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ESTIMATING THE RISK OF LANDSLIDING USING HISTORICAL EXTREME RIVER FLOOD DATA (NOTE)

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INTRODUCTION

The East Coast region in the North Island of New Zealand has a history of extreme river floods, often resulting from large rainfall of high intensity. These storms were generally cyclones of tropical origin. Shallow translational landsliding (< 3 m deep along the colluvium-bedrock interface) on steep slopes underlain by Tertiary bedrock, and deeper (3 - 10 m depth) earthflows and slumps on gentler slopes underlain by Cretaceous bedrock, have been associated with the most severe storms, particularly where indigenous forest was cleared for pasture around the turn of the century (Marden et al., 1991). Although such storms are infrequent, there were four over the last decade that resulted in considerable East Coast landsliding (December 1980: 580 mm over 8 days; April 1982: 220 mm over 3 days; July 1985: 290 mm over 2 days; March 1988: up to 900 mm over 5 days; Phillips et al., 1990).

We propose that extreme river floods provide a surrogate, with direct causal linkage, for severe rain storms associated with landsliding. East Coast rainfall is notoriously variable. In a classic account from Tutira station, Guthrie-Smith (1969) noted that a 432 mm fall over 2 days at his homestead corresponded with virtually no rainfall at a site where he was working only 5 km away. We employ a river's catchment area as a large areal rain gauge. Historical flood data can be analysed statistically to estimate likely frequencies of occurrence (e.g. Pearson, 1992). Our analysis is intended for use by non-hydrologists and deals only with extreme floods. It is analytically simple, but statistically rigourous. For land-use planning, we seek a probability statement to estimate the risk of slope instability in the river's catchment.

METHODS

As a case study, we analysed previously unpublished 20th-century flood-level measurements made by the Gisborne District Council for the Waipaoa River at Kanakanaia (38° 28'S, 177° 53'E, 40 masl), 32 km north of Gisborne (Fig. 1). The Waipaoa is a major regional river, flowing from the south-eastern Raukumara Range southward to Poverty Bay near Gisborne. The Kanakanaia gauging station has an effective channel width between the stopbanks of 100 m (gravel bed width = 80 m). Its upstream catchment area is 1580 km^2 with 86 % underlain by Tertiary strata and 14% by Cretaceous strata. River-level measurements were made using a Foxboro-type recording pressure diaphram (water level resolution = 30 to 50 mm) attached to a bridge pier just above the gravel bed. Additional measurements of cross-sectional area and average velocity were made in the river to establish parabolic rating curves relating water level and discharge rate. Average summer and winter river discharge rates at Kanakanaia are < 10 and 15 - 20 $m^3 s^{-1}$, respectively. We defined an extreme flood as discharge rates exceeding the average by 2 orders of magnitude (> 1500 $m^3 s^{-1}$), based on the experience of Gisborne District Council's hydrologists.

From the extreme flood data, we calculated intervals between events (Table 1). Using the time intervals, our first analysis determined if the intervals between floods were statistically independent. Autocorrelations up to a lag of 10 were calculated, and deemed significant if greater in magnitude than 2 standard deviations. The only deviation from significance was the "lag-of-two" autocorrelation between events two time intervals apart, with a probability of chance slightly less than 5%. However, we believe it was spurious that three of the largest intervals (3449, 2196 and 1949 d) in the series were separated by

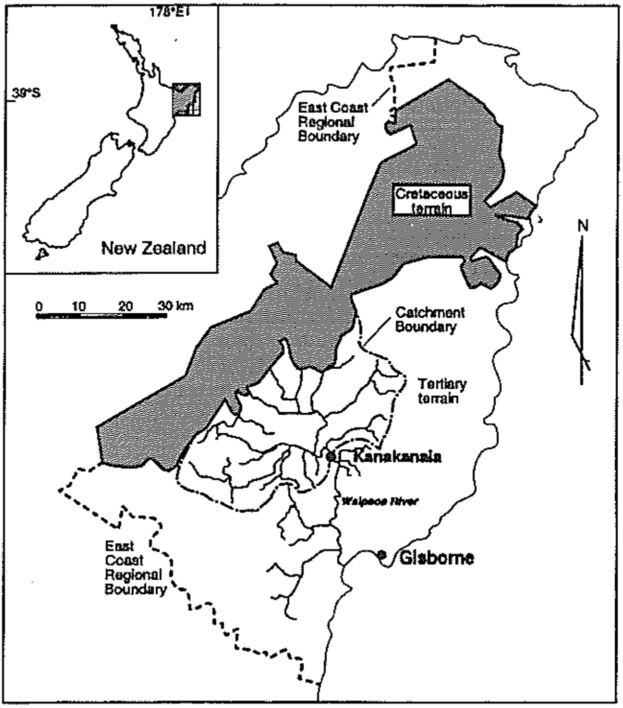

FIG. 1—Map showing the Waipaoa River, Kankanaia gauging station and the boundary of its 1580 km^2 catchment area. Also shown are the nearby city of Gisborne, boundary of the East Coast region, and the areas of Tertiary (steep) and Cretaceous (gentle, flatter; shaded on map) terrain.

two places. The intervals between floods were thus considered statistically independent. Homogeneity of the data set of 28 intervals was established by simulation analysis of 20,000 exponentially distributed variables (the required parameter q was estimated from our data set; see equation (1) and later results).

A histogram of extreme flood frequency and time intervals suggested the distribution was positively skewed. The calculated skewness was 0.77, and significantly greater than 0 ($p = 0.05$; Pearson and Hartley, 1972). Consequently, we examined an exponential model to represent the probability of occurrence of extreme floods as a continuous function of time.

The model was based on an assumption that the number of extreme floods follows a Poisson process, dependent only on time (Bickel and Doksum, 1977). It can then be shown that the time between consecutive extreme floods (t) is exponentially distributed (f(t)) with a parameter q equal to the average rate of occurrence as:

$$f(t) = \theta\ e^{-\theta t} \qquad (1)$$

where q is an inverse of the average time between floods equal to ($s/\Sigma t$) with s being the sample number of floods. Equation (1) is employed with $t > 0$ and $\theta > 0$. Goodness of fit between equation (1) and the data were tested for statistical significance using the Anderson-Darling test (Pearson and Hartley, 1972).

RESULTS AND DISCUSSION

There have been 29 extreme floods of the Waipaoa River since 1900 (Table 1). Regional landsliding was reported in association with these extreme floods in 1938 and 1948 (Cowie, 1957) and 1980, 1982, 1985 and 1988 (Phillips et al., 1990). However, quantitative data on landslide distribution, severity and soil loss and denudation values were available only for Tertiary terrain during the greatest flood in March 1988 (Cyclone Bola, Table 1). Intervals between floods ranged from 23 days to 9.4 years with an average of 2.9 years and a median of 2.7 years. The last extreme flood was in September 1988.

Autocorrelation analysis showed that the extreme floods were statistically independent events. Consequently, a higher frequency of extreme floods over the last decade could not be interpreted as a change or trend in occurrence. For example, there were 3 extreme floods during 1960.

The value of θ was equal to 0.34 (28 time intervals divided by 82.1 years; Table 1). The calculated Anderson-Darling statistic was 0.68, and the critical 15% upper-tail point was 0.92. There was thus insufficient evidence to reject the exponential function as a statistical model of extreme flood frequency. For estimating the chance of extreme floods, equation (1) can be integrated from 0 to t in order to define a cumulative probability function (F(t)) as:

$$F(t) = 1 - e^{-\theta t} \qquad (2)$$

Maximum deviations of observed frequencies from F(t) were +9% and -14%, although 16 of the 28 observations deviated by an absolute value of 5% or less (Fig. 2). Our data suggest a 25% chance that an extreme flood will occur in the Waipaoa catchment every year, while the model predicts a slightly higher 29% chance. The model overestimated chances of occurrence between the 2 and 4

TABLE 1-Occurrence of extreme floods of the Waipaoa River based on discharge rates (> 1500 $m^3 s^{-1}$) at Kanakanaia. Catchment area is 1580 km^2, effective channel width was 100 m and base discharge rates were 15-20 and < 10 $m^3 s^{-1}$ in winter and summer, respectively. Also shown is river level (m).

Date	River discharge rate ($m^3 s^{-1}$)	Time interval (days)	River level (m)
16 July 1906	3172		8.51
30 March 1910	3115	1353	8.44
18 May 1914	2832	1510	8.06
12 April 1918	2266	1425	7.14
23 September 1927	1926	3451	6.54
13 February 1932	2308	1604	7.27
19 February 1938	1572	2198	5.93
4 May 1938	1515	74	5.78
5 September 1943	1515	1950	5.78
7 March 1944	2455	184	7.45
13 May 1948	3965	1528	9.65
2 July 1950	3200	780	8.51
21 April 1954	2181	1389	6.99
24 April 1955	1501	368	5.78
15 July 1955	1926	82	6.54
14 July 1956	1841	365	6.38
13 April 1960	1643	1369	6.06
19 November 1960	2945	220	8.24
12 December 1960	2124	23	6.92
5 December 1962	1773	723	6.35
14 August 1965	905	983	6.57
4 May 1971	1656	2089	6.25
9 September 1976	1713	1955	7.23
27 December 1980	2756	1570	8.30
10 April 1982	2250	469	8.42
7 June 1984	1998	789	7.82
26 July 1985	1593	414	6.95
8 March 1988	5287	956	11.03
1 September 1988	3514	177	9.50

year time intervals, and underestimated chances for intervals beyond 5 years. Over 6 years, the observed chance of an extreme flood rose to 96% while the model gave an 87% chance. The last extreme flood occurred more than 6 years ago.

We tested a number of other models during preliminary analyses (results are not shown), but the exponential model developed here satisfied our needs. It is simple to use, adequately accurate, elementary to interpret, and involves definition of only one parameter. Finally, the exponential model is asymptotic with respect to maximal t.

For the erosion-prone 6000 km^2 of East Coast Tertiary terrain (ca 70% of the region), we believe that our probability assessment provides valuable quantitative information for land-use planning with implications for sustainability. It also highlights the considerable risk of storm-induced damage in the region. For

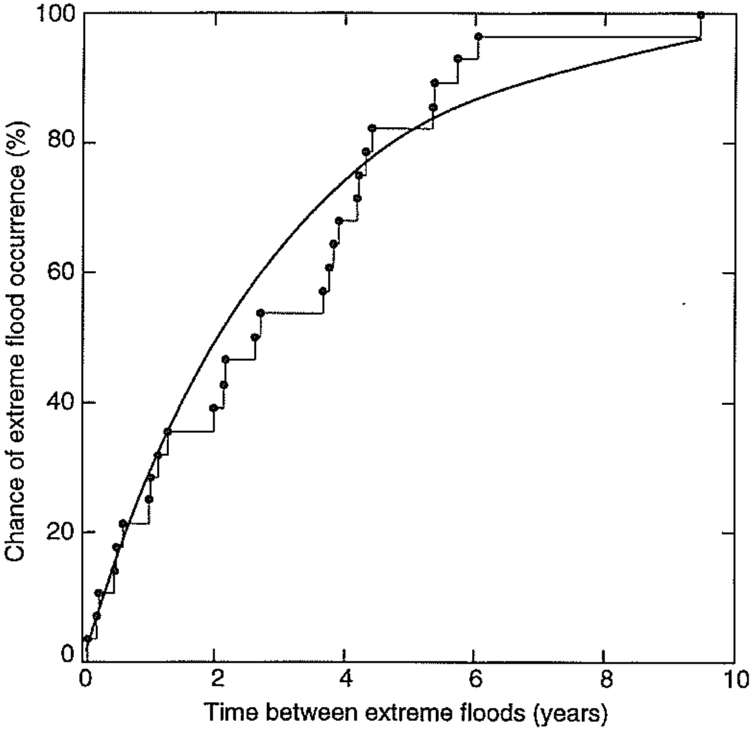

FIG. 2—The relationship of time (years) between extreme floods of the Waipaoa River at Kanakanaia (discharge rate > 1500 m^3 s^{-1}) and the chance of their occurrence. Analysis is based on time intervals between twenty-nine 20th century extreme floods, shown in Table 1. The lighter step function is the observations (data are shown as symbols) and the heavier curve gives expected chances for the cumulative exponential probability function described in the text.

example, one large flood-producing storm in the Waipaoa River is expected each decade. Given the association of severe rain storms with widespread hillslope failures, some current land-use practices on steep hill country may not be sustainable. During the largest flood-producing event in our record, Cyclone Bola, landslides on pastoral farmland underlain by Tertiary bedrock removed an average of 1631 m^3 soil ha^{-1} in the Uawa catchment, northeast of our study area (Marden et al. 1991). This is equivalent to a denudation value of 163 mm over the 4559 ha area assessed. Economic analysis suggested farm financial return was reduced for the following 4 years (Dr. C.J. Korte, Ministry of Agriculture, Gisborne, personal communication, 1988) in proportion to the percentage loss of grazed grassland that ranged from 8 - 32% (Marden et al. 1991). From historical evidence (eg, sequential photographs), the cumulative effect of successive storm-initiated landslides on Tertiary terrain has been a significant decline in farm productivity during this century. For example, during 1960 - 1986, the New Zealand government purchased 40,000 ha of East Coast farmland on Tertiary terrain for reforestation with *Pinus radiata* D. Don trees (Phillips et al. 1990). The stated aim was to reduce soil loss through a productive, more sustainable land use, based on the evidence that tree roots contribute to soil strength by significantly increasing its cohesion (eg, O'Loughlin and Zhang, 1986).

After being planted on farmland, a young stand of trees and the underlying soil may still be suseptible to damage by storm-initiated landslides. During Cyclone Bola, almost 10% of the newly established *P. radiata* forest area on Tertiary terrain was destroyed, with an average soil loss of 952 m^3 ha^{-1} (Marden et al. 1991), a denudation value of 95 mm over the 12,175 ha of affected forest. For stands older than 8 years, soil loss during Cyclone Bola was reduced to 217 m^3 ha^{-1}. Despite the risk of successive storms during a *P. radiata* rotation (ca 25 years), soil loss is likely to remain low, compared to pasture, until harvesting of the trees.

After harvesting, *P. radiata* root reinforcement of the soil deteriorates over a period of ca.6 - 8 years (O'Loughlin and Zhang, 1986). Depending on planting density, it takes about 2 years for a replacement tree crop root system to begin reinforcing the soil. With a standard planting density of 1250 trees ha^{-1}, there is a period of approximately 5 years after harvesting when root reinforcement is incomplete (Watson et al., 1994). There is an 82% chance of an extreme flood/storm during this period, based on our probability analysis. The possible risk of storm damage would obviously be increased by a delay in tree planting.

An alternative land-use for erosion-prone farmland is reversion to indigeneous forest. Compared with pasture, a 50 to 90% decrease in landsliding of Tertiary terrain was found in 10 to 15 year-old fully-stocked stands of regenerating scrub (Bergin et al. 1993). Indigeneous forest and regenerating scrub remain on only 16% of the East Coast region.

Increased afforestation with fast-growing tree species and retention of existing indigenous scrub and forest may thus reduce the risk of massive soil loss from Tertiary hill country during the inevitable future severe rain storms in the East Coast region. Although heavy rainfall is beyond human control, our proposed hydrological analysis provides a simple means of anticipating its occurrence, allowing informed development of soil conservation and land-use risk management strategies for erosion-prone terrain.

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