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Karst depression detection using IFSAR-DEM: A tool for subsidence hazard assessment in Panglao, Bohol

Kevin L. Garas, Madonna Feliz B. Madrigal, Ross Dominic D. Agot, Mark Carlo M. Canlas and Liza Socorro J. Manzano

Mines and Geosciences Bureau Central Office, Department of Environment and Natural Resources, Manila 1128, Philippines

Abstract　Karst studies employ high-resolution satellite images and geospatial data to identify and delineate geomorphic features that are critical to karst development and related hazard. This paper aims to determine the efficiency of Interferometric Synthetic Aperture Radar-derived Digital Elevation Model (IFSAR-DEM) to identify, quantify and characterize karst depressions using ArcGIS 10.0. The semi-automated karst depression/sinkhole detection method used water flow simulation approach that incorporated a) watershed delineation; b) sink-and-fill to extract depression features; c) sink-depth measurements and classification; and d) validation of detected karst depressions using Hyperspectral Google Satellite Image of 2013-2014 and Digital Terrain Model. The method was pre-tested in the assessment conducted in the Municipality of Panglao, Bohol. Initial closed-depression analysis using 1991 National Mapping and Resource Information Authority 1∶50,000 scale topographic map counted 15 sinkholes in Panglao. Using 5 m high resolution IFSAR-DEM, there are 820 sinkholes detected, 424 of which were delineated through detailed ground truth to validate the presence of karst depressions. Ground truth included basic morphometric analysis, such as common sinkhole size, shape and depth, to eliminate false positives. Threshold values in sink depth of >1.0 m and aperture size of >10 m were designated to distinguish true sinkholes with maximum accuracy. This GIS-based tool is deemed helpful to generate high-resolution karst subsidence susceptibility map that will guide local planners and engineers, as well as policy-makers, in land use and development planning.

Key words　karst, subsidence, sinkhole, IFSAR-DEM, GIS, Bohol
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0　Introduction

Sinkholes are one of the most common karst structures that are formed by the dissolution of the underlying carbonate rocks [1-2]. The 2013 M7.2 Bohol earthquake uncovered sinkholes in the southwestern Bohol affecting

First author: Kevin L. Garas (1991—), male, Senior Geologist, Geological Laboratory Services Section (GLSS), with an M.S.degree in Earth and Planetary Sciences. E-mail: kgaras91@gmail.com.
Corresponding author: Liza Socorro Juanico-Manzano (1961—), female, Section Chief, Geohazard and Engineering Geology Supervising Science Research Specialist, B S Geology with Master Degree in Environmental Management. E-mail: lizajmanzano@yahoo.com.
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infrastructures and communities. It is extremely unpredictable that could happen at a very slow subsidence rate or sudden collapse incident.

Sinkhole identification is an important task considering the associated safety and economic risks. It is not easy, however, to determine the development of sinkholes since it can be masked by natural and anthropogenic activities. Therefore, effective sinkhole identification should integrate a variety of investigative approaches that include geological, geophysical, and geomorphological analysis [3]. Classical geomorphological studies utilize aerial photograph interpretation to interpret karst topography [4]. However, visual interpretation of optical images is subjective as the quality of the image is influenced by seasonal conditions such as weather, vegetation and shadows.

One of the guiding tools used for mapping and identification of sinkholes and other related karst features is remote sensing. Remote sensing has been used in karst studies to identify limestone terrain, describe exokarst features, analyze karst depressions, and detect geological structures important to karst development [5]. Modern studies show that the use of high-resolution Digital Elevation Model (DEM) derived from satellite data of ASTER, SRTM [5] and LiDAR [6], is a rapid and accurate technique to extract karst depression features coupled with good field validation data.

In 2003, National Mapping and Resource Information Agency (NAMRIA) acquired high-resolution satellite images and remotely-sensed data through Interferometric Synthetic Aperture Radar (IFSAR) that can be used to generate accurate basemaps for resource mapping, land cover classification, geological surveys, and geohazard assessment. IFSAR is a technique that uses pairs of high resolution images to generate high quality terrain elevation maps, called Digital Elevation Maps (DEMs) using phase interferometry methods [7]. Airborne IFSAR-derived DEM from NAMRIA has 5 m by 5 m and 1 m vertical resolution which is useful in more detailed terrain interpretation.

Delineation of subtle karst depression using low resolution topographic maps on the relatively flat Panglao Island is challenging and prone to systematic error. The Municipality of Panglao is located in Bohol about 16. 1 km from the capital city of Tagbilaran (Figure 1). It is underlain by uplifted coral reef terraces and considered to be part of the Plio-Pleistocene Maribojoc Limestone Formation by previous workers [8]. However, re-

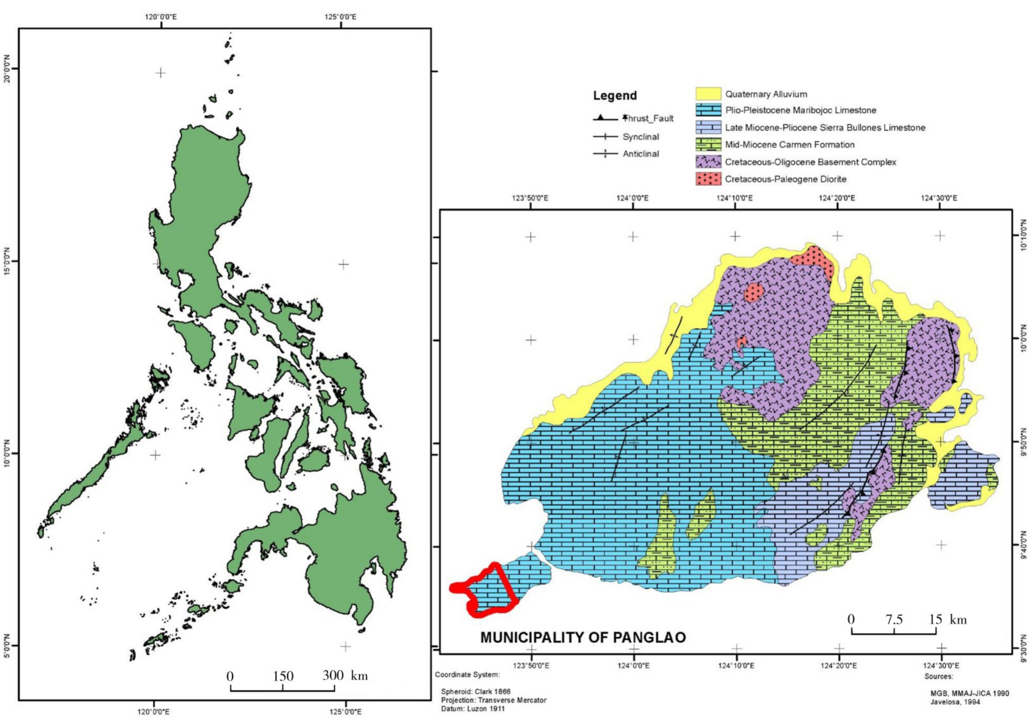

Fig. 1　Location map and geologic map of the Municipality of Panglao,Bohol Province

图 1　薄荷省旁劳市位置及地质图

sults of isotope dating suggests that the coral reef terraces in Panglao Island were formed during Late Pleistocene[9]. The lateral variations in the Holocene paleo mean sea-level, along with changes in notch depth and profile, suggest tilting of the island during the period [10]. Most of the natural drains are subterranean through the subsurface voids. Intermittent creeks that are dissecting the uplifted terraces led to the loss of their sediment loads and as a result, water flows into swallow holes and sinkholes, and ultimately into the Mindanao Sea. Sinkholes and cave openings are also present in the reef flats. Due to the geomorphologic and geologic characteristics, karst subsidence hazard has been a potential threat to the developing Municipality of Panglao.

This paper aims to a) develop a semi-automated method for karst depression (e. g. sinkhole) detection; b) validate the efficiency of IFSAR-derived DEM to identify karst depressions; and c) have a fast, systematic and cost-effective sinkhole inventory method for karst subsidence hazard assessment. This paper also aims to compare the morphometric attributes (size, shape and depth) of sinkholes gathered from the IFSAR-DEM interpretation and actual field measurements.

1 Methods

Manual delineation of closed karst depressions using topographic maps and aerial photos has been widely used in karst and sinkhole morphologic studies. However, hand-delineation is inefficient in a wide area and subjective to the geomorphologists' decision. In this subsidence hazard assessment, the team used available IFSAR-Digital Elevation Model (DEM) and IFSAR-Orthorectified Radar Imagery (ORRI) dated 2013 from NAMRIA, to determine the terrain attributes and the distribution of possible sinkholes. The Geological Information System (GIS) was utilized to obtain the morphometric attributes of sinkholes using IFSAR-DEM and the IFSAR-ORRI.

Using ArcGIS 10. 3 hydrologic toolset, raw elevation data was pre-processed or reconditioned to extract karst depression features within an area of interest (AOI). Processing of DEM involves the following procedures (Figure 2):

(1) Use of Fill tool to remove small imperfections in the data to create a hydrology-coupled DEM;

(2) Simulating flow direction to create a raster of sinks coded with depth;

(3) Using Watershed tool to determine sink areas or "catchment" from the steepest downslope neighbor of each cell;

(4) Zonal Statistics and Zonal Fill tools create raster of minimum and maximum elevations of the watershed for each sink; and

(5) Using Minus, the minimum value will be subtracted to maximum value to generate a "fill-difference" raster that represented the depth of depressions in the original surface.

Through data processing using the above methods, the extracted sinks were classified into different depth ranges. This was the basis of the selection of AOI during field assessment, as well as the basis of false sinkholes/false positive elimination. The detected depressions were then superimposed on a 1 : 10, 000 topographic map generated from the IFSAR.

Conventional geological and geomorphological techniques were applied in gathering field evidences to ground truth information obtained from the IFSAR-DEM interpretation. The assessment includes the study of lithological characteristics and its vertical and lateral distributions, as well as the delineation of various karst features such as sinkholes, uvalas, karst caverns, underground rivers and surface water flow directions. Their locations were obtained using the Global Positioning System (Garmin GPSMAP 78s), while the data gathered were plotted in the prepared basemap. Morphometric measurement of the sinkholes and other karst features were carried out using conventional 5 m steel tape, 100 m fiberglass tape and HILTI® PD5 laser range finder for more accurate dimensions especially on the wide and deep openings beyond 100 m.

2 Results

2. 1 Closed depression analysis on 1 : 50, 000 scale topographic map

Result of closed karst depression analysis shows

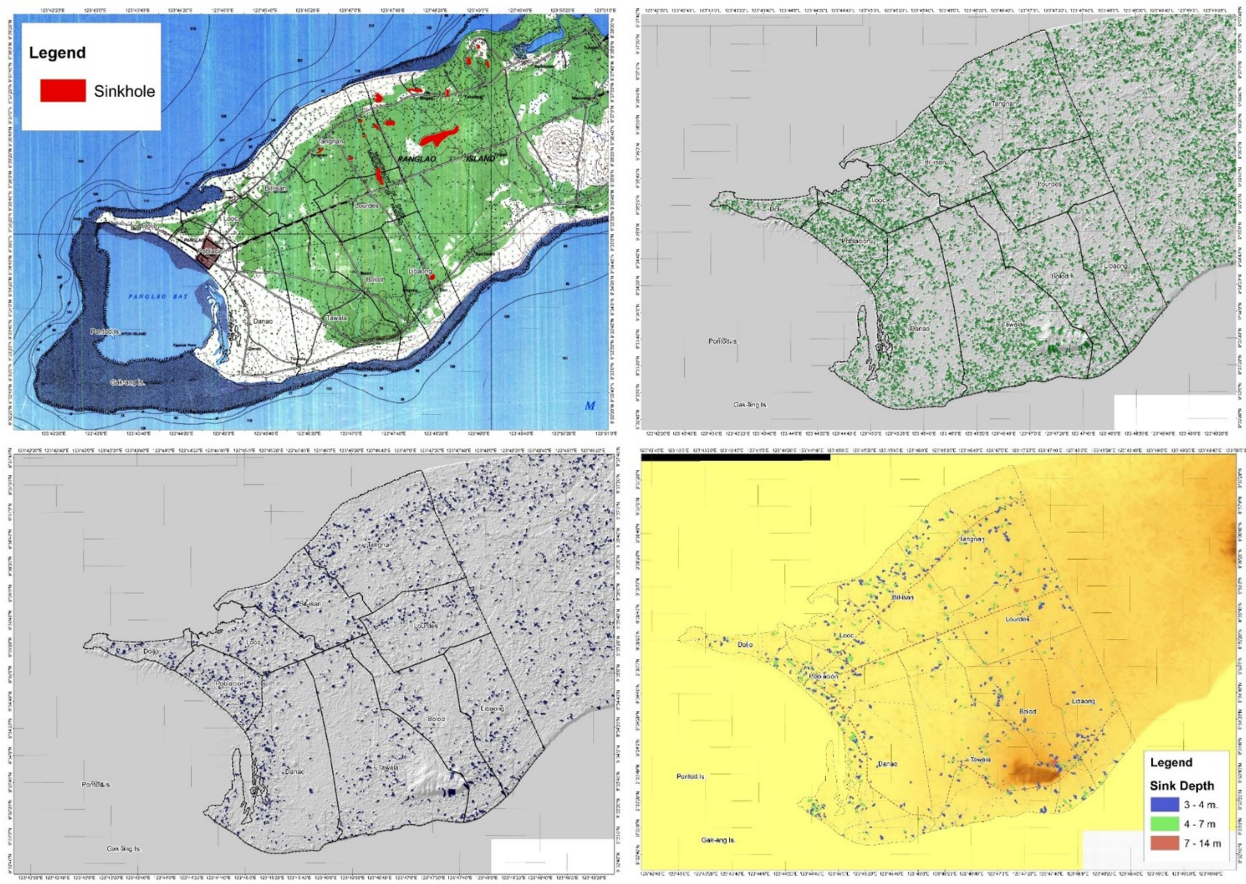

Fig. 2　Processing of IFSAR-DEM using ArcGIS 10. 3 hydrologic toolset to extract karst depression features classified in different sink depth ranges

图 2　基于 ArcGIS 10. 3 水文工具集的 IFSAR-DEM 处理提取不同下沉深度的岩溶洼地特征

that there are a total of 15 sinkholes in Panglao Island, based on the interpretation of the 1991 NAMRIA topographic map on a scale of 1 : 50, 000. The closed depressions are defined as areas with very limited size or no drainage on the regional scale. In karst landscape, these depressions normally correspond to sinkhole since they are the natural hydrogeological pathways of surface runoff into the underlying cavities. This method is useful for primary reconnaissance or semi-detailed work. However, the absence of larger-scale topographic map covering the Panglao area makes the method less accurate. In terms of its karst geomorphic characters, the Panglao Island is expected to be dotted by numerous, relatively shallow sinkholes due to the occurrence of near-surface, interconnected cave systems.

2. 2　IFSAR-DEM interpretation

There are a total of 820 sinkholes identified by the combined methods of actual geological and geomorphological assessment, IFSAR delineation and closed depression analysis using topographic map (Table 1). Out of 424 field-validated sinkholes, 417 were captured by the semi-automated karst depression detection using IFSAR-DEM, with an accuracy equivalent to 98. 35%. Seven sinkholes appear as false negatives and were not detected by the IFSAR delineation, probably because of their depths of shallower than 1. 0 m with smaller aperture diameters.

Several sink-depth layers of <1. 0 m, 1-2 m, 2-3 m, 3-4 m, 4-7 m and 7-14 m were prepared separately for comparative purposes. The topographic sink depth of more than 2 m showed a highly positive correlation between the IFSAR delineated sinkholes and the field validated ones. The result of measurement using ArcGIS revealed that the size of the sinkholes (with depth range of 2-3 m) ranged from 10 m to 200 m in diameter.

The method using IFSAR performs well in capturing karst depressions. However, result of field-validated inventory shows that this method has the highest confidence level in interpreting karst depressions. The total number of the IFSAR-identified depressions reaches 2, 376 which is nearly three times greater than the true sinkholes. Many of the sinkholes are unlikely to be true, and are mostly attributed to image artefacts or man-made excavations [11].

In order to increase the overall accuracy of the method, we considered several morphometric attributes that were used to eliminate the false positives. The IFSAR-DEM was utilized to extract the data with the sink-depth of more than 2 m and the aperture size of more than 10 m. The detected topographic sinks with a depth of less than 1 m were eliminated, with the intention of excluding the man-made structures such as small excavations/quarry, dug pits and septic tanks that could reflect on the image as false positives.

Visual estimation of the circularity thresholds of the detected depressions was also used to reduce the false positives. Linear depressions could be natural pathways of water such as gullies, ravines and stream channels and are not true closed depressions [11]. Since flow direction and watershed tools were used to delineate the sink areas, detection of surface water pathways was included in the interpretation. In some cases, the closed depressions were noted along the surface water pathways, especially in structurally-controlled landscapes.

Table 1 Sinkhole inventory results in the Municipality of Panglao from combined geological assessment, IFSAR delineation and topographic map

表 1 基于综合地质评估,IFSAR 和地形图得出旁劳市天坑分布表

Name of Barangay	Number of Sinkhole				Size Range of Aperture (meter)	
	Geological Assessment	IFSAR (DEM[a])	Contour map NAMRIA Topographic map	Total	Geological Assessment	IFSAR (DEM[a]) Depth Range 2—3 meters
Doljo	21	6	0	27	0. 6—30	15—120
Poblacion	38	44	0	82	0. 2—30	10—90
Looc	26	28	0	54	0. 5—50	10—60
Danao	38	60	0	98	0. 3—50	30—200
Tawala	64	65	0	129	5—50	30—200
Bil—isan	42	31	0	73	2—50	5—50
Bolod	40	31	0	71	0. 5—100	12—70
Lourdes	33	35	1	69	15—50	10—50
Tangnan	63	63	5	131	10—50	10—100
Libaong	59	27	0	86	0. 5—100	
Total	424	390	6	820		

[a]Digital Elevation Model

3 Discussion

3. 1 Spatial Distribution of Sinkholes in Panglao

Using ArcScene 3D Analyst Tool, the IFSAR-DEM data were transformed into 3D model to visualize the geomorphological expressions of the study area. The 3D DEM visualization used a color transform ramp from light blue (0-5 masl), beige (10-20 masl), green (20-30 masl), yellow (40-50 masl), and red to white (80-170 masl). The model showed the random distribution of sinkholes represented by red dots over the area of Panglao.

Topographically, the Panglao Island is characterized by dominant flat land to gentle slopes with an elevation gently rising from 5 to 30 masl. The karst landforms are dominated by sinkholes, caves, potholes and subterranean creeks which are products of solutional degradation of marine terraces. Generally, the landscape of the study area is differentiated into two types, namely the karstic uplifted coral reef terraces and the coastal landforms.

Coastal landforms include tidal and wave-cut notches, sea sinkholes and potholes. The tidal and wave-cut notches are evident in the northern and southern coastlines of the island. Sea sinkhole was observed in the submerged marine terrace in Barangay Looc. Several areas have pothole formation which is a common karst coastal landform.

The uplifted coral reef terraces have at least four levels. The first level that extends seaward is at the elevation of 5 masl, while the second level range from 10 to 20 masl, the third level at 20-30 masl and fourth 60-80 masl, with the terrace aging order from the lower to the higher level. Based on Table 1, there are two barangays with significantly high number of sinkholes. Barangays Tawala and Tangnan have 129 and 131 sinkholes, respectively. Southern Tawala is located in 20-80 masl near to the karst plateau while Tangnan is located in third level marine terrace at 20-30 masl.

Predominantly, the sinkholes found in the uplifted coral reef terraces are solution and cover-subsidence sinkholes. Generally, sinkhole apertures and circular depressions are at 1 m to 150 m across with a measured maximum depth of 10 m. Field measurements confirmed the presence of small karst sinks occur as solution pipes with a size of 0. 2-0. 5 m in diameter.

3. 2　Karst subsidence hazard in Panglao

Karst subsidence is the lowering of land surface due to sinkhole and cave collapse which might be triggered by a major earthquake. Sinkholes are common and natural feature of a karst landscape, but the consequences of its hazards, which resulted to the loss of lives and properties, are not fully known and understood by the concerned LGUs and communities.

Karst subsidence hazard is often associated with the collapse of covered type sinkholes. These are sinkholes that develop gradually and may remain undetected for a long period of time. The overlying sediments or overburden is usually permeable dominated by sandy soil materials. Commonly, the subsidence of sinkholes starts with hardly noticeable ground settlement or depression less than a meter deep. However, slow surface subsidence may be a precursor to imminent failure on a larger scale. The movement can be traced through hairline cracks on buildings, roads and bridges prior to extensive damage. The subsidence may be very slow or very fast where in damages can be low to catastrophic.

In the Panglao Municipality, majority of the sinkholes are solution and covered type sinkholes. These sinkholes become almost a permanent feature of the natural landscape in most barangays as shown in Figure 3. However, they always have a potential of being reactivated, especially some of the cave systems have been affected by the 2013 Bohol earthquake, and some sinkholes have been disturbed by infrastructure developments.

The subsidence susceptibility map will assist the concerned LGUs and development planners in locating sites that are less susceptible to the subsidence hazard, or the institutions in developing appropriate mitigation measures to create a subsidence proof design or innovate engineering intervention for the infrastructure development in the Panglao Island. Highly susceptible areas correspond to the red zones presented on the map. To delineate the boundaries of high hazard zone, parameters such as the presence of sinkholes and caves, tension cracks and subsiding road surfaces were considered.

4　Conclusion

High-resolution IFSAR-DEM interpretation is an efficient tool to sinkhole detection and precise guide for geologists during sinkhole inventory. Semi-automated sinkhole detection has several advantages such as fast scanning and processing over a large area, reduction of human errors during manual identification and practical data acquisition in inaccessible areas such as forests, deep gorges, etc. However, this is just a tool and needs to be validated in the field, in conjunction with geomorphic and morphometric analysis of sinkholes. Some of the selected sinks are actually human structures captured during the satellite data gathering. To eliminate

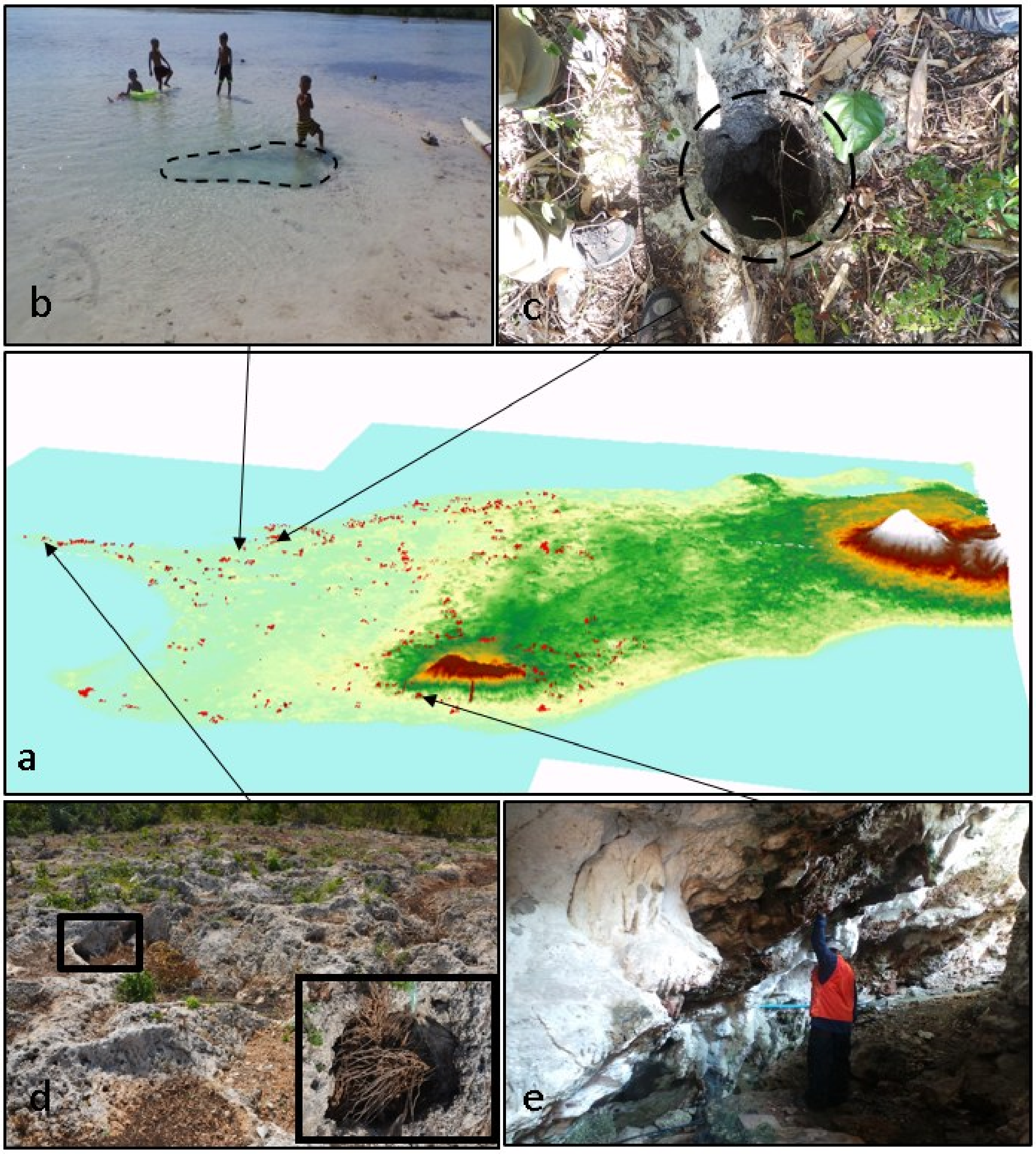

Fig. 3 Sinkholes and cave systems identified in the Municipality of Panglao, Bohol province
图3 薄荷省旁劳市发现的洞穴系统

the errors, careful interpretation using morphometric threshold criteria and field-validated measurements will reduce the number of false positives and other errors in the detection.

Combined data derived from ground truth information, the interpretation of IFSAR-DEM and 1∶50,000 scale topographic map, 820 sinkholes and more than 56 cave openings in the Panglao Municipality are identified. Out of 424 field-validated sinkholes, 417 are captured by the semi-automated karst depression detection using the IFSAR-DEM method, with an accuracy of 98.35%.

As the land of the Panglao Municipality is generally underlain by coral reef caps or the uplifted marine terraces, the occurrence of sinkholes and other karst features such as caves and subterranean creeks is very common in the study area. These marine terraces, which are believed to be the youngest member of the Maribojoc Limestone Formation, are characteristically porous, poorly bedded to massive, clast supported, less compacted, and highly fossiliferous with numerous solution cavities.

With the use of high-resolution IFSAR-DEM combined with detailed field observations, this study has generated a 1∶10,000 scale karst subsidence susceptibility map of Panglao (Figure 4) that can be used by local planners, engineers, developers and Local Chief Executives in enhancing their land-use zoning, creating disaster preparedness plan and making policies and regulations on the extent of development in karst terrain.

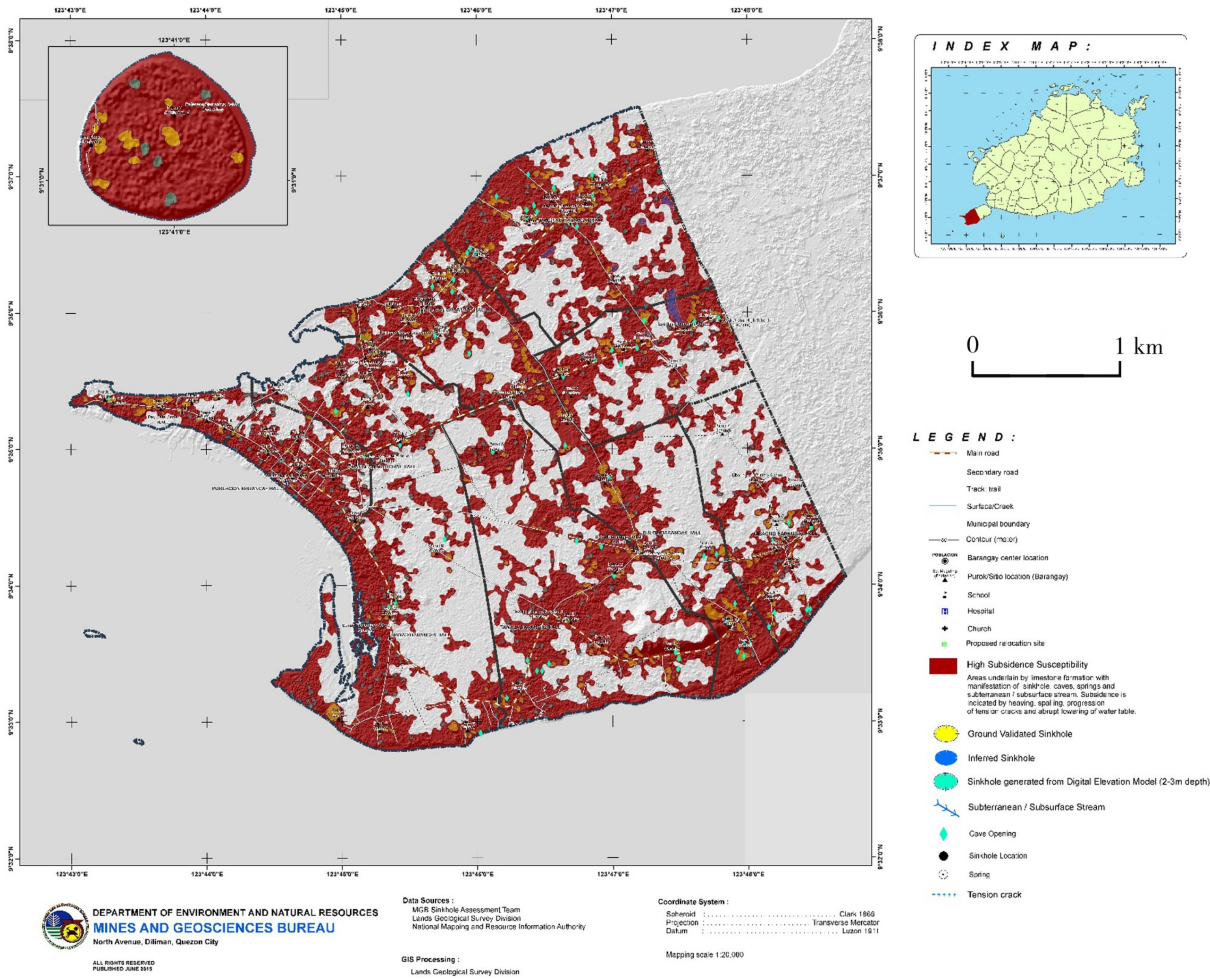

Fig. 4　Karst subsidence hazard susceptibility map of the Municipality of Panglao, Bohol province

图4　薄荷省旁劳市岩溶沉降易发区图

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IFSAR-DEM在岩溶洼地探测中的应用
——以薄荷省旁劳市沉降灾害评估为例

Kevin L. Garas，Madonna Feliz B. Madrigal，Ross Dominic D. Agot，Mark Carlo M. Canlas and Liza Socorro J. Manzano

（矿山与地球科学局，环境与自然资源部，马尼拉 1128，菲律宾）

摘要 岩溶研究中，通常会使用高分辨率卫星图像和地理空间数据识别、描绘岩溶发育及相关地质灾害发生的地貌特征。本文旨在利用ArcGIS10.0确定干涉合成孔径雷达数字高程模型（IFSAR-DEM）识别、量化和描述岩溶洼地。这种半自动岩溶洼地/天坑探测方法采用水流模拟法，并结合（1）流域划分；（2）下沉填充法提取洼地特征；（3）下沉深度测量及分类；（4）使用2013年至2014年谷歌高光谱卫星图像和数字地形模型对探测到的岩溶洼地进行验证。该方法已在薄荷省旁劳市进行的评估中进行了预测试。使用国家测绘资源信息局（菲律宾）1991年的1：50 000比例尺地形图进行的初步封闭洼地分析，发现旁劳岛有15个天坑。利用5米高分辨率IFSAR-DEM，共探测到820个天坑，其中424个根据详细的地面实况进行了描绘，以验证了岩溶洼地的存在。地表实况包含天坑大小、形状和深度等基本形态测量分析以消除误报数据。阈值设定为沉降深度大于1米，孔径大于10米，从而最大程度精确区分实际的天坑。这种基于GIS的工具有助于生成高分辨率岩溶塌陷易发区图，继而指导当地规划者、工程师及决策者进行开发规划和土地利用。

关键词 岩溶；沉降；天坑；IFSAR-DEM；GIS；薄荷岛

（编辑 庄 艳）