Taxonomy for rainfall events based on pollutant wash-off potential in urban areas

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Abstract: Conventional rainfall classification for modelling and prediction is quantity based. This approach can lead to inaccuracies in stormwater quality modelling due to the assignment of stochastic pollutant parameters to a rainfall event. A taxonomy for natural rainfall events in the context of stormwater quality is presented based on an in-depth investigation of the influence of rainfall characteristics on stormwater quality. In the research study, the natural rainfall events were classified into three types based on average rainfall intensity and rainfall duration and the classification was found to be independent of the catchment characteristics. The proposed taxonomy provides an innovative concept in stormwater quality modelling and prediction and will contribute to enhancing treatment design for stormwater quality mitigation.
Keywords: Rainfall characteristics; Rainfall event classification; Stormwater quality; Urban stormwater pollution

1. Introduction

The classification of rainfall events is commonly based in a hydrologic context since water quantity and flood mitigation were the primary concerns in the past. For example, Average Recurrence Intervals (ARI) is a common parameter used to classify rainfall events based on their return period and is usually employed for selecting design rainfall for hydrologic modelling and for designing hydraulic structures (Titmarsh et al., 1995).

In recent years, with increasing attention on stormwater quality, there have been considerable research efforts to investigate the relationships between rainfall characteristics and stormwater quality (eg. Deletic and Maksimovic, 1998; Kleinman et al., 2006). However, only limited attention has been given to the classification of rainfall events in the context of pollutant wash-off potential and stormwater quality (Shaver et al., 2007). This lack of in-depth knowledge can lead to inefficiencies in the treatment of stormwater quality due to inadequate design (Weiss et al., 2007). For example, the common approach in stormwater quality modelling is to assign stochastic pollutant parameters to a rainfall event irrespective of the underlying rainfall characteristics (Wong et al., 2002).

An approach of this nature does not take into account the variable nature of stormwater quality with rainfall characteristics despite the fact that past research has noted this relationship (Brodie and Rosewell, 2007; Herngren et al., 2005). This highlights the need for the development of practical approaches for classifying rainfall events according to their water quality response, for appropriate applications (Dong, 2009). This paper presents the outcomes of a research study undertaken to investigate the influence of rainfall characteristics on stormwater quality, which in turn formed the basis for the classification of rainfall events based on resulting stormwater quality.

2. Materials and methods

2.1 Study catchments

The study catchments were located at Gold Coast, Queensland State, Australia. The characteristics of the study catchments can be summarised as: Highland Park – extent 105.1 ha, impervious area 40%, mixed land use with a significant residential fraction; Alextown – extent 1.7 ha, impervious area 70%, townhouse development; Gumbeel – extent 1.2 ha, impervious area 70%, duplex housing; Birdlife Park – extent 7.5 ha, impervious area 46%, detached housing. The three smaller catchments with uniform, but different urban form are in effect subcatchments of the larger Highland Park catchment (for further details on the catchments, refer to Liu et al., 2012; Liu, 2011).

2.2 Data collection and sample testing

The four study catchments have been continuously monitored for water quality and rainfall since 2002 using automatic monitoring stations established at the catchment outlets to collect flow measurements and stormwater runoff samples. Flow measurements were undertaken using calibrated V-notch weirs and samples were collected by stage triggered, peristaltic pumping. Samples collected from each event were mixed in proportionate quantities to form event mean concentration (EMC) samples. The samples collected were tested for total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS) and total organic carbon (TOC). Sample testing was undertaken according to test methods specified in Standard Methods for the Examination of Water and Wastewater (APHA, 2005). Sample collection, transport and storage complied with Australia New Zealand Standards, AS/NZS 5667.1:1998 (AS/NZS, 1998).

A total of 41 rainfall events were selected for analysis after assessment of the available data. Intensity greater than a threshold value of 5 mm/h was considered as the start and end of a selected rainfall event. As Egodawatta et al. (2007) have noted, rainfall intensity lower than 5 mm/h does not have a significant effect on pollutants wash-off because of the low kinetic energy. Pollutant EMC data was not available for all of the four catchments for all the 41 rainfall events. The number of applicable rainfall events for the individual catchment were; Highland Park (18), Alextown (21), Gumbeel (17) and Birdlife Park (17), which amounted to 73 events in total. A further 153 rainfall events which occurred in the same period as the 41 events were also included in the analysis although these events only had rainfall characteristics recorded and not water quality data. This data was used to validate the rainfall event classification developed using the selected 41 rainfall events. Accordingly, antecedent dry days were determined as the number of days between individual rainfall events selected based on the specified minimum intensity threshold criteria.

2.3 Data analysis

In order to develop the rainfall classification in the context of water quality, the data analysis consisted of three steps. Firstly, a pre-analysis was undertaken for identifying appropriate rainfall parameters and to prevent correlating parameters overshadowing critical relationships between rainfall characteristics and water quality (Egodawatta et al., 2006). Six rainfall characteristics (average rainfall intensity AgI, initial rainfall intensity (10-min average) IniI, maximum rainfall intensity MaxI, Rainfall duration RD, rainfall depth RDep, antecedent dry days ADD) and pollutant EMC values (TN, TP, TSS and TOC) were investigated using a correlation matrix. Secondly, analysis was undertaken to investigate the relationship between rainfall characteristics and water quality in order to initially classify the rainfall events. This was conducted using Principal Component Analysis (PCA). PCA is an effective technique to explore correlation among variables and objects (Kokot et al., 1998). The number of significant principal components was selected using the Scree plot method (Adams, 1995). StatistiXL software (StatistiXL, 2007) was used for PCA. Finally, the original dataset consisting of rainfall characteristics and water quality was analysed to validate the classification.

3. Results and Discussion

3.1 Selection of rainfall characteristics

The selection of rainfall characteristics was based on the 41 monitored rainfall events used in the correlation matrix given in Table 1. It can be noted from Table 1 that three intensity parameters, AgI, IniI and MaxI display strong correlations (0.737 for AgI-MaxI and 0.668 for IniI-MaxI). RD and RDep also display a close correlation with a correlation coefficient of 0.735. RD, RDep and AgI are related to each other in their definition. However, ADD is an independent parameter as it has relatively lower correlation coefficients with the other rainfall parameters. As the three rainfall intensity parameters as well as rainfall duration and rainfall depth also show a close correlation, MaxI, IniI and RDep were removed from the analysis and AgI, RD and ADD were included in further analysis.

Insert Table 1

3.2 Relationship between rainfall characteristics and water quality

To initially classify rainfall events, water quality responses for different events was investigated based on the selected 41 rainfall events using PCA. Rainfall events were considered as objects and AgI, RD, ADD and EMC values of TSS, TN, TP and TOC were considered as variables, accordingly generating a data matrix (73×7). Figure 1 shows the resulting PCA biplots.

Insert Figure 1

According to Figure 1A, the rainfall events are clustered separately in the PCA biplot and named as Type 1, Type 2 and Type 3, respectively. It is also evident that these three clusters are not influenced by the study catchments. Most of the Type 3 rainfall events are projected on the positive PC1 axis and clustered together, whilst nearly all of the Type 1 rainfall events and all Type 2 rainfall events are projected on the negative PC1 axis and relatively scattered. This means that Type 1 and Type 2 events tend to generate high variation in water quality while Type 3 produce relatively low variation.

The AgI vector and ADD vector point in the same direction as all pollutant EMC vectors (see Figure 1A and 1B), which are all projected on the negative PC1 axis whilst the RD vector is opposite to the pollutant EMCs and is projected on the positive PC1 axis. This indicates that AgI and ADD are positively correlated with pollutant EMCs, whilst RD is negatively correlated with pollutant EMCs (Gnecco et al., 2005). Accordingly, it can be concluded that high average rainfall intensity and long antecedent dry days can generate relatively high pollutant EMCs whilst long rainfall durations have a dilution effect (Gnecco et al., 2005). Dilution could be attributed to the source limiting nature of the wash-off characteristics where most of the pollutants are removed by runoff at the initial stage (first flush) (Herngren et al., 2010; Passeport and Hunt, 2009).

Additionally, the AgI vector indicates a close correlation with all pollutant EMCs, whilst the ADD vector only indicates a close correlation with TOC. These observations confirm that average rainfall intensity would play the more important role in relation to water quality rather than antecedent dry days (Greenstein et al., 2004). This means that the ability to wash-off built-up pollutants has a more significant influence on receiving water quality rather than the pollutant build-up characteristics.

The two primary reasons for this behaviour being, firstly, pollutant build-up will reach equilibrium after a number of dry days. Accordingly, this will result in little difference in initial pollutant availability at the commencement of rainfall (Sartor et al., 1974; Vaze and Chiew, 2002). In this case, stormwater quality is dictated by the ability of a rainfall event to remove pollutants. Secondly, in the case of relatively low intensity rainfall events, due to low kinetic energy, only a fraction of build-up pollutants will be removed (Shaw et al., 2010). Therefore, stormwater quality is limited by the capacity of the rainfall for removing and transporting pollutants rather than the initially available load.

According to the PCA biplot given in Figure 1, the rainfall events can be classified based on rainfall characteristics and resulting water quality (Type 1, Type 2 and Type 3). Additionally, due to the fact that these three clusters are not influenced by the study catchments which have a diversity of characteristics, it confirms that the clusters are independent of catchment characteristics.

3.3 Classification of rainfall events

According to the results from PCA (Figure 1), the classification of rainfall events are closely related to the rainfall characteristics and the resulting water quality. In order to further investigate and validate the classification, it was necessary to analyse the original dataset.

Firstly, all rainfall events were plotted in an Intensity-Frequency-Duration (IFD) plot, which is a common approach for investigating rainfall characteristics (Rahman et al., 2002; Westra and Sharma, 2010). The standard IFD plot was developed based on the methodology provided in Australian Rainfall and Runoff (AR&R, 1997). Figure 2 shows the IFD plot for the 41 monitored rainfall events and the additional 153 rainfall events. Secondly, Table 2 gives the average rainfall intensity, rainfall duration and antecedent dry days for the 41 monitored rainfall events. As the PCA confirmed that the rainfall classification is independent of catchment characteristics, the dataset given in Table 2 is a combined dataset of the four catchments.

Insert Figure 2, Table 2

According to Figure 2, nearly all of the rainfall events are located below the 1 year ARI curve. This means that these rainfall events provide a suitable dataset for stormwater quality research as most typical stormwater treatment systems are designed for rainfall events less than 1 year ARI (Dunstone and Graham, 2005).

Additionally, it can be noted that the 41 monitored rainfall events are also separated into three groups. This is in agreement with the conclusion from the PCA and is based on average rainfall intensity and rainfall duration. About half of the Type 3 rainfall events (square symbol) display relatively longer durations (>2 h), but lower average rainfall intensity (<20 mm/h). The Type 2 event (triangular symbol) shows, both, high average rainfall intensity (>20 mm/h) and duration (>2 h) while Type 1 events (circular symbol) have higher average rainfall intensity (>20 mm/h) but shorter duration (<2 h). Furthermore, it was also noted that the 153 other rainfall events (labelled as * in Figure 2) generally distribute based on the proposed classification. This further validates the classification undertaken using the 41 monitored rainfall events.

According to Table 2, there is little difference in the antecedent dry days between the different rainfall types. These conclusions validate the classification of rainfall events to three types on the basis of average rainfall intensity and rainfall duration. For convenience of understanding, the three types can be illustrated with boxes as shown in Figure 2.

According to the pollutant EMC values given in Table 2, Type 1 rainfall events display the highest mean EMC values with 6.85 mg/L, 225.03 mg/L and 14.63 mg/L for TN, TSS and TOC, respectively, whilst Type 2 shows the highest TP EMC value (3.29 mg/L). Additionally, Type 1 displays the highest standard deviations for TN, TSS and TOC, whilst Type 2 has the highest standard deviation for TP. Type 3 rainfall events do not have high mean values and standard deviations for any pollutants, and in fact has the lowest mean values and standard deviations for TN and TP. In terms of relative standard deviations, Type 1 indicates the highest values for TN, TP and TSS and the second highest value for TOC compared with other two types. These outcomes are in agreement with the conclusions from PCA (Figure 1) and provide further confirmation that the classifications undertaken based on average rainfall intensity and rainfall duration in the context of water quality is valid. This implies that in modelling, water quality should be assigned based on different event types rather than using the traditional stochastic approach.

Additionally, it is also evident from Table 2 that not all of the high-average-intensity events (Type 1 and Type 2) have relatively long antecedent dry days. Particularly in the case of two of them, (031026 and 040224), the antecedent dry days are shorter than for over half of the Type 3 events. However, these events still generated high pollutant EMC values compared to the Type 3 events. This further confirms the inadequacy of the use of antecedent dry days for rainfall classification in the context of water quality.

4. Conclusions

This paper provides an innovative approach to logically classify a seemingly chaotic mix of natural rainfall events into three different types on the basis of average rainfall intensity and duration in the context of water quality. The types are, high average intensity-short duration, high average intensity-long duration and low average intensity-long duration. The novel rainfall classification provides the ability to select the appropriate rainfall events for water quality treatment design based on the required treatment outcomes which may differ between systems, between catchments or water quality objectives of receiving water bodies. This approach can also contribute to enhancing water quality modelling and prediction in contrast to conventional approaches where stormwater quality is solely considered as a stochastic variable, irrespective of the characteristics of the rainfall event.

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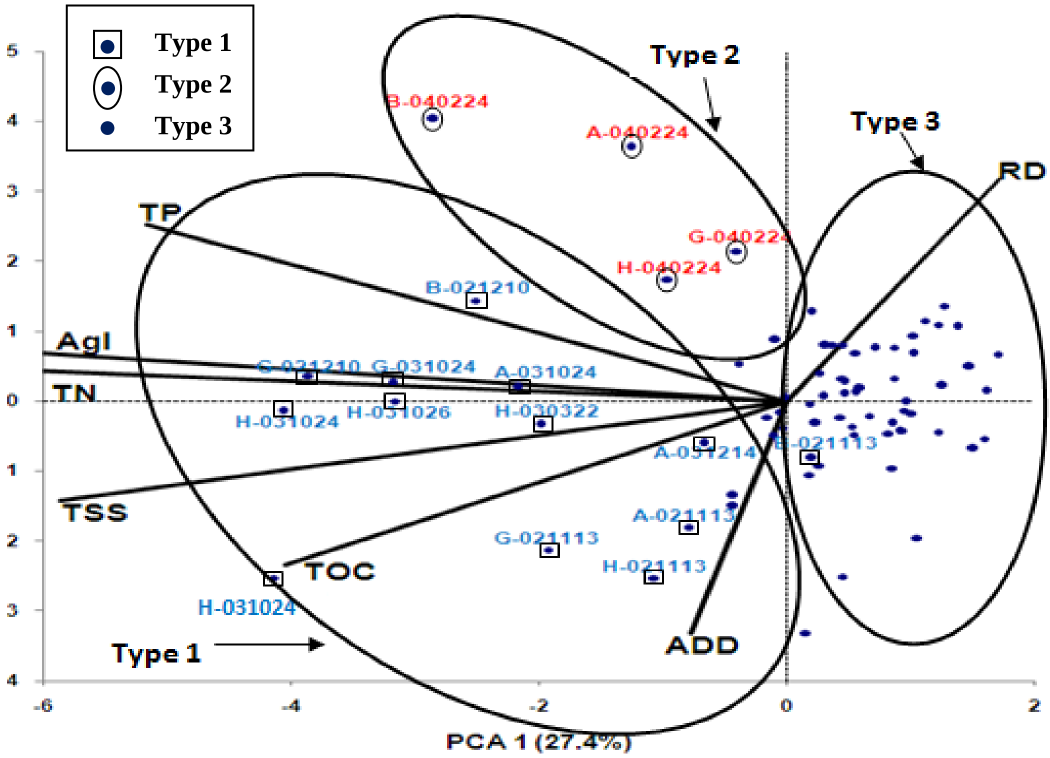
Figure captions

Figure 1 PCA biplots of the water quality data for the four study catchments

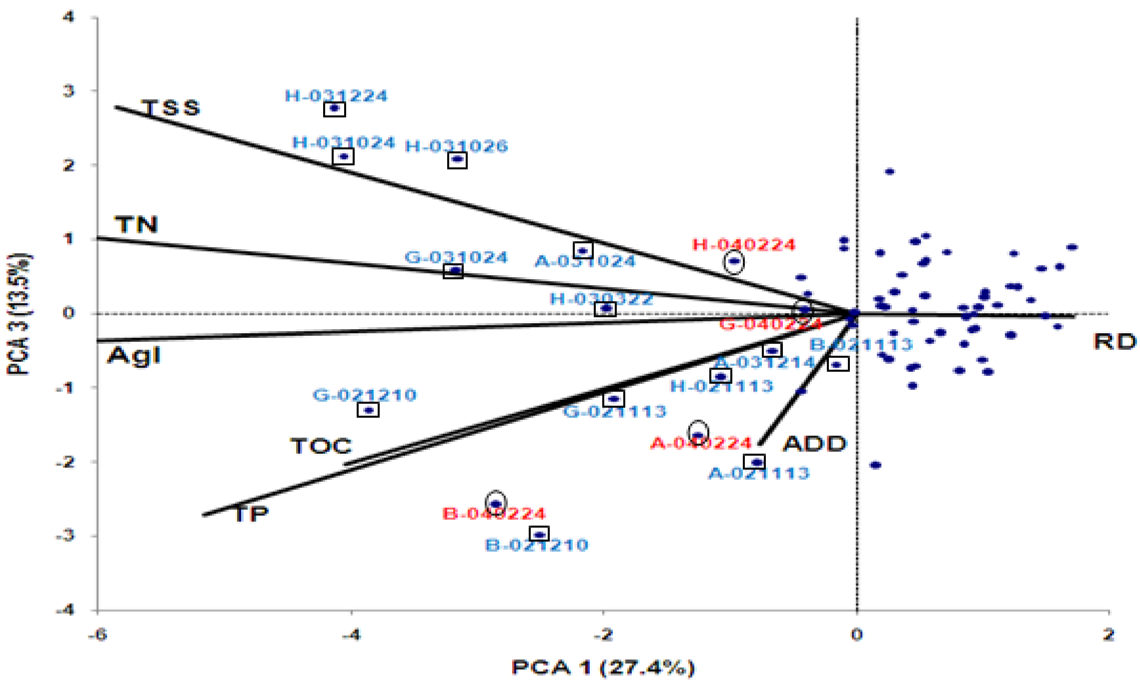
(Note: The first letter in the label, A, G, B and H, corresponded to the rainfall events for Alextown, Gumbeel, Birdlife Park and Highland Park catchments, respectively. The 6 digits following the first letter is the rainfall event date. For example, A-021113 represents the rainfall event which occurred on November 13th, 2002 at Alextown catchment. Other label names see Table 1)

Figure 2 IFD plot for the selected rainfall events

Note: Length of box illustrates the mean value of rainfall duration (h) within each rainfall type, and height illustrates the mean value of average rainfall intensity (mm/h) within each rainfall type. These mean values are for the 41 monitored rainfall events)



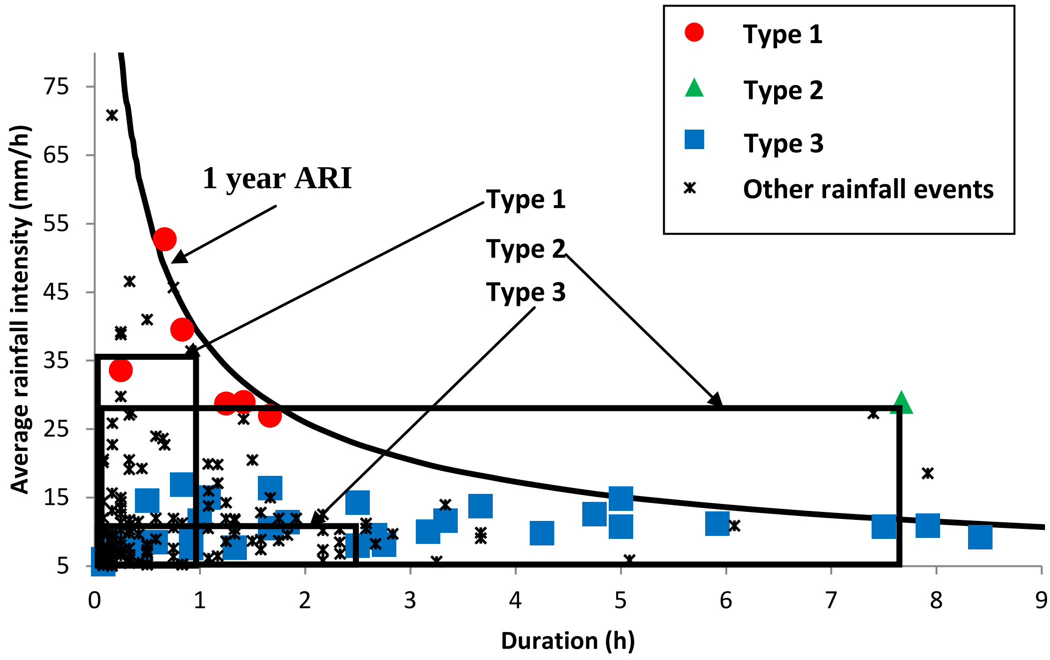
A. PC1 vs.PC2 biplot



B. PC1 vs.PC3 biplot

Figure 1 PCA biplots of the water quality data for the four study catchments

(Note: The first letter in the label, A, G, B and H, corresponded to the rainfall events for Alextown, Gumbeel, Birdlife Park and Highland Park catchments, respectively. The 6 digits following the first letter is the rainfall event date. For example, A-021113 represents the rainfall event which occurred on November 13th, 2002 at Alextown catchment. Other label names see Table 1)



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Note: Length of box illustrates the mean value of rainfall duration (h) within each rainfall type, and height illustrates the mean value of average rainfall intensity (mm/h) within each rainfall type. These mean values are for the 41 monitored rainfall events)

Table 1 Correlation matrix

	RDep	RD	AgI	ADD	IniI	MaxI	TN	TP	TSS	TOC
RDep	1.000									
RD	0.735	1.000								
AgI	0.398	-0.026	1.000							
ADD	-0.071	-0.204	0.055	1.000						
IniI	0.023	-0.148	0.301	0.003	1.000					
MaxI	0.341	-0.005	0.737	-0.061	0.688	1.000				
TN	0.203	-0.063	0.480	-0.085	-0.140	0.090	1.000			
TP	0.424	0.131	0.380	0.036	0.136	-0.092	0.207	1.000		
TSS	-0.008	-0.106	0.234	0.493	0.330	0.199	0.313	-0.016	1.000	
TOC	-0.063	-0.181	0.080	-0.085	-0.140	0.090	0.146	0.074	0.173	1.000

RDep=rainfall depth; RD=rainfall duration; AgI=average rainfall intensity; ADD=antecedent dry days; IniI=initial rainfall intensity; MaxI=maximum rainfall intensity; TN=total nitrogen; TP=total phosphorus; TSS=total suspended solids and TOC=total organic carbon

Table 2 The rainfall and stormwater quality characteristics

<table>
<tr><th colspan="2" rowspan="2">Rainfall events</th><th colspan="4">Rainfall characteristics</th><th colspan="5">Stormwater quality characteristics</th></tr>
<tr><th>Rainfall types</th><th>Average rainfall intensity (mm/h)</th><th>Rainfall duration (h)</th><th>Antecedent dry days (d)</th><th>Parameter</th><th>TN (mg/L)</th><th>TP (mg/L)</th><th>TSS (mg/L)</th><th>TOC (mg/L)</th></tr>
<tr><td rowspan="6">Type 1</td><td>021113[1]</td><td rowspan="6">High intensity (>20 mm/h)-short duration (<2 h)</td><td>26.9</td><td>1.6</td><td>16.2</td><td rowspan="2">Mean</td><td rowspan="2">6.85</td><td rowspan="2">1.16</td><td rowspan="2">225.03</td><td rowspan="2">14.63</td></tr>
<tr><td>031024</td><td>28.9</td><td>1.4</td><td>4.3</td></tr>
<tr><td>031214</td><td>28.7</td><td>1.2</td><td>8.0</td><td rowspan="2">SD[2]</td><td rowspan="2">5.99</td><td rowspan="2">1.25</td><td rowspan="2">260.89</td><td rowspan="2">5.75</td></tr>
<tr><td>021210</td><td>39.5</td><td>0.8</td><td>5.1</td></tr>
<tr><td>031026</td><td>33.6</td><td>0.2</td><td>2.5</td><td rowspan="2">RSD%[3]</td><td rowspan="2">87.44</td><td rowspan="2">107.76</td><td rowspan="2">115.94</td><td rowspan="2">39.30</td></tr>
<tr><td>030322</td><td>52.7</td><td>0.6</td><td>4.1</td></tr>
<tr><td rowspan="3">Type 2</td><td rowspan="3">040224</td><td rowspan="3">High intensity (>20 mm/h)-long duration (>2 h)</td><td rowspan="3">28.9</td><td rowspan="3">7.6</td><td rowspan="3">1.0</td><td>Mean</td><td>5.10</td><td>3.29</td><td>83.50</td><td>8.816</td></tr>
<tr><td>SD</td><td>1.49</td><td>3.06</td><td>57.33</td><td>2.15</td></tr>
<tr><td>RSD%</td><td>29.21</td><td>93.01</td><td>68.66</td><td>24.39</td></tr>
<tr><td rowspan="3">Type 3</td><td>Mean</td><td rowspan="3">Low intensity (<20 mm/h)-long duration (>2 h)</td><td>9.9</td><td>2.4</td><td>3.3</td><td>Mean</td><td>2.19</td><td>0.55</td><td>92.49</td><td>11.36</td></tr>
<tr><td rowspan="2">Range</td><td rowspan="2">5.3-16.8</td><td rowspan="2">0.08-8.4</td><td rowspan="2">0.1-26.5</td><td>SD</td><td>1.43</td><td>0.44</td><td>84.21</td><td>5.13</td></tr>
<tr><td>RSD%</td><td>65.30</td><td>80.00</td><td>91.05</td><td>45.16</td></tr>
</table>

[1]Rainfall event date (For example, 021113 represents the rainfall event which occurred on November 13th, 2002); [2]Standard deviations; [3]Relative standard deviations