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Characteristic Rainfall for Warning of Debris Flows

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Abstract: A characteristic rainfall is introduced to overcome the difficulties encountered in determining a critical rainfall value for triggering debris flow. The characteristic value is defined as the rainfall at which debris-flow occurrence probability shows a rapid increase, and can be used as a warning rainfall threshold for debris flows. Investigation of recorded debris flows and 24-hour rainfall data at Jiangjia basin, Yunnan Province, in southwestern China, demonstrates the existence of such a characteristic rainfall. It was found that the characteristic rainfall corresponds to the daily rainfall of 90% cumulative probability by analyzing the basin's daily rainfall histogram. The result provides a simple and useful method for estimating a debris-flow warning rainfall threshold from the daily rainfall distribution. It was applied to estimate the debris-flow warning rainfall threshold for the Subaohe basin, a watershed in the 2008 Wenchuan earthquake zone with many physical characteristics similar to those of the Jiangjia basin.

Keywords: Debris flow; Wenchuan earthquake; warning rainfall threshold; statistics of daily rainfall distribution

Introduction

Many rainfall-induced debris flows are mobilized from shallow landslides (Iverson et al., 1997; Gabet and Mudd, 2006). Both processes are due to an increase in pore water pressure caused by rainfall infiltration (Iverson, 2000). Physical and statistical models have been developed to find the correlation between their occurrence and rainfall (Caine, 1980; Montgomery and Dietrich, 1994), and different triggering criteria, i.e. thresholds, for shallow landslides and debris flows have been proposed (Caine, 1980; Cannon and Ellen, 1985; Wieczorek, 1987; Casadel et al., 2003; Chen et al., 2005; Godt et al., 2006).

However, the threshold depends strongly on local physiographic, hydrological and meteorological conditions, and is not unique. For instance, the 24h (24 hours) cumulative rainfall for triggering debris flows is larger than 100 mm in Taiwan whereas a rainfall with a 24h amount of 20~50 mm can easily cause debris flows in the Xiaojiang River basin in Yunnan. The intensity-duration threshold is also different in Seattle, Washington (Godt et al., 2006; Chen et al., 2005). Cannon and Ellen (1985) proposed that the rainfall intensity values should be normalized by the mean annual precipitation (MAP) in order to account for different climatic domains. Taking into account the difference in MAP and the annual number of rainy days (RDN), Wilson (1997, 2000) presented a procedure for transferring rainfall thresholds among different regions.

However, even for a certain basin, the rainfall threshold is not constant. For instance, a rainfall far below the threshold can trigger debris flows when material supplies or slope failures are extensive, as in the case of valleys suffering

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earthquakes (Cui et al., 2009; Lin et al.,2004) Therefore, it is hard to define the rainfall threshold both literally and physically.

Nevertheless, in most cases there exists a characteristic value of rainfall below which debris flows are unlikely to occur but above which they are likely. Compared with the critical rainfall, the characteristic rainfall is more accurate, and more suitable to serve as a warning threshold. But estimating the characteristic rainfall requires long-term data for debris-flow events and related rainfall, which is unrealistic for most debris-flow basins. For example, in the Longmenshan area of northwestern Sichuan Province, China, where a 8.0 Ms earthquake occurred 12 May, 2008, many debris flow events occurred after the earthquake and resulted in vast life and property losses. The local government is in urgent need of a reliable approach for calculating the warning rainfall threshold, but only one year of monitoring rainfall data in debris-flow-affected areas is not enough for deducing the characteristic rainfall.

This paper presents a simple approach to estimating the characteristic rainfall. The required data are only the local daily rainfall distributions. In general, debris flows are not as common as shallow landslides, and for most debris-flow basins only a single event may happen over many years. Because debris flows do not happen frequently, most rainfall processes and events do not trigger them. This implies that debris-flow warning rainfall is a low-frequency rainfall event. Such a connection between the characteristic rainfall and the statistics of daily rainfall was found by investigating the records of debris-flow and rainfall events from 2002 to 2008 at Jiangjia basin of the Xiaojiang River. Then, those results were applied to estimate the characteristic rainfall in the Subaohe basin in the 2008 Wenchuan earthquake area.

1 Study Areas

1.1 Physical settings

The study areas are Jiangjia and Subaohe basins (Figure 1). They share similarities in some physiographic, geological, and climatic characteristics (Table 1). Both are small upstream tributaries of the Yangtze River: Jiangjia to the Xiaojiang River and Subaohe to the Anchanghe River. The Jiangjia and Subaohe basins lie, respectively, in the Hengduanshan and Longmenshan Mountain areas in southwestern China, each with several large faults on which earthquakes happen frequently. Six earthquakes with magnitude > 5.5 Ms occurred in the Xiaojiang region in the years 1893, 1911, 1930, 1947, 1966, and 1985. The epicenter of the 6.5 Ms earthquake in 1966 was located at the mouth of the Jiangjia basin. Similarly, the Subaohe basin was located in the meizoseismal central area of the 2008 Wenchuan earthquake, and the Yingxiu-Beichuan Fault of Longmenshan passes by the basin's distal area, extending from Yingxiu (the epicenter of the earthquake) to Beichuan with a NE 35~45 degree orientation. In addition to the effects of intensive earthquakes, lithological units in the two areas primarily consist of metamorphic or clastic rocks such as slate, phyllite, and sandstone. These rocks are soft and readily weathered into disaggregated debris. The subtropical humid monsoon, under conditions of Pacific high pressure in summer, dominates both Xiaojiang and Beichuan's climate. More than 80% of the annual rainfall occurs in the summer rainy season at Jiangjia, compared to approximately 75% at Subaohe. Maximum annual rainfall is as high as 2340 mm in Beichuan County. Both of the study areas are characterized by altitudinal zonation of rainfall. Rainfall at high altitude can be twice that at low altitude. More

Table 1 Comparison of the two areas' physical settings

Basin	Area (km^2)	Relative elevation (m)	River system	Annual rainfall (mm)	Rainy season
Jiangjia	48.6	2227.0	Yangtze	700~1,200	Jun. to Sep.
Subaohe	106.3*	1710.0	Yangtze	1,100~1,500	Jun. to Sep.

***Note**: The area of Subaohe includes the adjacent basin of Weijiagou.

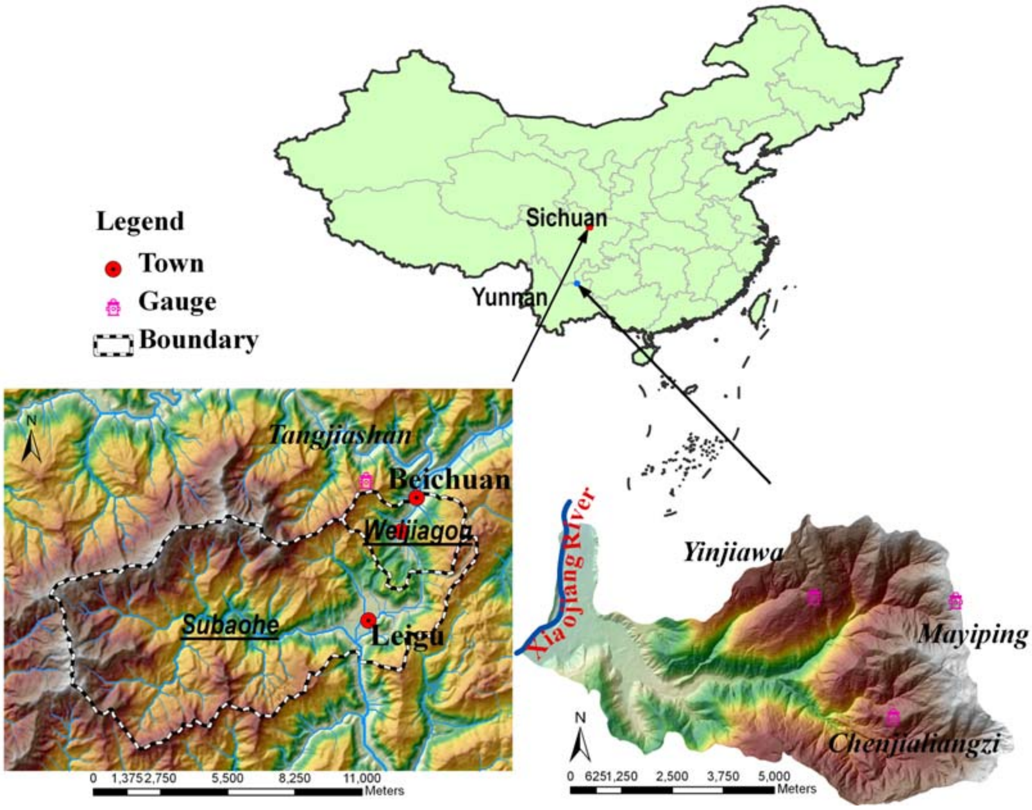

Figure 1 Maps of Jiangjia and Subaohe basins, showing rainfall gauging sites (Subaohe basin on the left, Jiangjia basin on the right)

information about the study areas and their debris flows can be found in Kang and Zhang (1980), Li et al. (1983), and Cui et al. (2005, 2009).

Under the influences of differing physical conditions, the two basins belong to transport-limited or supply-unlimited systems of debris flow formation (Bovis and Jakob, 1999). In contrast with weathered-limited or supply-limited systems, debris-flow activity of a supply-unlimited system is controlled primarily by rainfall conditions, and not dependent on the volume of debris material. For supply-unlimited basins, the relationship between rainfall and debris-flow occurrence can be observed more clearly because there are no limits on debris supply. Considering this similarity in condition, we can assume that the approach to determining the warning rainfall threshold on the basis of Jiangjia's data can also be applied to Subaohe basin.

1.2 Daily rainfall distributions at Jiangjia and Subaohe basins

Since 2002, Dongchuan Debris Flow Observation and Research Station (DDFORS), a facility of the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, has set up nine wireless rainfall gauges distributed in upstream and downstream portions of Jiangjia basin (Figure 1). The gauges can record rainfall once per minute and store the data. In addition, the station has installed monitoring instruments including ultrasonic sensors, geophone detectors, and video cameras in the middle reaches of Jiangjia. The occurrence time of the debris-flow events was determined from monitoring data and the station records.

However, we do not have similar instrumentation in the Subaohe basin. Just after the earthquake, the Chinese government constructed an automatic meteorological station in the vicinity of the Tangjiashan landslide next to the basin in order to monitor the Tangjiashan dammed lake (Figure 1). For our purposes, only one year of rainfall data is not adequate for calculating a significant cumulative rainfall histogram. Fortunately, daily precipitation distribution can be extracted from Tropical Rainfall Measuring

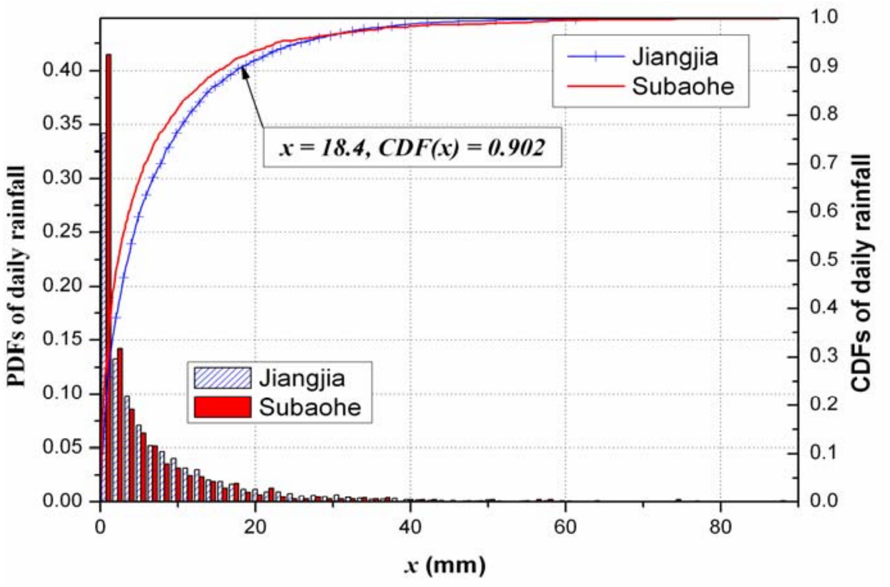

Figure 2 Histograms of daily rainfall at the Jiangjia and Subaohe basins (Jiangjia from 2002 to 2008; Subaohe from 1998 to 2008. The interval of each bar of the histogram is 1.5 mm.)

Mission (TRMM) published data. The extracted data is the mean rainfall over a 0.25° × 0.25° area (E 104°15'~104°30', N 31°45'~32°00') which lies in Beichuan County. Subaohe basin is approximately one-ninth of that area.

Probability density and cumulative distribution functions (PDFs and CDFs) of daily rainfall in the two basins (Figure 2) are defined as follows:

$$PDF(x) = \frac{N(R = x)}{N(0 < R < +\infty)} \ ,$$
$$CDF(x) = \frac{N(0 < R < x)}{N(0 < R < +\infty)} \qquad (1)$$

Here, R is rainfall value, and $N(...)$ is the number of rainy days with rainfall R satisfying the condition in the bracket. It is noted that more than 80 percent of daily rainfall at Subaohe is below 10 mm, and the percentage of light rainy days at Subaohe is greater than at Jiangjia. Our purpose is to find a linkage of the daily rainfall distribution to the characteristic rainfall correlating with debris flows at Jiangjia basin and then apply it to Subaohe.

2 24-hour Cumulative Triggering Rainfall at Jiangjia Basin

In order to find the linkage, we analyzed rainfall data measured by the Chenjialiangzi, Mayiping and Yinjiawa gauges in three main upstream tributaries of Jiangjia from which debris-flow materials are transported. 24-hour cumulative triggering rainfall, i.e. the sum of rainfall in the twenty-four hours before a debris-flow event, was utilized. Table 2 shows that debris flows can be triggered even if a rainstorm happens in only one tributary. Therefore, the maximum value of the three gauges is regarded as the 24h cumulative triggering rainfall.

It is noted that rainfall as low as 10.6 mm (for example, 21-Jul-2004) can trigger debris flow. However, we cannot say that the minimum value (10.6 mm) is the threshold at Jiangjia because we cannot conclude that a rainfall above 10.6 mm must lead to debris flow and that a rainfall below that figure will never trigger a debris flow. Rather, we can only deduce that the probability of debris-flow occurrence is very small when the rainfall is less than 10.6 mm. Chen (1985) proposed that rainfall during the twenty days before a debris-flow event would play a significant role on soil moisture content, and thus that effective antecedent rainfall of twenty days might dominate as a factor triggering a debris flow when compared with concurrent rainfall. From this point of view, the effective triggering rainfall was far greater than 10.6 mm for the event of July 21, 2004 for there

Table 2 24-hour cumulative rainfall before triggering of a debris flow from 2002 to 2008 in Jiangjia basin

Time of Triggering (T_0)	24 hour Cumulative Rainfall R_{24} before T_0 (mm)			Maximum Rainfall at the three gauges (mm)
	Chenjialiangzi	Mayiping	Yinjiawa	
18-Jul-2002 09:51	0.0	25.5	0.0	25.5
15-Aug-2002 00:50	24.8	11.7	9.9	24.8
16-Aug-2002 04:49	29.8	2.9	37.5	37.5
16-Aug-2002 15:51	35.3	19.5	39.6	39.6
20-Aug-2002 17:28	0.0	17.5	13.8	17.5
1-Sep-2002 16:04	36.3	0.0	3.4	36.3
12-Sep-2002 17:23	2.7	0.0	18.8	18.8
5-Jun-2003 22:21	23.3	39.4	3.2	39.4
11-Jun-2003 00:07	14.9	15.2	0.0	15.2
22-Jun-2003 21:38	3.8	34.2	0.0	34.2
18-Jul-2003 00:24	0.0	21.9	23.3	23.3
26-Jul-2003 13:23	22.7	26.7	9.9	26.7
10-Aug-2003 03:42	25.6	0.0	18.1	25.6
10-Aug-2003 23:27	23.4	10.3	39.4	39.4
26-Jun-2004 18:32	17.4	0.0	0.0	17.4
9-Jul-2004 11:20	0.0	0.0	15.8	15.8
19-Jul-2004 03:02	26.9	0.0	27.8	27.8
21-Jul-2004 17:57	***10.6***	***0.0***	***5.2***	***10.6***
31-Jul-2004 17:38	0.0	6.8	11.2	11.2
25-Aug-2004 12:40	16.1	5.9	22.0	22.0
30-Jul-2005 04:19	18.4	0.0	23.0	23.0
18-Aug-2005 02:30	40.9	0.0	37.3	40.9
5-Jul-2006 02:33	0.0	25.8	28.8	28.8
6-Jul-2006 03:35	0.0	23.4	9.0	23.4
15-Aug-2006 21:59	0.0	31.9	17.2	31.9
20-Aug-2006 23:45	0.0	4.4	18.5	18.5
10-Jul-2007 04:20	10.1	11.8	22.1	22.1
24-Jul-2007 06:30	17.7	18.1	18.4	18.4
25-Jul-2007 02:36	34.6	29.2	42.6	42.6
25-Jul-2007 14:24	43.1	54.3	37.9	54.3
30-Jul-2007 05:40	19.8	17.9	13.4	19.8
11-Aug-2007 14:27	22.3	15.8	33.7	33.7
14-Sep-2007 01:30	18.4	20.1	25.8	25.8

17-Sep-2007 15:12	20.9	23.9	27.7	27.7
1-Jul-2008 15:55	0.0	33.0	26.9	33.0
5-Jul-2008 06:26	0.0	19.6	19.9	19.9
11-Jul-2008 06:48	0.0	7.7	20.9	20.9
11-Jul-2008 17:46	0.0	14.1	32.8	32.8
22-Jul-2008 05:00	21.4	22.1	11.3	22.1
31-Jul-2008 00:15	4.3	0.1	15.0	15.0
3-Aug-2008 04:50	7.5	22.6	9.7	22.6
3-Aug-2008 20:10	11.2	25.2	17.0	25.2
4-Aug-2008 10:09	10.4	8.8	15.3	15.3
5-Aug-2008 13:56	0.1	11.7	17.3	17.3
8-Aug-2008 03:00	20.3	30.6	12.0	30.6
11-Aug-2008 02:16	16.0	0.7	18.4	18.4

were at least two intense rain storms, on July 9 and 19. But, as mentioned in the introduction, our purpose is to find the characteristic rainfall based on limited rainfall data but not to seek an absolute but uncertain value for triggering rainfall.

3 Determination of the Characteristic Rainfall

In order to determine the characteristic rainfall, a new variable, named the catastrophic ratio, is defined as:

$$P(x) = \frac{N_f(R_{24} > x)}{N(R > x)} \qquad (2)$$

where *P(x)* denotes the catastrophic ratio, N_f is the number of debris-flow events with R_{24} greater than *x*, and *N* is the number of rainy days of rainfall *R* greater than *x*. The variable describes the probability of debris flows when rainfall is greater than *x*.

The *P(x)* vs. *x* curve has three distinct sections (Figure 3): monotonously increasing, fluctuating, and decreasing sections. *P* increases linearly with *x* in the increasing section, which indicates that *N* decreases more rapidly than N_f as rainfall increases when $x < 18.4$ mm. As *x* reaches 18.4 mm, the curve fluctuates and *N* and N_f keep decreasing at similar rates. It is surprising that the maximum catastrophic ratio is 0.4, which means that the probability of debris-flow occurrence at Jiangjia is less than 40% no matter how large a rainstorm is. Beyond the fluctuating section of the plot (> 38.4 mm), the curve varies in a complex manner. *P* decreases generally with *x* in the last section. The variation in the catastrophic ratio indicates that the probability of debris-flow occurrence does not correlate absolutely with increasing rainfall. From 0 to 18.4 mm, the tendency for cause and effect increases. Between 18.4 to 38.4 mm, it fluctuates. When $x > 38.4$ mm, the probability decreases. The most dangerous rainfall values range between 18.4 to 38.4 mm. Then the first inflection point ($x = 18.4$ mm) can be defined as the characteristic value. The

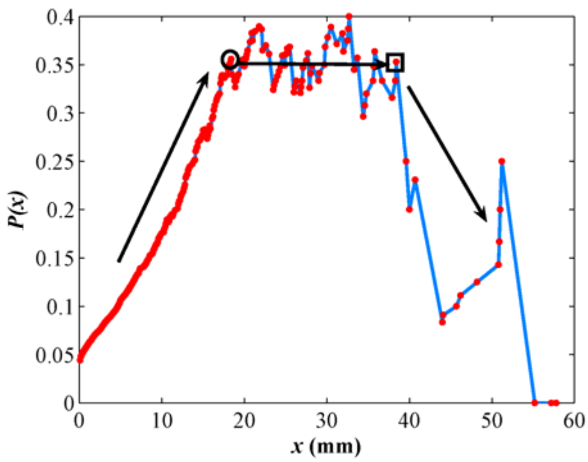

Figure 3 Catastrophic ratio *P(x)* versus rainfall *x* at Jiangjia basin from 2002 to 2008 (circle, $x = 18.4$ mm; square, $x = 38.4$ mm)

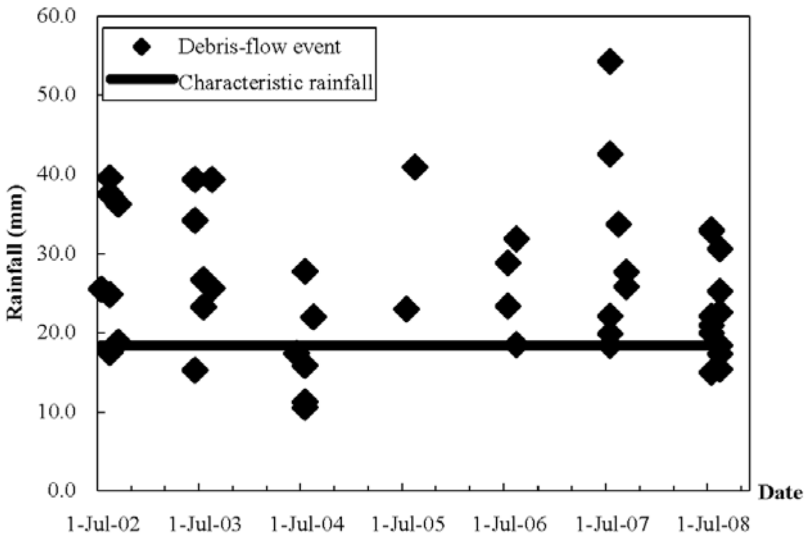

Figure 4 Debris-flow events and characteristic rainfall at Jiangjia

24h cumulative rainfalls in Table 2 and the characteristic rainfall are plotted in Figure 4.

Furthermore, it is noted that the inflection point corresponds with the rainfall value at which the cumulative probability is equal to 90% of the daily rainfall distribution of Jiangjia (Figure 2). This implies that daily rainfall with a 90% probability (R_{90}) can be used as the characteristic rainfall and that the rule can be applied to other similar basins such as Subaohe. The TRMM data at Subaohe reveals that the cumulative probability of daily rainfall reaches 90% when x = 16.2 mm. Based on the above analyses of Jiangjia data, that value (16.2 mm) seems to be the characteristic rainfall for Subaohe. However, considering the TRMM spatial resolution and the local altitudinal zonality of rainfall, the value needs to be rectified with local accurate rainfall data. Daily rainfall measured at the Tangjiashan gauge on September 23, 2008 was used as the rectification value. The measured value at the gauge is 173.8 mm while the TRMM rainfall on that day is 74.4 mm. Therefore, the rectified characteristic rainfall at Subaohe should be equal to 37.84 mm [= (173.8/74.4)*16.2]. As mentioned, that value is a good candidate for a debris-flow warning threshold at Subaohe basin.

4 Conclusions and Discussions

The characteristic rainfall, defined as the rainfall corresponding to the inflection point of debris-flow occurrence probability, is proposed as a value for warning of debris flows. The observed debris-flow and rainfall data at Jiangjia confirm the existence of such a characteristic rainfall by investigating the variation of the herein-defined catastrophic ratio. Further analysis of Jiangjia's daily rainfall histogram found that the characteristic value is in agreement with the daily rainfall with a 90% cumulative probability. Then, this finding is applied to Subaohe basin and is proposed as an estimated debris-flow warning threshold there. However, we must be careful in extending this finding to other basins where physiographic and geological settings are very different from the two study areas. The finding may be not universal and will require more case histories for verification. In spite of this, however, this method of estimating the warning rainfall threshold from the statistical characteristics of daily rainfall distribution has a significant advantage over traditional methods.

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