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Use of Rainfall Statistical Return Periods to Determine Threshold for Mass Wasting Events

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ABSTRACT

Recent attention has been focused toward determination of threshold rainfall levels in the estimation and prediction of mass wasting events (such as landslides, mudflows, debris flows, sloughs, earth movements, and so forth). The literature indicates use of a cumulative rainfall value as a threshold that correlates mass wasting occurrence versus rainfall depth occurrence. In the current article, the threshold concept is extended to use of rainfall return period estimates. Return period estimates are developed for the peak 1-day, 2-day, and successively larger continuous peak durations of rainfall, to duration sizes of 1 year. Such a return period peak duration rainfall analysis is prepared for each rainfall season in the rain gauge record, resulting in a historic summary of peak duration return frequency based on every possible peak rainfall duration. By using return period as a measure of the rainfall depth for each peak duration, one can correlate the rareness of rainfall occurrence to the rareness of the mass wasting events for those events substantially triggered by rainfall. A similar type of analysis can be developed for estimates of infiltration by using a selected infiltration relationship and then synthesizing the resulting estimates in the same way that the rainfall data are analyzed. Once the entire history of the rain gauge is analyzed for infiltration, return period estimates can also be developed for use in possible correlation to mass wasting events. A case study involving a catastrophic landslide in La Conchita, California, is considered as an example application.

INTRODUCTION

The use of a threshold concept for the correlation of significant rainfall events to mass wasting events is well known, and perhaps one of the earliest detailed presentations of such a concept is found in Campbell (1975). However, a search of the literature indicates that additional attention should be paid toward use of rainfall return periods (RPs) in the estimation of mass wasting event occurrences, leveraging advances in computing and rainfall data collection that support exhaustive statistical analysis. An advantage in using RP statistics is that not only can one assess whether a particular rainfall event is larger than another rainfall event, but one can also assess if either of the events being compared is significant with regard to frequency of occurrence. That is, if both events are common in the RP, then the relative magnitude of these rainfall events may not be as meaningful as it would be in the event that one of these events was relatively common while the other event was quite rare. Given that mass wasting events typically are relatively rare events, there may be an expectation that including the measure of rareness of rainfall occurrences may improve the correlation between rainfall and mass wasting events.

The concept of return frequency or RP is found in numerous applications in earth science. The concept of rainfall threshold in correlating mass wasting events (such as landslides, mudslides, mudflows, debris flows, sloughs, and so forth) with rainfall is considered in other publications (for example, see Wolman and Miller [1960] and Campbell [1975], among others). The underpinnings of the threshold approach indicate that sufficient rainfall within a particular duration of time can result in sufficient infiltration of water to cause saturation of the soils and transport of the water to deeper strata, in turn resulting in reductions in the factor of safety of the soil mass under consideration; this infiltration can subsequently trigger the mass wasting event. There are other causes of mass wasting events, such as earthquakes and fires (among others), but the current article only focuses on rainfall-triggered mass wasting events.

In addition to the usual rainfall depth measure, the concept of RP of the rainfalls may be used to establish thresholds. For any particular peak duration of rainfall, the measured rainfall depth has an associated RP (in years) that satisfies the property that larger RP values (i.e., rarer) correspond to larger depths of rainfall. In addition, use of the RP measure provides information regarding how rare the rainfall triggering events are. Use of RP aids in the development of risk assessment for such mass wasting events and guidance in prioritization of similar risk situations when one is allocating funds for risk reduction projects.

RP assessments are used in the geosciences as well as in many other fields of study. Zezere et al. (2008) assessed RPs of rainfall-triggered landslides in a region near Lisbon, Spain, in 2006 and identified that the weather patterns that created the antecedent moisture conditions prior to the slope failures comprised "considerably different synoptic atmospheric patterns" (Zerere et al., 2008). Frattini et al. (2009) have evaluated intensity-duration frequency curves versus initial water content for shallow landslides in northern Italy and have "demonstrated that antecedent rainfall must be taken into account in landslide forecasting" (Frattini et al., 2009). The authors then compared their results to the earlier works of Iida (2004) and D'Odorico et al. (2005). Iida (2004) concluded "that rainfall events with return periods <500 years and <1000 years trigger about 50% and 65% respectively of the total number of landslides over the long term" (Iida, 2004). D'Odorico et al. (2005) found that "hyetographs with a peak at the end of a rainfall event have a stronger destabilizing effect than hyetographs with a constant rainfall or with a peak at the beginning" (D'Odorico et al., 2005). Rosso et al. (2006) included rainfall intensity-duration relationships with their hill slope stability model and developed "a simple analytical model capable of describing the combined effects of duration and intensity of a precipitation episode in triggering shallow landslides." Salciarini et al. (2008) "present results to demonstrate how a transient infiltration model coupled with an infinite slope stability calculation may be used to assess shallow landslide frequency in the City of Seattle, Washington, USA." Use of RP assessment can be found in studies of ice, snowfall, stream levels, fire, earthquakes, droughts, and other events that may be relevant as factors in triggering mass wasting events.

In this article, we focus on rainfall-triggered mass wasting events and the correlation between rainfall RP and these occurrences. The threshold concept model is used as the basis for the correlation. It is noted that because a window of peak rainfall time durations and corresponding RPs is developed, there can be more than one peak duration involved in triggering a mass wasting event in the peak duration window. Consequently, since the relevant peak rainfall durations do not exactly correlate (and are not mutually independent events), the RP of a single threshold value will typically be larger in value (i.e., more rare) than the RP of the subject mass wasting events under study. That is, the occurrence of such mass wasting events may be more frequent than predicted by the RP of the rainfall threshold alone. Both rainfall and estimates of infiltration into the soils are considered as the primary trigger variables in determination of possible threshold. The methodology presented can be implemented using programs such as Microsoft Excel or a similar technology.

RAINFALL ANALYSIS

Mass wasting events typically can have several different triggers, including rainfall, earthquake, leaking water utilities, etc. Frequently the trigger is rainfall, as well as the accompanying hydrologic impacts of that rainfall, including groundwater-level changes and other effects on the structural integrity of the earth system under study. Therefore, a detailed statistical analysis of various durations of peak rainfall and the corresponding depths of rainfall is needed. Because of the tremendous volume of calculations, computer programming is appropriate, although commonly used spreadsheet software is adequate to accomplish the necessary procedures for shorter rainfall data records.

The approach used in this work is to first develop a continuous string of rainfall data (usually daily rainfall values) for the entire history of the target rain gauge. Once the data are checked for consistency and accuracy (usually by correlation to nearby rain gauges and investigations into the gauge history), they are then analyzed for "peak duration statistics," in which case the term "peak duration" refers to total duration of time of consecutive daily rainfall values. For example, a "5-day peak duration" refers to that 5-day interval of consecutive daily rainfall values that has the largest sum of rainfall (of course, there may be more than one such 5-day peak duration with this maximum total rainfall value). Using the 5-day duration as an example, once the peak 5-day duration of rainfall is identified, the time of occurrence is identified, and that duration is stored in the database as the number-one ranked 5-day rainfall. If there are other 5-day durations with the same peak total value, they are similarly handled in the ranking analysis. Then, the next largest total value of 5-day rainfall is identified and similarly handled. In this approach, all 5-day durations are examined and ranked in the relevant "ranking table" for the 5-day duration. For example, for 1,000 ordered daily rainfall readings, there would be 996 possible 5-day durations to be examined and ranked. The above procedure is repeated for all possible peak durations, from the 1-day duration through the duration corresponding to the entire rainfall record length. And for each peak duration ranking table, all durations are ranked according to total rainfall value, from largest to smallest.

The peak duration ranking tables can be used directly with local agency meteorology or hydrology statistical tables that give the RP (in years) of total rainfall in a particular peak duration. Some agencies term such statistics "depth-duration" statistics, "peak duration rainfall" statistics, or similar names. Sometimes such statistics are provided in terms of rainfall intensity instead of depth and are called "rainfall intensity-duration" statistics. Using these statistics, or equations, each peak duration developed in the peak duration ranking analysis can be assessed with regard to the RP of a particular total rainfall depth for a particular peak duration occurrence. This step of the analysis is useful in identifying not only the most significant rainfalls involved at a target rain gauge but also in assessing the rareness of occurrence of that rainfall. For example, a particular rainfall for the 10-day peak duration rainfall may be the number-one ranked occurrence, but it may still be a relatively "common" occurrence based on rainfall RP statistics.

A useful further step is to analyze all of the peak duration rainfall depths on a season-by-season basis and then to develop the corresponding RP estimates of those peak durations (on the season-by-season basis) for comparison of a particular rainfall season to another rainfall season. This approach to handling rainfall data is particularly advantageous in the identification of possible threshold values corresponding to other related effects, such as mass wasting events triggered by rainfalls, mudflows, and landslides, among other events. This type of analysis is found to be useful in the analysis of landslides in Southern California and represents the tool applied to the tragic La Conchita landslide of 2005 described in this article. (The methodology has been used in the analysis of other landslides in Southern California, with similarly good results in identifying thresholds for further study.)

Rainfall Data Pre-Processing

The first step in the analysis is the data acquisition. In the United States, rainfall data are generally available from the National Oceanic and Atmospheric Administration (NOAA) and from local state or county water resource departments. Each data provider typically has its own format and a unique set of quality control codes. Rather than attempt to deal with each data set in its native format, a pre-processing step translates the data into a common generic format while simultaneously conducting tests for data exceptions, such as faulty readings, statistically unusual readings, or garbled/repeated time stamps. If the data are ALERT or event data, then they are "binned" into the smallest interval size necessary for the study, usually into bins that are 5 minutes wide.

Peak Duration Rankings

The next step is to configure analysis parameters. A water year (WYR) is defined; usually one uses the default October 1–September 30 setting used by the NOAA. A hydrologic midnight is specified, if the data support readings more frequently than once per day. All peak duration intervals can be confined to those that occur entirely within the bounded WYR (i.e., a seasonal versus total-record analysis). If this constraint is employed, then both the start and end dates must occur during the same user-defined WYR. In contrast, with this constraint removed, only the end date is required to occur within a target season. This is used to eliminate peak durations that could overlap WYRs and is mainly a concern only for very large (over 180-day) intervals. Finally, the peak duration intervals are selected depending on the study details. A typical long-duration study looks at each integer-day interval between 1 and 365 (366 in leap years).

Once the study parameters are set, the model sweeps through the pre-processed data record and produces a set of tables of peak duration rankings by WYR. Each table contains the sorted peak durations for each of the set of selected intervals of interest. Further, an "aggregate" peak duration table is written, which contains only the top-ranked peak durations for each WYR.

Using these tables, one can find the maximum amount of rainfall during any arbitrary peak period of time (the "peak duration") over the entire course

Table 1. *Example top peak duration rankings of a daily rainfall record (interval size = 13 days).*

Interval End Date and Time	Rainfall Depth (in. [cm])	Ranking
January 10, 2005, 8:00	12.43 [31.57]	1
January 9, 2005, 8:00	12.35 [31.37]	2
January 11, 2005, 8:00	11.61 [29.49]	3
January 12, 2005, 8:00	11.52 [29.26]	4

of the study by ranking the resultant rainfall depths. Table 1 shows the first four entries (of several thousand) of the ranked consecutive 13 days of rainfall throughout the history of an example gauge. A similar ranking table is developed for all consecutive rainfall durations of {1, 2, 3, …, 364, 365 (Season)} days. Similarly, one can calculate how any time period's recorded rainfall compares to that of all other time periods of equal duration. Because we are dealing with historical data, we refer to each interval by its end date only.

Return Periods

Using the sorted peak duration ranking tables, one can calculate the RPs for every interval covered by the rainfall record. There exist a variety of methods for determining the RP of recorded rainfall for an arbitrary time period. In California, the California Department of Water Resources (DWR) is a typical source for creating RP depth-duration reference tables (CA DWR, 2009). DWR tables were originally developed in the mid-1950s using the most complete set of raw data records available at the time, and these tables have been regularly maintained and upgraded ever since. The tables are calculated using a Pearson III distribution with Kite's approximation, with regional skew and coefficient of variation values based on local geographic climate regions.

Step Size Granularity

During processing, granularity parameters are developed for the existing reference tables, whether they come from the DWR, the NOAA, or a county hydrology manual. There are two axes to consider: RP steps and interval duration steps. This is because the tables, by definition, use discrete bins over a continuous range of rainfall measurements versus time. As a comparison, the standard day-based RP intervals from NOAA Atlas 14, the CA DWR, and the Orange County Hydrology Manual are shown in Table 2 and compared to this current study.

Note that these sampling intervals grow wider apart as the interval size grows and that there exists a large gap between 60 and 365 days. This may be acceptable if one assumes that major storm events can be accurately described within a 2-month window; however, such an analysis may miss important longer-term events, such as a lengthy, saturating rainfall or an unusual successive series of major storms that occurred over many weeks. Similarly, the RP values are also discrete and are staggered farther apart as the values increase, thus: 2, 5, 10, 25, 50, 100, 200, 500, 1,000, and 10,000 years.

Table 2. *Return period interval sets by agency.*

Source	Return Period Intervals (days)
NOAA	1, 2, 4, 7, 10, 20, 30, 45, 60
CA DWR	1, 2, 3, 4, 5, 6, 8, 10, 15, 20, 30, 60, WYR
OCHM	1, 2, 3, 4, 5, 6, 8, 10, 15, 20, 30, 60, WYR
Current study	1………………… to ………………….. WYR (continuous)

NOAA = National Oceanic and Atmospheric Administration; CA DWR = California Department of Water Resources; OCHM = Orange County Hydrology Manual; WYR = water year.

Interpolation between Reference Points

Interpolation may be used to achieve a continuous analysis between the points in the RP reference table. A first-order approximation uses linear interpolation along both the interval (duration) and the RP (depth) axes. In this fashion, it is possible to evaluate the peak duration rainfall depth for an arbitrary interval size and to calculate its RP using the interpolated RP reference table. The current work focuses upon daily rainfall data and statistical analysis of such data, such as that accomplished by others, including governmental agencies. Such statistical analysis is subject to the probability distributions and other assumptions that form the underpinnings of those analyses. Therefore, different threshold RP values are possible given the different statistical assumptions used in the RP statistics.

As an example, we will evaluate the RP for a 13-day peak duration of 12.43 in. (31.57 cm). We start with the DWR reference table, as shown below in Table 3. We expand the bold entries in Table 3 along the time axis to obtain the 13-day duration reference values shown in Table 4. Next, we compare the measured 12.43-in. (31.57-cm) peak duration depth against the bookending RP table bold values to find the peak duration's RP, which in this example is estimated to be approximately 29 years. Other interpolation approaches are available and are options in the computer modeling application, specifically one based on a logarithmic interpolation relationship.

Table 3. *Depth-duration table for Gauge 221 (source: CA DWR website, accessed February 2009).*

	Return Period for Rainfall for Indicated Number of Consecutive Days												
	1	2	3	4	5	6	8	**10**	**15**	20	30	60	WYR
RP 2	2.16	2.93	3.47	3.82	4.10	4.40	4.74	4.98	5.33	5.77	7.29	9.64	14.46
RP 5	3.24	4.51	5.39	5.93	6.36	6.84	7.40	7.73	8.25	8.85	11.03	14.68	20.72
RP 10	3.97	5.59	6.65	7.29	7.82	8.41	9.11	9.51	10.13	10.85	13.40	17.94	24.70
RP 25	4.88	6.96	8.21	8.95	9.60	10.34	11.22	**11.69**	**12.44**	13.29	16.28	21.93	29.52
RP 50	5.54	7.97	9.35	10.15	10.89	11.73	12.74	**13.26**	**14.10**	15.05	18.34	24.81	32.96
RP 100	6.19	8.96	10.46	11.32	12.14	13.08	14.21	14.79	15.72	16.76	20.33	27.61	36.29
RP 200	6.84	9.95	11.55	12.47	13.37	14.41	15.66	16.28	17.30	18.44	22.27	30.36	39.55
RP 500	7.69	11.25	12.98	13.96	14.97	16.13	17.54	18.23	19.37	20.62	24.78	33.92	43.75
RP 1,000	8.32	12.24	14.05	15.07	16.16	17.42	18.95	19.69	20.91	22.25	26.65	36.59	46.88
RP 10,000	10.44	15.51	17.58	18.72	20.07	21.64	23.55	24.46	25.95	27.59	32.73	45.32	57.07

RP = return period; WYR = water year. See text for explanation of bold entries.

INFILTRATION ANALYSIS

Mass wasting is often triggered by accumulated soil water. As water saturates soil, the increase in positive pore pressure within the soil creates a loss of stability. Examples of this are seen in landslides, mudflows, and other mass wasting events. An infiltration capacity rate estimate may be used to calculate the infiltration into the soil system. To analyze infiltration, various procedures are available that can operate on the rainfall data. The common "phi-index" approach may be used with hourly data. The "Curve Number" approach may be suitable for estimating infiltration using daily data. Other methods may be used, depending on available data.

Analogous to the rainfall analysis described above, infiltration estimates are analyzed for a spectrum of peak duration time intervals, and then RPs are estimated using a choice among a variety of statistical approaches. For example, a normal distribution with parameters estimated on a peak duration–by–peak duration basis may be used.

There are several methods for estimating infiltration using daily rainfall or other durations of rainfall. For example, the U.S. Natural Resources Conservation Service (formerly the U.S. Soil Conservation Service) developed soil "curve numbers" that correlate 24-hour rainfall values to 24-hour runoff values.

Table 4. *Linearly interpolated expansion of the highlighted subsection of the depth-duration table in Table 3.*

	10	11	12	**13**	14	15
25	11.69	11.84	11.99	**12.14**	12.29	12.44
50	13.26	13.60	13.95	**14.31**	14.66	14.10

See text for explanation of bold entries.

Considerations of prior rainfall influences or "antecedent rainfall" effects are also accounted for in that methodology. If finer rainfall data are available, methods such as the phi-index or an exponential type of loss rate function, among others, can be employed to estimate infiltration. Once such infiltration estimates are determined, season length increments of infiltration can be assembled that are analogous to the season length rainfall data discussed previously. Then, the methodology employed to analyze and rank the rainfall peak durations can be used to analyze and rank "peak durations" of infiltration. Although agencies do not typically develop depth-duration statistics for infiltration, as they do for rainfall data, RP statistics can still be estimated by assuming an appropriate probability distribution, as is done for rainfall duration statistics. The authors found reasonable guidance in using a normal and also a log-normal distribution when estimating the RP of peak durations of infiltration.

Other effects influence the outcome of landslides and other such mass wasting events. For example, groundwater table elevations, the types of soil, and other such considerations are important elements in a predictive analysis for mass wasting events. This article does not consider these other factors but rather only attempts to correlate the triggering rainfall effects to the occurrence of the outcome of mass wasting events as a simple one-dimensional model. Including these other variables would represent a significant advance with regard to the overall predictive power for mass wasting events. From these two types of analyses (i.e., rainfall and infiltration), a correlation between rainfall or infiltration may be examined with respect to the mass wasting event history at a site. In order to illustrate the above procedure, a case study using the La Conchita landslides is examined below.

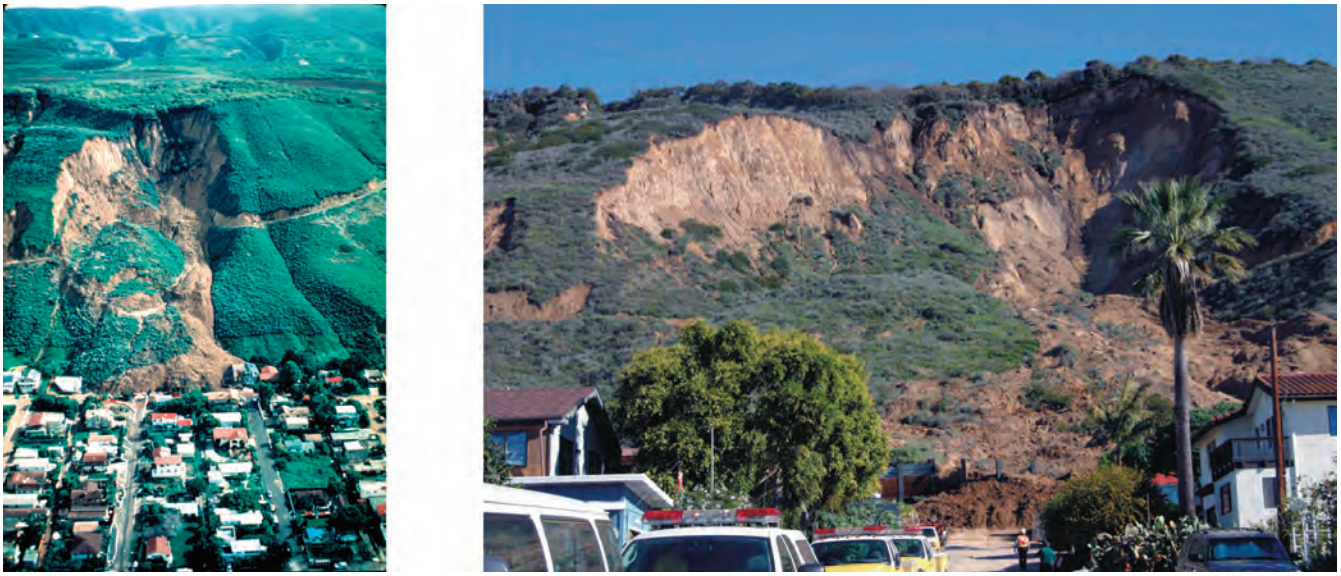

Figure 1. Views of the 1995 and 2005 landslides at La Conchita, California (source: USGS, 2004; Jibson, 2005).

APPLICATION PROBLEM

The bluff above La Conchita, California, has a long history of landslide events, with a major slide on March 4, 1995, and a tragic re-mobilization of that slide on January 10, 2005. (The latter slide was caught on tape by a news crew and can be viewed at http://www.youtube.com/watch?v=W4KWxglDL3o.) As described in Jibson's U.S. Geological Survey report, the bluff:

> consists of poorly indurated marine sediment of the Monterey and Pico Formations. The upper part of the slope consists of interlayered siliceous shale, siltstone, and sandstone of the Middle to Upper Miocene Monterey Formation. The lower part of the slope is siltstone, sandstone, and mudstone of the Pliocene Pico Formation (O'Tousa, 1995). Rock of both formations is very weakly cemented and has been regionally associated with extensive landslide activity (Morton, 1971; Harp and Jibson, 1995, 1996; Parise and Jibson, 2000). The two formations are in fault contact along the active Red Mountain Fault, which extends across the slope face. (Jibson, 2005)

Gurrola and Tierney from the University of California, Santa Barbara, Geology Department concluded that "the triggering mechanism for debris flows and mudflows appears to be prolonged, intense precipitation. The larger, complex slides may increase in activity months or even years after wet years and infiltration of rainwater to the subsurface environment …. Landslides similar to or larger than the 1995 and 2005 events may occur next year or in coming decades, during or shortly after intense rain" (Science Daily, 2005). Figure 1 shows aerial views of both mass wasting events.

The corresponding rainfall and infiltration analysis used all of the daily rainfall data (1967 through 2008) available through the County of Ventura for the nearby Seacliff Rain Gauge 221/A/B station (Ventura County Watershed Protection District, 2009). Rain Gauge 221 was the closest gauge to the study site, being 2 miles (3.22 km) to the southeast. Data from other local rain gauges were also analyzed in order to confirm the Gauge 221 statistical results. The rainfall RP table for Gauge 221 was obtained from the CA DWR ftp site referenced at CA DWR (2009); the available RP tabulation included the first 30 of the 40 years of available rainfall data.

As discussed previously, the entire rainfall data history of the Seacliff Gauge was analyzed, resulting in a sequence of nearly 15,000 daily rainfalls. These data were then scanned, sorted, and ranked for all possible consecutive n-day time intervals for {n = 1, 2, 3, …, 365 (Season)}; see Table 1 for n = 13. The size of each resulting ranking table depends on the n interval size. For example, in this application, for n = 1 there are 14,612 intervals ranked (October 1, 1966, through October 1, 2006). From the ranking tables, the peak rainfall depth can be determined for each of the n-day time durations for each season in the gauge record.

Next, using the DWR RP table for Seacliff 221, RP values are estimated for each entry in the ranking table, for each duration of {n = 1, 2, 3, …, 365 (Season)} and for each of the 41 seasons in the rainfall record at the subject gauge.

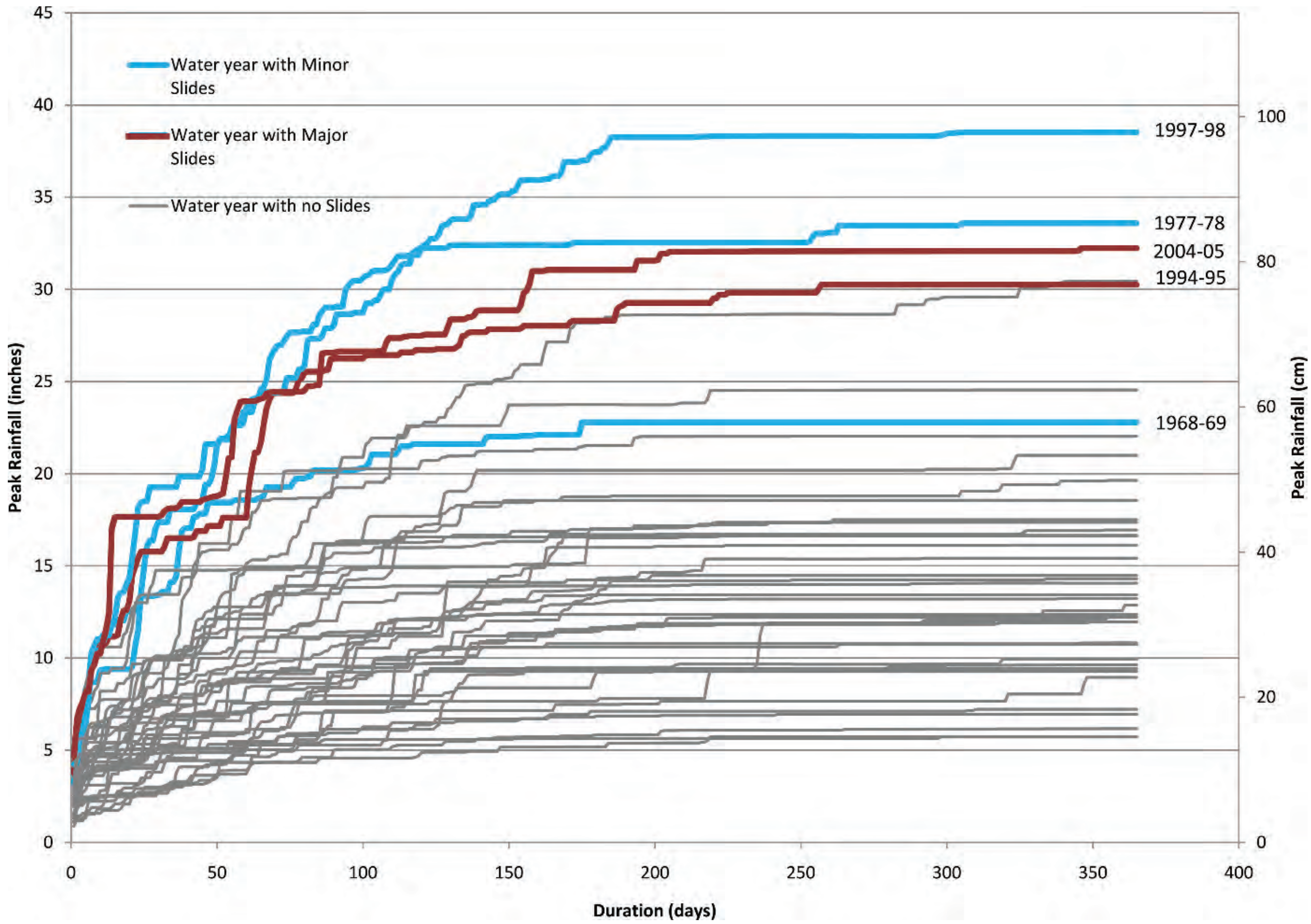

Figure 2. Peak rainfall depth versus peak rainfall duration for Gauge 221.

Plots of peak rainfall depth (in inches or centimeters) versus peak rainfall duration size (n, days) can be made for each season in the gauge record. The ensemble of these peak rainfall depths versus peak duration plots for Gauge 221 can be plotted together, as shown in Figure 2. (It should be noted that in the following figures, for clarity, only the most important years are plotted.) Another approach involves dividing the peak rainfall by the relevant peak duration length, yielding average rainfall intensity over the length of that duration in inches or centimeters per day, as shown in Figure 3.

By using RP statistics, such as the DWR analysis, the ensemble of plots of Figures 2 and 3 can be transformed into plots of RP versus peak duration, such as that shown in Figure 4. From the analysis approach leading to Figure 4, the information contained in Figures 2 and 3 is combined and ranked with respect to the respective occurrence probability, using RP as the measure. This approach not only compares magnitudes of rainfall between seasons but also provides the "rareness" of these rainfall occurrences, which then can be associated with the "rareness" of the mass wasting events. In Figure 4, the majority of the plots are "common events" of low RP (e.g., RP less than 2 years) and would normally be omitted from the new ensemble, leaving only the more significant (e.g., rarer) rainfall events.

From Figure 4, the key rainfall events are readily identified for further analysis and for assessment with respect to years of significant mass wasting. Furthermore, use of Figure 4 aids in assessing whether larger peak rainfall duration statistics are influenced by short-duration runoff-producing events versus more "soaking" rainfalls, in which a larger proportion of the rainfall infiltrates into the soil.

Various other analyses are simplified by use of the ranked data. For example, the timing of the rainfall peak durations can be illustrated by plotting a "stacking" diagram of peak duration timing, such as that shown in Figure 5. The "stacking" diagram shows when the heaviest periods of rainfall occurred over the course of the season. These rainfall periods are sorted by duration, with the longest duration

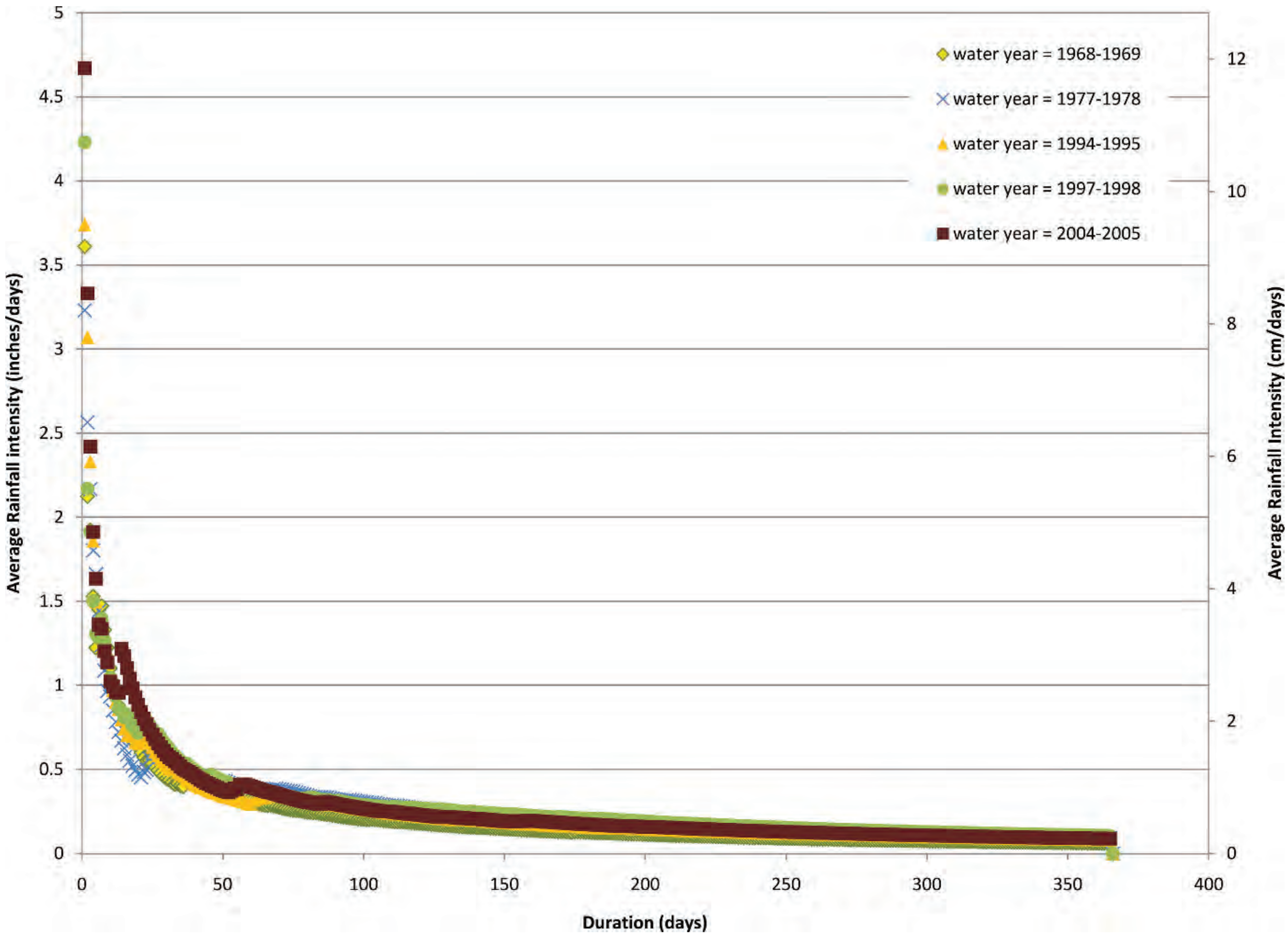

Figure 3. Average rainfall intensity at Gauge 221.

periods at the top of the chart and the heaviest short-duration periods at the bottom of the stack. Using this methodology, we can focus on whether rainfall was spread out over the WYR or if the storms were concentrated at a certain point in time. From Figure 5, one sees that many of the most intense rainfall peak durations occurred immediately prior to the La Conchita landslide, ending on the date of the landslide itself. The figure also shows that considerable rainfall occurred after the landslide event, but for the longer peak rainfall durations.

Infiltration, such as that estimated using a phi-index approach or a "Curve Number" approach, can be developed and plotted with respect to peak duration intervals (analogous to the rainfall analysis). Such an ensemble of plots containing significant "rarer" infiltration estimates is shown in Figure 6 for Gauge 221 (the more common RP seasons are omitted in the figure). Figure 6 illustrates the RPs of the infiltration estimates that were calculated to have infiltrated into the bluff at La Conchita, with the seasons normalized to the peak WYR for comparison.

Using the developed rainfall and infiltration statistical estimates and cumulative results, one can assess correlations of rainfall and/or infiltration estimates with mass wasting events, analogous to a threshold analysis. Various other forms of information are available for further analysis that may improve such a correlation for use in development of a possible predictive tool for use in risk management of sites vulnerable to mass wastings triggered by rainfall events.

Estimation of Threshold

Figures 2 and 3, which are typically used rainfall data displays, are not generally as helpful in identifying key triggering rainfall events as are the displays shown in Figures 4, 6, and 7. These figures demonstrate rainfall events that are not only exceptional in the rainfall record with regard to magnitude of

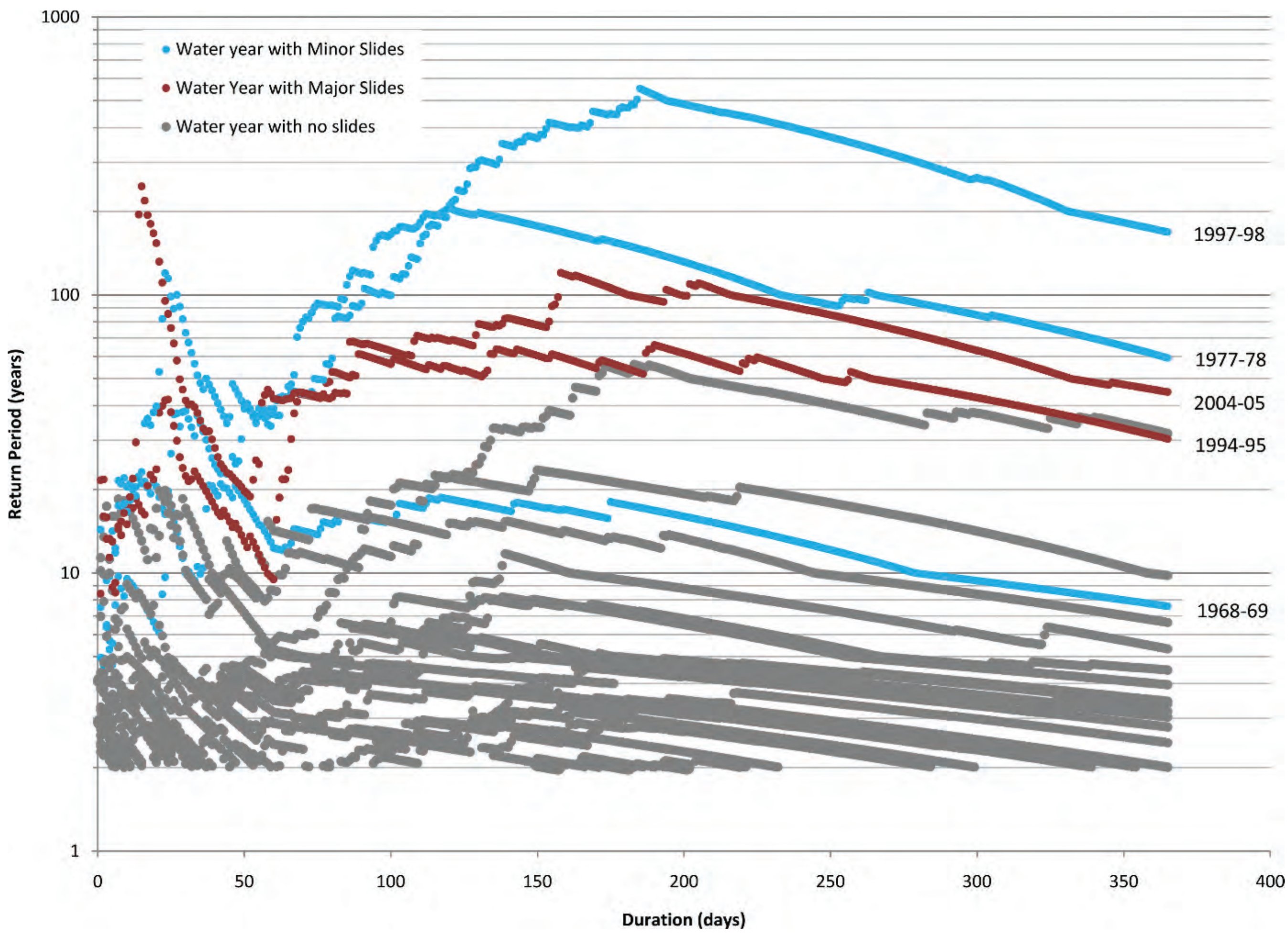

Figure 4. Rainfall return period (years) versus peak duration (days) for Gauge 221.

rainfall (or infiltration estimates), but are also exceptional in terms of RP. That is, the rare rainfall events are readily seen in these later figures. It is perhaps logical in situations where rainfalls trigger landslides that there may be a correlation between the rareness of the triggering rainfall (or infiltration) and the resulting outcome of landslide or mass wasting. This intuitive concept is readily visualized by the methodology results described in this article.

Geologic studies of the La Conchita study area, such as those of Jibson (2005), O'Tousa (1995), and others, indicate that significant mass wastings were triggered by rainfall that occurred in the storm seasons listed in Table 5. There are other historically documented mass wasting events at this site (including significant landslides, mudflows, and debris flows), but the rain gauge record for Gauge 221 did not extend prior to year 1966. In addition, the authors discounted the "dry slides" recorded in 1988 and 1990–1991, which appear to have been caused by spring activity rather than rainfall. From the analysis presented above, one can isolate those particular rainfall peak duration versus RP plots for further examination. Figure 7 shows a combined plot of the candidate mass wasting rainfall statistical plots.

Table 5. *Landslide activity versus top return period rainfall seasons at Gauge 221 (where rain data are available).*

Rainfall Season (October 1–September 30)	Documented Landslide Activity
1968–1969	Minor debris flow
1977–1978	Minor slide/mudflow
1994–1995	Major slides on March 4, March 10
1997–1998	Minor slides/mudflows
2004–2005	Major slide on January 10

In the determination of a candidate rainfall threshold value, the predictive power of the threshold equation is measured not only by the successful prediction of mass wasting events given rainfall data but also by the prediction of no mass wasting given such rainfall data. The typical statistical measure occurs by a count of "false positives" (i.e., threshold equation predicts a significant mass wasting but no

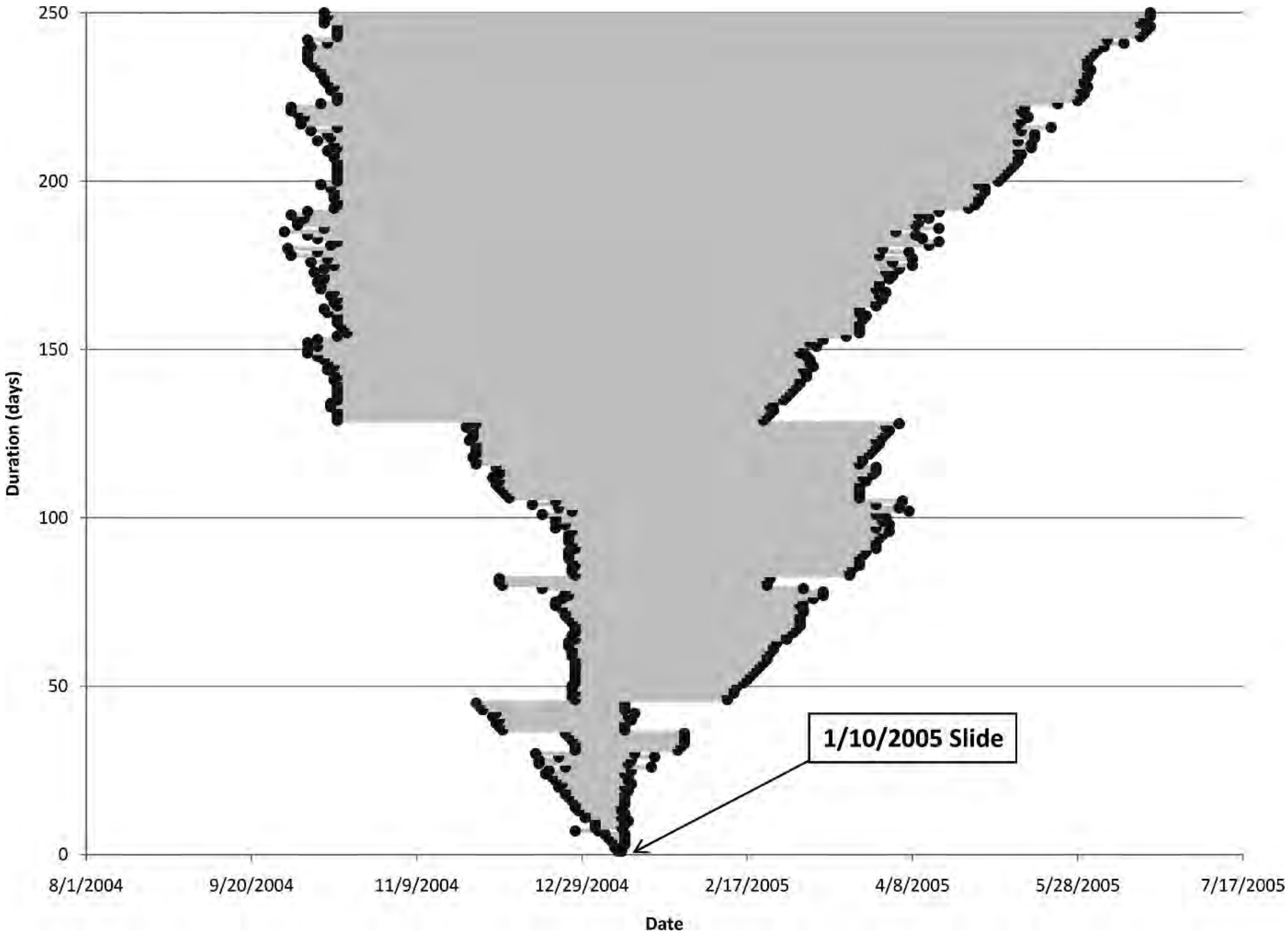

Figure 5. "Stacking" diagram of rainfall peak duration intervals for the 2004–2005 season at Gauge 221.

such movement occurs) and "false negatives" (i.e., threshold equation predicts no significant mass wasting but a significant mass wasting does occur). In the subject case study, there are 40 years of rainfall data to assess the accuracy of the threshold equation. From Figure 7, candidate threshold values and peak durations may be estimated.

In the current analysis, different thresholds are possible depending on the selected peak duration of rainfall being focused upon. For example, longer-duration peak rainfall intervals contain shorter-duration rainfall intervals that similarly could have thresholds defined that differ from the longer-duration rainfall interval. Further research is needed with a larger database of events in order to build a composite peak rainfall duration (or set of durations) that explain the various mass wasting events possible. In order to provide a higher level of confidence in providing safety, one may lower the threshold estimate, thus capturing smaller rainfall events that may trigger mass wasting events not properly represented in the available data set.

For the case study considered, a RP threshold is suggested by the RP value of about 40 years for the peak rainfall duration interval size of about 10 days to 30 days, as shown in the box on Figure 7. The available rainfall data and corresponding RP statistics point to the peak duration size with the RP threshold because of the very high correlation between mass wasting events and the target threshold and the very high correlation between rainfall quantities and no mass wasting events for rainfall amounts that are below the stated threshold. Figure 7 shows the suggested peak rainfall duration interval and also the possible RP threshold.

Several complications exist in the development of such a threshold equation. For example, the occurrence of a significant mass wasting event may actually result in a stabilization of the remaining earth mass, causing a possible increase in the threshold. Similarly, a mass wasting event may leave a much more unstable earth mass remaining that easily moves with a smaller rainfall threshold value. Activities of man, such as stabilization methods, may alter the subject earth

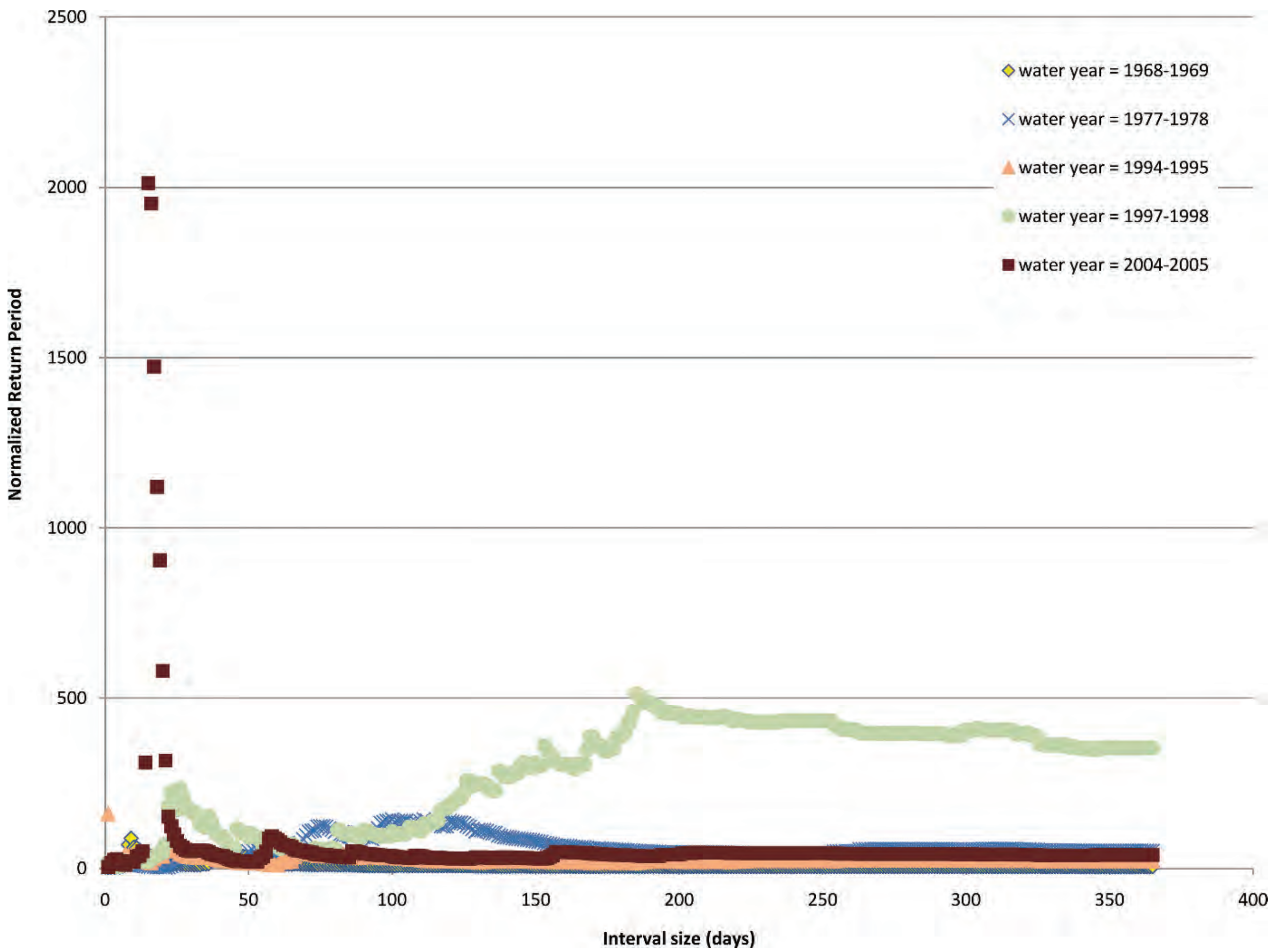

Figure 6. Infiltration return period versus peak duration for select Gauge 221 hourly data, using phi-index = 0.4 in./hr.

mass threshold level. For example, a "Winterization Plan" was implemented at the example La Conchita site following the 1995 mass wasting event; this plan may have helped stabilize the site during the winter storms of 1997–1998.

With sufficient data, confidence bands may be estimated that can be used to better apply the threshold equation for risk analysis that accommodates such possibly random geologic outcomes from mass wasting events. Another complication is the underpinnings in use of a threshold equation; for example, a causal connection between rainfall and significant mass wastings is needed in order to establish the validity of using such a relationship. Although such a causal linkage is typically readily established by examination of the rainfall trends in relationship to the sequence of mass wasting events, the underpinnings of that relationship should be understood in order to describe how rainfall contributes to or triggers the mass wasting, particularly when the available data are limited in record length. Generally, a probability analysis is useful if it assumes that the threshold equation outcomes and the mass wasting events are both mutually independent random events. In such a probability analysis, an assessment can be made with regard to the probability that two such sequences of outcomes came from mutually independent events. Such an analysis evaluates the occurrence frequency of false positives and false negatives. Another rough check on the threshold equation is to assess the frequency of occurrence of the mass wasting events over the data record and to compare that frequency against the RP estimates associated with the rainfall threshold value developed from the various plots described above.

From the above analysis, a threshold RP is estimated that corresponds to the available data for mass wasting events and the corresponding rainfall that triggered those mass wasting events. Of course, in this particular example, a single threshold RP appears to adequately relate mass wasting to the triggering rainfall. However, the figures accompanying the

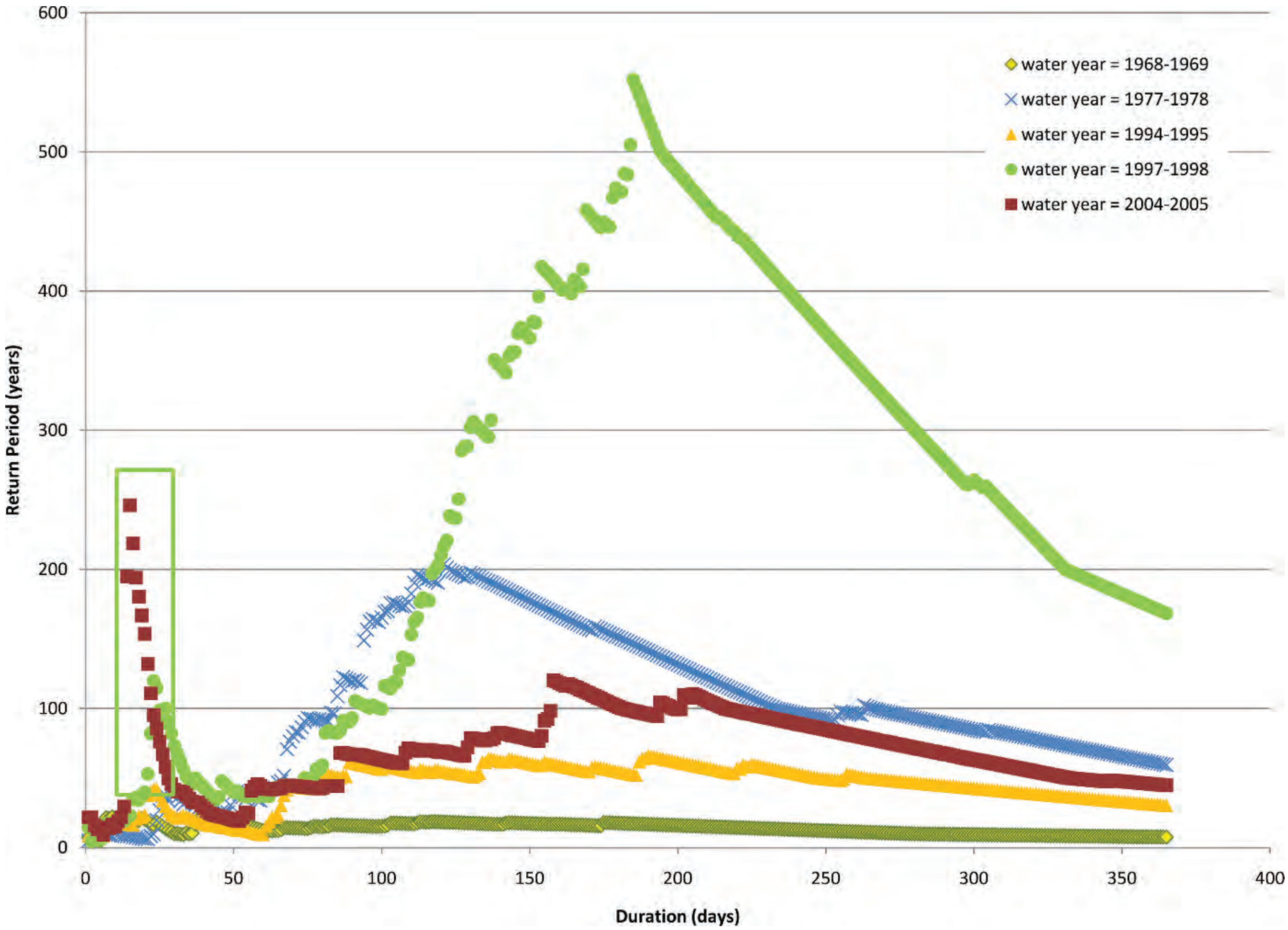

Figure 7. Return period of rainfall peak durations for candidate seasons at Gauge 221. (Note: a return period threshold of about 40 years is suggested for the peak rainfall duration interval size of about 10 to 30 days, as shown in the box.)

above analysis demonstrate that there are numerous peak rainfall durations being considered simultaneously in the threshold development, and, therefore, statistical conclusions need to be conditioned with respect to the correlation between these various peak rainfall durations. For example, the peak 20-day rainfall is very likely not independent of the peak 21-day rainfall, and, therefore, there exists a correlation that increases the probabilities related to the RPs of those two example peak durations versus what occurs if they are treated as independent random variables. Consequently, the threshold developed in the above analysis should not be interpreted as meaning that the threshold RP value is the RP of the mass wasting events. Indeed, the data show that the relative frequency of mass wasting events may be significantly higher than indicated by the RP of the threshold rainfalls. This is the case because the various peak rainfall durations are mutually dependent random variables, whereby one or more of these peak rainfall durations can simultaneously exceed the threshold value RP. Another issue involves partitioning the mass wasting events into sub-classes that distinguish between types of events. For example, some mass wasting events may be shallow slide events, others may be mild mudflows or debris flows, and still others may be massive landslides, among other classifications. Each of these partition classes may have a respective threshold to be differentiated from the other thresholds. Such a more-detailed threshold formulation would obviously require considerable data. Further considerations include development of thresholds on a peak duration class basis. For example, the data may show that the peak rainfall 1-day through 7-day durations may represent a class that is distinguished from the 8-day through 3-week durations of peak rainfalls, and so forth. The data may indicate that the rainfall peak durations may be partitioned into classes simply defined as "short," "mid-ranged," and perhaps "long-term" classes, such as 1 week and less, greater than 1 week but less than 3 months, and greater than 3 months, respectively.

Wolman and Miller's (1960) classic study indicates that an inherently unstable soil mass left intact by multiple small, high-frequency events will be subject to a single, massive, low-probability rainfall event, and our own analysis shows that the probability (intensity-duration curve) is a function of duration as much as of intensity. Again, considerable data may be needed in order to establish such partitioning of the data in a significant way. In the subject analysis presented, no data partitions were involved.

The analysis conducted for this particular landslide-prone area is subject to the available data, as are other forms of correlation analysis. Consequently, there is a sensitivity in the prediction power of the threshold developed to new data and for refinement of the threshold magnitude itself. A possible aid in the use of such a threshold involves under-estimation of the threshold in order to provide a factor of safety or higher level of confidence in the predictive capability of the method. As a result of the potential risks of damage and loss of life, consideration of such a factor of safety or higher confidence level may be appropriate.

Given an estimated threshold value for rainfall, various uses of these statistics may possibly be available, including the development of warning systems to reduce risk of injury or damage during rainfall seasons or storm events that become possible candidates for triggering additional significant mass wasting events. Of course, such a warning system would be rough at best, with an associated failure rate in predicting mass wasting events or in predicting a mass wasting event that does not occur. Another possible use of these statistics may involve risk assessment, where rainfall statistics may be used to estimate mass wasting event risk and frequency.

CONCLUSIONS AND FUTURE WORK

An approach is presented for analyzing rainfall peak duration statistics of the entire record of rainfall data (in an exhaustive manner) in order to aid in determining possible thresholds of rainfall for predicting mass wasting events (that are triggered by rainfall). The approach is extended to the analysis of infiltration estimates in an analogous manner.

The concept of using the rainfall RP for a given event (at a given rain gauge) to estimate the threshold for landslide initiation, rather than focusing only on the absolute rainfall quantities, has been developed into an application that can be readily used with spreadsheet computer software in common use. An advantage of the RP approach is that it allows one to make meaningful comparisons between the data from rainfall-triggered landslide events in several different regions with marked differences in long-term rainfall climates. The authors acknowledge that a 100-year storm in the La Conchita region, however, might have much different absolute rainfall amounts than a 100-year storm in Northern California, so a comparison of absolute amounts between the two regions might be misleading, while the RPs might be a better predictor of landslide activity, as noted by Wilson (2009).

For the example considered, it is observed that rare large depths of rainfall occurred at the subject site for particular peak durations of rainfall of approximately 2 weeks in duration. By comparing the occurrence of such large rainfall depths (at this peak duration) to the occurrence of mass wasting events such as landslides and mudflows, one may conclude that a critical duration of rainfall events that trigger such mass wasting events is approximately 2 weeks in length. Furthermore, based on the rareness of these particular rainfall depths, one may conclude an approximate threshold that corresponds to the concluded peak rainfall duration of about 40-year return frequency. Of course, the data available enable the above correlation to be drawn, but these data are not sufficient to exclude other possible peak durations of rainfall as additional potential triggering events.

Both approaches provide RP estimates of peak duration depths of rainfall (or infiltration) for possible use in defining such thresholds. The methodology is programmable on available spreadsheet software programs. The methodology offers value in the understanding of (among other topics) risk analysis and in the prediction of mass wasting events that are triggered by rainfall.

REFERENCES

California Department of Water Resources (CA DWR), 2009, *Rainfall Depth-Duration-Frequency Data*: Electronic document, available at ftp://ftp.water.ca.gov/users/dfmhydro/Rainfall%20Dept-Duration-Frequency/

Campbell, R. H., 1975, *Soil Slips, Debris Flows, and Rainstorms in the Santa Monica Mountains and Vicinity, Southern California*: U.S. Geological Survey Professional Paper 851.

D'Odorico, P.; Fagherazzi, S.; and Rigon, R., 2005, Potential for landsliding: Dependence on hyetograph characteristics: *Journal Geophysical Research*, Vol. 110: F01007.

Frattini, P.; Crosta, G. B.; and Sosio, R., 2009, Approaches for defining thresholds and return periods for rainfall-triggered shallow landslides: *Hydrological Processes*, Vol. 23, No. 10, pp. 1444–1460.

Harp, E. L. and Jibson, R. W., 1995, Inventory of landslides triggered by the 1994 Northridge, California earthquake: U.S. Geological Survey Open-File Report 95-213.

Harp, E. L. and Jibson, R. W., 1996, Landslides triggered by the 1994 Northridge, California earthquake: *Bulletin Seismological Society America*, Vol. 86, No. 1B, pp. S319–S332.

Iida, T., 2004, Theoretical research on the relationship between return period of rainfall and shallow landslides: *Hydrological Processes*, Vol. 18, pp. 739–756.

Jibson, R. W., 2005, *Landslide Hazards at La Conchita, California*: U.S. Geological Survey Open-File Report 2005-1067.

Morton, D. M., 1971, Seismically triggered landslides above San Fernando Valley, *California Geology*, Vol. 24, No. 4–5.

O'Tousa, J., 1995, La Conchita landslide, Ventura County, California: *Association Engineering Geologists AEG News*, Vol. 38, No. 4, pp. 22–24.

Parise, M. and Jibson, R. W., 2000, A seismic landslide susceptibility rating of geologic units based on analysis of characteristics of landslides triggered by the 17 January, 1994 Northridge, California earthquake: *Engineering Geology*, Vol. 58, pp. 251–270.

Rosso, R.; Rulli, M. C.; and Vannucchi, G., 2006, A physically based model for the hydrologic control on shallow landsliding: *Water Resources Research*, Vol. 42: W06410.

Salciarini, D.; Godt, J. W.; Savage, W. Z.; Baum, R. L.; and Conversini, P., 2008, Modeling landslide recurrence in Seattle, Washington, USA: *Engineering Geology*, Vol. 102, No. 3, pp. 227–237.

Science Daily, 2005, *Recent Landslides in La Conchita, California Belong to Much Larger Prehistoric Slide*: Electronic document, available at http://www.sciencedaily.com/releases/2005/10/051023123104.htm

U.S. Geological Survey (USGS), 2004, *Landslide Types and Processes, USGS Fact Sheet 2004-3072*: Electronic document, available at http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html

Ventura County Watershed Protection District, 2009, *Historical Rain and Stream Data Server*: Electronic document, available at http://portal.countyofventura.org/portal/page?_pageid=876,1686932& _dad=portal&_schema=PORTAL

Wilson, R. C., 2009, personal communication, U.S. Geological Survey, Menlo Park, CA.

Wolman, M. G. and Miller, J. P., 1960, Magnitude and frequency of forces in geomorphic processes: *Journal Geology*, Vol. 68, pp. 54–74.

Zezere, J. L.; Trigo, R. M.; Fragoso, M.; Oliveira, S. C.; and Garcia, R. A. C., 2008, Rainfall-triggered landslides in the Lisbon region over 2006 and relationships with the North Atlantic Oscillation: *Natural Hazards Earth System Science*, Vol. 8, pp. 483–499.