of low-impact development stormwater control measures, including bioretention, rain gardens, vegetated swales, porous pavements, infiltration trenches, and dry (infiltration) wells,[1] green roofs, rainwater harvesting swales and, soakaways are the most common.[28] For urban flood control, the combination of several LID practices would be more effective than a single LID practice.[17] The criteria used to determine the feasibility of each LID practice are often based on specific technical guidelines.[29] Factors influencing the site Selection criteria for LID practice include contributing drainage area, study area soil type, slope, and available space for LID.[28] Then, based on the criteria described in the literature[28] and after field observation, four LID practice types—bioretention, infiltration trench, permeable pavement, and rain barrel—were applied for the reduction of stormwater runoff in this town. With these LID practices, only the reduction of surface runoff quantity was involved in this study.

Design of low impact development simulation scenarios

In this study, four different simulation LID scenarios were developed to evaluate their runoff reduction performance. The simulation scenarios were: No implementation of Low Impact Development Technique; Low Impact Development Technique based on infiltration; Low Impact Development Technique based on water storage; Low Impact Development Technique based on the combination of infiltration and water storage. In SWMM, several LID types are created and then added to the corresponding subcatchment area by changing parameters according to the actual situation. Based on the principle of water balance, the SWMM model calculates the real-time inflow and outflow of the subcatchment area.

No implementation of low impact development technique

No implementation of the LID technique scenario is considered a base case scenario, and in this case, the effects of LID practices were not considered.

Infiltration based low impact development technique

This scenario consists of bioretention, infiltration trench, and permeable pavement Low Impact Development practices that temporarily store and infiltrate stormwater into soil. The details of each of these Low Impact Development practices have been described as follows;

Bioretention

Bioretention is the landscaped depression that receives runoff from the catchment, especially from an impermeable surface.[30] Bioretention systems have been recognized as efficient in promoting groundwater recharge, infiltration, evapotranspiration, and pollutant load reduction in addition to runoff volumes and peak flow reduction.[24] This type of LID practice has demonstrated excellent performance for decreasing the concentrations and loads of pollutants in the protection of waterways from polluted urban runoffs[31] and has proven to be an effective system for managing a high volume of stormwater runoff and enhancing the water quality.[15,32] Their study results found that bioretention can reduce stormwater runoff by up to 26% at its best performance. A reduction in stormwater runoff logically led to a reduction in flood events. The bioretention system consists of three sections: surface, soil mix, and gravel storage layer. The surface layer receives both direct rainfall and runoff from drainage areas, and the soil layer contains an amended soil mix that can support vegetative growth. The soil layer receives infiltration from the surface layer and loses water through ET and by percolation into the storage layer below.[33] Based on the land uses of the underlying surface, their area coverage, and topography, we propose bioretention in the relatively sparsely populated areas. The parameter values for bioretention design and planning were fixed from the literature. Tables tabulated in Appendix 3 and 4 below indicate the feasible site for bioretention development and the design parameters of this LID practice.[28]

Infiltration trench

Infiltration trenching is a low-impact development practice and is an underground trench that is packed with permeable and porous media to control urban stormwater and increase infiltration, which can capture pollutants such as heavy metals. This LID practice is not recommended to be used in seriously contaminated regions.[34] Infiltration trenches might provide numerous advantages, such as the reduction of urban flooding, recharging of groundwater, and the improvement of water quality.[34] Infiltration trench is a rectangular trenches lined with geotextile fabric, typically long and narrow, and filled with clean aggregate that are used to provide storage and facilitate the infiltration of runoff into the subsurface.[35] In this study area, based on the area coverage, available feasible sites, and population density, an infiltration trench is proposed for sparsely populated areas. The design and planning parameters of this LID practice suggested in different papers were used for the design of this practice in this study. The tables tabulated in Appendix 5 and 6 indicate a feasible site for bioretention development and the design parameters of infiltration trenches.

Permeable pavement

Permeable pavement is a porous infrastructure that allows for collecting and infiltrating surface runoff as well as recharge. This LID practice is widely used to resolve the problem of increasing urban stormwater runoff and reducing environmental pollution. Permeable pavement can likely improve the capacity of locally managed stormwater relying on underground storage while recharging the groundwater under the condition of environmental safety. For the time being, the permeable pavement LID structure can also act as a load-bearing structure with a relatively smooth surface for low-speed vehicle movement. A pervious layer or an open gradation friction layer of this LID practice is used as a highway overlay, and its porous characteristic is the main design goal to reduce traffic noise instead of the infiltration of the native soil in the application.[34] Permeable pavement consists of fewer fine aggregates than old-style concrete or asphalt, and the larger pore spaces[35] which allow the percolation and temporary accumulation of stormwater and are used for runoff reduction.[36]

Designed[24] the permeable pavement on all roads, except primary and secondary roads corresponding to Interstate highways, US highways, state highways, and county highways. The simulation result showed that individual LID practices can reduce 3–40% of the average annual runoff. In this study area, permeable pavement was designed to be implemented on walkways, and other roads on which heavy vehicles are not transported, in parks, and on Mesqel fields. For this study, the parameter values for permeable pavement design and planning were fixed as recommended in various literatures and tabulated in Appendix 7.

Low impact development technique based on water storage

This technique represents LID practice based on water storage (Rain barrel). In addition to a runoff reduction rain barrel can be used to reduce demand for domestic water to be used for toilets washing, and other purposes.

Rain barrel

A rain barrel is a container that collects storm runoff from urban rooftops during storm events to realize effective stormwater management and provide for domestic water supply during such activities as toilet cleaning, drip irrigation, and laundry washing. The rain barrel is contributing to the reduction of peak runoff volume and water contamination. Rain barrels can be mostly placed in the corners of backyards, and they can also be used for decorative designs. Moreover, rain barrels make use of their unique capacity to supplement water demand by capturing stormwater; in this manner, they decrease water bills, and in areas with limited space, they provide rainwater for storage, which can eventually enhance the capacity for water management.[34,24] Designed a rain barrel to store runoff from 50% of the roof area. Similarly, in this study, a rain barrel is proposed to receive stormwater runoff from 50% of the roof area. Because half of the roof area was assumed to be served by another downspout.[27]

Low Impact Development technique based on the combination of infiltration and water storage

This scenario consists of a combination of scenario 2 and scenario 3. Areas of various LID types are tabulated in Appendix 8,9,10,11.

Results

The current condition of the existing drainage system in the study area

As investigating from field observation, in Nekemte town, urban administrators and public authorities have not yet adopted nature-based drainage management systems like low-impact development. The town has not been well planned, and there is a lack of public and private green space. The existing stormwater management in this town was still dominated by conventional stormwater management. This type of old stormwater drainage system in towns was usually constructed to collect and convey excess surface runoff, protecting the public from flooding. However, most of these systems have lost functionality and capacity to convey stormwater runoff. Their service level has declined due to a lack of regular maintenance, aging, solid waste disposal in drains, siltation, and the absence of rehabilitation. Moreover, the dense development in the study area worsens the situation by creating large impermeable surfaces, which increase overland runoff. As a result, the existing drainage network cannot handle the generated runoff, leading to flash floods and water quality degradation. The existing drainage system in this study area is generally classified into closed and open drainage channels. Closed drainage channels constructed by concrete are found along main asphalt roads. Open drainage channels, constructed by masonry are found along cobblestone, gravel, and some of the earthen roads. In various places, in this study area access roads serve as wide-open channels with severe erosion and flooding problems.

Drainage channels along the main road from Round One to Bakejama are partially clogged due to solid waste accumulation. The networks between 02 Gulit (a small marketplace in 02 Kebele) and the prison compound are fully blocked by waste and sediment. As a result, the clogged drains cause street and walkway flooding, water intrusion into homes and fences, road damage, pollution, unsanitary conditions, refuse buildup, and stagnant water. Pollutants carried by stormwater runoff from the upper subcatchment to the downstream areas have led to refuse accumulating on streets and around nearby houses throughout the study area. Field observations also revealed that parts of the road were damaged by flooding due to inadequate drainage facilities. In general, the existing drainage in this study area is inadequate due to the absence of proper systems, poor solid waste management, lack of sufficient green areas, and the increase in impermeable surfaces caused by urbanization.

Possible mitigation measure

In addition to conventional stormwater management, low-impact development (LID) practices are needed in this town to manage flooding on-site and reduce stormwater runoff at the source. Providing dustbins or garbage containers, along with proper waste collection and disposal systems, will help reduce waste dumping on roads and drains, making drainage cleaning and maintenance more manageable. Covering open drains and installing intermediary screens within channels can capture debris and solid waste. Regular and periodic drain cleaning and maintenance are essential for effective urban drainage management, particularly before the rainy season begins. Dedicated urban stormwater drainage facilities should be constructed so that roads are not used as open drainage channels, thereby preventing road degradation.

Peak runoff reduction rates by various low impact development types

In this study, four low-impact development (LID) types: bioretention, infiltration trench, permeable pavement, and rain barrel were designed, as described in the methodology section, to reduce flood peaks and serve as alternatives to conventional drainage systems. These LID practices were simulated under four scenarios to reduce stormwater peak runoff at or near its source. Using the SWMM 5.1 model, the reduction rates of peak runoff for the base case (no LID), LID infiltration, LID storage, and LID combination scenarios were evaluated. The results indicated peak runoff reductions of 32.2% for LID infiltration, 19.3% for LID storage, and 33.2% for the LID combination scenario. The maximum reduction of 33.2% was achieved with the LID combination, while the minimum reduction of 19.3% occurred in the LID storage scenario. Overall, all proposed LID practices effectively reduced runoff, with the efficiency ranking as follows: Base Case (no LID) < LID Storage < LID Infiltration < LID Combination. In similar way in previous study performs best in the reduction of peak flow by 32.5 % and in preventing flooding disasters flood mitigation than other scenarios.[38] This peak runoff reduction capacity of various LID types various due to feasible site for implementation of the LID practices, LID size, the watershed amount flows toward the practices Table 1.

Table 1 Reduction rates of peak runoff by various LID practice types\

No		Base case (with no LID)	LID infiltration	LID storage	LID combination
1	Peak runoff (m^3/s)	54.29	36.79	43.79	36.26
2	Percentage of reduction		32.20%	19.30%	33.20%

Our study is supported by the related study done by[38] Observed maximum peak runoff reduction rates of 1.46%, 29.76%, and 31.8% with LID storage, infiltration, and combination respectively. A study[6] have assessed reduction effect of roof runoff with low impact development practices, and it was revealed from the study result that LID practices effectively reduce roof runoff. Also, a study done by[24] showed 3-47% runoff reduction by using three LID practices at various implementation levels that used in mitigating urban flood risk.

Evaluation of flood level in links with runoff simulated with LID combination

The flood level in the drainage conduits was assessed by comparing the simulated runoff results with no LID and with LID combination. As indicated in figure below for the simulated runoff with no LID practice, the flood level in link 13 was flooded, but when this channel was simulated with LID combination it becomes adequate. This reduction of flood level in drainage conduit revealed that, how the LID is effective in peak runoff reduction. So, rather than focusing on only maximizing drainage cross-sections, developing low-impact development practice in this study area play a great role in stormwater management, which provides additional benefits in addition to runoff reduction like reduces the pollution transported with runoff, increases the aesthetics of the environment, increases the recharge rate of groundwater and decreases the water demand required for domestic water.

As it was observed from Figure 3 the application of LID practice influences the protection of the receiver by decreasing the stormwater runoff flows towards the existing drainage conduits, which makes it possible to decrease the process of washing out contaminants collected in the drainage network.[25] Moreover,[39] demonstrates that LID practice significantly alleviates the urban flooding risk, by reducing up to 80% of runoff volume. As it was revealed from Figure 4 When the LID was designed in this study area the performance of drainage channels increases and effective runoff reduction in various channels were observed.

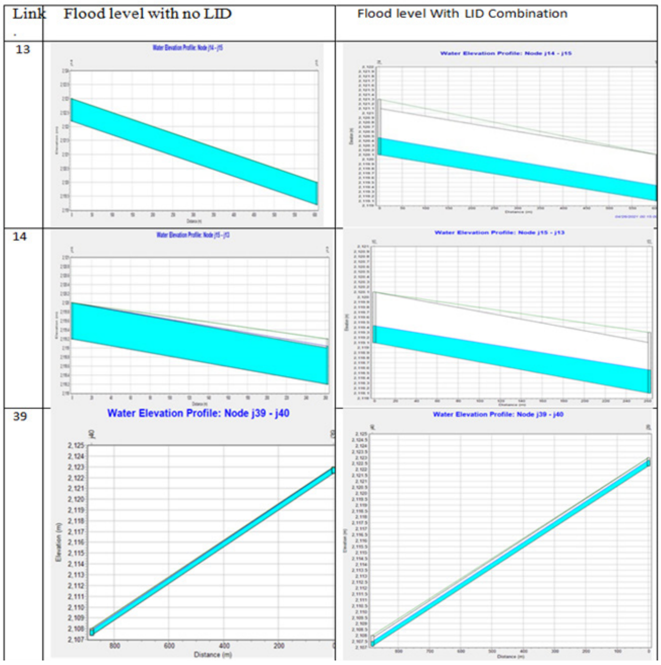

Figure 3 Comparison of flood level in links.

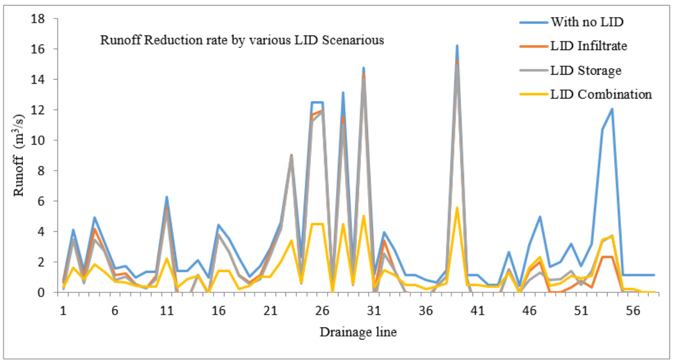

Figure 4 LID performance evaluation for different scenarios in various Drainage line.

Drainage performance evaluation with LID combination

Under this section the performance of the existing drainage conduits with the simulated runoff before and after designed LID combination was evaluated. With no LID practice the simulation result revealed that out of 58 links 35 links were inadequate. But when we evaluate these existing drainage conduits with LID combination practice only 10 links were found inadequate to safely convey the generated runoff. So, as it was observed from the study result, developing LID combination in this study area showed that the increase in the performance of the existing drainage conduit by 71.34% by reducing over flooded in link section. In addition to drainage conduit over flooding reduction capacities, all LID techniques have made contributions to recharging groundwater storage and can support by providing domestic water to be used for household gardening, and w Aater to be used for toilets washing and other purposes. Similarly, the previous study also showed that LID combination techniques reduced urban flood by 70%.[18]

Conclusion

The use of Low Impact Development practice in urban area offers many benefits, not only from a technical point of view but also for the lives of dwellers. The main drawback of most conventional drainage conduits is the inability to infiltrate stormwater into the earth and the absence of vegetation, which not only has aesthetic importance but also the ability to treat this stormwater before further management. This study provided a strategy for optimizing the design of LID Practice facilities for urban stormwater management to reduce urban stormwater runoff. The results obtained as an effect of the carried-out works made it possible to draw the following conclusions:

I. A decreasing runoff flow rate in the drainage network allows for a reduction in the volume of local flooding. This confirms the results obtained by[25] the application of LID practice and classical means of delaying rainwater runoff, which significantly influence the protection of the receiver by reducing the amount of runoff in channels, which results in a reduction in the process of washing out pollutants collected in the drainage conduit network.

II. Implementation of LID combination facilities performs much better in runoff reduction than LID infiltration and storage facilities.

III. Infiltration LID practice facilities are more effective in peak flow reduction at subcatchments 1–8 and 30-32;

IV. LID combination practice mitigates floods dramatically in various subcatchments compared to the LID infiltrate scenario and the LID storage scenario.

V. The limitations of conventional stormwater management systems and the basic awareness of LID practices should be recognized. Parts of the engineering company and local government staff have noticed the benefits of LID practices.

VI. Although the majority of the hydrological performance of the drainage was found to be safe, with various subcatchment due to attenuating peak runoffs.

Recommendations

Practical recommendation

The study result revealed that all the proposed LID practice is effective in runoff reduction on the existing congested drainage channel overflows and associated pollutant loads. Most of the existing drainage channels in this study area were partially filled with sediments and solid wastes while some of the opened drainages were totally filled. Such problems can be solved by covering open drains, installing intermediary screens within drainage channels, performing a scheduled system of cleaning and maintenance to ensure the drainage channels receive periodic care and maintenance. The town municipality and the residents should provide periodic cleaning and maintenance of the drainage line before the rains begin. Providing necessary existing conditions like a municipal trash collection and disposal system that sufficiently removes debris and wastes from the town at the proper place are needed. Also, creating awareness is required to change the attitude of the community towards the poor managements of solid and liquid wastes, which helps to make as the drainage systems could be able to serve efficiently and to avoid the blockage of drainage by these wastes. Rehabilitation measures should be provided for the damaged drainage line occurred in some parts of the study area to reduce the flooding problem. All considerations, such as an appropriate design method that depends on the catchment area, future expansion of urbanization, and other factors shall be taken into account during the detailed design of the drainage facilities so as the structure's capacity shall accommodate the design flood. According to the availability of the feasible site in this study area LID practices was proposed to be implemented in addition to conventional stormwater management to achieve the best performance of stormwater management in reducing peak runoff, enhancing infiltration, groundwater recharge, to reduce the receiving water pollution and to increase the town aesthetic.

Scientific recommendation

The stormwater management system adopted in this study area was conventional types of drainage systems. Reliance only on this type to manage stormwater has caused water quantity, and quality problems and altered urban hydrology as urbanization contribute to most of the impermeable surface. Hence, proactive measures should be taken to manage stormwater runoff at the source like LID besides these the existing conventional drainage system. Rainwater management through Low Impact Development (LID) enhances traditional drainage by promoting infiltration rather than rapid runoff conveyance. This approach reduces drainage loads, filters pollutants, minimizes surface runoff, and improves groundwater recharge. LID systems can be implemented in green spaces or residential areas with simple designs and relatively low costs, making them both practical and sustainable.

Drainage area, available free space for LID practice, surface slope, soil type and land use land cover of the areas are factors to be considered for proposing LID practice at feasible site. All considerations, such as an appropriate design method that depends on the catchment area, future expansion of urbanization, and other factors shall be taken into account during the detailed design of the drainage facilities so as the structure's capacity shall accommodate the design flood. Local authorities can use the findings of this study to guide recommendations for reducing disaster risk, controlling urban flooding, and revitalizing urban areas. The findings suggest further research integrating LID design with urban aesthetics, construction costs, land suitability, rainwater reuse, and community acceptance, as these practices can reduce runoff and pollutants from impervious surfaces, protecting downstream water quality, preserving watershed hydrology, and mitigating urban flood inundation caused by increasing urbanization.

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Author contributions

H.K Prepared methodology, collected the input data for simulation, organized the paper, and wrote the paper. A.K. provided useful advice and editing.

Declarations

Ethics approval: All procedures performed in studies are in accordance with the ethical standards.

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