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Implication of Directly Connected Impervious Areas to the Mitigation of Peak Flows in Urban Catchments

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Abstract: The existence of impervious areas is one of the most distinguishing characteristics of urban catchments. They decrease infiltration and increase direct runoff in urban catchments. The recent introduction of green infrastructure in urban catchments for the purpose of sustainable development has contributed to the decrease in directly connected impervious areas (DCIA) by isolating existing impervious areas, and consequently, has also contributed to flood risk mitigation. This study coupled the width function-based instantaneous hydrograph (WFIUH), which is able to handle the spatial distribution of the impervious areas, with the concept of the DCIA to assess the impact of decreasing DCIA on the shape of direct runoff hydrographs. Using several scenarios for typical green infrastructure and the corresponding changes of DCIA for a test catchment in Seoul, South Korea, this study evaluated the effect of green infrastructure on the shape of the resulting direct runoff hydrographs and reducing peak flows. The results showed that the changes in the DCIA immediately affect the shape of the direct runoff hydrograph, and decrease peak flows by up to 12% depending on spatial implementation scenarios in the test catchment. This study demonstrates the importance of the DCIA concept for the evaluation of green infrastructures in urban catchments, enabling quantitative assessment of the spatial distribution of impervious areas, and also changes to the DCIA by various types of green infrastructure. The results of this study also suggest that more effective and well-planned green infrastructures could be introduced in urban environments for the purpose of flood risk management.

Keywords: urban catchment; drainage network; directly connected impervious area; width function; green infrastructure

1. Introduction

Broadly, the surface of an urban catchment can be divided into three distinct areas: impervious areas that are directly connected to the drainage system, such as roads, parking lots and, in some cases, roofs; additional impervious areas that are not directly connected; and pervious or semi-pervious areas consisting of lawns, gardens, and park lands [1]. The existence of impervious cover is one of the most distinguishing characteristics of urban catchments compared to natural ones, affecting both the quantity and quality of runoff [2]. Therefore, impervious cover is an important factor in the hydro-environmental analysis of urbanization impacts [3–5]. Understanding the contribution to runoff hydrographs from pervious and impervious surfaces is crucial for the hydraulic design of stormwater systems, as well as for modelling non-point source pollution [1]. In a general sense, urbanization is accompanied by an increase in impervious cover and, consequently, increases in both surface runoff [6] and flood risks [7–9].

The concept of directly connected impervious areas (DCIA) refers to a subset of impervious cover that is directly connected to a drainage system or a water body via continuous impervious surfaces [10].

The concept of DCIA is important, in that it is regarded as a better predictor of stream ecosystem health than the total impervious area (TIA) [2]. Researchers have found that the concept of DCIA improved the accuracy of runoff predictions [11], and also yielded more accurate results for water quality analysis [12]. In addition, DCIA is considered to be responsible for the majority of stream alterations due to urbanization [13–15].

DCIA is a key concept in better assessing green infrastructure, which has been receiving more attention recently. The term green infrastructure has been used in different ways in different contexts, but it basically refers to a natural process that is actively adopted to urban environments. The United States Environmental Protection Agency (USEPA) describes it as a cost-effective, resilient approach to manage wet weather impact that provides many community benefits [16]. The elements of green infrastructure include practices, methodologies, and systems that use or mimic natural processes, such as infiltration, evapotranspiration, retention or detention, and so forth. The adoption of green infrastructure in urban catchments for the purpose of sustainable development considerably contributes to the isolation or mitigation of the impact from existing impervious areas and, consequently, a decrease in the DCIA [15,17–20]. For example, surrounding a parking lot with vegetated swales isolates the impervious areas, which were previously connected directly to the main drainage system or a water body. Therefore, the concept of DCIA is crucial in terms of the evaluation of green infrastructure both in water quantity and quality.

For this reason, it is very important to accurately distinguish the DCIA from the total impervious area (TIA). The measurement of impervious areas in an urban catchment is challenging due to complex structures, materials, and different states of development in urban areas. It is even more complicated to identify DCIA, because it requires consideration of surface and subsurface runoff processes, flow paths, and drainage structures and their connectivity. The empirical relationship between TIA and DCIA as a function of land use was the first choice for researchers to easily obtain the DCIA [21–23]. USEPA [24,25] also adopted Sutherland's equations [23] to estimate DCIA based on land use types. However, land use categories are not often clearly distinguished, meaning that results can vary depending on the individual choices. Recently, a methodology based on a precise GIS database has been widely accepted among researchers to distinguish DCIA from TIA [12,26,27]. For example, Lee and Heaney [12] used polygon type coverage for every impervious surface and road boundaries from planimetric CAD drawings. They estimated DCIA with different levels of methodology for the analysis. Sahoo and Sreeja [27] determined DCIA by integrating remote sensing data, digitized drainage networks, and a DEM of the study area. The methodology determines DCIA based on a detailed impervious surface map compiled from various sources such as aerial photographs, satellite imagery and results from site surveys merged into a GIS database. The connectivity of impervious areas to a drainage system is a primary factor in identifying DCIA from TIA. Furthermore, it is able to consider surface flow directions to distinguish DCIA.

In spite of the active implementation of green infrastructure in urban environments for a sustainable and resilient society, the impact of green infrastructure on the direct runoff hydrographs is often not fully quantified. The aim of this study is to evaluate potential methodologies with the GIS database to identify and calculate the DCIA, and also to propose a methodology for assessing the impact of green infrastructure on the resulting direct runoff hydrographs of an urban catchment. This study couples the width function-based instantaneous hydrograph (WFIUH) [11], which handles the spatial distribution of the impervious areas, with the concept of the DCIA to assess the impact of decreasing DCIA on the shape of the hydrographs. Two types of green infrastructure (permeable pavement, redirection of rooftop runoff to infiltration areas) are introduced to different locations to show the importance of the spatial distribution of DCIA and, therefore, the strategic implementation of green infrastructure in an urban catchment.

2. Methodology

2.1. Study Area and Land Cover Data

In this study, three subcatchments (6.50 km^2 in total area) in the Shinweol Basin in Seoul, South Korea, were investigated as shown in Figure 1. The Shinweol Basin is a highly developed area with a mixture of residential and commercial areas. Drainage loads in the basin are mostly conveyed through underground networks of drainage structures, such as pipes and culverts that have replaced open channels and streams throughout the history of the city development. The Shinweol Basin, including the subcatchments in this study, suffered from heavy rainfall events in 2010 and 2011. The aftermath of the flood damage in 2010 and 2011 was severe. The Seoul Metropolitan Government implemented several structural projects, such as deep tunnels with diameters up to 10 m and depths of 50 m to keep and drain overflows. In addition, design criteria and design standards for urban drainage structures were re-evaluated and re-established. This study used a GIS database of the drainage network from the city government that includes pipes with diameters from 300 mm, and multiple box structures with single widths up to 4.5 m. Among 15 operational gauging stations in the Shinweol Basin, three gauges (Shinweol 1, Shinweol 3, and Hwagok 2) were used for validation and calibration purposes in this study. The flow data was collected and recorded every 10 min.

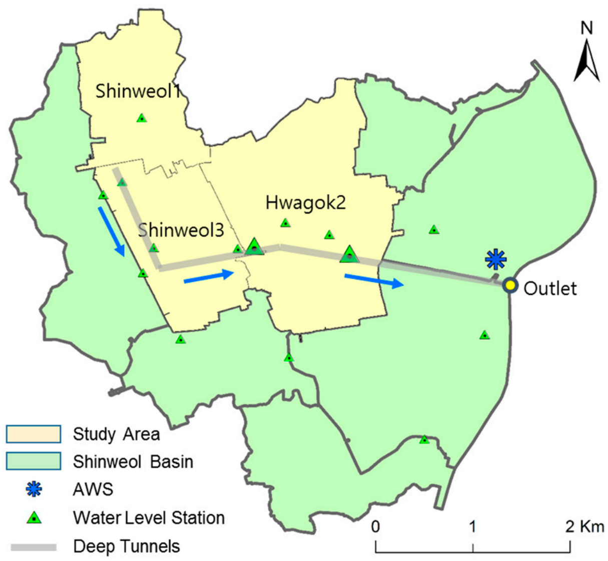
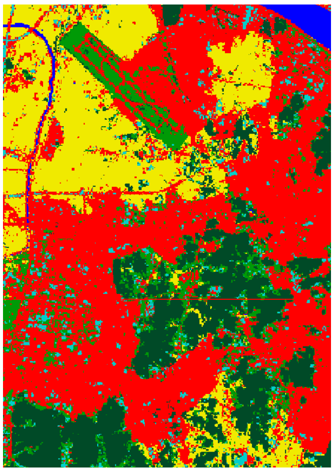
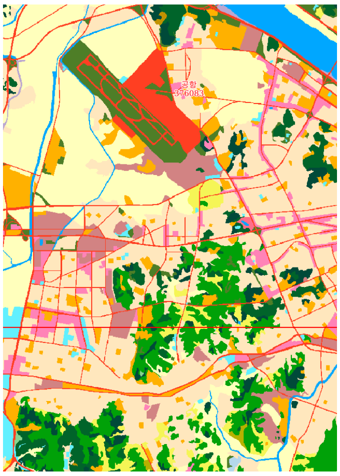
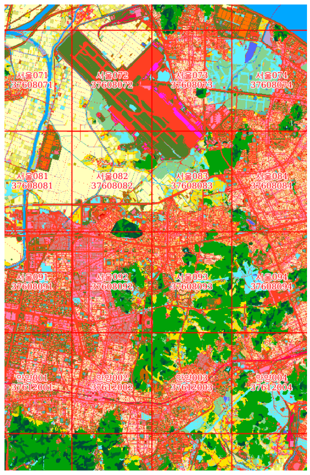


Figure 1. Study area in Shinweol Basin, Seoul, South Korea. Precipitation data with 10-min time intervals obtained from the Automated Weather System (AWS) in the basin.

2.2. Land Cover Data and Estimation of DCIA

In order to estimate TIA and DCIA, this study used high-resolution land cover data developed by the Ministry of Environment between 2013 and 2014 in Korea. This was built from various sources from satellites and air-photographs, with a spatial resolution of 1 m. The data sets were divided into three levels: low-level, mid-level, and high-level land cover data. Table 1 shows each land cover level and its characteristics. High-level land cover data describes the land use, with 41 land use classifications to identify the impervious areas. Figure 2 shows the high-level land cover data for the entire Shinweol Basin, where impervious areas could be obtained from the data.

Table 1. Land cover classification (Ministry of Environment, South Korea).

Low-level Land Cover Data	Mid-level Land Cover Data	High-level Land Cover Data
		
· Spatial resolution: 30 m · Classification: 7 items · Map scale: 1:50,000 · Data: Landsat TM satellite image	· Spatial resolution: 5 m · Classification: 22 items · Map scale: 1:25,000 · Data: Landsat TM + IRS 1C, SPOT5, Arirang 2 satellite image	· Spatial resolution: 1 m · Classification: 41 items · Map scale: 1:5000 · Data: Arirang 2, IKONOS satellite image, Air-Photographs

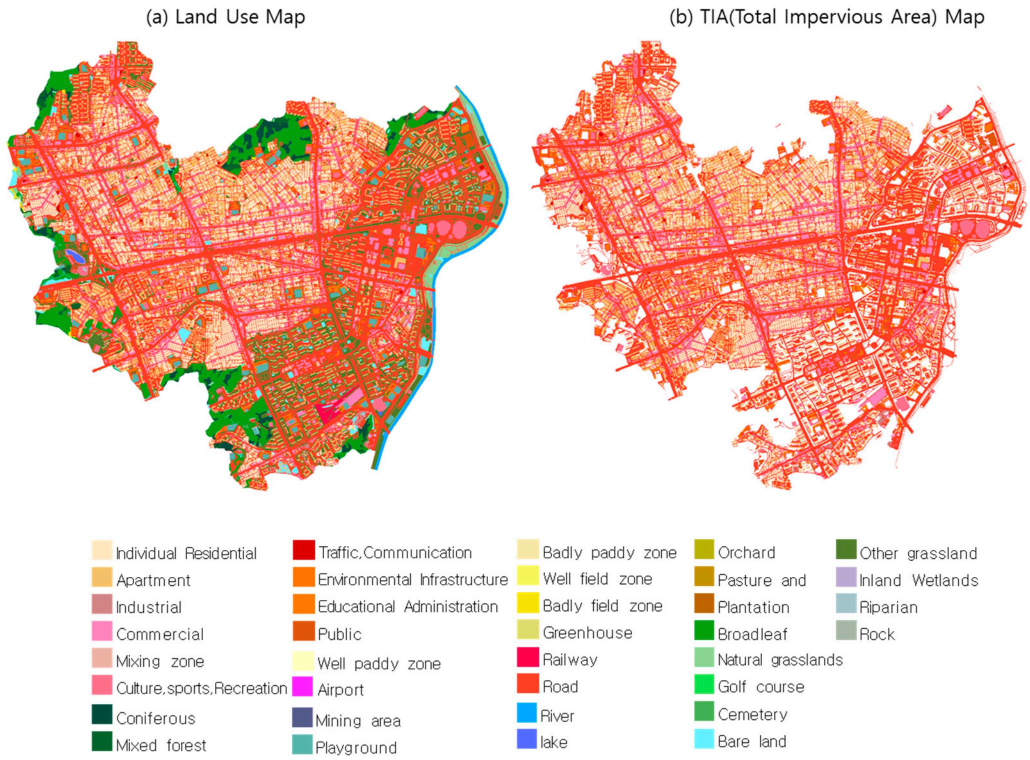


Figure 2. Land use map and total impervious area map identified from the detailed land use cover data of the Shinweol Basin.

In this study, the DCIA was obtained in four steps. First, isolated impervious areas (IIA) surrounded by pervious cover and remote from the storm drainage network were removed (Case 1). A threshold value of 1 meter was used to determine the IIA. Second, additional isolated impervious areas were identified even in areas directly connected to a main drainage system by considering flow directions obtained from the digital elevation model (Case 2). Case 2 distinguishes impervious areas that are connected to the main body of impervious areas as shown in the land cover map, but which are not connected to the drainage network. If other adjacent DCIAs are to the downstream of these impervious areas considering flow direction, these impervious areas remain as DCIA, but are otherwise removed. The flow directions were obtained from the DEM. Third, the land cover for schools and gardens were removed as these typically include pervious areas not identified by the land use cover (Case 3). Finally, apartments were removed, as they commonly include pervious pavement, raingardens, playgrounds, and green alleys (Case 4). Schools, gardens, and large apartment complexes were not deemed to be totally disconnected, in view of the detailed land cover, but regional characteristics were reflected in these facilities and buildings, which typically include elements of green infrastructure, such as pervious pavement, raingarden, green corridors, and alleys. However, classifying all apartments as DCIA should be done cautiously, because classification is highly dependent on regional characteristics, and further study on this is required. During the process of identifying DCIA, satellite imagery and drainage networks were also overlaid on the land user cover and taken into account for identification purposes. Figure 3 shows the basic procedure for determining DCIA using the threshold value. Figure 3a shows an impervious area connected to a road with a narrow path, the width of which is less than or equal to 1 meter. Using the buffer function in a GIS application, the boundary shrinks (Figure 3b) then expands back to its original boundary (Figure 3c), but the impervious cover is no longer connected to the drainage system as shown in Figure 3d.

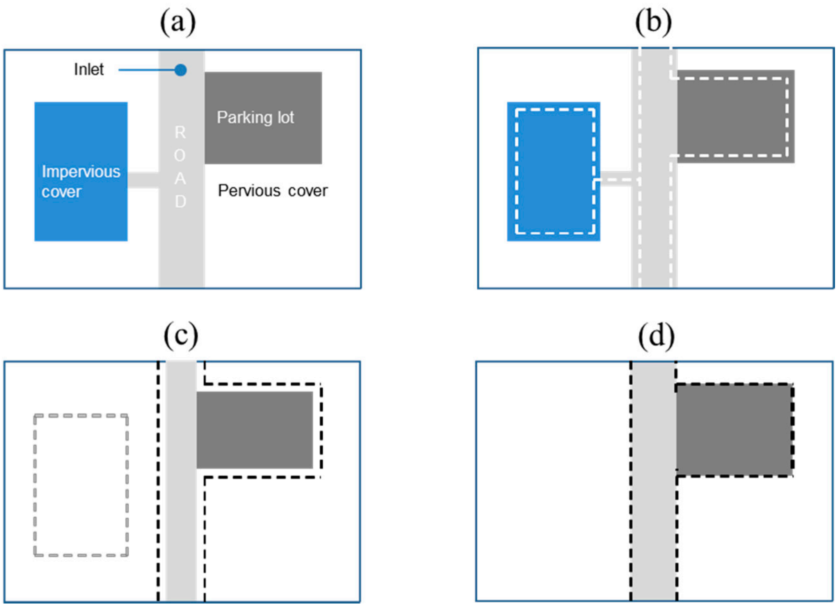


Figure 3. A procedure for determining DCIA using the threshold value and the buffer function in a GIS application.

2.3. Hydrological Modeling Using WFIUH and SWMM

The original approach for WFIUH [28] was a grid-based model, but it has not been applied to urban areas. This study utilized a methodology that conceptualizes the contributing area of an urban catchment [11,29,30] based on the DCIAs that are directly connected to the main drainage network, isolated impervious areas (IIAs) that need to travel through pervious areas to get to the drainage network, and pervious areas. The contribution of the pervious areas can be further divided into excess rainfall amount (ExPerv) and infiltrated rainfall amount (InPerv). Traditionally, no design is considered for the urban drainage media [31]. In contrast, this study includes the contribution from infiltrated rainfall (InPerv). In order to include the contribution from different parts of an urban catchment, this study introduces a hydrological response function at the outlet of a drainage network as:

$$h_i(t) = \sum_{j=1}^{n_w} (W_i(j\Delta x) \cdot f(j\Delta x, t) * g_i(t))\Delta x \quad (1)$$

where i = 1 for contribution from excess rainfall in DCIA, i = 2 for excess rainfall in IIA, i = 3 for ExPerv, and i = 4 for InPerv. Here, $W_{,i}$ is a width function obtained from the reconstructed network in a lattice. The term n_w is the maximum distance of the width function. In Equation (1), f is a response function of the main drainage network, and g is a response function for each contribution from DCIA, IIA, ExPerv, and InPerv, as shown in Figure 4. The response from the main drainage network is obtained from the solution of an advection-diffusion equation [32,33]:

$$f(i\Delta x, t) = \frac{i\Delta x}{\sqrt{4\pi D_1 t^3}} \exp\left[-\frac{(i\Delta x - c_1 t)^2}{4D_1 t}\right] \quad (2)$$

where c_1 and D_1 are the celerity and diffusion coefficient of the main drainage network, respectively. The response function from excess rainfall in DCIA, IIA, and ExPerv is given as:

$$g_i(t = 0) = 1, \text{ otherwise } 0; \text{ for } i = 1, 2, 3 \quad (3)$$

The flow path of the contribution from InPerv is not explicitly identified. Therefore, it is assumed that g_4 has the same form as in Equation (4), which is a solution of an advection-diffusion equation:

$$g_i(t) = \frac{\Delta x}{4\sqrt{\pi D_2 t^3}} \exp\left[-\frac{(\Delta x - 2c_2 t)^2}{16 D_2 t}\right]; \text{ for } i = 4 \quad (4)$$

where c_2 and D_2 are the celerity and diffusion coefficient of flow paths for InPerv. D_2 is assumed to be on the same order of hydraulic conductivity, and c_2 needs to be calibrated. Table 2 lists rainfall for each contributing area before and after saturation in pervious areas, where I_{imperv} denotes the excess rainfall considering depression storage only in impervious areas, and I_{perv} denotes the excess rainfall considering depression storage as well as infiltration in pervious areas. In Table 2, r_i is the impervious ratio of the catchment (TIA/total catchment area), and r_c is the area of IIA divided by the total impervious area (IIA/TIA). The term r_b is the contributing ratio of the infiltrated water to runoff that needs to be calibrated. Once calibrated, r_b represents the condition of the drainage system. For example, when r_b is bigger, the hydrograph at the outlet can be obtained as the sum of the convolution of the response function from each area and the corresponding rainfall as follows:

$$Q(t) = \sum_{i=1}^{n_c} h_i * I_i \quad (5)$$

where i = 1 for DCIA, i = 2 for IIA, i = 3 for ExPerv, and i = 4 for InPerv, respectively.

In this study, a detailed SWMM was used as a reference for hydrological modeling. The model consists of 7120 links and 6821 nodes, and the model (roughness coefficient) calibration is based on the observed flow data from 2012. All pipes and culverts with diameters equal to or bigger than 300 mm were included in the model. The cross-sectional geometry of the pipes or box culverts was collected from the GIS database of the city government.

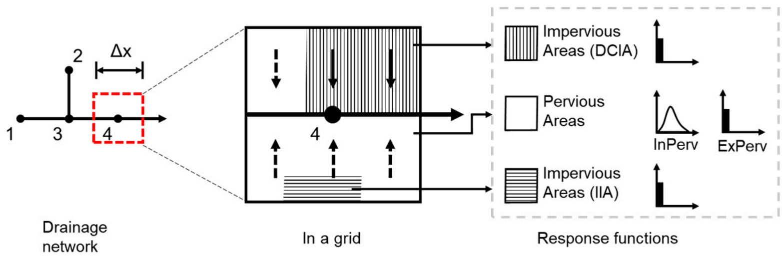


Figure 4. Response functions from each area (DCIA, IIA and pervious areas) contributing to runoff hydrographs.

Table 2. Rainfall intensity for each contributing area in an urban catchment.

Contribution	Saturation Condition	
	Before Saturation	**After Saturation**
DCIA	$I_1 = (1 - r_c) I_{imperv}$	$I_1 = (1 - r_c) I_{imperv}$
IIA	$I_2 = 0$	$I_2 = r_c I_{imperv}$
ExPerv	$I_3 = 0$	$I_3 = I_{ExPerv}$
InPerv	$I_4 = \left(1 + \frac{r_i r_c}{1 - r_i}\right) r_b I_{InPerv}$	$I_4 = r_b I_{InPerv}$

3. Results and Discussion

3.1. Estimation of DCIA with Stepwise Methods

Figure 5 and Table 3 show the DCIA using the methods described in Section 2.2. The blue areas are the isolated impervious areas identified in Case 1 to Case 4 in Figure 5. Table 3 shows that DCIA is close to TIA in Case 1. Figure 5a shows the DCIA where the apparent isolated impervious areas surrounded by pervious cover were removed (Case 1). The result illustrates that the discernable isolated impervious areas are very uncommon, and most of the impervious areas are interconnected with each other in the study catchments. Figure 5b shows the DCIA where additional isolated impervious areas, which were identified by flow directions, were removed (Case 2). In this case, the DCIA was reduced by 11% in Shinweol 1 subcatchment but less than 1.5% in other two subcatchments. The results show that DCIA was not reduced much in the study area even after considering the flow directions to identify isolated impervious areas. Figure 5c shows the DCIA where the land covers for schools and gardens were removed. This typically includes pervious areas not identified by land user cover (Case 3). In this case, the DCIA was reduced by from 2.2% (Shinweol 3) up to 12.2% (Shinweol 1). Finally, Figure 5d shows the DCIA when apartments with pervious pavement, raingardens, playgrounds, and green alleys were removed (Case 4). As mentioned earlier, the study area includes highly developed areas where most areas have impervious cover. The ratio of impervious area is high, from 85% (Hwagok 2) to 95% (Shinweol 3). Moreover, the ratio of DCIA compared to TIA is high, from 85% (Shinweol 1) to 96% (Shinweol 3), even if IIA is identified by the various methods and steps shown in Table 3. Most notably, subcatchment Shinweol 3 has a high imperviousness ratio (95%) and high DCIA ratio (96%).

Table 3. DCIA calculated for the study area.

Catchment	Area (km^2)	TIA (km^2)	DCIA (km^2)			
			Case 1	**Case 2**	**Case 3**	**Case 4**
Shinweol 1	1.524	1.368	1.364	1.216	1.197	1.159
Shinweol 3	1.725	1.674	1.674	1.670	1.636	1.605
Hwagok 2	3.255	2.773	2.770	2.726	2.658	2.632

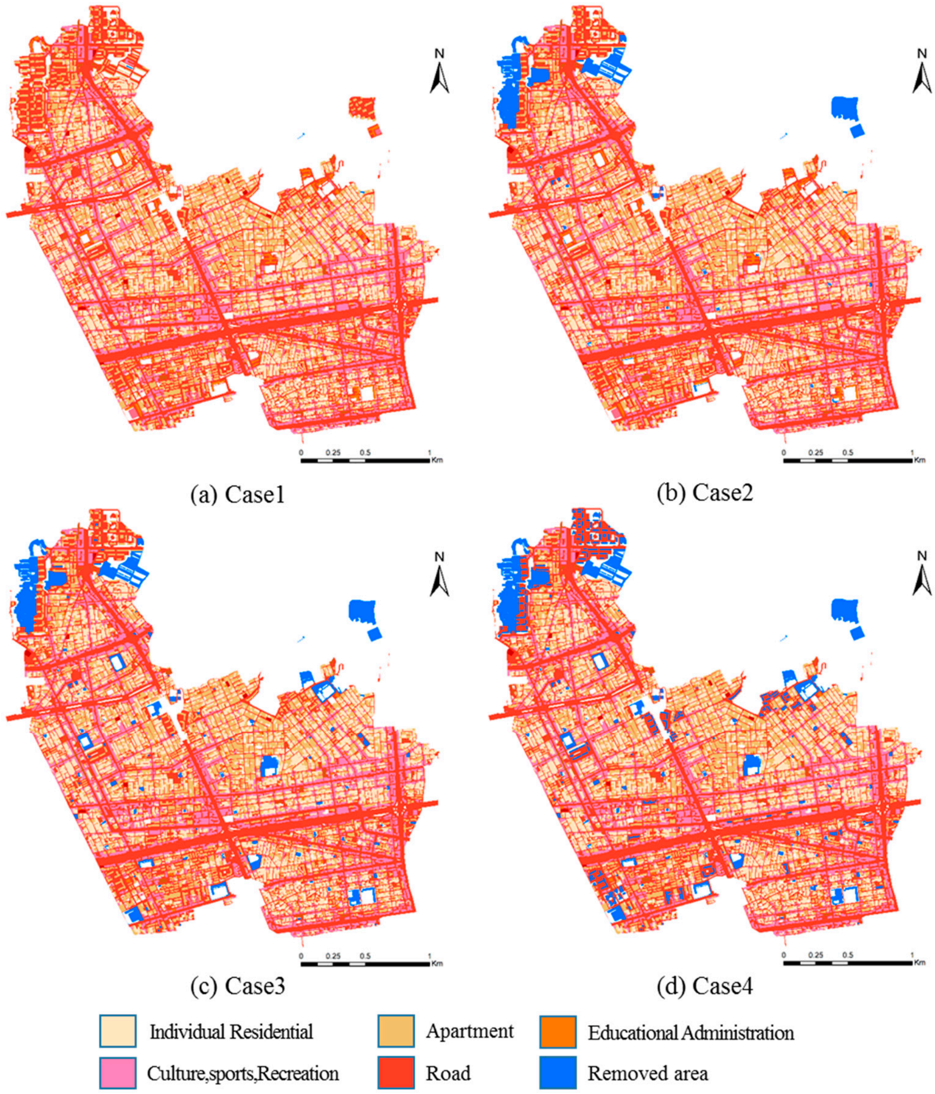


Figure 5. Land use map and total impervious area map identified from the detailed land use cover data of the study area.

3.2. Hydrological Response Estimation with WFIUH

Figure 6 shows the direct runoff hydrographs estimated by WFIUH compared to observation and the detailed SWMM at the two flow observation stations, Shinweol 3 (Figure 6a–c) and Hwagok 2 (Figure 6d). Note that Figure 6c,d were observed on the same date, but at different stations. Shinweol 3 is located upstream. Figure 6a shows the resulting hydrographs considering the stepwise method (Case 1 to Case 4) described in the previous section. The results indicate that Case 4 shows the best estimation compared to the observed flows. The result demonstrates how important the estimation of the DCIA is in terms of flow estimation in urban catchments. It is also interesting that identification of the DCIA using a specific method, such as apparent isolated impervious areas (Case 1), would result in a biased estimation of the runoff hydrographs. Therefore, the estimation of the DCIA should be conducted cautiously, and the results should be verified using an appropriate hydrological model that is able to assess the effect of the DCIA at various urban catchment scales. WFIUH is a simple conceptual model that is capable of handling the DCIA in an urban catchment. It also shows a good estimate of the direct runoff hydrographs compared to observation as well as the highly detailed and heavy SWMM model.

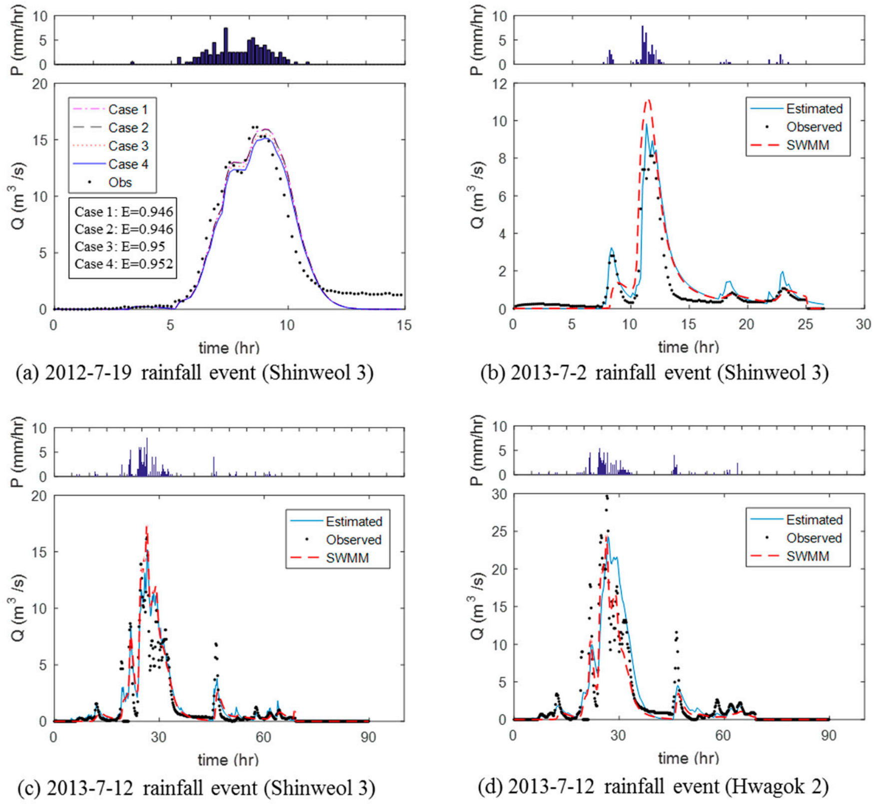


Figure 6. Runoff hydrographs estimated by WFIUH compared with observation and detailed SWMM.

However, the changes of the DCIA are very small for the two subcatchments, Shinweol 3 and Hwagok 2, and resulted in slight changes of peak flows as shown in Figure 6a. As shown in Table 3, the DCIA was reduced after identifying IIA mostly at subcatchment Shinweol 1, compared to the other two subcatchments. Unfortunately, WFIUH was not applied to Shinweol 1 because the subcatchment area was too small. Alternatively, Figure 7 shows the inverse proportionality of the peak flows and the DCIA reduction ratio for the storm event of 19 July 2012. The relationship is very linear, because the ratio of the DCIA linearly decreases with the contributing rainfall (as shown in Equation (5) and Table 3). The result shows the peak flow sharply decreases with decreasing DCIA. The decreasing ratio of peak flow is 5 m^3/s per 10% decrease in the DCIA, which is equal to a 1.1% peak flow decrease per 1% decrease in the DCIA.

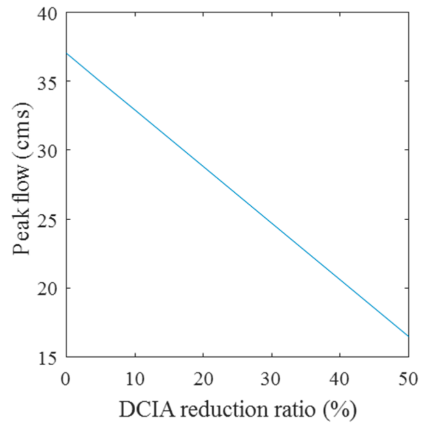


Figure 7. Peak flow as a function of DCIA reduction ratio at Shinweol 3 for the storm event on 19 July 2012.

3.3. Resulting Direct Runoff Hydrographs Depending on Implementation Scenarios of Green Infrastructure

Based on the results from the previous sections, this study evaluated the impact of spatial planning for green infrastructure on the shape of the resulting direct runoff hydrographs. To accomplish this, three scenarios for green infrastructure for the test catchments are introduced, as shown in Table 4 and Figure 8. Scenario 1 converts existing impervious surfaces, such as individual residential and apartment parking lots, which were identified as DCIA, to permeable pavement. Scenario 2 includes the redirection of rooftop runoff to infiltration areas. Scenario 3 includes the implementation of both Scenario 1 and 2. This study applied the above scenarios separately to the upstream, mid-stream, and downstream catchment areas, depending on the distance from the outlet of the test catchment, to evaluate the impact of the spatial planning of green infrastructure. In this study, the reduction factors, which were suggested by USEPA [14], were used for implementation of typical green infrastructure. This reduction factor refers to the reduction ratio of DCIA from its original state. For example, if the reduction factor is 0.25, the area of DCIA is reduced by 25%. The disconnection coefficient suggested by USEPA (2014) is 0.25 for Scenario 1 and 0.15 for Scenario 2. Even though the disconnection coefficient is smaller for Scenario 2, the changes in the DCIA for Scenario 1 are bigger than in Scenario 2. This is because the application area for the permeable pavement is much larger than the rooftop redirection, as shown in Figure 8. The ratio of the DCIA compared to TIA for each scenario is applied separately to the upstream, mid-stream, and downstream areas of the test catchment.

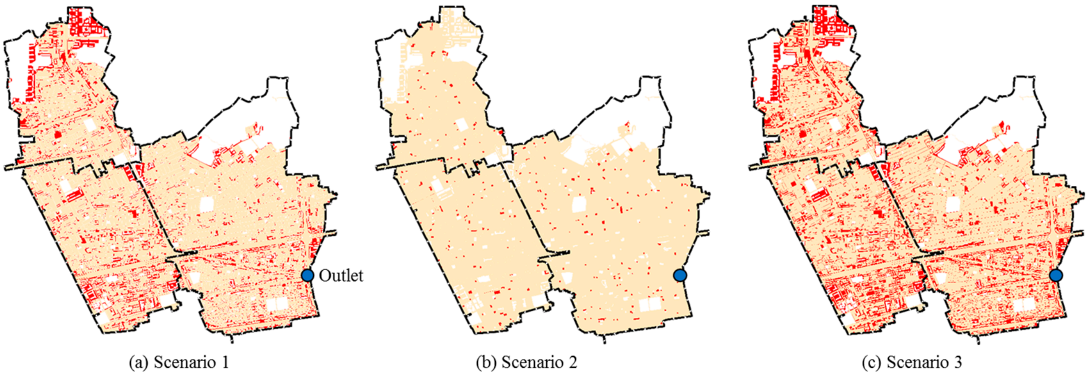


Figure 8. DCIA reduction scenario maps (red areas) where two types of green infrastructure were applied: (**a**) permeable pavement (Scenario 1), (**b**) redirection of rooftop runoff to infiltration areas (Scenario 2), and (**c**) Scenario 1 + Scenario 2 (Scenario 3).

Table 4. DCIA reduction scenarios for the test catchment.

Scenario	Description	DCIA (%)			
		Present	Applied to Upstream	Applied to Midstream	Applied to Downstream
Scenario 1	Convert roads, individual residential and apartment parking lots to permeable pavement	82.95	63.76	81.41	74.27
Scenario 2	Redirection of rooftop runoff to infiltration areas		74.94	91.57	79.91
Scenario 3	Scenario 1 + Scenario 2		62.69	79.93	73.34

Figure 9 shows how changes in the DCIA ratio were applied to WFIUH based on grids. The scenario map (Figure 6) was averaged on grids based on the WFIUH runs. When Scenario 1 is applied to upstream areas, the map shows clear differences, with low DCIA ratios in the upstream areas compared to the other two maps for Scenario 1. Scenario 2 shows little difference, but Scenario

3 results in maps similar to those for Scenario 1. Figure 10 shows the resulting hydrograph for the application of Scenario 3 to the entire catchment where the peak flow was reduced by 12%. It should be noted that the storm event was not large enough to examine the contribution of a delayed response from permeable areas; that is, the thick tail was not shown, as in Seo et al. [11] for hypothetically greater storms. Table 5 lists the resulting peak flows by introduction of green infrastructure for the entire basin, upstream areas, mid-stream areas, and downstream areas, respectively, for Scenarios 1, 2, and 3. The results show that the peak flow can be reduced by 12% for Scenario 3 compared to the current state. Scenario 2 shows a 0.5% to 1% decrease in peak flows due to little changes in the DCIA as shown in Figure 9.

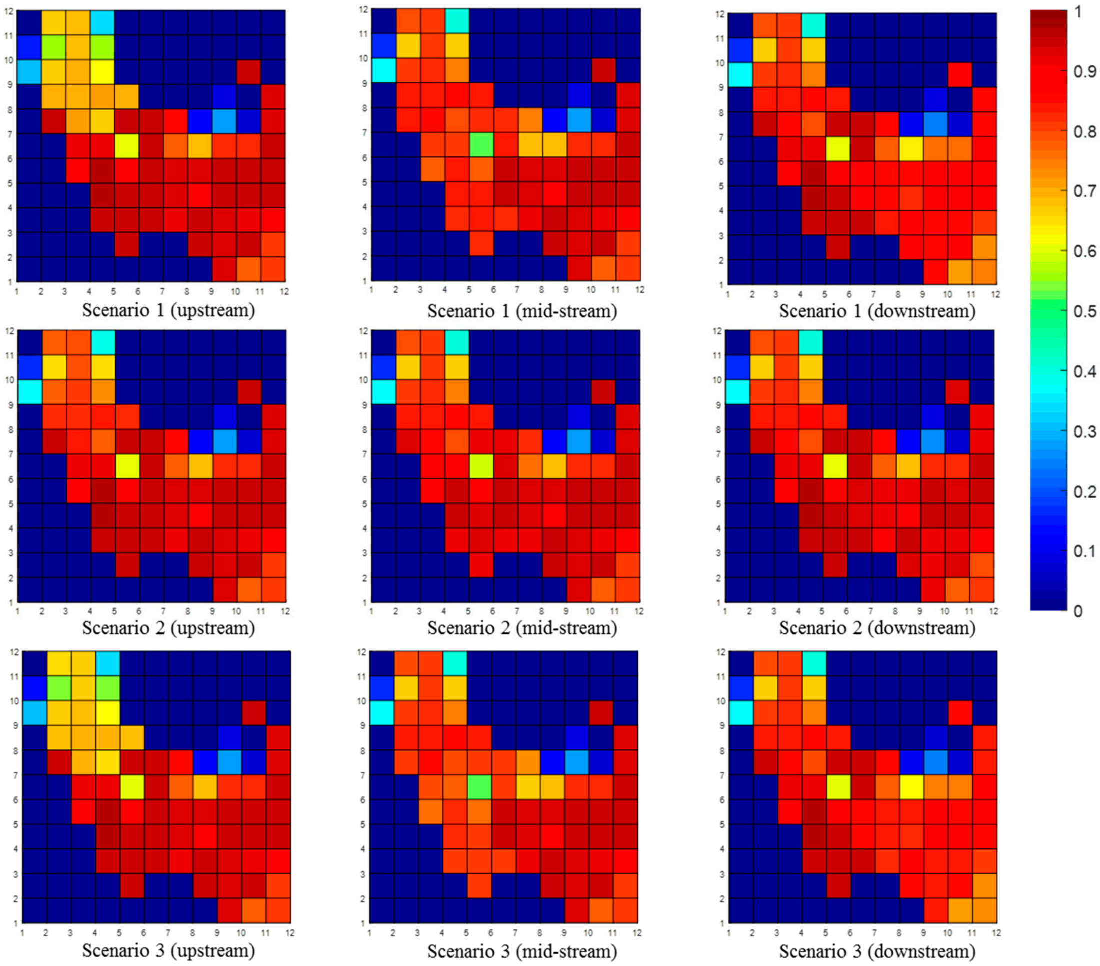


Figure 9. Application of Scenarios to WFIUH by changing the DCIA ratio on grids. The DCIA ratio is the DCIA divided by the TIA. Therefore, the closer the DCIA ratio is to 1, the more likely it is that most of the impervious area is directly connected to the drainage network. Conversely, the closer the DCIA ratio is to zero, the less direct connection to the drainage network in the impervious area.

Table 5. Resulting peak flows by application of green infrastructure.

Application Areas	Peak Flows (m^3/s) for the Storm Event on 12 July 2013			
	Current State	Scenario 1	Scenario 2	Scenario 3
Entire catchment	36.96	32.98 (−11%)	36.39 (−2%)	32.48 (−12 %)
Upstream areas		36.09 (−2%)	36.83 (−0.5%)	36.03 (−3%)
Midstream areas		35.61 (−4%)	36.73 (−1%)	35.39 (−4%)
Downstream areas		35.19 (−5%)	36.74 (−1%)	34.97 (−5%)

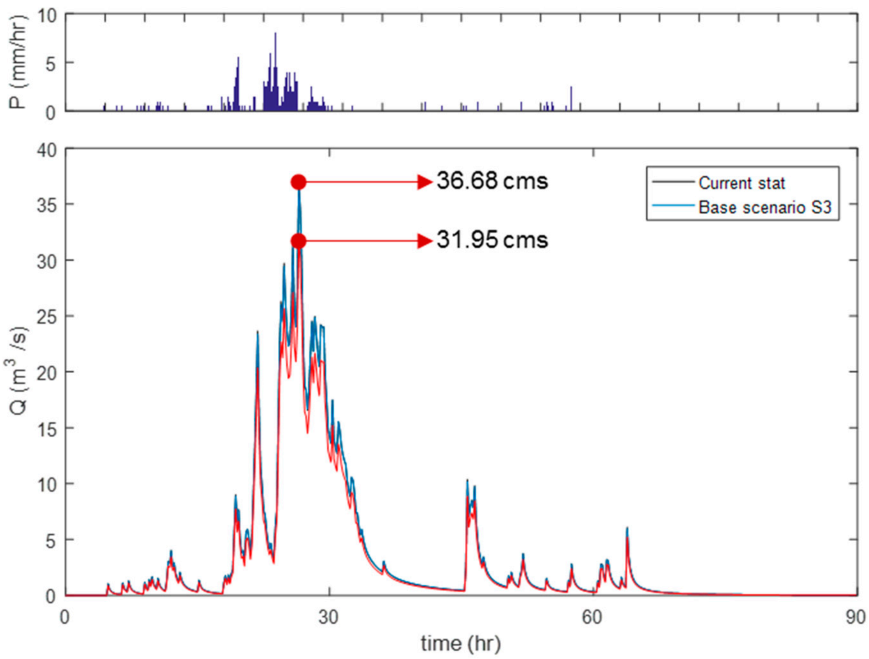


Figure 10. Resulting hydrograph for the application of Scenario 3 to the entire catchment with peak flow reduction of 12 % for the storm event on 12 July 2013.

In spite of the limitations of this study, which was confined to specific catchments on specific spatial and temporal scales, the results showed that the difference in peak flows depend on the location of the implementation. It implies that strategic planning for green infrastructure in urban environments will improve the run-off issues. Table 5 shows that if Scenario 1 is introduced, there will be a difference in peak flow reduction from −2% to −5%, depending on the location of the application. The reduction of peak flows is not quite as impressive when implementing the potential green infrastructure in this study. This is due to the selection of measures for which simulations were conducted using more realistic and potential alternatives in the test catchment.

4. Conclusions

Researchers have found that the DCIA of an urban catchment is a more accurate factor for evaluating the changes in hydrological regimes than the TIA. This study assessed the impact of green infrastructure in urban catchments, focusing on their effect on decreasing DCIA. To accomplish this, three implementation scenarios of green infrastructure for the test catchment were introduced, focusing on the effect of spatial implementation planning. Coupled with the WFIUH, which is able to consider the spatial distribution of the impervious areas considering DCIA, the results showed that changes in the DCIA immediately affect the shape of the direct runoff hydrograph and decrease peak flows, depending on spatial implementation scenarios. The results imply that estimation of the DCIA should proceed with caution, and the results should be verified using an appropriate hydrological model that is able to assess the effect of DCIAs on a catchment scale. WFIUH could be a good alternative due to its simplicity, and also the capability of handling DCIA in urban catchments. It also provides good estimates of direct runoff hydrographs compared to observation, and even the highly detailed heavy SWMM model. Although the disconnection coefficient suggested by the US EPA is quite empirical and can be improved on a site-specific base, it still implies the importance of DCIA in the evaluation of green infrastructures. The quantitative assessment of the spatial distribution of the impervious areas and the changes in the DCIA suggest that more effective strategic planning of green infrastructure should be introduced in urban environments for flood risk management. This study left the quantitative cost-benefit analysis based on the suggested approach to future study.

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