The Investigation and Management of Precipitation Infiltration in Urban Area of Taipei

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Abstract: In-site surveying soil hydraulic conductivity in the practical infiltration situation using GIS, for a rainfall had been quantified assessment in Taipei. Result shows that the practical hydraulic conductivity in an area is positively related to the rainfall types, the coefficient of soil hydraulic conductivity, and the effective infiltration rates in this district surveyed. To inject precipitation into groundwater is the most important way to help urban soil ecosystem. The maximum infiltration capacity (referred as MIC) is 5.19~47.21(m^3/hr) in this survey found in a great space variability, and infiltration capacity in most urban areas will need to be improved. The most effective ways improving the real infiltration quantity would promote: (1) the coefficient of soil hydraulic conductivity by improving the compounds of the soil; (2) the ratio of infiltrative area by changing the pavement material to be pervious one in urban areas and; (3) the duration or the delay for infiltration after rainfall. All these results could be made guidelines to regulate the urban plan and users. This work will be helpful to building user, architects, urban designers and city decision makers.

Key-words: Soil hydraulic conductivity, Infiltration, Rainfall, Urban ecology, GIS, Stormwater, MIC.

1. Introduction

Due to the rapid development of the urbanization, the pavement of urban construction and facilities cause the decrease of the infiltrative area, thus insufficient penetration of precipitation into ground which has seriously deteriorated the urban hydrology cycle as a result of decreasing infiltration and inflow. This is a major issue in urban stormwater management. Moreover inadvertent soil compaction at the urban lot scale reduces infiltration rates, which can lead to increase stormwater runoff, and to enhance urban heat island (referred as UHI)[7, 17], consequently endangers the whole ecosystem and air quality of urban area [3-5, 12]. In Taipei the UHI intensity patterns have an increasing tendency with 0.011^{o}C in monthly average for the past ten years, this is an alarming feature [7, 8]. Thus, an effective mitigation strategy for UHI effects, such as increasing green area as well as infiltration area study [6, 14] etc. is very urgent in the city. The infiltration investigation and management were conducted in this study; this work is also related with the conduct of water supply and distribution systems, of urban runoff and water conservation, and water demand operation. In order to further understand rain infiltration in urban it is very important to investigate the effects of grid scale heterogeneities, especially infiltration process in urban area. Although many cities have provided regulations for vegetation and open space, however, an efficient model to manage infiltration and to quantify precipitation infiltration in urban area are still in an infant stage. One of the most pronounced features of the land surface is its heterogeneity [16]. Merz, et al. [10] demonstrated, by their data analysis and simulations, that the effect of spatial variability for the infiltration process is the great importance. Brito et al. [1] used GIS to identify maximum infiltration areas and evaluated aquifer vulnerability to delineate a protection strategy for municipal water supplies, and they argued that the critical step is to analyze hydrogeological parameters by grades of infiltration and to combine delimiting the most favorable aquifer recharge areas. Locally infiltrating stormwater into the ground instead of discharging to conventional pipe sewers is increasingly considered as a means of controlling urban stormwater runoff [11]. In some aspects stormwater infiltration is more effective for runoff reduction and abatement of pollution discharges than detention basins. A hydrological micro-model used by Merz et al. [10] can analyze the effect of urban development on infiltration and runoff, and evaluate a number of practices designed to enhance on-site infiltration. Many formulations of the infiltration capacity have been presented, e.g., the formulas of Horton [2] and Philip [13], who defined their infiltration capacity as the maximum rate at which infiltration can occur, are widely used.

In this study, for managing infiltration for the whole urban area we take into consideration within urban environmental regulations to survey: (1) the coefficient of soil hydraulic conductivity (K) that would be different from every region, (2) the effective infiltration rate of area (R) that depends on its land use type and the rainfall type, and (3) its duration (T). Based on an empirical survey of the soil hydraulic conductivity in micro scale in Pei-Tou district of Taipei, Taiwan, the practical infiltration situation was studied in this work. The purposes of this study are focused on: (1) estimating infiltration of precipitation in urban areas; (2) comparing rainfall types, and (3) evaluating the real infiltration quantity for a rainfall event. Furthermore, by the end of this study, we expect that a general concept of the management of infiltration could be extended to apply to whole urban areas.

2. Site, Method and Measurement

2.1 Site location

To investigate the soil hydraulic conductivity, this work chose Pei-Tou district in Taipei city as studied area to carry out the measurement of infiltration (Fig.1). It is rather flat topographically on this site. Land use types in this district include housing, commercial, facilities such as parks and schools, etc. This site was divided in 25 grids, the area in every grid is 100m*100m and matched up to the geographic coordinates in order to be operated in GIS on urban plan. Fig. 2 shows the equipment of Canadian Guelph Permeameter 2800K1 was adopted by this study in order to survey the accuracy of coefficients of soil hydraulic conductivity for every grid on the site. Instead of using parametric inference for infiltration [3], the precipitation would be conveyed and stacked up on GIS on the site with local mean coefficient of soil hydraulic conductivity.

2.2 The estimation of precipitation infiltration in urban areas

The capability for infiltration in an area is correlated to coefficient of soil hydraulic conductivity, the effective infiltration area rate, the duration for infiltration etc. The infiltration volume could be calculated by Darcy law:

$$V = Ki \tag{1}$$

where V = the velocity of the water flow, K = coefficient of soil hydraulic conductivity, i = the hydraulic slope. If the profile area for infiltration is A, the quantity (q) of water flow passing the soil in one period "T" would be

$$q = VAT = KiAT \tag{2}$$

Because the site has not any slanting, so the hydraulic slope i = 1, thus the infiltration quantity would be:

$$q = KAT \tag{3}$$

According to Darcy law, the infiltration quantity is positively correlated to the coefficient of soil hydraulic conductivity (K), the conductive area (A) within a unit of time. In this study, through the practical conducting of coefficient of soil hydraulic conductivity, the conductive area and the real infiltration quantity on the site would be calculated.

2.3 Coefficient of soil hydraulic conductivity

Depended on the coefficient of soil hydraulic conductivity, the total infiltration quantity is one of the most important parameters for the precipitation management. It is bound up with soil natures, such as particles, organic matters, ground cover, capillarity, water capacity etc. The coefficient of soil hydraulic conductivity from local measurement for each grid on the site would be calculated as [15]:

$$Kfs = CQs / (2\pi H^2 + C\pi a^2 + 2\pi H / \alpha) \quad (4)$$

where Kfs is coefficient of soil hydraulic conductivity, C is coefficient of configuration, Qs is infiltration quantity, H is water level high in Permeameter, a is measured radius in soil, and α is coefficient of soil structure. Through several holing operations in Guelph Permeameter, the change of the coefficient of soil hydraulic conductivity could be obtained for every single grid.

Fig. 3 shows the variation of soil hydraulic conductivity coefficient would change in term of time. At beginning the value is the highest. After water was injected gradually, the velocity for infiltration would approach a constant value, named the saturated permeability (Table 1). Generally, it would be taken as the coefficient of soil hydraulic conductivity. Shown in Table 2 is the surveyed coefficient of soil hydraulic conductivity on the site. For conducting this experiment we chose 20 spots to operate for infiltration on the site, in the end only 16 samples were considered as effective. The local average coefficient of soil hydraulic conductivity would be calculated as following:

$$Ka = KrPr + KcPc + \ldots + KmPm = 1.92\text{E-}06 \quad (5)$$

where Ka (m/sec) is local average coefficient of soil hydraulic conductivity, the parameter Kr, Kc,…and Km are soil hydraulic conductivity in different zoning. Pr, Pc,…and Pm are percentage of area in zoning.

Fig.4 shows percentage of area for various zonings on the site, that include residential, commercial, school, green belt, institution, public facilities, and road (impermeable). Their percentage of area are 20.75%, 22.26%, 15.39%, 11.46%, 2.92%, 5.51%, and 21.72%, respectively.

2.4 The ratio of infiltrative area

The development in urban area leads to the rapid decrease of green land and of many impermeable area. In the city the pavement material used in building structures, roads, parking lots etc. is mostly asphalt or concrete, In Taipei city the impermeable area covers only 36%, but in downtown region it can reach to 79%. Previous results studied by Liu [9] indicated the infiltrative ratio in urban areas of Taiwan can be applied in this study.

3. Calculating Infiltration Parameter

3.1 The maximal infiltration capacity (MIC)

MIC is defined as the maximal infiltrating quantity per unit of time and area. In this study, the coefficient of soil hydraulic conductivity Ka is measured empirically for every grid on the site. The conductive area is calculated by the percentage of infiltrative area for various zonings in a grid of 100m*100m each. The study site was divided into 25 grids, and their respective MICs were measured (Table3). Retaining rainwater is much more positive effect in urban area of Taipei and can improve the urban climate. The MICs ranged from 5.19~47.21(m^3/hr) in this survey with a great space variability, and infiltration capacity in most urban areas needs to be improved. Regarding to calculating MIC, taking grid 08 as an example: its area in residence zone is 3455 ㎡, commercial 1217 ㎡, school 2720 ㎡, Parks and Green 638 ㎡, other public facilities 127 ㎡, road 1843 ㎡, and there is no public institution. Thus its MIC for this grid 08 is

$$\begin{aligned} q &= KAT \\ &= .92\text{E-}06\text{x}(3455\text{x}0.22+1217\text{x}0+2720\text{x}0.35+638\text{x}0.82+0\text{x}0.22+127\text{x}0.13)\text{x}3600 \\ &= 15.60(m^3/hr) \quad (6) \end{aligned}$$

Thus MIC for Grid 08 would be 15.60(m^3/hr), consequently the MIC for each grid can be calculated respectively. Results of MIC pointed out that infiltration capacity differs enormously in various grids as shown in table 3, which means that there is plenty of sites needed to be enhanced the infiltration capacity. And total 25 Grids were measured and summed.

3.2 Real Infiltration Quantity (RIQ) of a rainfall

RIQ would not be recorded on the MIC unless the rainfall is in high-intensity type. Fig.5 demonstrates the comparison between the MIC and the precipitation, and the RIQ in a grid for each rainfall type could be calculated. The RIQs in various areas have rather big range, the highest is over 10 times than the lowest (Fig. 6). This suggests that an insufficient injection of precipitation into groundwater can easily induce UHI effect. It is worth to note that increasing infiltration is very pressing due to great variation of RIQs in the investigated area. It helps not only for ecology but also good for precipitation management with canalization system. In addition, we will recommend urban managers or designers to take the potential of natural and artificial infiltration into consideration by planning and design of canalization in this city.

3.3 Comparison of three rainfall types

Fig. 7 shows that based on data collected from National Central Weather Bureau, Taiwan from1997-2001, we have generalized three types of rainfall including high-intensity, middle-intensity, and low intensity rain by the arithmetic mean values of precipitation, in total 308 rainy days from these four years. They were recorded by 1/4, 1/2 and 3/4 if a day of precipitation exceeded 10mm, which was called an effective precipitation rain. The rain quantities of three types, from high to low, are 87.1mm, 27.4mm and 13.1mm respectively. Nevertheless, The RIQ is also closely bound up to the rainfall type. The three types include (a) high-intensity rain, (b) middle-intensity rain, and (c) low-intensity rain, by means of choosing the much closer precipitation records by hours on these days 26th, 27th and 21st Sep. 2001.

4. Conclusion

Injection of precipitation into groundwater is the most important way for regeneration of urban soil ecosystem. Our findings in the most effective ways to promote the real infiltration quantity are: (1) to increase the coefficient of soil hydraulic conductivity by improving the compounds of the soil, (2) to increase the ratio of infiltrative area by changing the pavement in urban areas, and (3) to increase the duration or the delay for infiltration after rainfall. All these concepts could be applied in the urban plan and regulated to canalization. The model proposed in this study allows not only a reliable presenting the effects of the random spatial variability of K and R, which are significant values of the corresponding coefficients of variation, but also has a crucial role in determining the expected field-scale infiltration rate.

In the near future, we will combine land preservation and infiltration-based storm water management to yield the hydrologic response closest to existing urban area investigated. Furthermore, due to water retention being one important aspect of ecological urban, measures to promote urban stormwater infiltration need to be developed promptly [11]. In short, this work was part of an effort to develop, test, and recommend policies and practices for urban infiltration planning and for protecting water resources.

References:

[1]Brito, MG., Costa, CN., Almeida, J.A., Vendas. D., Verdial, P.H., Characterization of Maximum Infiltration Areas Using GIS tools, *Engineering Geology 85* (1-2), 2006, pp.14-18.

[2]Horton, RE., The Role of Infiltration in the Hydrological Cycle. *EOS Trans AGU* 14, 1993, pp.446-460.

[3]Huang, CH., Liao, MC., The Institution of the Permeating of Precipitation in Urban Areas, *J. of architecture* 40, 2002. (in Chinese)

[4]Huang, CH., Lin, WZ., Su, YH., Microclimate Observation of Aerosol Distribution at Urban Campus Building Adjoining Heavy Traffic Roadside in Taipei, *WSEAS Transactions on Environment and Development* 6(2), 2006, pp. 785~791.

[5]Huang, CH., Lin, WZ., Tsai, FM., Simulation Indicates Aerosols Distribution Influenced by Urban Building Forms in Case of Taipei Campus, *WSEAS Transactions on Environment and Development* 6 (2), 2006, pp.778~784.

[6]Kronaveter, L., Shamir, U., Kessler, A., Water-sensitive Urban Planning: Modeling On-Site Infiltration, *J. of Water Resources Planning and Management-ASCE* 127 (2), 2001, pp. 78-88.

[7]Lin, WZ., Tsai, HC., Wang, CH., Chou, C., The Characteristics and Estimation of the Urban Heat Island of a Subtropical City in Taiwan, *IASME Transactions* 3(2), 2005, pp. 336-345.
[8]Liu, SC., Lin, CY., Shiu, CJ.**,** Wang, CH., Liu, GR., Mega-Suburb Heat-Island Effect over Taiwan's Western Plain, *BAQ 16 Dec. 2002-18, Dec. 2002, Hong Kong SAR.*
[9]Liu, Y.M, The Infiltration Situation in Taipei City, Master Thesis, National Ceng-kung University, 2001. (in Chinese)
[10]Merz, B., Bardossy, A., Schiffler GR, Different Methods for Modelling the Areal Infiltration of a Grass Field under Heavy Precipitation, *Hydrological Processes* 16 (7), 2002, pp.1383-1402.
[11]Mikkelsen, PS., Jacobsen, P., Fujita, S., Infiltration Practice for Control of Urban Stormwater, *J. of Hydraulic Research* 34 (6), 1996, pp. 827-840.
[12]Pauleit, S., Duhme, F., Assessing the Metabolism of Urban Systems for Urban Planning, *Urban Ecology*, Berlin: Springer Verlag, 1998, pp.65-69.
[13]Philip, JR., The Theory of Infiltration, 1. The Infiltration Equation and Its Solution. *Soil Sci* 83, 1957, pp. 345-357.
[14]Shu, R.T., Liu, C.L., Parametric Inference for Infiltration Application, *J. of Chinese civil and hydraulic engineer,* l.8 (2), 1996, pp.231. (in Chinese)
[15]Talsma, T., Hallam, PM., Hydraulic Conductivity Measurement of Forest Catchments, *Aust. J. Soil Res.* 30, 1980, pp.139-148.
[16]Zeng, XM., Zhao, M., Su, BK., Tang, JP., Zhang, YJ., Chen, J., Effects of Subgrid Heterogeneities in Soil Infiltration Capacity and Precipitation on Regional Climate: a Sensitivity Study. *Theor. Appl. Climatol.* 73, 2002, pp. 207-221.
[17]Oke, TR. The Energetic Basis of the Urban Heat Island. *Q. J. R. Met. Soc.* 108, 1982, pp. 1-24.

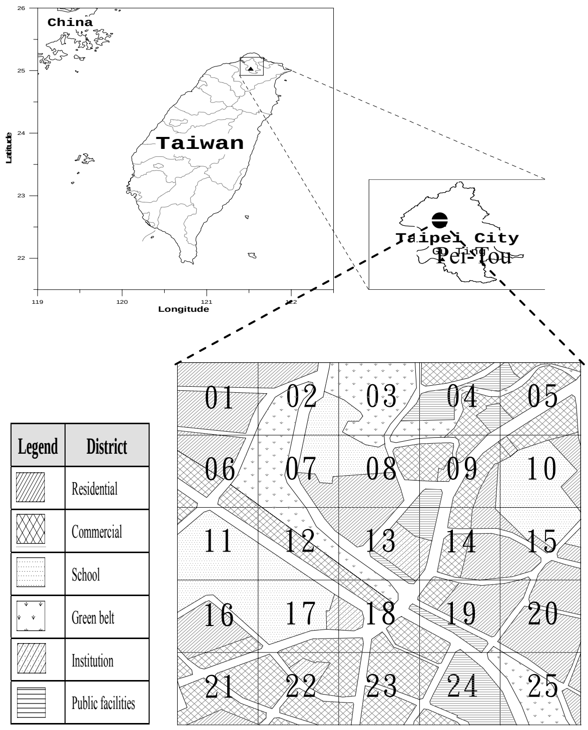

Fig. 1. Study location and the conductive area was calculated by the percentage of infiltrative area for various zonings in a grid(100m*100m). This site was divided into 25 grids district of Pei-Tou in Taipei city of Taiwan.

Fig. 2. (a) The equipment of Guelph Permeameter 2800K1 was used in this study.

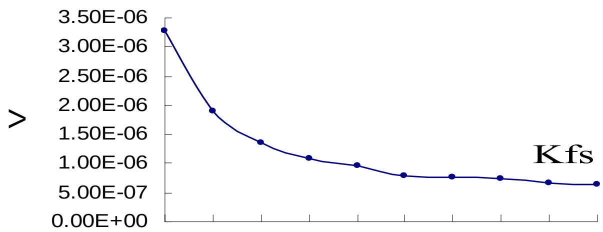

Fig. 3. The coefficient of soil hydraulic conductivity (V : infiltration rate, T : time) approached to a stable value from highest value in the beginning.

Table1. A measuring record of the infiltration capability of precipitation.

Record of the Infiltration capability of precipitation (Sampled on Hole[a] ：01)								
Reading No.	**Time (min)**	**Period (min)**	**Reading (cm)**	**Reading Difference (cm)**	**velocity(cm/min)**	**R (m/sec)**	**Qs (m3)**	**Kfs (m/sec)**
01	2	2	34.3	10.7	5.35	8.92E-04	3.49E-04	3.29E-06
02	4	2	40.5	6.2	3.1	5.17E-04	2.02E-04	1.91E-06
03	6	2	44.9	4.4	2.2	3.67E-04	1.44E-04	1.35E-06
04	8	2	48.4	3.5	1.75	2.92E-04	1.14E-04	1.08E-06
05	10	2	51.5	3.1	1.55	2.58E-04	1.01E-04	9.53E-07
06	12	2	54.1	2.6	1.3	2.17E-04	8.49E-05	7.99E-07
07	14	2	56.6	2.5	1.25	2.08E-04	8.16E-05	7.68E-07
08	16	2	59	2.4	1.2	2.00E-04	7.84E-05	7.38E-07
09	18	2	61.1	2.2	1.1	1.83E-04	7.18E-05	6.76E-07
10	20	2	63.2	2.1	1.05	1.75E-04	6.86E-05	6.45E-07
11	22	2	65.3	2.1	1.05	1.75E-04	6.86E-05	6.45E-07
12	24	2	67.4	2.1	1.05	1.75E-04	6.86E-05	6.45E-07

a. This is a sample record for Hole 01. Place located at Qihu park. Date is Mar.10, 2002, 16:30; Zoning is green, weather in sunny, and facility is park.

Table 2. Surveyed coefficients of soil hydraulic conductivity of the study site

Zoning	**Kfs (m/sec)**					
1.Residential	1.39E-05	4.52E-07				
2.Commercial	N.A. (almost fully constructed)					
3.School	6.15E-08	3.07E-08	3.62E-06	3.01E-07		
4.Green belt	3.01E-06	1.51E-06	9.04E-07	2.92E-07	6.45E-07	3.07E-07
5.Institution	9.22E-08	2.41E-06				
6.Pub.Facilities	1.21E-06	3.01E-06				

Table 3. The Maximal Infiltration Capacity (MIC) for each grid (Unit :(m^3/hr))

Grid 01 12.92	**Grid 02** 26.59	**Grid 03** 47.21	**Grid 04** 12.28	**Grid 05** 4.70
Grid 06 13.75	**Grid 07** 31.81	**Grid 08** 15.60	**Grid 09** 3.68	**Grid 10** 19.28
Grid 11 18.24	**Grid 12** 18.46	**Grid 13** 14.32	**Grid 14** 7.02	**Grid 15** 15.34
Grid 16 15.88	**Grid 17** 16.84	**Grid 18** 5.91	**Grid 19** 7.52	**Grid 20** 12.94
Grid 21 1.32	**Grid 22** 1.76	**Grid 23** 0.00	**Grid 24** 6.44	**Grid 25** 28.80

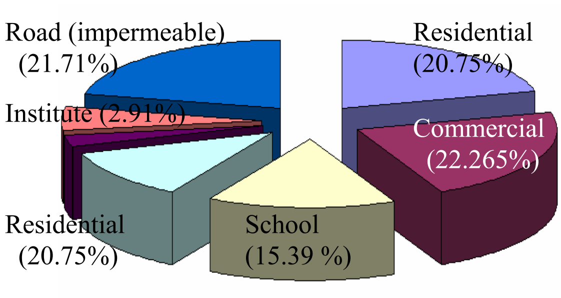

Fig. 4. Percentages of area for various zonings of the study site.

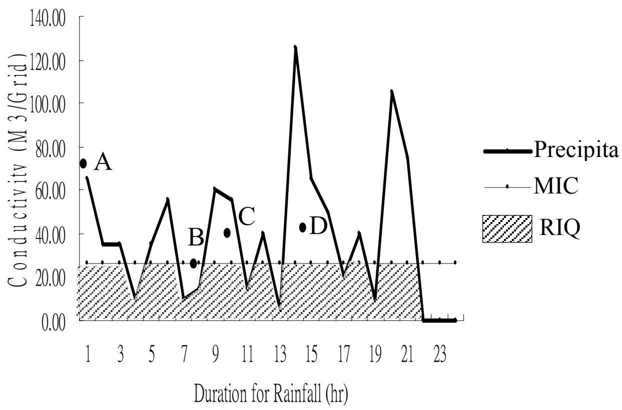

Fig. 5. The Real Infiltration Quantity (RIQ) for Grid 02 by high-intensity rain. Point A means start raining, point B means that MIC is more than the precipitation and all rainfall would conduct into the ground of the study site. Point C means that the precipitation was more than MIC, and can not entirely infiltrate, thus a part of rainfall became runoff on surface. D means most rainfall is runoff when the high-intensity rain.

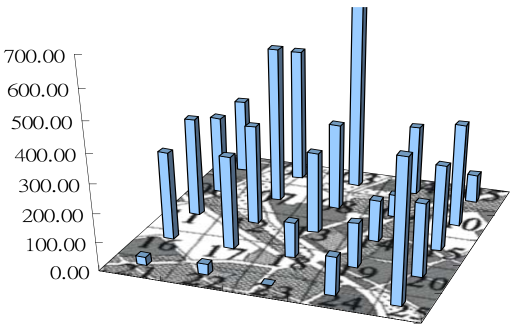

Fig. 6. The Real Infiltration Quantity (RIQ) for a high-intensity rainy day (unit: m³/grid/day). In this survey this site was found in great space variability, the highest is over 10 times than the lowest. This suggested the infiltration capacity in most urban areas will need to be improved.

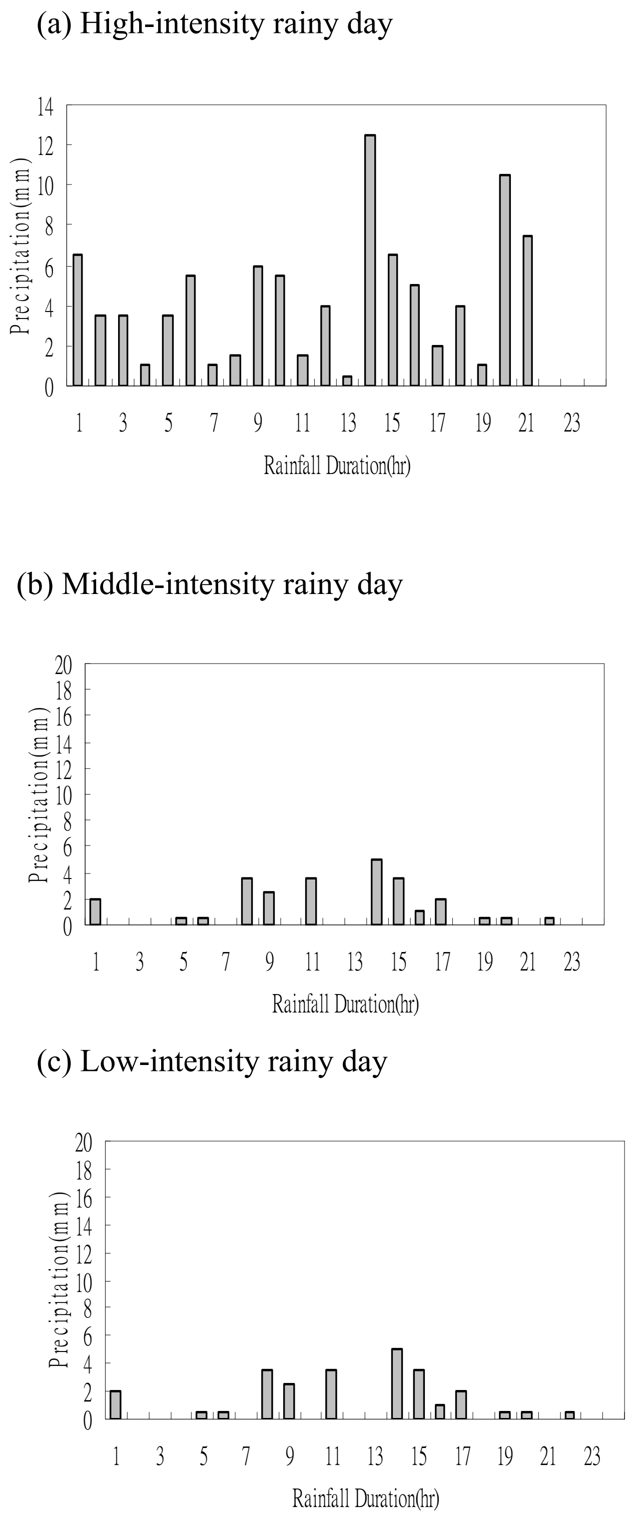

Fig. 7. Three sampling rainfall types. (a) high-intensity rainy day: total precipitation in 24hr is 92.5mm, surveyed in 26th Sep. 2001, (b) middle-intensity rainy day: total precipitation in 24hr is 25.5mm, surveyed in 27th Sep. 2001, and (c) low-intensity rainy day: total precipitation in 24hr is 12.0mm, surveyed in 21th Sep. 21, 2001.