The PSR-based approach to categorize an urban drainage basin

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Abstract

This research aims to develop a PSR-based categorization method for an urban drainage basin. A dramatic increase in urban flooding in the era of climate change is a global phenomenon. Recently, a range of efforts have been made to overcome extreme urban flooding with the concepts of Low Impact Development (LID) and Korea's Total Urban Flood Mitigation Strategy (TUMS). Both the TUMS and LID concepts recognize a limited role of traditional, structural hazard mitigation measures in coping effectively with the flooding problem, and emphasize the emerging role of urban planning and design. Given that, various urban design techniques have been introduced to minimize the volume of urban runoff, to enhance rainwater holding capacity in urban areas and to control the speed of urban runoff, etc. These techniques are to be applied in consideration of any physical and sociocultural characteristics of the urban drainage basin. And, the urban drainage basin is to be categorized into different types based on hydrologic characteristics of the basin, such as slope, shape, and soil type, and also on sociocultural ones, such as population density and land use. The lack of a scientific approach to identify different types of urban basin in consideration of sociocultural factors, however, makes the urban planning or design measures to be strategically applied throughout the urban area. This research proposes a new identification or categorization method based on TUMS' PSR, which refers points, sites, and regions, respectively. This PSR-based identification method is designed to help to establish local context-based flooding hazard mitigation goals and strategies and also place the right countermeasures in the right place, resulting in the enhancement of the efficiency and effectiveness of the current urban planning or design measures.
Keywords: urban flooding, LID, hazard mitigation, drainage basin.

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1 Introduction

Heavy rains due to recent climate changes increase the frequency and extent of flood damage in urban areas, and in order to prepare for these circumstances, the concept of Total Urban Flood Mitigation Strategy (TUMS) [1] has been introduced. The concept emphasizes the importance of land use planning in consideration of urban flooding hazard as well as the preparation of comprehensive disaster prevention measures using Low Impact Development (LID) urban design techniques. The LID urban design techniques are developed to reduce the volume of urban runoff, to control the speed of urban runoff or to increase the holding capacity of stormwater in urban areas [2–4]. These techniques should be implemented and applied separately in consideration of the hydrologic characteristics of the urban drainage basin as well as the sociocultural characteristics such as land use and building density (or population density). However, the objective categorization system to subdivide the urban drainage basin by applying these characteristics comprehensively is inadequate so that it is difficult to arrange and use LID urban design techniques strategically. Therefore, this research is based on the PSR concept proposed as part of Total Urban Flood Mitigation Strategy (TUMS) and aims to present the categorization method for urban drainage basin using the Basin Tool which is one of ArcGIS's spatial analysis tools.

2 The PSR concept and LID

2.1 The PSR concept in TUMS

The occurrence of hydrometeorological disasters such as flooding and typhoon started to increase constantly and significantly since the 1950s and has been rapidly increasing since the late 1990s [5]. Most of natural disasters (over 90%) occurred in Korea is originated from storm and flooding. That is, flooding damage due to storm (61.3%) and flood (28.0%) account for more than 89% of natural disasters occurred within the recent 10 years (1998–2007) [5].

Since damage from storm and flood become intensified, the importance of comprehensive urban flooding mitigation or management has been emphasized in Korea and the relevant researches are in progress actively. Sim [1] introduces the concept of 'Total Urban Flood Mitigation Strategy (TUMS)' in which all integral parts of city are claimed to play their active roles in urban flooding hazard mitigation and proposes the PSR concept. The PSR concept provides the theoretical frame for categorizing urban drainage basin by dividing the whole urban drainage basin into P (Point or Line), S (Site), and R (Region) and it also contributes to the establishment of customized urban disaster mitigation goal. In other words, under the PSR concept, P (Point or Line) is the point or facility where disaster occurs so that it requires hazard mitigation or prevention facilities; and S (Site) is the directly affected area which requires active urban planning measures such as development restrictions, reinforcement of land use regulation, and relocation. On the other hand, R (Region) is the region which triggers the damage of S indirectly. It, however, has wider area unlike the other two, so that it is difficult to establish the standardized disaster mitigation goal and strategies. In other words, it is necessary to establish the customized disaster mitigation goal and strategies in consideration of the hydrologic and sociocultural characteristics of each constituent part that forms R. Therefore, based on the PSR concept, this research aims to present the categorization or subdivision method focusing R region.

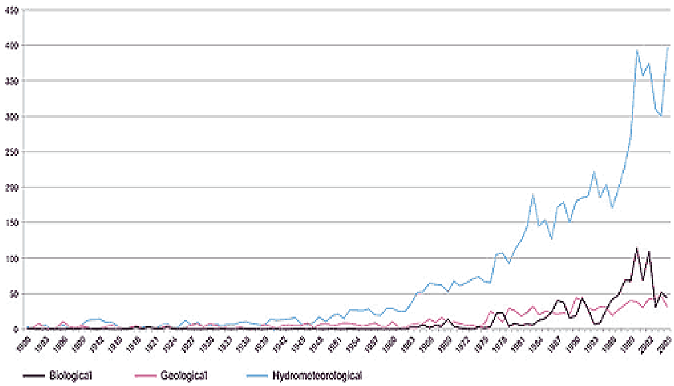


Figure 1: Number of people reportedly affected by disasters 1990–2008 (source: http://www.happyheartsfund.org/disstat.php).

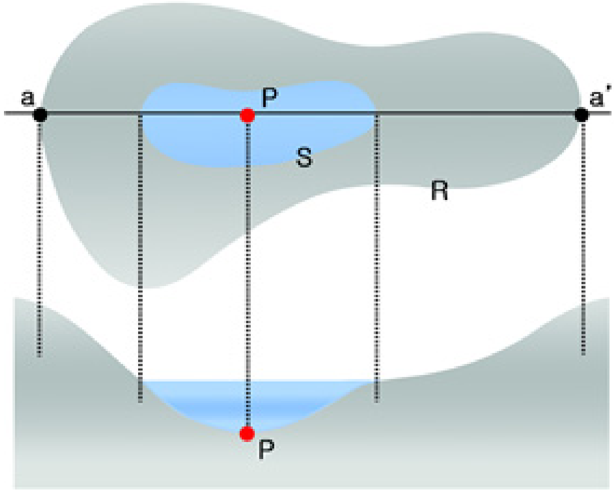


Figure 2: PSR concept.

2.2 LID

According to the TUMS, region with damage triggering effect (R) is the area where it is highly necessary to introduce and apply various flooding mitigation urban design measures to prevent or minimize the triggering effect, and applicable urban design measures can be drawn through the recent LID-related research and cases which are actively in progress. LID aims to improve the hydrologic soundness of a developed area, of which the soundness level is similar to the natural condition before development [2–5], and for this goal, LID has three strategic goals for stormwater runoff management, which include the improvement of rainwater holding capacity, the improvement of rain water permeability on the ground and the reduction of non-point source (NPS) pollution. Among the LID techniques developed under these three goals, LID measures aiming to the improvement of rainwater holding capacity and improvement of water permeability on the ground were mainly reviewed in this research. However, the measures closely related to the reduction of NPS pollution such as "bioswale" and "conservation buffer facility" shown in Figure 3 also contribute to the delay of rainwater runoff speed and improvement of holding capacity, so the suitability test for the constituent parts or units of R is carried out for all LID measures and facilities mentioned in Figure 3.

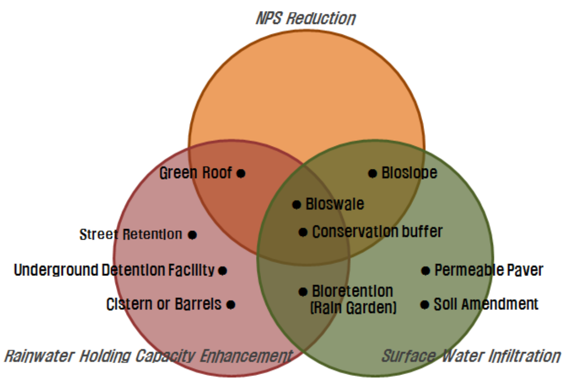


Figure 3: LID main measures for the suitability test.

3 Categorization method for urban drainage basin

3.1 The PSR-based categorization for urban drainage basin

In order to categorize urban drainage basin using GIS based on the PSR concept, the DEM (Digital Elevation Map) is to be established first and the DEM is created from surface elevation data such as the contour map. And, this DEM is used as basic input data of ArcGIS Hydrology analysis which is required for the categorization.

3.1.1 Identification of P (point or line) and S (site)

The identification of P (point or line) and S (site) in the urban drainage basin is possible through repetitive flooding experiences in the relevant urban area or advanced hazards vulnerability analysis. And, the order of establishing P and S is not important. For instance, in case frequently flooded zone due to heavy rain exists in a specific urban area, the relevant flooded zone can be identified as S, and the point with the lowest elevation in the relevant S can be set as P. On the other hand, in case it is possible to determine the accurate point of cause regarding flooding hazard such as levee failure, river overflow, or stormwater overflow, P is to be set first and then the based on P, the flooded zone can be inferred and set as S based on P. In most cases, P can be indicated with a point, but in case the point of causing damage is linear such as overflow or wave overtopping, it can be indicated with a line.

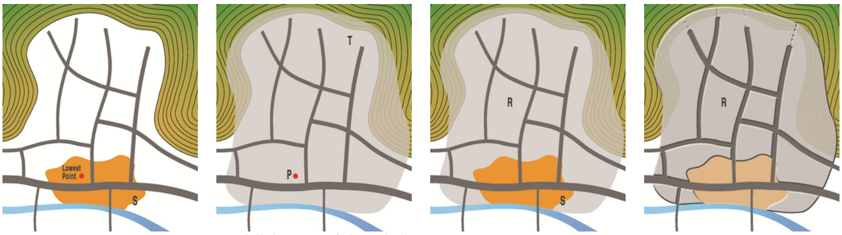
The boundary of S can be set based on the future rainfall projection result in consideration of previous heavy rain-related weather data. In some cases, all areas below the highest flood level in the past can be set as S or the boundary of S can be set based on the flood level in 100-year, 50-year or 30-year frequency level. On the other hand, in case of an area with significant change in the heavy rain condition expected due to climate change, the boundary of S can be set based on the future prediction value under the climate change scenario such as the representative concentration pathway (RCP). However, political decision based on land use, population density and existence of main facilities in the relevant area is required for determining the boundary of S finally. And, according to the relevant decision, the boundary of S can be set conservatively or precautionary.

3.1.2 Identification of R (region)

All drainage basin types where stormwater runoff flows into the lowest point of P set above fall under potential R. In order to draw the potential R first, ArcGIS's Basin Tool is used. The Basin Tool sets the catchments basin of stormwater runoff by identifying the ridge between basins according to the difference in elevation and the direction of runoff based on the DEM. All areas except for S in the whole drainage basin drawn through the Basin Tool is set as final R, and R is divided into units to reflect the hydrologic and sociocultural characteristics of detailed drainage basin that forms R. For dividing R into constituent units, it is divided first based on the blocks having the arterial roads or semi arterial roads in R as the boundary in order to reflect the hydrologic and sociocultural characteristics of relevant area easily. Figure 4 shows the establishment procedure for R and the concept of unit block division of R.

3.1.3 Categorization of R (region) based on hydrologic characteristics

The unit block of R is categorized based on the hydrologic characteristics first. And, the flow pattern of stormwater runoff on the ground and the average degree of slope in the block are considered as the hydrologic characteristics in this research. The flow pattern of stormwater runoff on the ground inside of the block can be divided into the outflowing type where stormwater runoff on the ground flows out the surrounding blocks and the inflowing type where stormwater runoff on the ground gathers inside the block. In order to determine whether the type of each unit block is the outflowing type or the inflowing type, ArcGIS's flow direction tool and flow accumulation tool are used in this research. The flow accumulation analysis determines each cell in the relations with its surrounding cells based on the flow direction analysis. In this research, the cells where the stormwater runoff flows in from more than 8 surrounding cells are regarded as the inflowing type cells, and in case the inflowing type cells account for more than 30% of the whole cells in the unit block, the relevant block is categorized as the inflowing type block.



Identification of S's Lowest Point

Establishment of the whole drainage basin (T) using the basin tool (based on the lowest point)

Identification of R (R = T – S)

Division of R based on arterial or semi arterial roads

Figure 4: Procedure of R-zone division.

Also, for other hydrologic characteristics, the average degree of slope in the block is considered in this research. And, the unit blocks of R are categorized on the basis of 4% presented as the standard of judgment by Lynch and Hack [7] for urban utility construction or design in this research. In other words, if the average degree of slope in the unit block is over 4 %, the relevant block is considered as the steep slope type, and if the average degree of slope is less than 4 %, the relevant block is considered as the gentle slope type.

The unit blocks of R are divided into 4 types based on the standard for determining types mentioned above. The first type is the gentle slope outflowing type, and stormwater falling on the relevant block tends to flow out slowly to the outside of the block, not the inside of the block. Therefore, it is advisable to establish the heavy rain-related main disaster mitigation goal for the relevant block for introducing widely distributed infiltration methods which are considered to be effective due to gentle slope in reducing stormwater runoff to the outside. The second type is the steep slope outflowing type, and stormwater falling on inside the block of the relevant type tends to flow out fast to the outside of the block. Therefore, it is advisable to set delaying the speed of stormwater runoff by actively using dispersed detention methods rather than the infiltration method of which efficiency is in doubt due to steep slope as the main mitigation method.

The third type of unit block is the gentle slope inflowing type, and stormwater in the relevant block tends to gather into a specific location in the block slowly. Therefore, it would be possible to establish the goal for restricting the outflow to the outside through the dispersed or centralized infiltration methods. Lastly, the

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fourth type of unit block is the steep slope inflowing type, and stormwater in the relevant block tends to gather into a specific location in the block fast. Therefore, it is necessary to find locations in the block where local flooding is expected in the block of the relevant type and establish measures as well as make efforts to delay the speed of stormwater inflow to a specific location through the dispersed detention method. Table 1 shows 4 types of unit blocks in consideration of the hydrologic aspects, hazard mitigation management goal for each type and main methods.

Table 1: R unit block types in consideration of the hydrologic characteristics and major mitigation goals and methods for each type.

		Surface runoff direction	
		Outflowing	**Inflowing**
Slope	**Gentle** **(< 4%)**	**Type I: gentle slope outflowing type** Major goal(s): Reduction of stormwater runoff to the outside Major method(s): Dispersed placement of infiltration methods	**Type III: gentle slope inflowing type** Major goal(s): Restriction of stormwater runoff to the outside Major method(s): Concentrated placement of infiltration methods
	Steep **(≥ 4%)**	**Type II: steep slope outflowing type** Major Goal(s): Delay of stormwater runoff speed to the outside Major method(s): Dispersed placement of detention methods	**Type IV: steep slope inflowing type** Major goal(s): Finding areas with concern of local flooding and establishing the relevant measures Delaying the stormwater runoff speed to a specific location Major method(s): Concentrated placement of detention methods

3.2 Selection of detailed mitigation measures in consideration of sociocultural characteristics

The reason why main roads are used as the boundaries of R unit blocks in this research is to reflect sociocultural characteristics actively rather than to draw the hydrologic characteristics of unit block easily. And, the sociocultural characteristics of unit block which could be considered include physical characteristics such as land use and building coverage ratio of unit block, average ground area size of building, average floor area ratio and roof shape and non-physical characteristics such as population density, land value and local economy conditions. The main hazard mitigation methods for the 4 types drawn based on the hydrologic characteristics are again divided into 2 measures, and the arrangement type of the methods is divided into the dispersed type and the centralized type. However, it is advisable to decide and introduce the detailed measures for each method based on the sociocultural characteristics of relevant

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unit block. For instance, in case a specific block falls under "steep runoff type", it is appropriate to introduce the dispersed detention method. However, it is necessary to decide which of various dispersed detention methods to be introduced to the site based on the consideration of sociocultural characteristics. In other word, in case the roof shape of the building in the relevant block is the gable shape, it is advisable to install cistern barrels on the ground rather than the roof, and in case of the building with flat roof, stormwater detention through rooftop greening may be considered preferentially.

Similarly, the average building coverage ratio and land use in the block may also have a significant effect on the selection of mitigation measure. In case the building coverage ratio is relatively high, the introduction of rooftop greening measure or underground retention facility may be advantageous, and on the other hand, in case the building coverage rate is low and abundant green exists in the unit block, the dispersed arrangement of conservation buffer and small and medium size ecological retention facility may be reviewed actively. Besides these physical and sociocultural factors, non-physical and sociocultural factors such as the financial support capacity of local governments and the participation degree of residents should be actively considered in the process of selecting the final mitigation measures to be introduced. For instance, in case the participation degree of residents is high, it would be possible to introduce the rainwater cistern to be installed in each building, but if not, the effectiveness of the cistern which requires voluntary management by each resident may be decreased significantly. The following section 3 will provide an explanation on a series of process from the categorization of urban drainage basin types based on the hydrologic characteristics to the decision of detailed introduction measures for each type reflecting the sociocultural characteristics targeting a frequently flooded zone located in Busan, Korea.

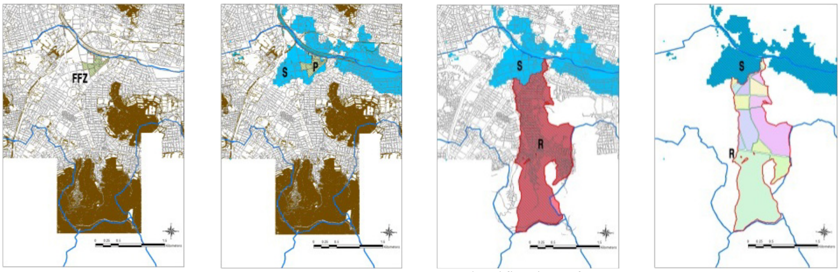
4 Site application

4.1 Introduction of the site

The target site to apply the categorization method for urban drainage basin and the measures to draw introduction measures for each type proposed by this research is the area including the frequently flooded zone (FFZ) designated by Busan metropolitan city government. The relevant frequently flooded zone with an area of 136 m^2 falls under the lowland near the stream in urban area which is called Oncheon-cheon, and this is the area where flooding occurs frequently due to localized heavy rain during the rainy season in summer.

4.2 Identification of P, S, and R

Given that the FFZ is located near the stream in urban area, accumulation of urban runoff is the main cause for flooding. It is, therefore, difficult to determine the accurate point of damage cause (P). Therefore, the lowest point in the relevant frequently flooded zone is determined as the point of damage cause (P) in this research, and all areas below 5.19 m which is the planned flood level falling under 100-year frequency are set as S in a broad sense to emphasize the preventive aspect. For setting R, the whole drainage basin T with P as the reference point is drawn using the Basin Tool which is ArcGIS's analysis tool and the direct damaged area (S) is excluded.



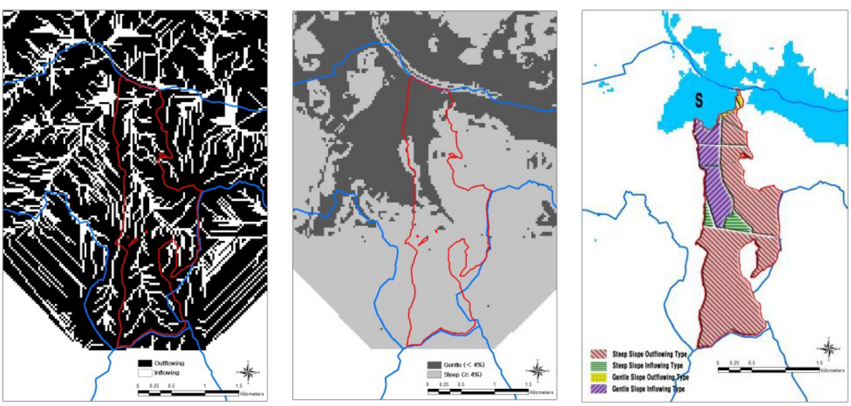
Location of the Site | Identification of P and S | Identification of R (R = T – S) | Division of R

Figure 5: Procedure of R-zone division.

4.3 Categorization of R

In order to divide R into constituent unit areas or blocks, the road networks on the relevant area are overlapped over the DEM. Next, the blocks having arterial roads or semi arterial roads as the boundaries among various levels of road hierarchy are established, and each established block is considered and categorized as the constituent unit of R.

The flow accumulation analysis and slope analysis is carried out using ArcGIS based on the DEM established for categorizing R unit block. And, the whole unit blocks are categorized into 4 types as shown in Figure 2 based on 30% of the inflowing type cells and a slope of 4%.



Result of accumulation analysis | Result of slope analysis | Four types of R constituent blocks

Figure 6: Categorization of the constituent blocks.

4.4 Selection of urban design flood mitigation measures suitable for the context

The selection of urban design mitigation measures is carried out at first by considering the goals, methods and placement pattern for each type stated in Table 1. In case it is similar to the flatland type as Types I and III, infiltration measures and facilities are reviewed preferentially rather than detention measures and facilities. And, in case of Type I, the dispersed arrangement is proper, so water permeability pavement, green watercourse and conservation buffer related facilities which are advantageous for dispersed arrangement in comparison to other detention facilities may become the target of prior review. On the other hand, in case of Type III, the introduction of infiltration facilities using the flat land can be reviewed preferentially. However, it is advisable to determine the areas where water catchment are possible in the unit block and then arrange the facilities concentrated. Therefore, it is possible to review preferential introduction of ecological detention-related facilities and relevant soil improvement measures that are favorable for centralized detention. The target urban design measures or facilities for prior review for each type drawn through similar process are as shown in Table 2.

Table 2: Major and supplementary urban design measures for each R unit block type.

Type	Type I	Type II	Type III	Type IV
Major method	Dispersed placement of infiltration methods	Dispersed placement of detention methods	Concentrated placement of infiltration methods	Concentrated placement of detention methods
Supplementary method	Dispersed placement of detention methods	Dispersed placement of infiltration methods	Concentrated or dispersed placement of detention methods, dispersed placement of infiltration methods	Dispersed placement of detention or infiltration methods
Priority measures	Permeable pavement, bioswales, conservation buffer	Cisterns, roof gardens, underground detention facilities	Biore(de)tention, soil amendment, etc.	Underground detention facilities, etc.
Supplementary measures	Cisterns, roof gardens, underground detention facilities	Permeable pavement, bioswales, conservation buffer	Underground detention facilities, cisterns, roof gardens, underground detention facilities, permeable pavement, bioswales, conservation buffer	Cisterns, roof gardens, underground detention facilities, permeable pavement, bioswales, conservation buffer

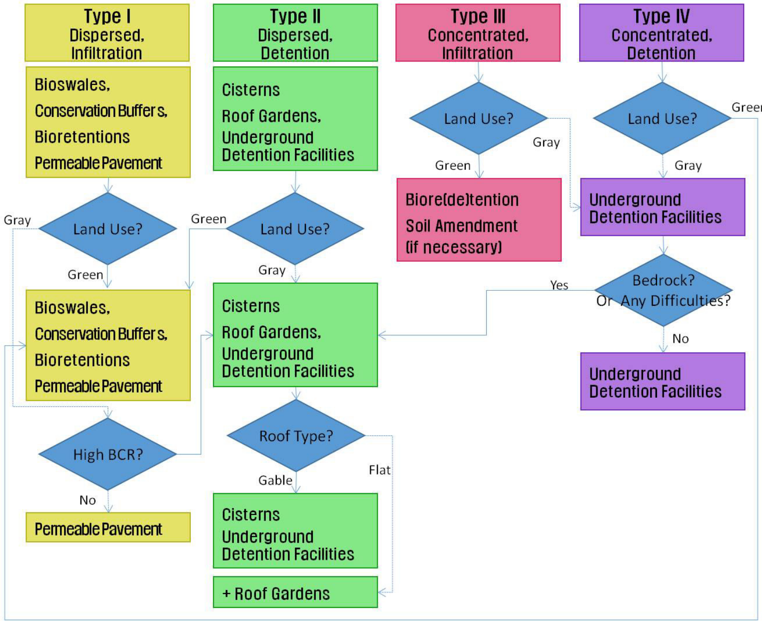


Figure 7: Urban design measure selection process.

However, for the target urban design measures for prior review presented in Table 2, only the hydrologic characteristics of the relevant block are considered, and the sociocultural factors are not reflected. Therefore, it is possible to narrow down the priority options for appropriate urban design measures or facilities through the review of sociocultural factors, and in some cases, it is possible to select only among the urban design mitigation measures or facilities which fall under the secondary or supplementary measures. For instance, in case the main land use is for commercial business and building coverage ratio in the block is high even if the relevant unit block falls under Type III, it would be difficult to introduce the centralized detention facility. Therefore, it is necessary to consider both dispersed infiltration facilities and centralized detention facilities for this case. For the method to draw urban design measures introduced experimentally through this research, land use, building coverage rate and roof types are considered as sociocultural factors. Figure 7 shows an example of the urban design measure selection process in consideration of R unit type and its sociocultural conditions.

5 Conclusion

This research aims to present the method to divide urban drainage basin on the PSR concept of TUMS in Korea in order to contribute to the strategic arrangement of urban design flood mitigation measures. The region (R) among the whole urban drainage basin regarding the frequently flooded zone is divided into constituent unit blocks based on the arterial road network, and the divided unit blocks were categorized into 4 types based on the hydrologic characteristics of each block. In this research, the main flooding hazard mitigation or management goals were established first according to the hydrologic characteristics, and the detailed urban design measures which were considered proper for each block in consideration of both hydrologic and sociocultural characteristics were proposed in the aspect of major measures and secondary (or supplementary) measures. For selecting proper urban design measures or facilities for implementation, it would be possible to review the urban design measures or facilities among major methods first, and in case it is difficult to introduce the relevant facility due to sociocultural factors and it is possible to consider secondary option. It is to be appropriate to review the urban design facilities titled as secondary measures.

This research has been carried out in order to contribute to the establishment of an automated decision-support system. And, the system is being developed to efficiently deal with urban flooding hazard in Korea, which hazard is expected to become worsen in the future. The verification of the hydrologic criteria used for this research's R categorization is to be done in following research. Following research is also to focus on identifying other significant sociocultural factors which affect the local suitability of urban design mitigation measures and on improving the algorithm for the decision making process.

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