A Quantitative Approach for Classifying Governance Unit of Watershed Management and Flood Mitigation Based on a Long-term Landslide Inventory

Cheng-Chien LIU[1, 2*], Ming-Hsun KO[2], Huei-Lin Wen[2], Kuei-Lin FU[3] and Shu-Ting CHANG[3]

[1] Dept. of Earth Sciences, National Cheng Kung University (Tainan, 70101 Taiwan)
[2] Global Earth Observation and Data Analysis Center, National Cheng Kung University (Tainan, 70101 Taiwan)
[3] Watershed Conservation and Management Division, Soil and Water Conservation Bureau (Nantou, 54044 Taiwan)
*Corresponding author. E-mail: ccliu88@mail.ncku.edu.tw

Extreme weather makes it difficult to estimate the intensity of typhoon rainfalls, which results in aggravating landslide potential and hazards in forested watersheds. To increase the efficiency of operations and management, it is needed to monitor landslide evolvement continuously, assess quantitatively the classification of landslides, as well as, establish landslide management plans. Take the Qingquan watershed in Wufeng Township, Hsinchu County for example, large-scale landslides occurred in four potential debris flow torrents when Typhoon Aere hit Taiwan in 2004. The Qingquan watershed is classified as 22 optimum watersheds after being processed by hydrologic analysis. The result from overlaying landslide data sheet of these 22 optimum watersheds from 2005 to 2016 shows major landslides occurred mostly during typhoon Aere. After typhoon Aere, vegetation recovery in the landslide zones was getting better, despite landslides occurred sporadically. Only in 2008, landslides occurred near Tuchang bulao caused severe damage. Two large-scale landslide zones, where the average rate of landslide occurrence is higher than 10%, are Debris-flow source areas. Several large-scale landslides occurred by two sides of Shangping Creek flowing through Tuchang bulao, Qingquan bulao, and Minduyou bulao, which are defined as low stability zone and severe landslide. Unstable levels determined by the long-term landslide data sheet of each watershed can serve as a tool to quantify the classification measures of mountain management and flood control of management units. Chinese version of this paper can be referred to [*Liu, et al.* 2017].

Key words: forest watershed, landslide susceptibility, landslide inventory, watershed management and flood mitigation, unstable index

1. INTRODUCTION

Extreme weather events caused by global warming intensify rainfalls. Together with high mountains, broken terrains, and frequent earthquakes, Taiwan has one of the highest erosion rates in the world [*Dadson, et al.* 2003] and is one of the places on Earth that is most vulnerable to landslides [*Dilley, et al.* 2005]. Taiwan's government, therefore, has been endeavoring to manage watersheds and mitigate the issue of flooding by developing various measures. This paper proposes a quantitative approach for classifying governance unit of watershed management and flood mitigation based on a long-term landslide inventory, with the intention to evaluate their effects and facilitate the planning.

Large-scale landslides occurred in four potential debris flow torrents in the Qingquan watershed in Hsinchu County when Typhoon Aere hit Taiwan in 2004. This watershed is classified as 22 optimum watersheds after being processed by hydrologic analysis. The result from overlaying landslide data sheet of these 22 optimum watersheds from 2005 to 2016 shows major landslides occurred mostly during Typhoon Aere. After Typhoon Aere, vegetation recovery in landslide areas was getting better, despite landslides occurred sporadically. Only in 2008, landslides occurred near Tuchang Tribe causing severe damage. Two large-scale landslide areas, where the average rate of landslide occurrence is higher than 10%, are debris-flow source areas. Several large-scale landslides occurred by two sides of Shangping Creek flowing through

Tuchang Tribe, Qingquan Tribe, and Minduyou Tribe, which are defined as low stability zone and severe landslide zone. Unstable levels determined by the long-term landslide data sheet of each watershed can serve as a tool to quantify the classification measures of mountain management and flood control of management units.

2. LANDSLIDE INVENTORY

To establish landslide database and assist Taiwan government in improving mountain management, disaster prevention, disaster reduction, and the restoration of degraded areas, the Forest Bureau had commissioned a 7-year project, Application of satellite optical imagery to islandwide landslide interpretation and disaster analysis, since 2011. By using the Formosat-2 owned and operated by Taiwan, images with a lower ratio of cloud coverage from 2005 to 2016 were selected based on the features of mobility as well as high spatiotemporal resolution. After having the selected images processed by the Formosat-2 automatic image processing system [*Liu* 2006] and the expert landslide and shaded area delineation system [*Liu* 2015] to interpret landslide disasters, this project establishes a 12-year regional landslide inventory.

Traditional fieldwork is time- and manpower-consuming and is unable to provide comprehensive information instantly. Manual delineation is the most accurate method to interpret landslide disasters [*Kumar, et al.* 2006, *Singhroy* 1995, *Singhroy, et al.* 1998] however, it inevitably generates inaccuracy and consumes time as well as manpower. Although automatic classification methods such as supervised classification [*Nichol and Wong* 2005, *Nichol and Wong* 2005], unsupervised classification [*Dymond, et al.* 2006], and ratio image [*Cheng, et al.* 2004] can save manpower and time, the accuracy is limited and the landslide inventory is therefore unreliable.

Through the normalized difference vegetation index (NDVI), the greenness index, and the intensity of panchromatic band, the expert landslide and shaded area delineation system [*Liu* 2015] can automatically and accurately delineate the non-vegetation area and the shaded area, as shown in **Fig. 1** Then, based on the concept of region growing, the unconnected data in the layer of non-vegetation area and shaded area can be separated into independent units by the system to generate geographic information. Then, in light of standard interpretation, experts' experiences, previous aerial images, 3D false-color image of Taiwan, and ASO Taiwan Image supplier and service System, interpreters select and cut potential landslide units to determine landslide location. Shadow as well as vector layer of landslide areas can be quickly selected and outputted. Not only can this method be used to reduce the time of manual delineation, but it also ensures the accuracy of manual interpretation. Through comparing with 25cm aerial photography manually interpreted in the same area by the Aerial Survey Office, the average accuracy is 98%.

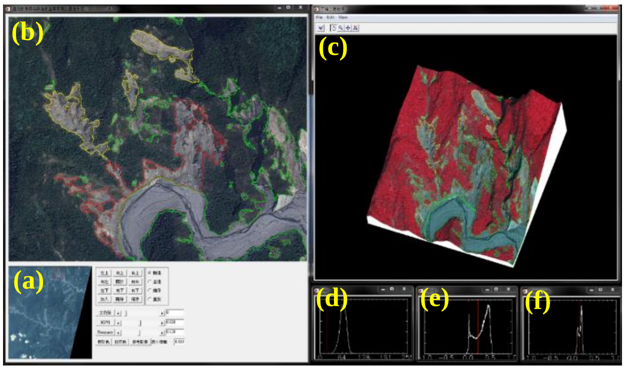

Fig. 1 Introduction to Expert Landslide and Shaded Area Delineation System and user interface. (a)True-color FORMOSAT-2 image; (b) In red frame, proposed image enhancement algorithms, maintaining same resolution as (a); (c) Standard false color composite processing of a digital terrain model could be transposed, rotated and scaled; (d) Histogram of the panchromatic image; (e) Histogram of NDVI; (f) Greenness histograms. The red line is defined by a local threshold determined by the system. The green line (non-vegetation area) and white line (shaded area) also are defined in the same method. Image interpreters would hit the red line, and export the blue line (shaded area) and the yellow line (landslide area) based on some data, such as the interpretation policy, expert experience, early stage images, 3D false color image of Taiwan, images from Taiwan Image Service and Supplier System [*Liu* 2015].

The aerial images shot by Formosat-2 from 2005 to 2016 and the landslide inventory are available to use after approval made by the Forest Bureau. The multi-temporal landslide inventory has been

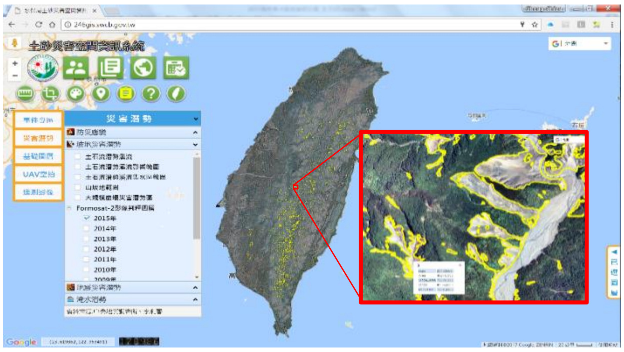

Fig. 2 Applied of satellite images shoot by FORMOSAT-2 from 2005 to 2016, and landslide data sheets of years. Vector tiles approved by Forestry Bureau are shared to the system built by SWCB.

published in the form of vector map on the Soil and Sand Disaster Spatial Information System (http://246gis.swcb.gov.tw) established by the Soil and Water Conservation Bureau (SWCB), as seen in **Fig. 2**.

3. APPROACH

3.1 Governance unit of watershed management and flood mitigation

The Soil and Water Conservation Bureau is responsible for soil conservation and flood mitigation in the upstream slopeland. To make the best use of budget, the government divides watersheds into governance units based on the classification of soil conservation and flood mitigation, and furthermore uses protected targets, potential debris flow torrent, and landslide ratio as standards to make a budget. The ratio standard and implementation strategy are shown in **Table 1**. Among all the standards of interpretation, some critical principles are associated with the condition of stability:

Table 1 Quantified the classification measure of mountain management and flood control of management units.

Class	Principle	Strategy
Maintenance area (level A): previous management has effectiveness; low disaster risk area	Initiation zone: landslides have been stabilized Transportation zone: the necking zone has been dredged Accumulation zone: the riverbed changes has been stabilized	The inspection and maintenance of structures The monitoring of watershed condition The program of disaster prevention and evacuation
Staging management area (level B): previous management has not completed, but the assessment shows the management is effective in reducing disaster risk	Initiation zone: the landslide rehabilitation has not been completed Transportation zone: partial necking zone is dredged Accumulation zone: the sediment deposition potential remains high	Yearly management project and rolling-wave planning The program of disaster prevention and evacuation
Fundamental protection area (level C): previous management has no obvious effectiveness; high disaster risk area	Initiation zone: Large landslides are difficult to rehabilitate so that engineering works cannot be carried out Transportation zone: large sediment production; the reoccurrence of necking zone Accumulation zone: the riverbed accumulation is serious	Adopting low intensity construction method before relocation Adopting temporary mitigation and prevention of disaster and fundamental disaster control Enhancing disaster prevention and evacuation

whether the landslide area has been rehabilitated and reaches stability; whether the necking zone has been dredged; whether the riverbed changes in the accumulation zone has been stabilized, or is the problem of accumulation still serious and the sediment deposition potential remains high? Since these critical principles are associated with stability, a method quantifying conditions of stability should be proposed.

Watersheds and gradients are used to divide areas while discussing landslides; however, the areas would be variant if discussed from different perspectives. From the perspective of debris flow, it can be divided into the initiation zone, the transportation zone, and the accumulation zone. From the perspective of geological condition, the classification standard includes the property of rock formation, the geological structure, and the cause of landslide. To avoid divergent policies made by distinct decision makers, there should be a general classification method for classifying governance units regarding geomorphologic characteristics of watershed.

3.2 Optimum Watershed

Concerning the work of mountain management and flood mitigation, classifying governance units of watershed is the principal task to have temporal and spatial variation under control, and quantifies whether governance units reach stability. With the condition fulfilled, the government is able to make a budget based on priority. The original aerial images used to produce landslide inventory may vary in different shooting periods depending on varied degree of cloud coverage, which will cause the aerial image variant at different times. A landslide area may be divided into two or more portions on account of the influence of cloud coverage. The variation of landslide cannot be interpreted correctly if we only analyze a certain landslide area. From the perspective of management, however, the government should classify all landslides with similar geomorphologic characteristics for regional governance. Since the areas that have not collapsed in landslide regions are crucial areas to determine whether the collapse will expand or occur in the future, it is necessary to make a plan, monitor, and manage. The task of classifying governance units of watershed means to establish a classification method.

This study proposes the method of classifying landslides based on the concept of optimum

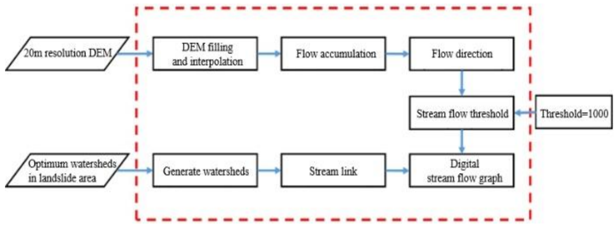

Fig. 3 The procedure of classifying watershed management units based on the optimum watershed size.

watershed. Initially, use Digital Elevation Model (DEM) to analyze accumulated flow, and then find suitable thresholds to determine the classification of watersheds. Once the amount of watershed composed of severe landslide (10 hectares) reaches maximum value, the watershed classified based on the threshold of flow is the optimum watershed. The detailed procedure for classifying watershed management units is shown in **Fig. 3**.

The idea of classifying landslide area by optimum watershed is derived from the concept of hydrology. The DEM used in Taiwan has high accuracy and high resolution, making the data of hydrology as well as geomorphology more accessible to get. The numerical result reveals that even in distinct areas the outcome of result has its consistency and reproducibility. The concept of optimum watershed is firstly proposed to investigate the variation of landslides and correct the influence of shadow on landslide area in the project of "Application of satellite optical imagery to islandwide landslide interpretation and disaster analysis" delegated by the Forest Bureau. The range of optimum watershed is consistent with the "compartment boundary" set by the Forest Bureau.

3.3 Instability index

In terms of the size of observation area, we can use optimum watersheds to define and calculate the instability index as the standard deviation of annual landslide area. In terms of the time period of observation, we should use as much data obtained from 2005 to 2016 as we could to discuss the instability index. After processing the information of landslide variation, we can be certain that whether the quantification of slopelands qualify the condition of stability. One thing should be noted is that the area of each optimum watershed is distinct. Considering the influence of shadow in different periods varies dissimilarly, correcting the shadow is indispensable. The total area of landslide, however, cannot be compared directly. With the 12-year landslide inventory, we can determine the standard deviation of annual landslide area to get the result of landslide variation. If the value of standard deviation is low, it implies that the variation of the very landslide area is slight and relatively stable; in contrast, if the value of standard deviation is high, it implies that the variation of the very landslide area is huge and relatively unstable.

To represent varying degree of the stability, this study proposes to use the instability index with five levels shown as **Table 2** to deal with the statistics of standard deviation regarding the landslide area of optimum watersheds. Then, uses Jenks natural breaks classification method to calculate the instability index and determine the degree of stability of optimum watersheds in the research region. One point need to be emphasized is that the threshold determined by Jenks natural breaks classification method is not an absolute value and is not necessarily suitable for other research regions. However, we can get an absolute value if we analyze all the data of slopelands in Taiwan. By using the threshold, we can quantify the degree of variation of each governance unit, assess the hot spots where collapse easily take place, and update the latest upriver situation to evaluate current management practices and future planning.

Table 2 Grading scale chart of unstable levels.

Unstable levels	Grading scale	Explanation
1	Stable zone	Landslides never occurred or only a few landslides occur in this area with good natural restoration, not easily been destroyed
2	Low active landslide zone	Some landslides occur, but the area of landslide is small or the restoration of landslide becomes obvious
3	Unstable landslide zone	Some landslides occur with massive area of landslide, or the restoration of landslide is less obvious
4	Severe landslide zone	Massive area of landslide or the area where landslides occur frequently
5	Large-scale landslide area	The area where large-scale landslides occur

4. RESULT AND DISCUSSION

Take the sub-watershed of Qingquan in Wufeng Township as example; Typhoon Aere devastated this area in 2004, causing four potential debris flow torrents and large-scale landslide. The main protected targets include Tuchang Tribe, Qingquan

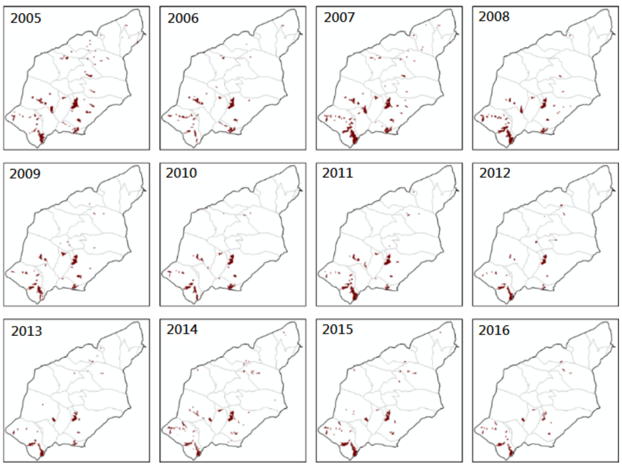

Fig. 4 Locations of landslides over years of 22 optimum watersheds of the Qingquan watershed in Wufeng Township, Hsinchu County.

Tribe and Minduyou Tribe. With the hydrological analysis and landslide layer interpreted from 2005 to 2016 as seen in **Fig. 4**, there was a severe landslide occurred during Typhoon Aere. In spite of fragmentary collapse, the landslide area gradually restored. The most serious natural disaster was the landslide near Tuchang Tribe in 2008.

We can get **Table 3** based on the result of instability index. There are two large-scale landslide areas in Qinquan watershed and the average landslide ratio is more than 10%. As for two sides of river embankment of the Shangping Creek, the average landslide ratio is between 2 to 5%. In light of the principle of classification, the Qinquan watershed

Table 3 Landslide hazard areas of years and the unstable levels (UL) of 22 optimum watersheds of the Qingquan watershed in Wufeng Township, Hsinchu County.

No	Watershed Area (ha)	Landslide hazard areas of years (ha)												SD	UL
		2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016		
20894	11.23	0.37	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01110	4
21735	324.94	9.36	5.81	9.98	6.36	3.81	4.11	4.75	1.46	2.56	4.05	2.71	1.80	0.00843	4
21897	372.25	18.69	11.93	14.92	11.09	11.71	11.19	10.75	7.65	7.41	10.33	9.08	3.93	0.01003	4
22062	108.72	1.13	1.11	1.52	1.04	2.51	1.14	0.95	0.00	0.00	1.30	0.54	0.70	0.00620	4
22253	298.04	16.24	10.24	29.37	29.58	15.86	15.17	21.38	14.67	12.43	16.27	19.87	13.98	0.02062	5
20610	150.57	0.53	0.42	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.16	0.00	0.00128	2
20759	11.29	0.18	0.00	0.29	0.33	0.00	0.00	0.21	0.00	0.14	0.00	0.00	0.00	0.01130	5
20928	163.21	0.47	0.10	0.00	0.00	0.19	0.00	0.00	0.70	0.71	0.36	0.36	0.38	0.00162	3
21045	89.31	0.32	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.00	0.00126	2
21084	106.23	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00029	1
21100	155.90	1.84	1.10	1.42	0.00	0.00	0.39	0.00	0.10	0.20	0.00	0.00	0.00	0.00420	3
21191	270.83	1.16	0.23	0.50	0.00	0.51	0.18	0.70	0.47	0.29	1.27	1.09	0.83	0.00153	2
21414	145.41	2.46	0.00	1.47	0.54	0.00	0.27	0.00	0.00	0.10	0.42	0.70	0.00	0.00520	3
21704	277.64	0.83	0.00	0.32	0.36	0.21	0.00	0.00	0.20	0.00	0.11	0.00	0.00	0.00089	2
22057	76.77	4.40	5.41	5.81	4.12	3.36	5.82	2.34	1.40	2.07	0.23	0.00	0.00	0.02899	5
22061	7.39	0.12	0.12	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00853	4
22191	117.37	0.06	0.21	0.39	0.00	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00120	2
21628	73.18	0.00	0.16	0.00	0.00	0.39	0.00	0.00	0.77	0.00	0.00	0.00	0.00	0.00327	3
20713	175.81	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00073	2
21512	58.93	0.00	0.00	0.17	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00098	2
21793	10.98	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00026	1
21320	207.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.22	0.00	0.00040	1

is classified as region B+. Based on the classification method proposed in this study, the instability index of 22 optimum watersheds shows that a part of region is severe landslide zone whereas a part of region is stable zone. The result of analysis provides varied perspectives for current management and future planning.

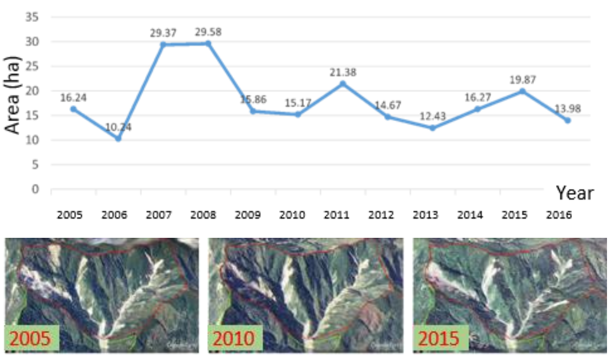

Fig. 5 Landslide hazard areas of years of optimum watershed, No.22253, of the Qingquan watershed in Wufeng Township, Hsinchu County, and its satellite images in 2005, 2010 and 2015. The unstable level is 5, and classified as large-scale landslide zone.

With historical images and topography, this study then nests the result of instability index in Google Earth to represent the large-scale landslide area. Take the optimum watershed of No. 22253 as an example (**Fig. 5**). Its original area is 298.01 hectares; after Typhoon Aere, the area of collapse is 16.24 hectares and the area keeps expanding to 29.58 hectares in 2007 to 2008, and the average landslide ratio is about 9.92%. The area of collapse remains 13.98 hectares until 2016. The instability index is five, which can be counted as large-scale landslide zone.

Take the optimum watershed of No. 21735 as an example (**Fig. 6**). Its original area is 324.94 hectares. The collapse is located in the tributary of Tuchang River and potential debris flow tureen of DF044. The historical curve chart reveals that the landslide area gradually stabilizes, from the area of 9.36 hectares in 2005 to the area of 3.81 hectares in 2009. The instability index is four, which can be

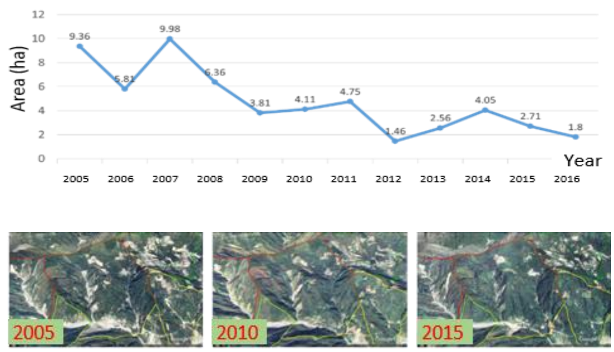

Fig. 6 Landslide hazard areas of years of optimum watershed, No. 21735, of the Qingquan watershed in Wufeng Township, Hsinchu County, and its satellite images in 2005, 2010 and 2015. The unstable level is 4, and classified as severe landslide zone.

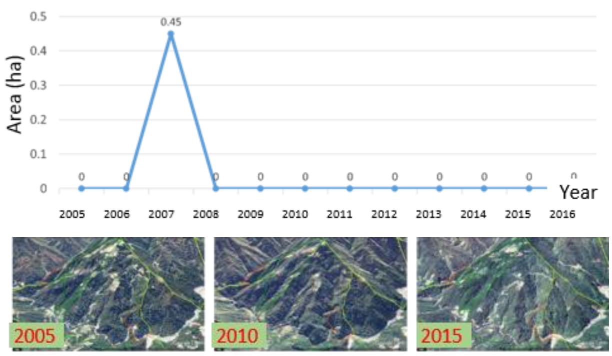

Fig. 7 Landslide hazard areas of years of optimum watershed, No. 20713, of the Qingquan watershed in Wufeng Township, Hsinchu County, and its satellite images in 2005, 2010 and 2015. The unstable level is 2, and classified as stable zone.

counted as severe landslide zone. Then, take the optimum watershed of No. 20713 as an example (**Fig. 7**). The area of watershed is 175.81 hectares. Maipalai Creek is seldom influenced by rainfall on account of the location of leeward. This area is stable, except the collapse (the area of 0.45) in 2007. The instability index is 2, which can be counted as stable zone.

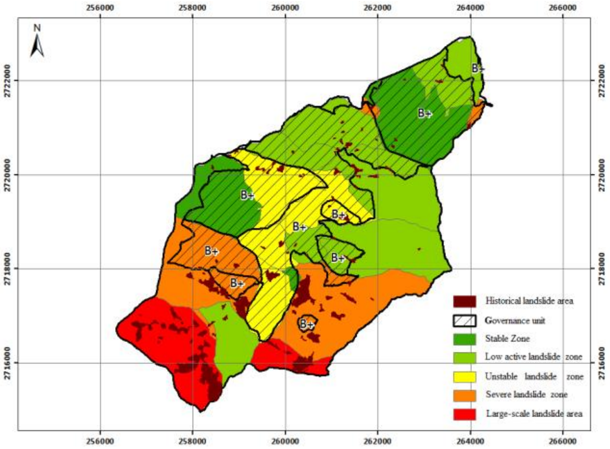

Fig. 8 The outcome of applying the classification qualified measures of mountain management and flood control of management units to watersheds of the Qingquan watershed in Wufeng Township, Hsinchu County.

Fig. 8 shows the quantified result of 22 optimum watersheds in Qinquan watershed by using the classification method proposed in this study. The multi-temporal landslide inventory of 2005-2016 reveals that numerous significant landslide events took place in Qinquan watershed; nonetheless, the distribution of collapse is not even, for it mainly takes place in optimum watersheds.

The slash and grid blocks represent the region B+. Most of the areas are relatively stable, whereas some collapse events take place in a few optimum watersheds. The instability index quantifies the trend of collapse in each district over time, which not only highlights the location of hot spot but also helps to find the regions where the collapse continues to deteriorate, to stabilize or to restore. This study demonstrates that quantifying the instability index based on multi-temporal landslide inventory provides the method of quantification and grading for mountain management and flood mitigation.

This study proposes a method of classification as well as grading based on multi-temporal landslide inventory by taking Qinquan watershed as an example to demonstrate that the instability index is able to quantify collapse in each district over time. However, the thresholds determined by the Jenks natural breaks classification method is not an absolute value, which is primarily used to assess the hot spots in regions where the collapse easily takes place. Therefore, the thresholds are not necessarily suitable for other research regions. In the future, an absolute threshold will be acquired after analyzing the data of the slopelands in Taiwan. With the thresholds, the geomorphology variation of each governance unit can be quantified and analyzed, and the main hot spots of collapse can be evaluated. Additionally, after the completion of engineering, the thresholds can be used to update the upriver situation for the purpose of evaluating current and future strategies in terms of management as well as planning.

The engineering mainly centers on the region where collapse easily takes place. The method of comparing the area of management with the area of landslide or the area of watershed is not an ideal way to highlight the effectiveness of management.

Suppose applying the method proposed in this study to divide the watershed into optimum watersheds and find out unstable or severe landslide area by using the instability of index. The variation of landslide area before and after engineering can be analyzed and the standard deviation can be calculated, which reveals that the instability index of optimum watersheds is apparently decreased, manifesting the effectiveness of management and the achievement of quantitative evaluation.

While applying the aerial images shoot by Formosat-2 from 2005 to 2016 and the multi-temporal landslide inventory, it should be aware that the result might vary because of varied degree of cloud coverage. To acquire the variation of landslide area, it is necessary to consider the influence of shadow and revise the area of landslide. Furthermore, the following conditions should be taken into consideration when referring to the task of mountain management and flood mitigation: controlling the landslide condition in initiation zone, getting through the bottleneck in transportation zone and analyzing the variation of river. Similarly, the river as well as the area of vegetation should be taken into account while calculating the instability index. Apart from the discussion of landslides caused by natural disasters, how to quantify the influence of human development and the importance of protected targets are goals worth striving for.

5. CONCLUDING REMARKS

This paper demonstrates that the unstable levels determined by the long-term landslide data sheet of each watershed can serve as a tool to quantify the classification measures of mountain management and flood control of management units.

ACKNOWLEDGMENT: This research is funded by Soil and Water Conservation Bureau, Council of Agriculture, Taiwan ROC, under Contract Nos. 106AS-7.3.1-SB-S2, as well as Ministry of Science and Technology of Taiwan ROC, under Contract Nos. MoST 106-2628-M-006-002. Chinese version of this paper can be referred to [*Liu, et al.* 2017].

REFERENCES

Cheng, K. S., C. Wei, and S. C. Chang (2004): Locating Landslides Using Multi-Temporal Satellite Images, in Monitoring of Changes Related to Natural and Manmade Hazards Using Space Technology. Kidlington, Oxford, U.K.: Elsevier, pp. 296-301.

Dadson, S. J., N. Hovius, H. Chen, W. B. Dade, M.-L. Hsieh, S. D. Willett, J.-C. Hu, M.-J. Horng, M.-C. Chen, C. P. Stark, D. Lague, and J.-C. Lin (2003): Links between Erosion, Runoff Variability and Seismicity in the Taiwan Orogen, Nature, 426, pp. 648-651.

Dilley, M., R. S. Chen, U. Deichmann, A. L. Lerner-Lam, M. Arnold, J. Agwe, P. Buys, O. Kjekstad, B. Lyon, and G. Yetman (2005): Natural Disaster Hotspots: A Global Risk Analysis, pp. 29.

Dymond, J. R., A. G. Ausseil, J. D. Shepherd, and L. Buettner (2006): Validation of a Region-Wide Model of Landslide Susceptibility in the Manawatu-Wanganui Region of New Zealand, Geomorphology, 74, pp. 70-79.

Kumar, K. V., T. R. Martha, and P. S. Roy (2006): Mapping Damage in the Jammu and Kashmir Caused by 8 October 2005 M-W 7.3 Earthquake from the Cartosat-1 and Resourcesat-1 Imagery, International Journal of Remote Sensing, 27, pp. 4449-4459.

Liu, C.-C. (2006): Processing of Formosat-2 Daily Revisit Imagery for Site Surveillance, IEEE Transactions on Geoscience and Remote Sensing, 44, pp. 3206-3214.

Liu, C.-C. (2015): Preparing a Landslide and Shadow Inventory Map from High-Spatial-Resolution Imagery Facilitated by an Expert System, Journal of Applied Remote Sensing, 9, pp. 096080-096080.

Liu, C.-C., M.-H. Ko, H.-L. Wen, K.-L. Fu, and S.-T. Chang (2017): A Quantitative Approach for Classifying Governance Unit of Watershed Management and Flood Mitigation Based on a Long-Term Landslide Inventory, Taiwan Forestry Research Institute, Taipei: Taiwan Forestry Research Institute, pp. 75-92. (in Chinese with English abstract)

Nichol, J., and M. S. Wong (2005): Detection and Interpretation of Landslides Using Satellite Images, Land Degradation & Development, 16, pp. 243-255.

Nichol, J., and M. S. Wong (2005): Satellite Remote Sensing for Detailed Landslide Inventories Using Change Detection and Image Fusion, International Journal of Remote Sensing, 26, pp. 1913-1926.

Singhroy, V. (1995): Sar Integrated Techniques for Geohazard Assessment, in Natural Hazards: Monitoring and Assessment Using Remote Sensing Technique, ed. by R. P. Singh, and R. Furrer, pp. 67-78.

Singhroy, V., K. E. Mattar, and A. L. Gray (1998): Landslide Characterisation in Canada Using Interferometric Sar and Combined Sar and Tm Images, in Remote Sensing: Inversion Problems and Natural Hazards, ed. by J. Susskind, V. Singhroy, and S. Tanaka, pp. 465-476.