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Analysis of the Effects of Securing Baseflow and Improving Water Quality through the Introduction of LID Techniques

Jeongho Han [1] and Seoro Lee [2,*]

[1] Agriculture and Life Sciences Research Institute, Kangwon National University, Chuncheon-si 24341, Gangwon-do, Republic of Korea; hanjeongho24@kangwon.ac.kr
[2] Department of Regional Infrastructure Engineering, Kangwon National University, Chuncheon-si 24341, Gangwon-do, Republic of Korea
* Correspondence: srlee@kangwon.ac.kr

Abstract: Rapid climate change and increasing water use have led to various problems in small- and medium-sized urban streams during dry periods, such as stream drying, water pollution, and ecological degradation, reducing their physical and ecological functions. Ensuring adequate baseflow and improving water quality during these critical periods are essential for maintaining urban stream health. While previous studies have explored the effects of Low Impact Development (LID) techniques (e.g., green roof, rainwater harvesting system, permeable pavement, infiltration trench) on infiltration and groundwater recharge, they have primarily focused on general flow regimes rather than dry and low-flow periods. This study specifically evaluates the effects of LID techniques on securing baseflow and improving water quality during dry periods, utilizing the SWAT-MODFLOW model and the Web-based Hydrograph Analysis Tool (WHAT) system. The results show that LID techniques reduce peak flow by an average of 27% and secure an additional 43% of baseflow during dry periods. Suspended solids (SS) and total phosphorus (T-P) concentrations were reduced by 15% and 41%, respectively. These findings demonstrate the effectiveness of LID techniques not only in managing stormwater runoff during flood events but also in maintaining baseflow and water quality during dry periods, thus providing valuable insights for sustainable urban watershed management.

Keywords: LID; baseflow securing; water quality improvement; SWAT-MODFLOW; WHAT

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1. Introduction

Rapid changes in climate have altered rainfall patterns, increasing vulnerability to natural disasters such as droughts and floods. This makes the stable management and securing of available water resources more challenging. Additionally, urbanization has led to an increase in impervious surfaces, which amplifies stormwater runoff while reducing evapotranspiration and groundwater infiltration, thus disrupting the natural water cycle [1,2]. As a result, small- to medium-sized urban streams face various issues, such as road flooding, stream drying, water pollution, and ecological degradation [3]. To maintain the environmental and ecological sustainability of these streams, restoring a healthy water cycle is crucial.

Baseflow, which is the groundwater that infiltrates through permeable layers to contribute to streamflow, forms the majority of flow during mid-range and low-flow conditions, excluding the high-flow periods of summer [4]. Ensuring adequate baseflow during dry periods is essential to support aquatic ecosystems, water quality, and overall stream health [5,6]. Traditionally, methods such as retention basins, constructed wetlands, and groundwater recharge areas have been used to manage baseflow and water quality. These methods offer benefits such as flood mitigation and pollutant removal, yet often lack the capacity to integrate effectively within densely built urban areas.

In comparison, Low Impact Development (LID) offers a promising solution for urban settings. As a stormwater management approach, LID techniques aim to restore the water cycle to conditions similar to those before development. LID techniques such as green roofs, rainwater harvesting systems, permeable pavements, and infiltration trenches have proven their positive effects, such as increasing infiltration and groundwater recharge, reducing direct runoff [7–12], and decreasing pollutant loads from impervious surfaces [13–15] on an annual or seasonal basis in urban water management.

Securing baseflow during dry and low-flow periods in urban streams is particularly crucial in maintaining streamflow and supporting water quality and aquatic ecosystems. Therefore, a closer analysis of LID's impact on baseflow during the dry season is necessary. An accurate quantification of baseflow contributions requires a model that can simulate complex interactions among surface water, subsurface flows, and aquifers. The SWAT-MODFLOW model [13] is particularly suited for this purpose, as it enables integrated watershed-scale simulations that capture the dynamic exchanges between surface and groundwater systems through soil profiles.

This study quantifies baseflow contributions in urban streams through integrated watershed-scale surface and groundwater modeling with the SWAT-MODFLOW model. To achieve this, the SWAT-MODFLOW model was used to simulate streamflow with LID applied, and the Web-based Hydrograph Analysis Tool (WHAT) [14] was used to separate baseflow from the simulated streamflow. The results indicate that LID techniques are effective in reducing runoff, enhancing infiltration, and securing baseflow during dry periods. By improving water quality and sustaining streamflow, these findings contribute to developing sustainable urban watershed management strategies, highlighting LID's potential to enhance urban resilience and ecological health.

2. Materials and Methods

This study employs an integrated approach to evaluate the impact of LID techniques on baseflow and water quality in urban sub-watersheds of the Sindun Stream watershed, focusing on dry and low-flow periods. First, the SWAT-MODFLOW model was calibrated to simulate streamflow considering surface and groundwater interactions at the watershed scale. Following this, the effects of selected LID techniques (green roofs, permeable pavements, infiltration trenches, and rainwater harvesting systems) were assessed for their efficiency in enhancing baseflow and reducing pollutants across different seasons and flow regimes. To analyze the baseflow contribution, the WHAT was used to separate it from the simulated streamflow. The following sections will address the details of each material and method used for this research.

2.1. Study Area and LID Application Sites

This study focuses on the Sindun Stream watershed, a local stream originating from Sindun-myeon, Icheon-si, Gyeonggi-do, Republic of Korea, and flowing into the Bokha Stream (Figure 1). The Sindun Stream watershed consists of 34.6% forest (18.5 km^2) and 32.8% agricultural land (17.6 km^2), with a large alluvial aquifer that facilitates active interaction between surface water and groundwater [15]. Particularly, during winter and early spring, significant amounts of groundwater are used for water curtain cultivation, which greatly affects the flow of nearby streams [16]. Additionally, the lower region of the Sindun Stream contains urban areas covering 11.3% (6.1 km^2) of the total watershed, where groundwater is heavily used for domestic and industrial purposes. Pollutants discharged from the urban areas also significantly impact the water quality of the Sindun Stream.

In this study, three urban sub-watersheds in the lower Sindun Stream (LID-1, LID-2, LID-3) were selected to evaluate the effects of LID techniques on securing baseflow and improving water quality (suspended solids, SS; total phosphorus, T-P) during dry periods. These selected sub-watersheds have urban areas comprising over 20% of their total area (Table 1) and are identified as regions where the reduction of streamflow during dry periods raises concerns about water quality and ecological degradation, thus necessitating measures for securing baseflow and improving water quality.

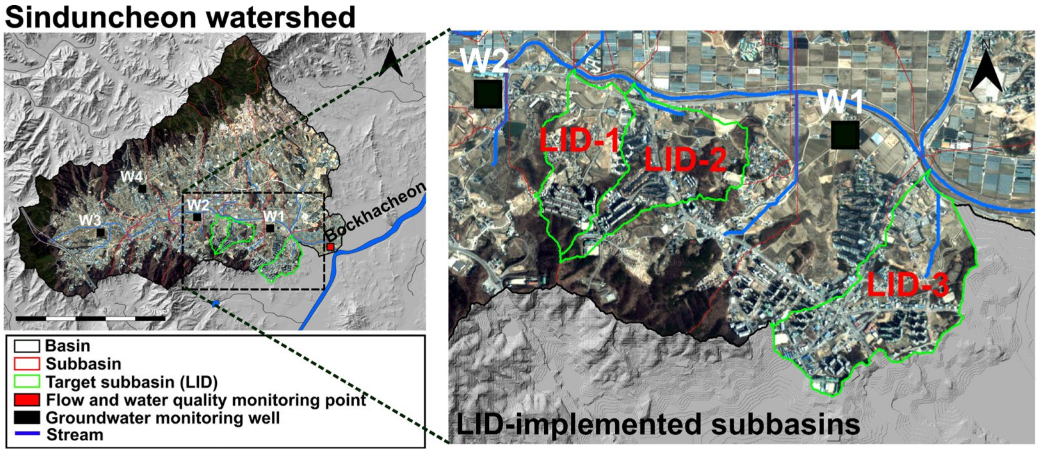

Figure 1. The location map of the study area.

Table 1. Land cover area and proportion by targeted sub-watersheds.

Classification	LID-1		LID-2		LID-3	
	Area (km^2)	% of Total	Area (km^2)	% of Total	Area (km^2)	% of Total
Urban	0.116	22.8	0.176	27.4	0.332	32.4
Agriculture	0.074	14.6	0.085	13.2	0.201	19.6
Forest	0.129	25.4	0.134	20.7	0.093	9.1
Grassland	0.072	14.0	0.085	13.2	0.127	12.4
Wetland	0.001	0.2	0.004	0.6	0.005	0.5
Bare land	0.015	3.0	0.047	7.3	0.078	7.6
Etc.	0.102	19.9	0.113	17.6	0.189	18.4
Total	0.510	100.0	0.644	100.0	1.026	100.0

2.2. SWAT-MODFLOW Model Overview and Setup

In this study, the SWAT-MODFLOW model [13] was used to evaluate the effects of LID techniques in selected urban sub-watersheds within the Sindun Stream watershed. SWAT-MODFLOW integrates the Soil and Water Assessment Tool (SWAT), developed by the United States Department of Agriculture-Agricultural Research Service (USDA-ARS), with the MODFLOW groundwater flow module, developed by the United States Geological Survey (USGS) [17]. SWAT-MODFLOW was chosen for its ability to simulate hydrological processes involving surface and groundwater interactions, using SWAT's surface and subsurface simulation modules alongside MODFLOW's packages, such as Recharge, River, Stream, Well, and Drain, for comprehensive groundwater modeling.

To operate the SWAT-MODFLOW model, input data are required for both SWAT (topography, land cover, soil maps, meteorological data) (Figure 2) and MODFLOW (groundwater flow analysis). We used a 5 × 5 m resolution Digital Elevation Model (DEM) created from 1:5000 digital topographic maps obtained from the National Geographic Information Institute (https://www.ngii.go.kr, accessed on 30 June 2024). A 1:25,000 land use map was acquired from the Environmental Geographic Information Service (https://egis.me.go.kr, accessed on 30 June 2024), and a 1:50,000 soil map was sourced from the Rural Development Administration (http://soil.rda.go.kr, accessed on 30 June 2024). All these datasets were resampled to a consistent spatial resolution of 30 m to ensure compatibility within the SWAT-MODFLOW model. Daily meteorological data, including precipitation, wind speed, relative humidity, maximum and minimum temperatures, and solar radiation, were collected from three nearby weather stations (Icheon, Janghowon, Baeksa) through the Korea

Meteorological Administration (https://www.weather.go.kr, accessed on 11 May 2023). The model was set up for the period 2013–2021, including a three-year warm-up period.

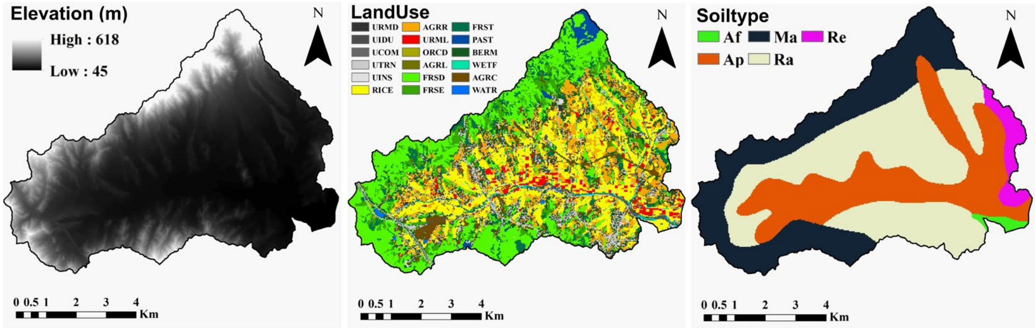

Figure 2. SWAT input data for the Sindun Stream watershed.

ModelMuse 4.2.0 [18] software was used to define the modeling domain and to determine the spatial distribution of hydrogeological parameters such as hydraulic conductivity and storage coefficients. The model domain consisted of grid cells measuring 200 m × 200 m, creating 44 rows and 56 columns. The area outside the watershed was considered a no-flow condition and set as inactive grid cells. The aquifer structure of the watershed was simplified into a single alluvial layer and a permeable bedrock layer. The alluvial layer was treated as an unconfined aquifer, while the bedrock layer was modeled as a confined and unconfined aquifer in a transition zone. The bottom elevation and horizontal hydraulic conductivity of each layer were interpolated spatially from borehole logs, in-situ permeability tests, and slug tests [19,20] (Figure 3).

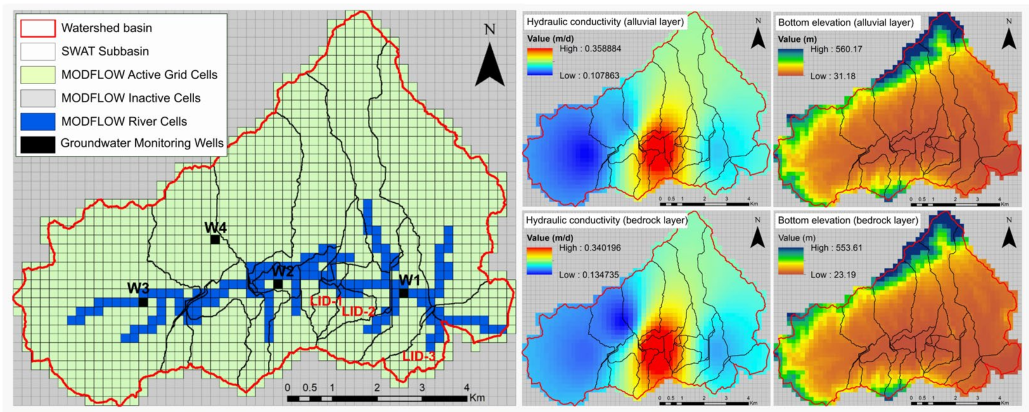

Figure 3. MODFLOW modeling area and input data for hydrogeological parameters.

The vertical hydraulic conductivity for the active grid cells was assumed to be one-tenth of the horizontal hydraulic conductivity. The storage coefficients for the alluvial and bedrock layers were derived from aquifer test data for Icheon, provided by the Korea Rural Community Corporation [21]. The recharge package in MODFLOW was used to define the boundary conditions for the recharge rate between the surface and the aquifer, and the river package was employed to establish the time-dependent head boundary conditions. This allowed the calculation of the water exchange between the stream and the aquifer based on stream water levels from the SWAT model and groundwater levels from MODFLOW. Additionally, to account for the groundwater pumping effect from the water curtain cultivation facilities in the watershed, a well package was set up using water balance monitoring data from water curtain cultivation [16].

The SWAT-MODFLOW model was used to simulate streamflow, water quality, and groundwater levels from 2016 to June 2021. The model was calibrated using flow observation data during normal conditions at the downstream end of the Sindun Stream from 2019 to 2021, as well as groundwater level data from two wells (W1 and W2 in Figure 1) located near the target sub-watersheds [19,20]. Model parameter optimization was performed using a combination of the automated calibration tool, SWAT-CUP 2019 (Calibration and Uncertainty Program) [22], and manual trial-and-error methods. Within SWAT-CUP, sensitivity analysis is inherently conducted as part of the calibration process, which allows us to identify and prioritize parameters based on their influence on streamflow. Although we did not present these sensitivity analysis results separately, they were integral in guiding parameter adjustments and optimizing model performance. Calibration performance was then evaluated using the coefficient of determination (R^2) and percent bias (PBIAS), metrics commonly employed to evaluate SWAT model performance [23]. The R^2 value ranges from 0 to 1, with values closer to 1 indicating a higher correlation between predicted and observed values. Generally, an R^2 value of 0.5 or higher is considered satisfactory for model performance [24,25]. PBIAS measures the percent error between predicted and observed values, with lower values indicating higher model efficiency.

2.3. Application of LID Technique Effects

In this study, the selected LID techniques for application in the urban sub-watersheds (LID-1, LID-2, LID-3) included green roofs, permeable pavement, infiltration trenches, and rainwater harvesting systems, which were commonly applied to urban areas and showed their effectiveness [7–9,12,26–28]. Green roofs involve planting vegetation on rooftops, which helps retain rainwater, reduces runoff, and promotes evapotranspiration. Permeable pavements allow water to infiltrate through porous materials, reducing surface runoff and enhancing groundwater recharge. Infiltration trenches are shallow, gravel-filled channels that facilitate rapid stormwater infiltration, which directly aids groundwater recharge. Lastly, rainwater harvesting systems capture and store rainwater, reducing the demand for surface water during dry periods and enabling a slower release to sustain baseflow.

Since urban areas in the land use map used for this study were classified into residential and commercial areas, we applied different combinations of LID for each land use: green roofs and rainwater harvesting systems in residential areas and permeable pavements, infiltration trenches, and rainwater harvesting systems in commercial areas (Table 2). The application areas of LID in each sub-watershed were determined considering the areas of residential and commercial areas.

Table 2. LID techniques and their coverage areas in target sub-watersheds.

Sub-Watershed	Area (km^2)	Application Area (km^2)		LID
LID-1	0.510	Residential	0.022	Green roof, rainwater harvesting system
		Commercial	0.005	Permeable pavement, infiltration trench, rainwater harvesting system
LID-2	0.644	Residential	0.022	Green roof, rainwater harvesting system
		Commercial	0.013	Permeable pavement, infiltration trench, rainwater harvesting system
LID-3	1.026	Residential	0.059	Green roof, rainwater harvesting system
		Commercial	0.043	Permeable pavement, infiltration trench, rainwater harvesting system

The efficiency of each LID technique was based on the values proposed by Arnold et al. [29]. For green roofs, the reduction efficiencies for SS and T-P were set at 85% and 25%, respectively. For permeable pavements and infiltration trenches, the SS reduction efficiency was set at 80%, while T-P reduction was set at 80% for permeable pavements and 60% for infiltration trenches. For rainwater harvesting systems, the reduction efficiencies for SS and T-P were set at 80% and 50%, respectively. The effectiveness of LID techniques on baseflow and water quality improvement during dry periods was evaluated by comparing the average baseflow and water quality concentrations between November and March, representing the dry season.

2.4. Baseflow Separation and Contribution Analysis Using WHAT

In this study, to evaluate the effects of LID applications on securing baseflow, WHAT was used to separate baseflow from simulated streamflow data before and after LID implementation. WHAT is a program developed to allow users to easily separate baseflow through a web interface. It employs the Local Minimum method (LMM) from the HYSEP (Hydrograph Separation Program) developed by the U.S. Geological Survey (USGS) [30], as well as the BFLOW filter [31] and the Eckhardt filter [32], both of which are based on digital filters for baseflow separation. Among these, the Eckhardt filter (Equation (1)) is widely used in South Korea for baseflow separation, as it improves upon the BFLOW filter by better reflecting aquifer characteristics [33,34].

The Eckhardt filter uses two key parameters: the "a" parameter, which is estimated through typical streamflow recession analysis, and the maximum value of the Baseflow Index ($\mathrm{BFI_{max}}$) Equation (2). The default values proposed by Eckhardt [32] for various aquifer types are commonly applied.

$$b_t = \frac{(1-\mathrm{BFI_{max}})ab_{t-1} + (1-a)\mathrm{BFI_{max}}Q_t}{1-a\mathrm{BFI_{max}}} \quad (1)$$

$$BFI = \frac{\sum_{t-1}^{n} b_t}{\sum_{t-1}^{n} Q_t} \quad (2)$$

where b_t is the baseflow at time t ($\mathrm{m^3\ s^{-1}}$), b_{t-1} is the baseflow at time $t-1$ ($\mathrm{m^3\ s^{-1}}$), Q_t is the total streamflow at t ($\mathrm{m^3\ s^{-1}}$), $\mathrm{BFI_{max}}$ is the maximum baseflow index value, and n is the total number of observations.

While the Eckhardt filter considers the characteristics of the watershed's aquifer, it has limitations in that it uses a single set of parameters to separate baseflow over the entire period [35]. In South Korea, streamflow variations due to precipitation are significant, so it is necessary to perform baseflow separation considering different flow conditions or seasonal characteristics. To address this, Yang et al. [35] developed the web-based WHAT2020 (Web-based Hydrograph Analysis Tool 2020) (https://app.envsys.co.kr/what2020/, accessed on 30 June 2024), which incorporates flow conditions (high flow, moist conditions, mid-range conditions, dry conditions, low flow) and seasonal (spring, summer, fall, winter) characteristics into the baseflow separation process. In WHAT2020, the "a" parameter and corresponding $\mathrm{BFI_{max}}$ for each group of flow conditions or seasons are used in baseflow separation. The "a" parameter is calculated using the gradient descent method from machine learning, while $\mathrm{BFI_{max}}$ is derived using a reverse estimation filter. Additionally, the web interface provides users with the baseflow separation results, including the "a" parameter, $\mathrm{BFI_{max}}$, Flow Duration Curves (FDC), and seasonal flow distributions.

Before evaluating the effects of LID techniques in the urban sub-watersheds, this study quantified the baseflow contribution to the streamflow in the Sindun Stream watershed. The BFI was calculated using the baseflow separation results from the WHAT. Furthermore, the baseflow separation results considering flow conditions and seasonal characteristics were derived using WHAT2020, and the resulting BFI values were compared to those calculated using the original WHAT. The streamflow data required for baseflow separation were obtained from the calibrated SWAT-MODFLOW model simulation for the period from January 2016 to October 2020.

3. Results and Discussion

3.1. Evaluation of SWAT-MODFLOW Model Applicability

The parameters selected for model calibration were based on studies that used SWAT for streamflow simulation [4,12,25]. The optimal values for these parameters are listed in Table 3. The calibration results for streamflow at the downstream point of the Sindun Stream watershed show an R^2 value of 0.71 (Figure 4), indicating that the simulated streamflow is considered satisfactory when compared to the evaluation criteria proposed by Moriasi et al. [23]. However, the PBIAS value was −35.4%, suggesting an overestimation of the simulated streamflow compared to observations. This low PBIAS value can be attributed to the concentration of observations in low-flow conditions, with only one high-flow data point (approximately 5.4 $m^3 s^{-1}$). Although the model overestimated most low-flow observations, the high-flow point offset this variation, yielding a higher R^2 but poor PBIAS. Additional high-flow observations could improve simulation accuracy by balancing the model's calibration for both low- and high-flow conditions.

Table 3. Parameters used for flow and groundwater level calibration.

Parameter	Description	Value
r_CN2.mgt	Soil Conservation Service (SCS) runoff curve number for moisture condition II	0.19
r_SOL_K(1).sol	Saturated hydraulic conductivity (mm/h)	0.19
r_SOL_AWC.sol	Available water capacity of the soil layer	0.5
v_ALPHA_BF.gw	Base flow recession constant (1/days)	0.5
v_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	600
v_GW_DELAY.gw	Delay time for aquifer recharge (days)	5
v_REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	100
v_GW_REVAP.gw	Groundwater "revap" coefficient	0.18
v_RCHRG_DP.gw	Deep aquifer percolation fraction	0.90
v_SHALLST.gw	Initial depth of water in the shallow aquifer [mm]	4900
v_DEEPST.gw	Initial depth of water in the deep aquifer [mm]	9900
v_LAT_TTIME.hru	Lateral flow travel time	9.90
v_ESCO.hru	Soil evaporation compensation factor	0.59
v_SLSOIL.hru	Slope length for lateral subsurface flow	103.05
v_CH_K(2).rte	Effective hydraulic conductivity for the main channel (mm/h)	443.5

'r_' indicates that the default parameter is multiplied by (1 + a given value). 'v_' indicates that a given value will replace the default parameter.

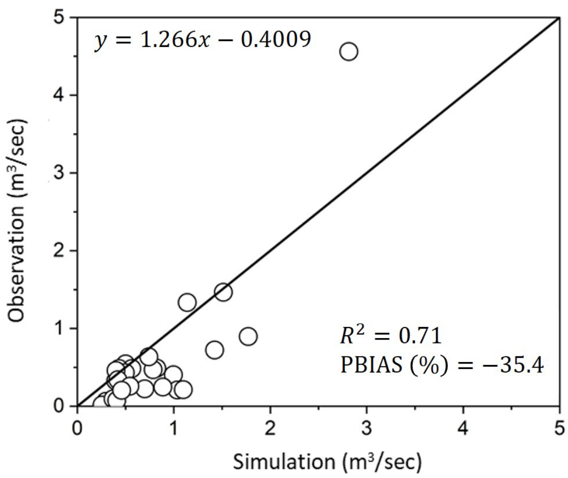

Figure 4. Scatter plot of observed and simulated streamflow.

Figure 5 compares the simulated groundwater levels with the observed groundwater levels at GW1 and GW2 wells. The calibration results show R^2 values of 0.67 and 0.64 and PBIAS values of 0.24% and −0.47%, respectively. These results indicate that the model generally performs well in simulating groundwater levels. Notably, the observed groundwater level fluctuations at GW2 were larger than those at GW1, likely due to the higher hydraulic conductivity of the aquifer, which makes the groundwater level more responsive. However, the model showed some difficulty in accurately capturing the rise and fall patterns of groundwater levels during periods with little rainfall compared to periods of summer rainfall. This is likely due to the fact that individual anthropogenic influences—such as water use in water curtain cultivation facilities and direct water abstraction from streams during farming seasons—were not accounted for in the model.

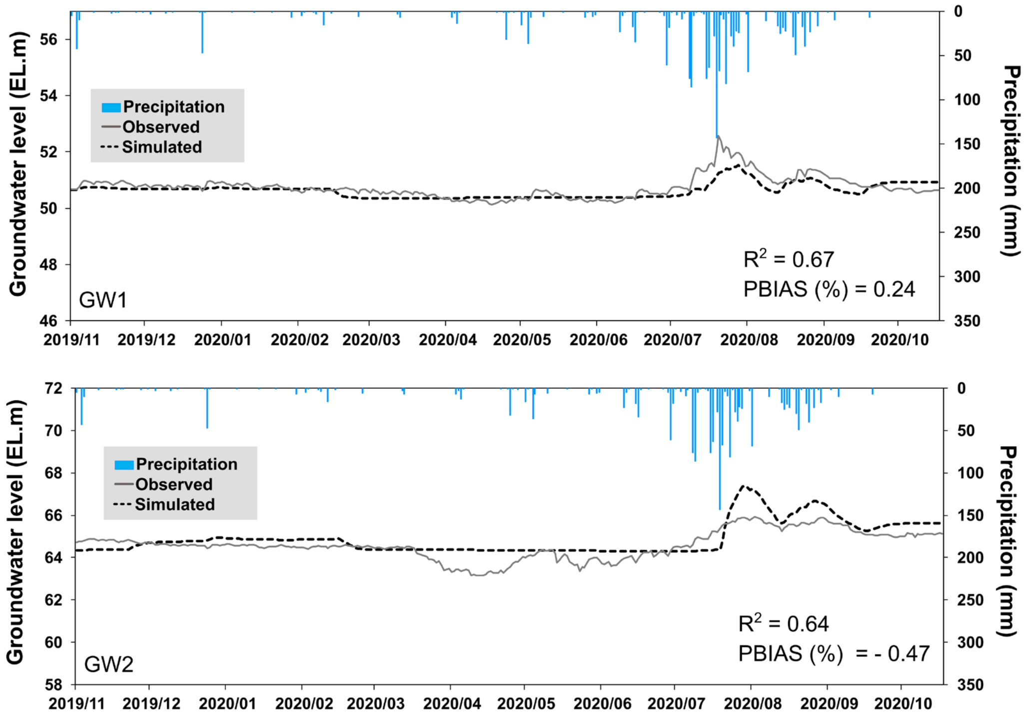

Figure 5. Time series of observed and simulated groundwater level.

The calibration performance for SS and T-P was evaluated with R^2 values of 0.91 and 0.72, respectively, indicating a good fit. However, the PBIAS values were −240.6% and 33.9%, suggesting that the prediction performance was somewhat poor. This may be due to the lack of specific calibration for water quality parameters. Furthermore, since the calibration was based solely on streamflow monitoring data during non-rainfall periods, the model likely struggled to accurately simulate the characteristics of SS during rainfall events. Future model calibration should incorporate additional streamflow and water quality monitoring data during rainfall events to improve model accuracy.

3.2. Results of Baseflow Separation by Flow Conditions and Season

Baseflow contributions for the Sindun Stream watershed were analyzed using a BFI by flow conditions and season (Figure 6). The average baseflow calculated for the Sindun Stream watershed using WHAT was 0.700 $m^3 s^{-1}$, with a BFI of 0.67. Notably, the average baseflow from October to February was 0.443 $m^3 s^{-1}$, a decrease of approximately 48.7% compared to the average baseflow of 0.862 $m^3 s^{-1}$ during the non-water curtain cultivation period. This reduction is due to the continuous use of groundwater near the stream, which lowers groundwater levels and subsequently affects baseflow, as suggested by Yang and Chi [36], who analyzed the correlation between groundwater levels and baseflow. This finding indicates that if the lowered groundwater levels during the water curtain cultivation period do not recover quickly, it could lead to reduced streamflow during agricultural activities [37]. Therefore, measures such as increasing groundwater recharge to mitigate the decrease in groundwater levels during agricultural activities are necessary for stable groundwater management.

The BFI, considering flow condition characteristics, was calculated as 0.86, which is higher than the BFI calculated over the entire period (Figure 6a). Compared to the average BFI of 0.55 (ranging from 0.42 to 0.70) for the Han River basin estimated using the WHAT by Hong et al. [38], this value was overestimated. Specifically, the "*a*" parameter calculated by the Eckhardt filter for different flow conditions was 0.778 during high flow, 0.954 during moist conditions, 0.986 during mid-range conditions, 0.974 during dry conditions, and 0.988 during low flow. The lower "*a*" parameter during high flow, caused by the sharp decrease in flow, likely led to an overall higher estimation of baseflow [39].

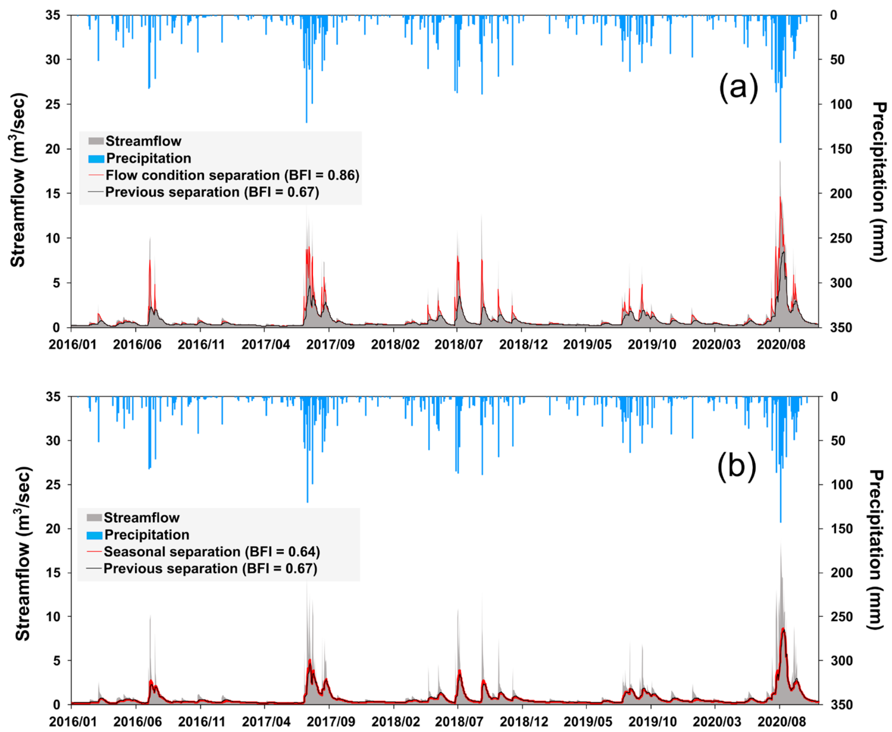

Figure 6. Results of baseflow separation results considering (**a**) flow condition and (**b**) seasonal characteristics. 'Previous separation' in each plot refers to a conventional baseflow separation over the entire simulation period.

In contrast, the BFI, considering seasonal characteristics, was calculated as 0.64, showing little difference from the BFI calculated over the entire period (Figure 6b). These results suggest that seasonal baseflow separation is more suitable for the Sindun Stream watershed than flow variability-based separation. The "*a*" parameter calculated by season was lowest in summer at 0.943, while it was 0.964 in spring, 0.966 in fall, and 0.985 in winter, indicating a gradual decline in flow across the seasons. The analysis showed that baseflow contributed an average of 91% of streamflow during dry and low-flow periods, with an average of 68% in winter and spring (Table 4), indicating significant variation depending on the period analyzed. While studies like Hong et al. [38] and Han et al. [40] provide baseflow contribution data for the Han River basin, which includes the Sindun Stream, direct comparisons are challenging because they did not divide the streamflow period and analyze baseflow contribution by flow regimes or seasons. However, given the variability of baseflow contributions throughout the periods, this study highlights the need for flow regime-specific baseflow analysis, particularly to assess the impact of LID in urban streams during dry periods.

Table 4. Average flow and baseflow by flow condition and season, and baseflow contribution.

Classification		Streamflow (m^3 s^{-1})	Baseflow (m^3 s^{-1})	Ratio of Baseflow (%)
Flow condition	High flows	5.104	4.172	81.7
	Moist condition	0.984	0.879	89.3
	Mid-range flows	0.471	0.432	91.7
	Dry condition	0.348	0.314	90.2
	Low flows	0.232	0.212	91.4
Season	Spring (Mar.–May)	0.534	0.342	64.0
	Summer (Jun.–Aug.)	2.146	1.281	59.7
	Autumn (Sep.–Nov.)	0.974	0.702	72.1
	Winter (Dec.–Feb.)	0.453	0.327	72.2

3.3. Effects of LID Techniques on Baseflow and Water Quality Improvement during Dry Periods

Figure 7 shows a comparison of the baseflow hydrograph and the FDC for streamflow before and after the application of LID techniques. As the baseflow increased due to the application of LID techniques in the target sub-watersheds, streamflow increased in all flow conditions except during the flood season. In contrast, the threshold flow (corresponding to the 10% exceedance flow on the FDC) for differentiating the flood season in each sub-watershed decreased by an average of approximately 27%, indicating the peak flow attenuation effect. The 10% exceedance flow threshold provides insight into the flood season's peak flow levels, indicating the flow rate that is exceeded only 10% of the time. This threshold reduction highlights the LID techniques' ability to mitigate peak flow events, which is consistent with findings from previous studies on rainfall retention through LID [9,27].

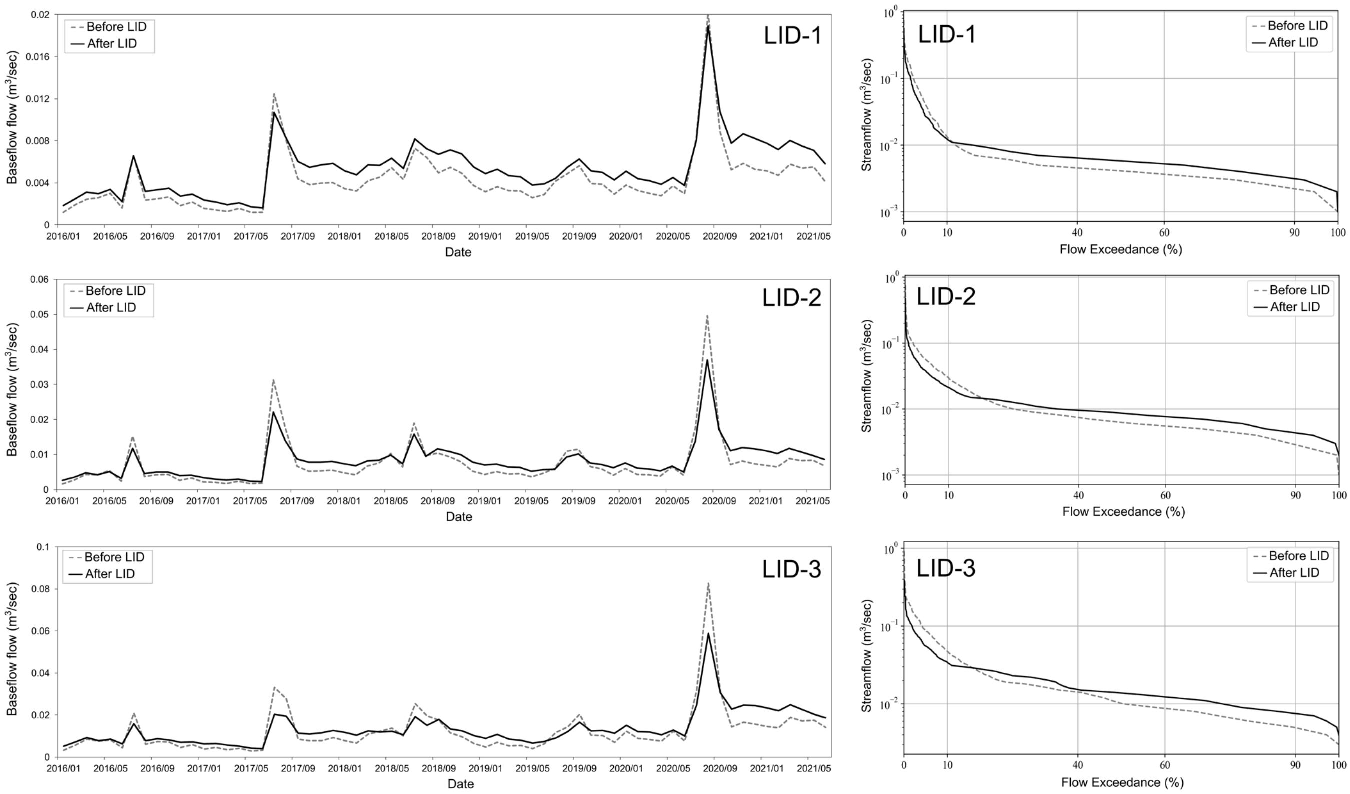

Figure 7. Comparison of baseflow and FDC before and after LID application.

Figure 8 compares the BFI and the average baseflow during dry periods, calculated before and after the application of LID techniques. In the LID-1, LID-2, and LID-3 sub-watersheds, the BFI increased from 0.39 to 0.53 (36%), from 0.55 to 0.67 (22%), and from 0.56 to 0.69 (23%), respectively, with an overall average increase of approximately 27% (Figure 8a). An increase in the BFI indicates a greater proportion of baseflow in the overall streamflow, which is critical for sustaining aquatic ecosystems and maintaining streamflow during dry periods. During dry periods, the average baseflow increased by 43.7% in LID-1, 42.6% in LID-2, and 43.3% in LID-3, with an overall average increase of about 43% (Figure 8b).

Additionally, the concentrations of SS and T-P in the LID-1, LID-2, and LID-3 sub-watersheds decreased by approximately 15% and 41%, on average (Table 5). This outcome is likely due to the combined effects of reduced stormwater runoff and increased infiltration from the application of LID techniques. The reduction in stormwater runoff directly lowers the pollutant load entering streams during rainfall events, while the increase in infiltration promotes deeper percolation into the soil. This enhances natural filtration processes such as pollutant adsorption and microbial degradation in the soil, resulting in improved water quality [41,42]. In addition, the relatively higher reduction effect of LID on T-P than that of SS also aligns with other studies [27,28]. This could be attributed to the finer particle size of phosphorus, which allows for more effective filtration as it percolates through soil and substrate layers. The increased retention time provided by LID techniques also enhances the interactions between phosphorus and soil particles, allowing for greater adsorption and microbial uptake. Furthermore, during dry periods, the mobility of T-P in dissolved form or associated with fine particles is higher than that of SS, which is less mobile and more dependent on sufficient runoff [2,43].

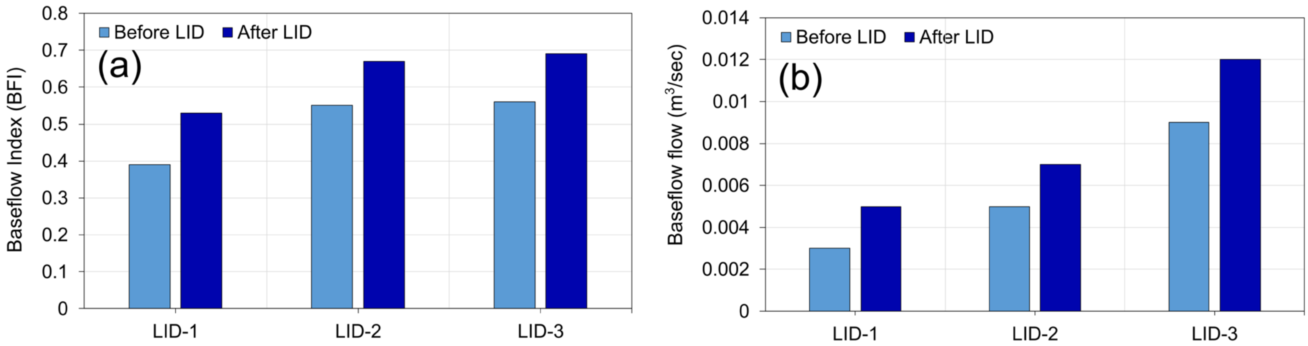

Figure 8. Comparison of (**a**) BFI and (**b**) dry season baseflow before and after LID application.

Table 5. Comparison of water quality concentration improvement due to LID application.

Sub-Watershed	SS			T-P		
	Before LID (mg/L)	After LID (mg/L)	Reduction (%)	Before LID (mg/L)	After LID (mg/L)	Reduction (%)
LID-1	138.70	119.87	13.6	0.050	0.029	42.0
LID-2	28.23	24.86	11.9	0.054	0.030	44.4
LID-3	34.36	27.97	18.6	0.048	0.030	37.5

These findings demonstrate that LID techniques not only mitigate peak flows during flood seasons and summer but also have a positive impact on securing baseflow and improving water quality during dry periods. Although the application of LID techniques in this study was limited to a specific area, the application of LID techniques in larger-scale urbanized dry areas, beyond the scope of this study, could help secure the necessary baseflow and improve water quality in downstream watersheds and sub-watersheds during dry periods.

4. Conclusions

This study evaluated the effects of various LID techniques (green roof, rainwater harvesting system, permeable pavement, and infiltration trench) on baseflow contribution and water quality during dry and low-flow periods using the SWAT-MODFLOW model and WHAT. In the Sindun Stream watershed, these LID techniques were applied to three urban dominant sub-watersheds. The results showed that the LID applications reduced peak flows during the flood season and increased baseflow by approximately 43%, and improved SS and T-P concentrations by 15% and 41%, respectively, under low-flow conditions. These findings demonstrate the effectiveness of LID in increasing baseflow contribution and improving water quality in urban streams, where over 91% of streamflow during low-flow periods and 68% during winter and spring depends on baseflow. While this study applied a combination of LID techniques, limiting direct comparison with studies that assessed LID techniques individually, the results suggest significant benefits for urban water management. Further research is needed to assess individual LID techniques under varied design conditions (e.g., location, capacity, material type) to refine these findings.

Securing baseflow is essential for maintaining the health of aquatic ecosystems and enhancing urban ecosystem resilience. This study provides valuable insights for developing sustainable watershed management strategies, such as urban ecological restoration projects. However, to more accurately assess the long-term effects of LID on water quality, additional monitoring data and further model validation are needed, particularly during rainfall events. The findings of this study offer important guidance for addressing the challenges of declining groundwater levels and reduced baseflow due to climate change and urbanization.

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