Application of Rainstorm Nowcast to Real-time Warning of Landslide Hazards in Hong Kong

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1. INTRODUCTION

Hong Kong is a vibrant city and a leading economy in the region, with a population of over seven millions and a leading economy in the region. Common to all metropolises, there is an extremely high demand of developable land to support the growth of economic and social infrastructures in Hong Kong. Out of its 1,100-km^2 land area, more than 70% of Hong Kong's landmass is hilly terrain. While land reclamation partly eases the problem, a substantial portion of developable land is created by reforming the hilly terrain. This results in many urban developments being located over or near to man-made slopes and steep hillside (Fig. 1).

Over southern China, the active southwesterly monsoon, monsoon troughs and tropical cyclones can bring intense and prolonged rainfall, especially in spring and summer. In Hong Kong, it is not uncommon to find daily rainfall records exceeding 300 mm. Amongst the various impacts brought about by heavy rain, Hong Kong is prone to landslide hazards for its steep hilly terrain, tropically weathered soil mantle, man-made slopes and dense housing near hillside. Except for the fast-moving rainstorm types such as supercell thunderstorms and squall lines, all other rainstorm types common in Hong Kong have the potential to trigger landslides [1]. In particular, the rainbands associated with quasi-stationery low-pressure troughs over the coast of southern China could have the highest impact on slope stability as the groundwater regime and soil properties could have been changed upon prolonged infiltration of rainwater.

On average, three to four hundred landslides are reported to have occurred in Hong Kong each year. The record rainfall of 3,343 mm in 1997 brought more than 550 landslides to the territory in the year. While the majority of the landslides was of relatively small scale causing minor disruptions to the city, a few landslide events proved their highly destructive and catastrophic nature. In the early 1970s, Hong Kong experienced a number of disastrous landslides, including the notable events in 1972 at Po Shan Road and Sau Mau Ping (Fig. 2) where 67 and 71 people died respectively. These catastrophes led to the establishment of the Geotechnical Control Office (now the Geotechnical Engineering Office (GEO) under the Civil Engineering and Development Department of Hong Kong) in 1977 to mitigate landslide risks and enforce slope safety. Landslide risk in the early 1980s were mainly associated with squatter huts constructed on hilly terrain. GEO implemented a Slope Safety System targeted at reducing landslide risk, including retrofitting substandard slopes, implementing control on geotechnical works, setting geotechnical standards, public education and enhancing slope maintenance. The Administration also carried out a policy of non-development clearance of squatter huts that were threatened by dangerous slopes. The effectiveness of the slope safety system was manifested in the declining trend of fatalities due to landslides over the years. Although landslides still occur from time to time, sometimes with serious consequences, their scale and severity have been decreasing as indicated by the significant reduction in the number of fatalities in recent years (Fig. 3).

A Landslip Warning System (LWS) is in operation in Hong Kong to alert the public to the risks of landslides during heavy rain situations. The issuance of landslip warning also triggers emergency responses among the government departments, mobilizing staff and other resources to deal with landslide incidents. This paper will discuss the design and operation of the LWS.

2. LANDSLIDE - RAINFALL CORRELATIONS

Most landslides in Hong Kong are triggered by heavy rainfall and a good understanding of the relationship between landslides and rainfall is crucial in the design and operation of the LWS. Landslide and rainfall correlations have been evolving over the years largely in response to the availability of more accurate landslide records and the advances in information technology as well as better slope performance resulting from the implementation of the Slope Safety System.

Lumb [2] reported the first study on landslides and rainfall correlation in Hong Kong in 1975. In this study, the occurrence of serious landslide events was related to 24-hour rainfall and antecedent rainfall in the previous 15-day. At that time, only a limited number of raingauges was available. The first LWS was largely based on Lumb's correlation. The purpose of landslip warning at that era was to provide a forewarning, particularly addressed to squatters, of rainfall situation which might lead to the onset of a significant number of landslips. Squatters were then strongly advised to temporarily evacuate from their dwellings on steep slopes.

In 1984, Brand *et al* [3] reported a second study on the landslide and rainfall correlation, the results of which were largely adopted as the basis for the issuance of landslip warning between mid-80s and late-90s. In the study, landslides and rainfall records over a 20-year period were reviewed. The occurrence of landslide was found to be strongly related to certain rainfall thresholds based on the amounts of rainfall in 24 hours or the rainfall in one hour. Rainfall exceeding these thresholds (175 mm in the preceding 24 hours or 70 mm in one hour respectively) would trigger the issuance of the landslip warning. Slight refinements to these thresholds were introduced by Permchitt and Massey [4] .

Pun *et al* [5]carried out a comprehensive review of the landslip warning criteria based on the data collected in the period 1984-1996. Major achievements included: (i) identified areas with relatively high landslide density, called "vulnerable" areas; (ii) establishment of linear relationship between the landslide density, ρ, and the rolling 24-hour rainfall, R_{24}, on a log-log scale over the "vulnerable" areas; (iii) a proposal that the landslip warning criteria be based on the total number of predicted landslides over the territory, N_{24}, as given by the above landslide-rainfall correlation model and its issuance should be considered whenever N_{24} exceeded certain pre-defined threshold value. In operation, each reference raingauge was assigned with a vulnerable area, A, according to the past history of reported landslides and the number of registered slopes in its neighbourhood. Given a distribution of R_{24}, ρ, at each affected raingauge could be deduced using the correlation model. The predicted number of landslides associated with each affected raingauge would be given by the product $\rho \cdot A$. N_{24} was then a simple summation of $\rho \cdot A$ over all affected raingauges. The landslide frequency model was an important development, as it provided a prediction on the number of landslides that is used as a basis for issuing landslip warning. This refined correlation model was subsequently adopted in the Landslip Warning System from 2000 to 2003. This is a more realistic model as the previous models described in Lumb [2] and Brand *et al* [3] used only the amount of rainfall as the threshold to trigger the issuance of landslip warning. Another important change is the deletion of the one-hour rainfall criterion because the study by Pun *et al* [5] showed that high-intensity one-hour rainfall is not a necessary or sufficient condition for widespread occurrence of landslides. The study also showed that high 15-day or 30-day antecedent rainfall increases the number of sizeable landslides but not the total number.

In 2003, Yu *et al* [7] expanded the landslide-rainfall correlation model to cover the whole of Hong Kong. Major changes put forward by Yu *et al* included: (1) correlating maximum rolling 24-hour rainfall, R_{24}^*, with landslides frequency (i.e. failure probability), f, instead of landslide density; (2) use of analyzed rainfall values on grid cells instead of raingauge data; (3) explicit consideration of different slope types and hence different failure probabilities. In this model, the territory was divided up into 40×40 grid cells, each having a planar area of 1.5 km by 1.2 km. About 700 of these grid cells contain land area. The spatial distribution of different type of man-made slopes in each cell was determined from the GEO Catalogue of

Slopes which registered all sizeable man-made slopes in Hong Kong (Fig. 4). In the study, about 118 rainstorms in 1984-2001 with a maximum rolling 24-hour rainfall exceeding 50 mm were analyzed. Isohyets of R^*_{24} (Fig. 5) were prepared for all these rainstorms and statistical analysis was performed for different slope types. A new set of bi-linear correlations between f and R^*_{24} in semi-log plot was determined for 4 common types of slopes in Hong Kong (soil cut slopes, rock cut slopes, fill slopes and retaining walls). Fig. 6 shows the overall correlation for soil cut slopes. As f was determined as the averaged frequency over different slope types in Hong Kong, the correlations are not location specific. Given a grid analysis of R^*_{24}, the landslide frequencies for all slope types in a grid cell can be readily found according to the correlations. The predicted number of landslides in a grid cell is calculated as the sum of all the landslide frequencies multiplied by the number of slopes, n, in a cell. The total number of predicted landslides for Hong Kong is obtained by summing over the number of landslides over all grid cells, i.e. N_{24} is the summation of $f \cdot n$ over all slope types and all grid cells. The criteria for issuance of the landslip warning remained unchanged, i.e. N_{24} exceeded the same pre-defined threshold number.

3. THE LANDSLIP WARNING SYSTEM

The LWS was first introduced by GEO in 1977 to warn the public of landslide dangers during prolonged heavy rainfall. Since 1984, the LWS is jointly operated by GEO and HKO. Whenever the warning criteria are met, the two departments will jointly consider the necessity for issuing the warning. Once the decision is made to issue the landslip warning, a warning bulletin will be issued to the public immediately via the electronic media and the internet. When the Landslip Warning is in force, the warning message is broadcast regularly on radio and television to remind the public to take appropriate precautionary measures. For examples, pedestrians are advised to avoid walking or standing close to steep slopes and motorists to avoid driving in hilly areas or on mountain roads, especially at places where signs of dangerous hillside or retaining walls are erected. When the landslide situation is becoming serious, the public is advised to stay in a safe shelter or home. The major LWS information flow is shown in Fig. 7.

Operation of the LWS requires the knowledge of both the recorded and forecast rainfall intensity in real-time. The recorded rainfall data was acquired by an extensive network of 110 automatic raingauge units over the territory (Fig. 8). Out of 110 raingauges, 86 of them are operated by GEO and 24 by HKO. The rainfall data are transmitted to the control centres at 5-minute intervals. Computer programs are developed to capture and analyze the real-time rainfall data in a rolling 24-hour period. In the current version of the LWS, the rainfall-landslide frequency models developed by Yu *et al* [7] are coded in the computer programs to facilitate automatic monitoring and assessment of the landslip warning criteria.

While actual rainfall is required for deciding whether the warning criteria is reached or not, forecast rainfall is also desirable to give advance alert to HKO and GEO, as well as other government departments to mobilize resources to deal with the aftermaths of landslide incidents. Currently, HKO provides 1-hour and 3-hour forecast rainfall as inputs to the Landslip Warning System. The section below describes how the forecast rainfall is used to provide an advance alert to the forecasters on the chance of reaching the landslip warning level in the next 1 to 3 hours.

4. NOWCASTING APPLICATION IN SUPPORT OF LWS OPERATION

Rainstorm is often volatile and erratic in nature, with typical life span ranging from tens of minutes to several hours. Given its volatile nature and a small forecast area such as Hong Kong, a forecasting tool at high spatial resolution, of the order of one kilometre or less, and with the ability to detect, analyze and forecast at short turn-around time is essential for effective rainstorm prediction. Nowcasting techniques present an effective strategy to meet the challenge. The HKO has developed and operated a nowcasting system named SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems) which provides quantitative precipitation forecast (QPF) to support the operation of the LWS.

The workflow of the QPF module of SWIRLS is outlined in Fig. 9 and described in detail in the companion paper by Wong [8]. In essence, SWIRLS converts radar signal power into rainfall intensity using a dynamic correlation function, calibrated in real-time based on raingauge data. To make a very-short range forecast on the movement of the radar-rainfall, SWIRLS firstly derives their motion vectors by a technique called TREC (Tracking of Radar Echo by Correlation). Next, SWIRLS carries out a time integration* from 0 to 3 hours by extrapolating the radar-rainfall field according to the TREC motion vectors in 6-minute time steps. At each time step, radar-rainfall is accumulated at each grid cell to generate the 1- to 3-hour forecast rainfall distributions over Hong Kong.

To provide some lead time before the landslip warning criteria are met as determined by the actual 24-hour accumulated rainfall, a landslip alert module was developed in SWIRLS to make use of forecast rainfall to predict when the warning criteria is likely to be reached. The SWIRLS Landslip Alert (SLA) module takes full account of the rainfall-landslide frequency correlation but uses the rolling 21-hour actual rainfall plus a 3-hour SWIRLS rainfall forecast to make up the rolling 24-hour rainfall, thus providing a lead time of up to 3 hours. Ideally, a perfect 3-hour forecast could provide a 3-hour lead time. Based on this partial forecast rainfall field, the SLA module then calculates the predicted number of landslides, denoted as

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* Extended to 6 hours since 2006 with the introduction of Semi-Lagrangian advection method.

N_{21+3}, updated every 6 minutes. When the predicted number of landslides reaches the warning criteria (current 15), SWIRLS will provide visual and audio alarms to alert the forecasters. The workflow of the SLA module is shown on Fig. 7 in conjunction with the LWS.

5. PERFORMANCE

Verification studies on the performance of the LWS have been carried out recently. Although the landslide-rainfall correlation model had undergone a major change in 2004, namely switching from a landslide-density based to landslide-frequency based model (see Section 3), all SLA and landslip warnings issued in the period 2001-2005 (hereafter referred to as the verification period) were included in the study to ensure statistical significance.

Table I summarized the cases used for the present verification. Listed in Table I were the time records of issuance of the SLA and attainment of the landslip warning criteria. The actual times of issuing the landslip warning were also listed for reference. Although the attainment time of the landslip warning criteria is objective and tracked automatically, it should be noted that the issuance of the landslip warning and its timing are joint decisions of GEO and HKO with additional factors taken into consideration, e.g. whether or not the rainstorm is departing or weakening. In Table I, the second column from the right recorded the lead times of SLA with respect to GEO's timing. Here, late or missing alerts were counted towards negative lead times whereas false alerts are discounted from the lead time statistics.

Table II recorded the predicted and reported numbers of landslides for all the landslide events occurred during the verification period. For the extended rainy spells in Table II with consecutive warnings issued within one or two days, the reported and predicted numbers of landslides during each such rainy spell were pooled together and counted under one single landslide event. As a result, the number of landslide events was less than the numbers of SLA or landslip warnings listed in Table I.

Table III summarized all the verification statistics for the SLA and the GEO landslide-rainfall correlation model, including: H (number of "hit"), F (number of "false alarm"), M (number of "miss"), N (total number of predictions = H+F), POD (probability of detection = H/(H+M)), FAR (false alarm ratio = F/(F+H)), CSI (critical success index = H/(H+M+F)), PIL (percentage of ideal lead time = actual lead time / ideal lead time) and the frequency distribution of different SLA lead times. In forecast verification, a "false alarm" generally refers to a prediction that does not occur. For the SLA, a "false alarm" refers to an alert that the landslip warning criteria is expected to reach in the next 3 hours, i.e. $N_{21+3} \geq 15$, but the landslip warning criteria is not reached in reality. In the landslide-rainfall correlation model and landslip warning, a "false alarm" refers to an event when the landslip warning criteria is indeed reached (i.e. $N_{24} \geq 15$) and the warning issued, but the number of landslides reported is less than 15.

For easy appreciation, the results in Table I-III were plotted on Fig. 10-12 respectively. In summary, SLA was able to provide advance alerts to forecasters, with average lead times of 92 minutes against the attainment time of the warning criteria. If compared to the issuance time of the landslip warning, SLA was issued 108 minutes in advance on average. As shown in Table I and Fig. 10, half of the alerts had lead times longer than 1 hour, although the distribution peaked at the 0-1 hour range. As shown in Fig. 11, SLA achieved a skill level (CSI) of about 61% with relatively high POD (82%) and low FAR (30%). As the skill level of nowcasting based on extrapolation is expected to drop rapidly with increasing forecast range [9], say beyond 2 hours, the observed PIL of 53% was not surprising.

As shown by the histograms in Fig. 11, the skill level (CSI ~78%) of the prediction by the landslide-rainfall correlation model is considerably higher than that of SLA, with perfect detection (100% POD) and very few false alarms (only 2 out of 9 issued warnings). The success of the landslide-rainfall correlation model can also be seen in the scatter plot of predicted versus reported number of landslides (Fig. 12). As shown in Table IV and Fig. 13, the numbers of forecast landslides based on the prediction of N_{21+3} (i.e. SLA) were actually quite close to those predicted with recorded 24-hour rainfall.

6. FUTURE DEVELOPMENT

The verification results discussed above showed that the Landslip Warning System was generally effective and the SLA provides useful and timely guidance to forecasters. There were, however, some cases where the SLAs provided short lead times or even time lags (Table I), especially in cases where there were rapid intensification of the rainstorm. This is exemplified by the rainstorm case of 19 August 2005. The 3-hour rainfall forecast for the day (rainfall maps not shown) had been seriously under-predicting the intensity until a time closer to the attainment of the warning criteria (at 20:15 HKT). The reason was that the rainbands affecting Hong Kong actually intensified rapidly during the latter half of the 3-hour forecast period. As SWIRLS assumed that both the rainfall intensity and the echo motions would persist during the forecast period, any rapid storm intensification and/or significant evolution in the environmental steering flows could lead to serious errors in the forecast rainfall. Nevertheless, at around 19:00 HKT, SWIRLS started to capture the actual intensification of the rainbands and eventually be able to issue a SLA at 20:06 HKT.

To address the above issues, HKO recently implemented two major enhancement to SWIRLS, namely (a) the introduction of the Semi-Lagrangian advection technique to extend the forecast lead time and (b) a new QPF system in the form of RAPIDS (Rainstorm

Analysis-Prediction Integrated Data-processing System), which blends SWIRLS nowcasts with Numerical Weather Predication model forecasts to improve on rainstorm development from 3 to 6 hours. RAPIDS is described in more details by Wong et al [9].

To further improve on rainstorm forecasting in the future, enhancements to the forecasting systems, including SWIRLS and NHM, themselves and new ways of representing the forecast information are worthy of exploration. For examples, introducing growth-decay capability to SWIRLS and employing more advanced data assimilation technique to ease the spin-up problem of NHM are future possibilities. To account for the inherent uncertainty and forecast errors in NWP models, probabilistic representation is perhaps a better way to move forward. Whether the landslide-rainfall correlation model can make use of probabilistic forecasts is another area requiring further research.

At the same time, it is expected that the landslide-rainfall correlations are reviewed from time to time. The performance of slopes is improving as a result of the implementation of the Slope Safety System and the correlation models become outdated. GEO will continue its effort in improving the correlation models that meet the challenges of changing environment and rising expectation of the public. Study on the effect of antecedent rainfall on slope performance and classifying the landslide risk in accordance with their consequences could further enhance the robustness of the Landslip Warning System. Hitherto, the landslide frequency models are developed based on reported landslides on man-made slopes and adjusted for landslides in natural hillside. Another challenge is to provide a more statistically sound correlation for landslides in natural hillside and rainfall pattern, which may require an entirely different approach from that used for landslides in man-made slopes.

In conclusion, both the SLA and the landslide-rainfall correlation model were shown to be generally effective. The landslip warnings were issued in an accurate and timely manner. The successful operation of the Landslip Warning System is attributable to the synergy of both the geotechnical service and weather service of Hong Kong. The successful application of rainstorm nowcast products to forewarning of landslide hazards is made possible through a close collaborative effort between the researchers and operational staff from both services.

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Table I. Time records of SLA and landslip warnings issued during the period 2001-05. Also shown (right-most two columns) are the lead times of SWIRLS Landslip Alerts w.r.t. the records of GEO and CFO*. ("F" and "M" represent cases of false alarm and missing respectively.)

Year	Date	Issuance Time (HKT hh:mm)			SLA Lead Time (hr : min)	
		SWIRLS Landslip Alert	**GEO** Warning Level	**CFO** Landslip Warning†	**GEO**	**CFO** (*for reference only*)
2005	Aug-19	20:06	20:15	21:00	0:09	0:54
	Jun-24	09:36	03:40	10:15	M	0:39
2004	Aug-29	14:36	14:50	15:30	0:14	0:54
2003	Sep-15	12:06	-	-	F	F
	Sep-03	07:48	-	-	F	F
	Jun-11	02:30	-	-	F	F
	May-05	05:42	09:40	07:30	3:58	1:48
	May-04	17:06	-	-	F	F
2002	Sep-17	00:18	00:35	01:30	0:17	1:12
	Sep-15	02:30	03:25	03:45	0:55	1:15
	Aug-10	11:12	10:45	11:00	M	M
	Aug-10	02:36	04:40	-‡	2:04	(*discounted*)
	Aug-06	11:48	-	-	F	F
2001	Sep-08	00:00	02:55	03:30	2:55	3:30
	Sep-01	21:54	22:20	22:45	0:26	0:51
	Aug-30	13:12	14:20	15:30	1:08	2:18
	Jul-15	15:36	-	-	F	F
	Jul-06	15:00	17:25	18:00	2:25	3:00
	Jun-27	13:54	13:05	15:45	M	1:51
	Jun-12	11:48	12:30	14:15	0:42	2:27
	Jun-12	01:18	02:30	-#	1:12	(*discounted*)
	Jun-08	04:12	05:55	07:45	1:43	3:33
	Jun-06	05:00	08:25	06:00	3:25	1:00

Note: * *The Central Forecasting Office of HKO, also known as the Hong Kong Meteorological Centre.*

† *Please refer to Section 5 for factors affecting the issuance time of the landslip warning.*

‡ *Warning not issued due to rainbands departing Hong Kong;*

Warning not issued due to rainbands moving away from major vulnerable areas.

Table II. Landslip warnings issued over the period 2001-05 and the corresponding numbers of landslides.

Landslip Warning Periods			No. of Landslides	
Start (HKT hh:mm)	**End** (HKT hh:mm)	**Duration** (hour : min)	**Predicted**	**Reported**
2005/08/19 21:00	2005/08/22 06:15	57 : 15	292.7	229
2005/06/24 10:15	2005/06/25 07:45	21 : 30	32.7	66
2004/08/29 15:30	2004/08/30 06:15	14 : 45	18.6	12
2003/05/05 07:30	2003/05/06 07:00	23 : 30	118.3	89
2002/09/17 01:30	2002/09/17 12:45	11 : 15	54.3	38
2002/09/15 03:45	2002/09/15 20:30	16 : 45		
2002/08/10 11:00	2002/08/10 15:00	04 : 00	13.2	14
2001/09/08 03:30	2001/09/08 08:45	05 : 15		
2001/09/01 22:45	2001/09/02 10:00	11 : 15	38.1	42
2001/08/30 15:30	2001/08/30 23:15	07 : 45		
2001/07/06 18:00	2001/07/07 09:50	15 : 50	21.0	6
2001/06/27 15:45	2001/06/28 07:25	15 : 40	27.5	19
2001/06/12 14:15	2001/06/12 17:45	03 : 30		
2001/06/08 07:45	2001/06/08 17:00	09 : 15	25.0	78
2001/06/06 06:00	2001/06/06 14:00	08 : 00		

Note: *(i) In the extended rainy spells with consecutive warnings issued within one or two days, the reported and predicted numbers of landslides in each such spell were grouped together and counted under one single event, contributing to one data point in the scatter plot of Fig. 12.*

(ii) Landslides reported outside the landslip warning periods were not counted.

Table III. Verification statistics of SWIRLS Landslip Alert and GEO Landslide-rainfall correlation model over the period 2001-05.

Statistical Measures	**SWIRLS Landslip Alerts (w.r.t. attainment of warning criteria)**	**Landslide-rainfall Model (w.r.t. reported landslides)**
H	14	7
F	6	2
M	3	0
N	20	9
POD	82 %	100 %
FAR	30 %	22 %
CSI	61 %	78 %
PIL	53 %	-
<0 lead	3	-
0-1 hr lead	6	-
1-2 hr lead	3	-
2-3 hr lead	3	-
>3 hr lead	2	-

Note: The statistical measures listed here correspond to the plots in Fig. 10 and Fig. 11.

Table IV. Comparison on the predicted numbers of landslides by SLA and GEO Landslide-rainfall correlation model for the period 2004-06 (up to June 2006).

Landslip Warning Periods		**No. of Predicted Landslides**	
Start (HKT hh:mm)	**End (HKT hh:mm)**	N_{21+3} **(SLA)**	N_{24} **(GEO)**
2006/06/09 14:30	2006/06/09 17:20	30.8	40.0
2006/06/02 14:00	2006/06/02 22:15	29.1	20.0
2006/05/03 02:30	2006/05/03 13:00	42.0	40.0
2005/08/19 21:00	2005/08/22 06:15	261.4	292.7
2005/06/24 10:15	2005/06/25 07:45	46.8	32.7
2004/08/29 15:30	2004/08/30 06:15	16.8	18.6

Note: N_{21+3} *and* N_{24} *represent the maximum predicted numbers of landslides in SLA and GEO, which are based on the rainfall accumulations* R_{21+3} *and* R_{24} *respectively (see Section 2 for detailed definitions).*

Fig. 1 Bird’s eye view of Hong Kong Island — land reclamation and hillside high-rises are characteristics of the metropolitan.

(a)

(b)

Fig. 2 Two major historical landslide events in Hong Kong: (a) the Po Shan Road Landslide in 1972; (b) the fill-slope failure at Sau Mau Ping in 1972.

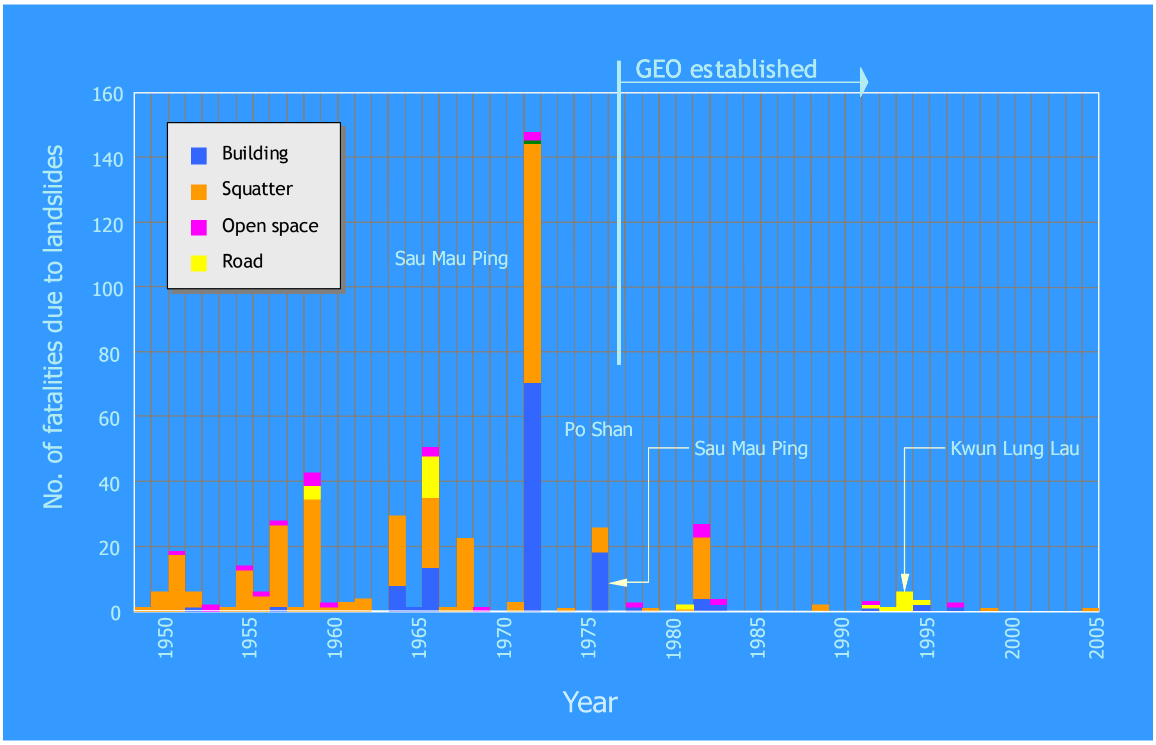

Fig. 3 Fatalities due to landslides in Hong Kong.

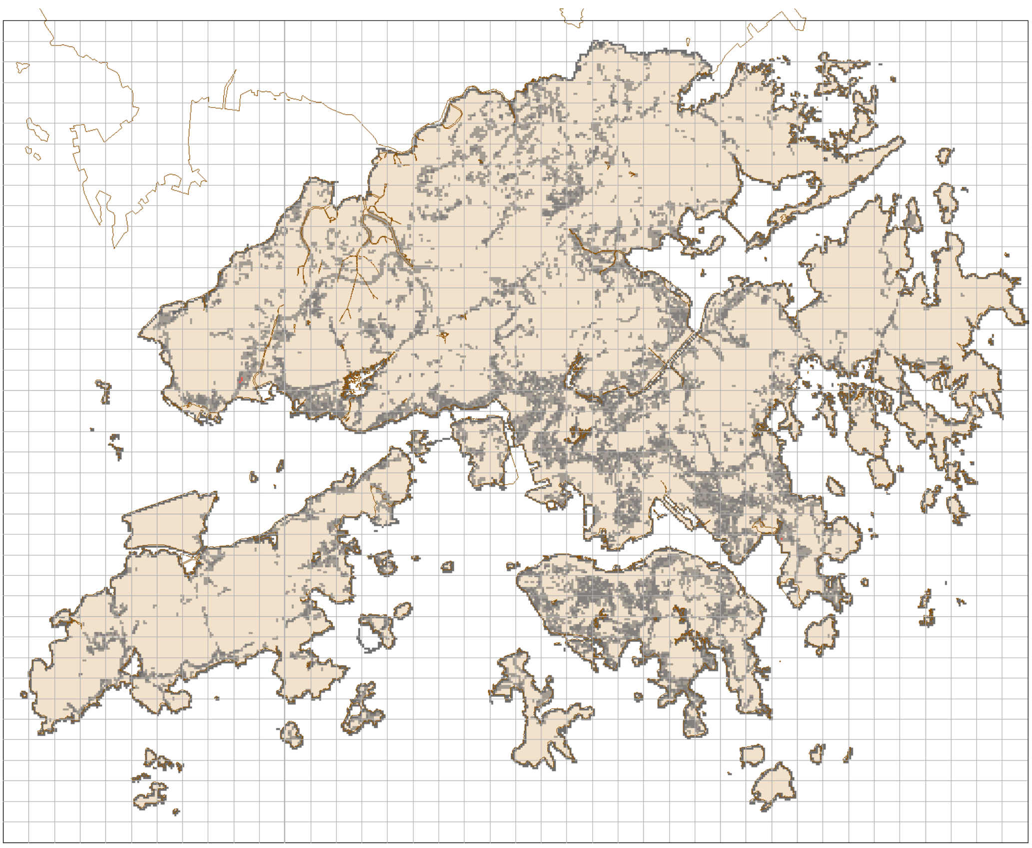

Fig. 4 Spatial distribution of man-made slopes (grayed areas) in Hong Kong. The grid lines indicate the discretization of the territory into 1,600 cells.

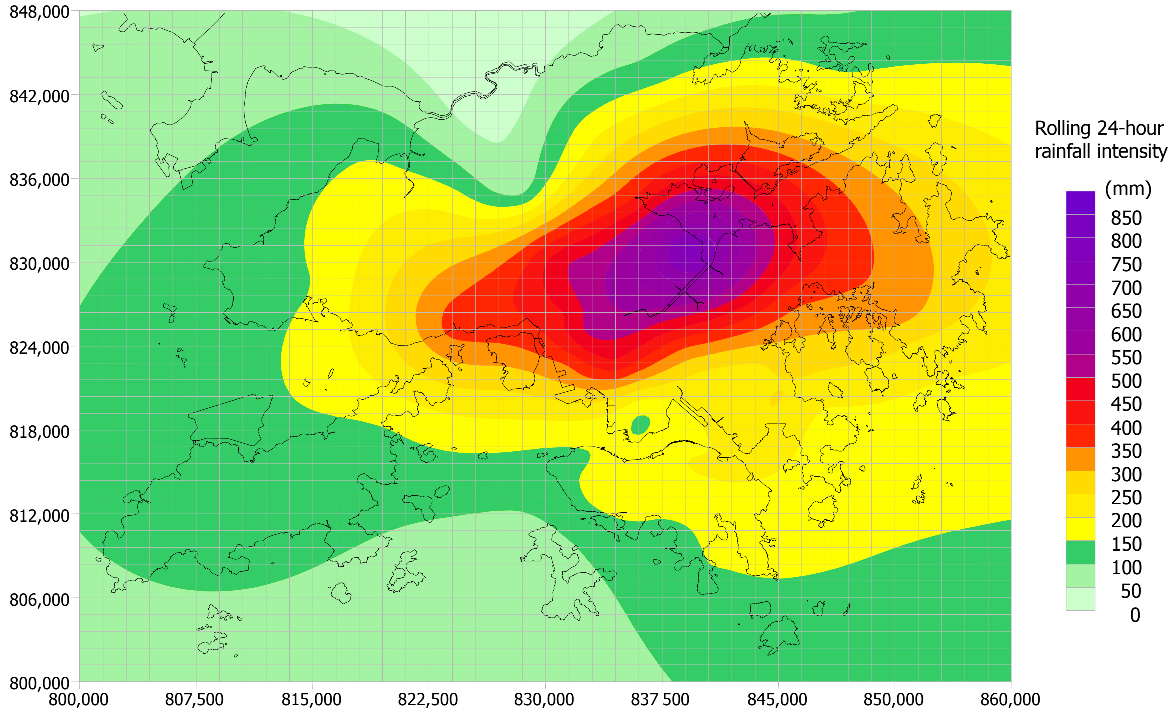

Fig. 5 Example of rainfall isohyet analysis to determine the spatial distribution of rolling 24-hour rainfall over the 1,600 grid cells of Hong Kong.

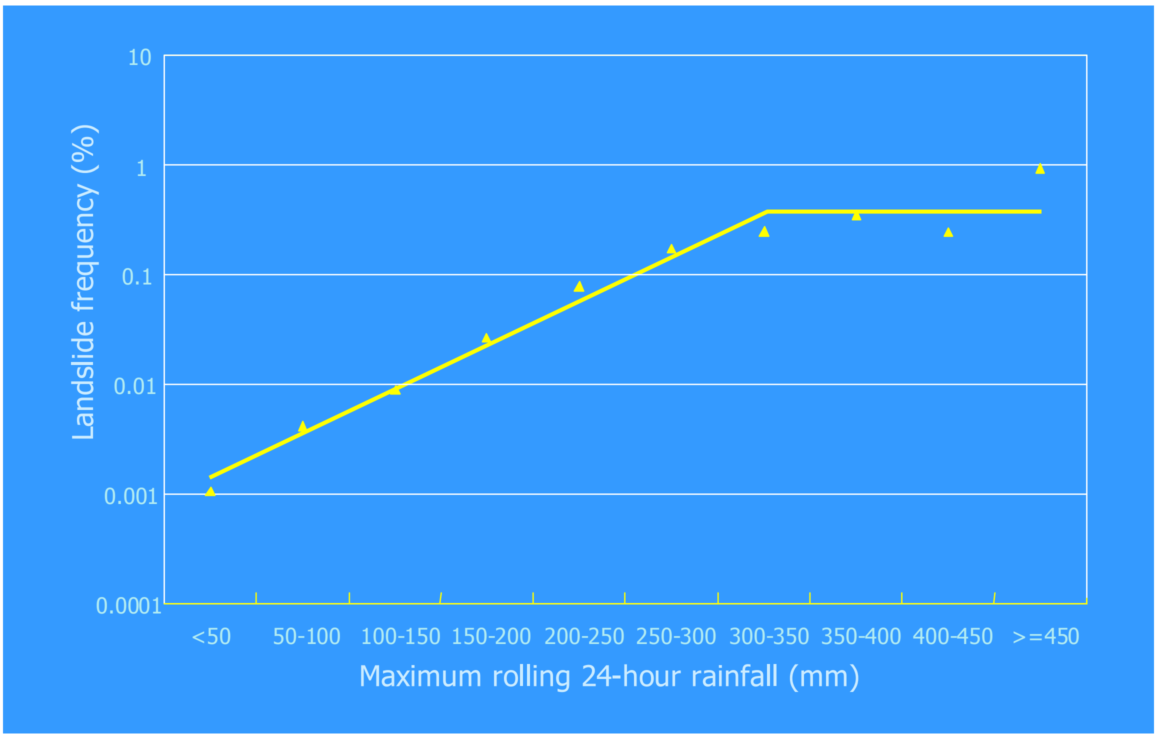

Fig. 6 Overall correlation between landslide frequency and maximum rolling 24-hour rainfall for soil cut slopes in Hong Kong.

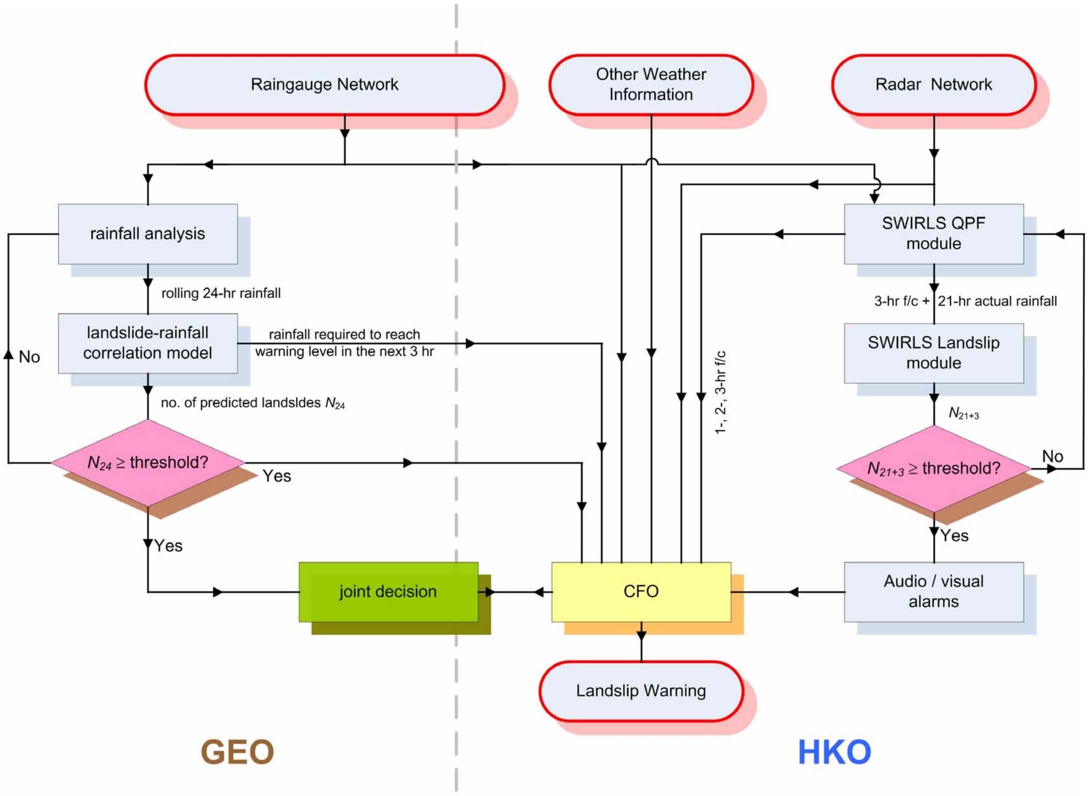

Fig. 7 Major information flow in landslip warning operation.

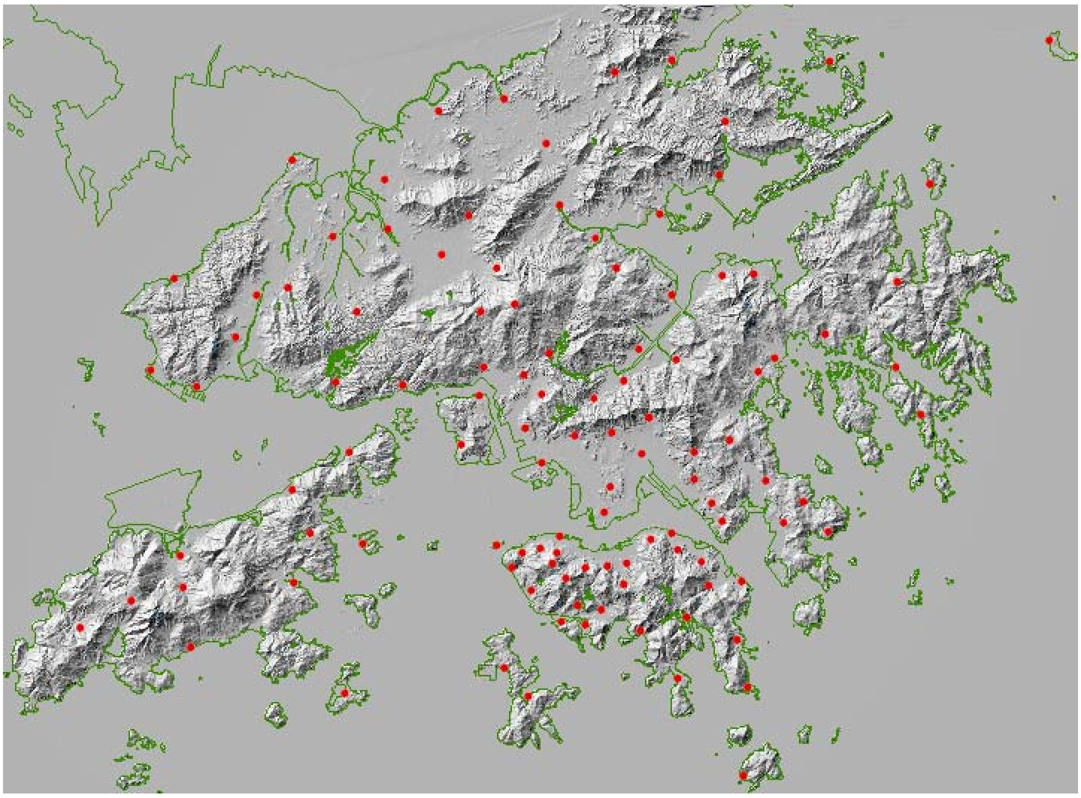

Fig. 8 Locations of automatic raingauges managed by GEO and HKO.

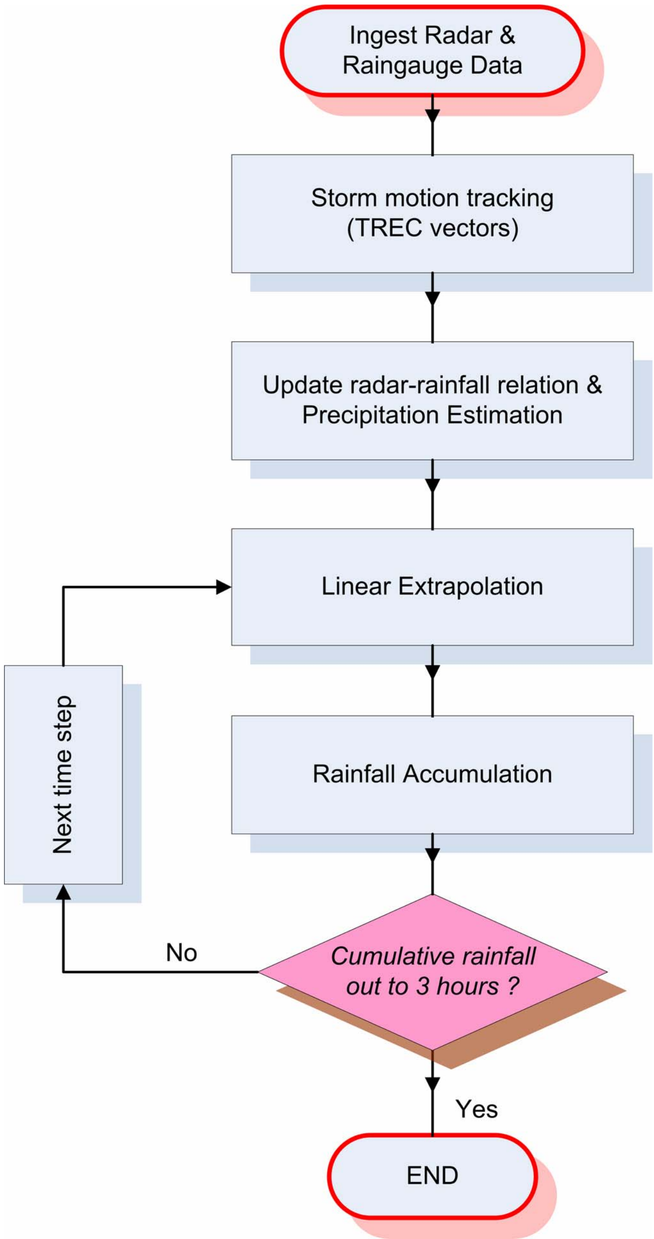

Fig. 9 Workflow of SWIRLS rainfall forecast module. (Starting from 2006, the time integration step has been changed to use Semi-Lagrangian advection and the rainfall accumulations extended up to 6 hours. For details, see Wong [8].)

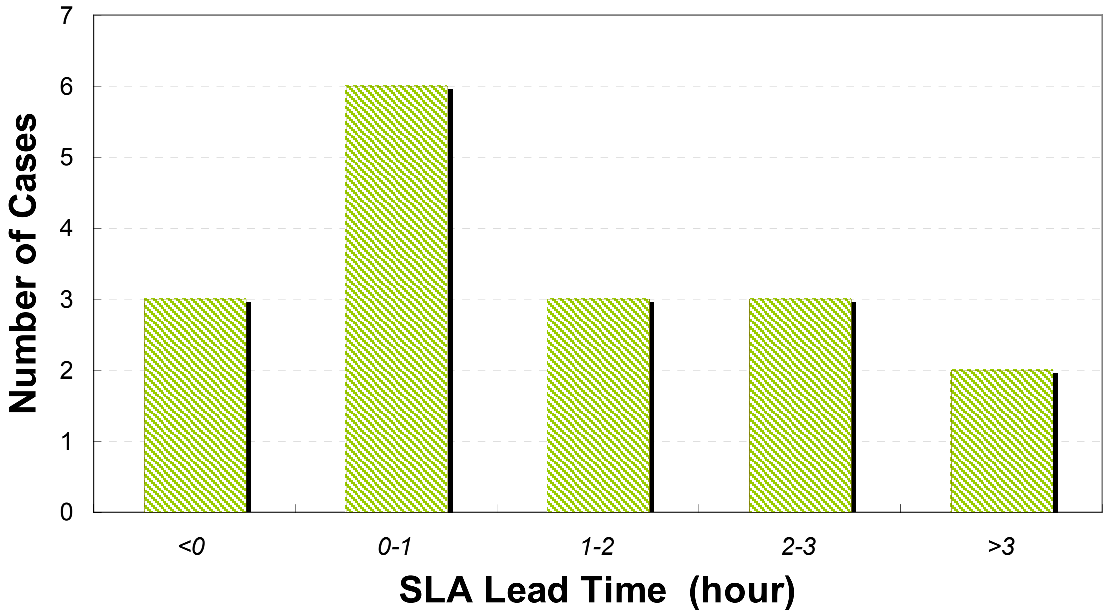

Fig. 10 Lead time analysis for the SWIRLS Landslip Alert (SLA) over the period 2001-05. Lead times were measured against the time the warning criteria were met according to GEO's records. Late or missing predictions are counted towards negative lead times and summarized under the "<0" bin.

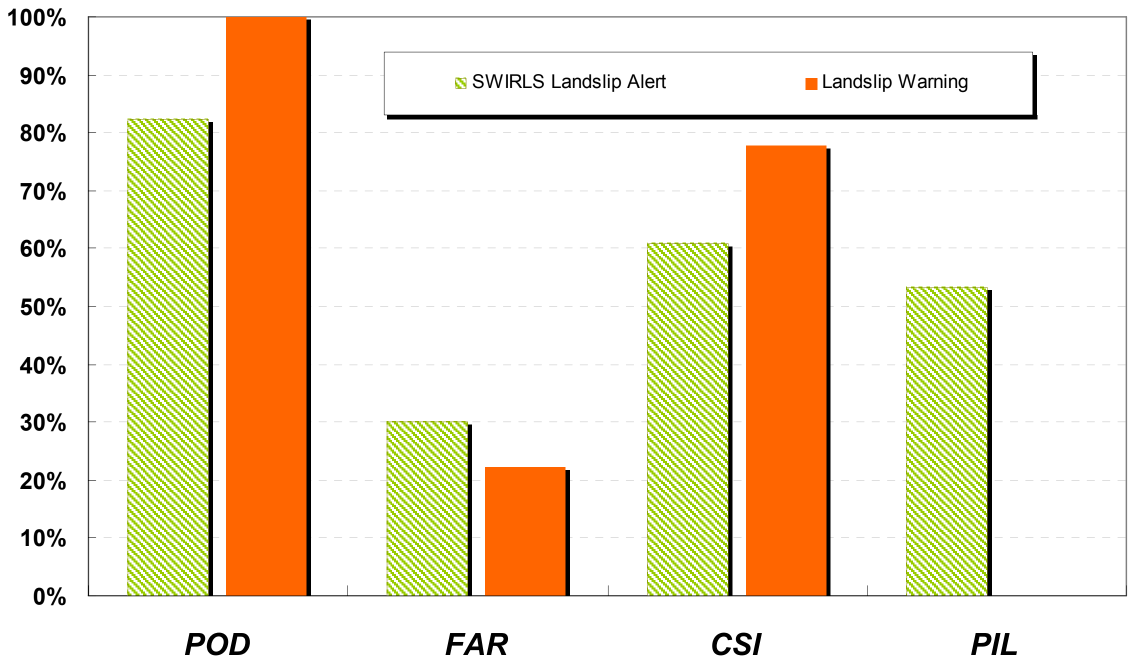

Fig. 11 Performance of the SWIRLS Landslip Alert (striated green) and the landslip warning (orange) over the period 2001-05. The statistical measures of POD, FAR, CSI and PIL stand for probability of detection, false alarm ratio, critical success index and percentage of ideal lead time respectively (see Section 5 for detailed definitions).

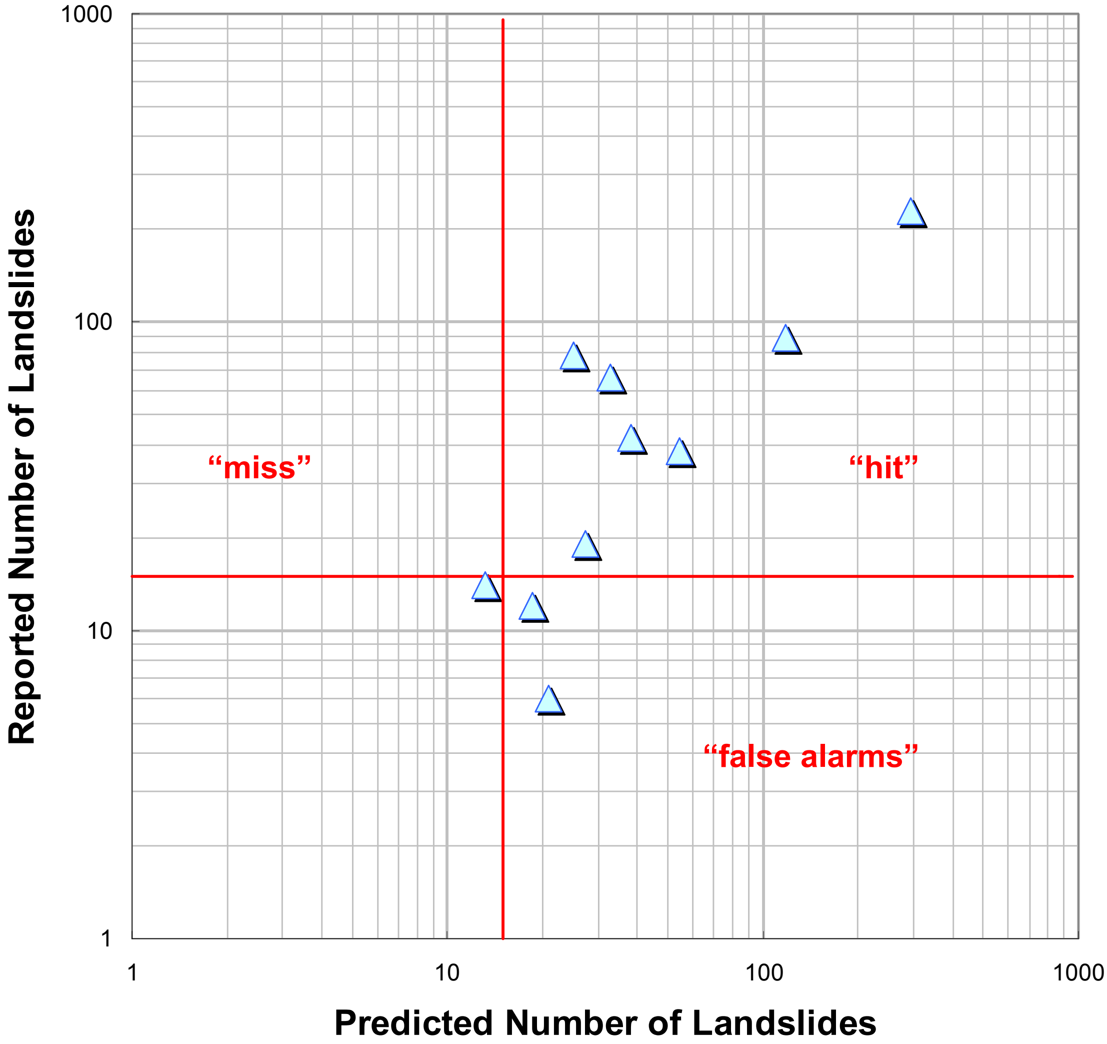

Fig. 12 Performance of the Landslide-rainfall correlations over the period 2001-05. The red lines mark the threshold number (15 landslides) used to set the warning criteria in the Landslip Warning System.

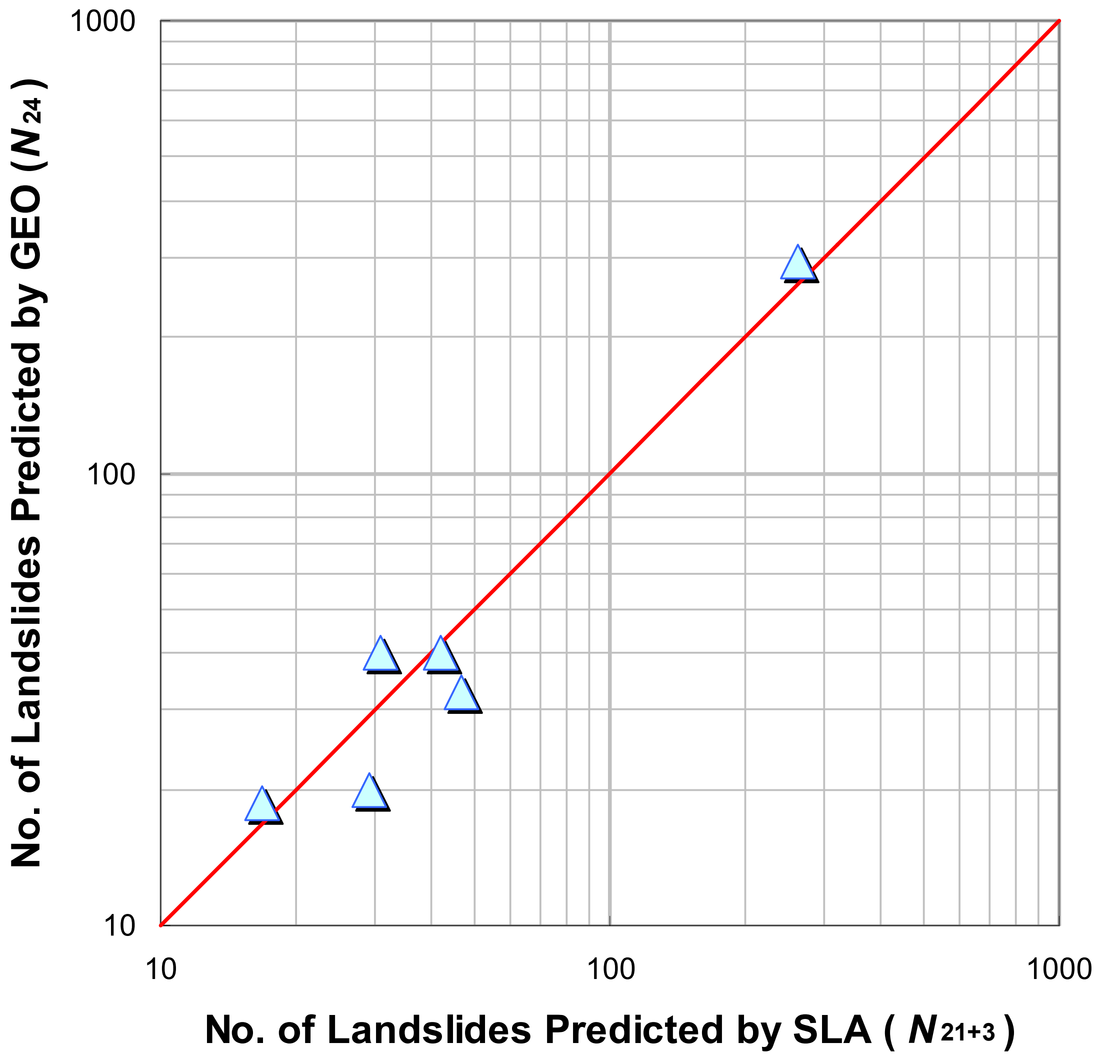

Fig. 13 Comparison of the landslide predictions by SWIRLS Landslip Alerts (i.e. N_{21+3}) and the landslide-rainfall correlation model of GEO (i.e. N_{24}) for cases in 2004-2006 (up to June). The diagonal red line indicates a perfect match.