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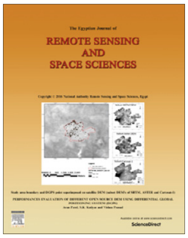

**RESEARCH PAPER**

# DSM derived stereo pair photogrammetry: Multitemporal morphometric analysis of a quarry in karst terrain

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**KEYWORDS**

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**Abstract** Bukit Merah karst has been deteriorating dramatically over 40 years due to intensification of human activities as a result of fast rate of lateral urbanization and extensive dimensional expansion of surface mining activities for instance, quarrying. Application of morphometric techniques to karst landforms provides a quantitative measurement and analysis of the configuration of karst landform variations. The objective of this study is to demonstrate the viability of using an integrated approach based on digital terrain model (DTM) derived time-series of steriopair aerial photography for monitoring the long-term geological karst response to environmental changes. The aerial photo stereo pairs were used to extract digital terrain model of the years 1981 and 2004, which in turn produced the TIN profiles of selected karst sites in the study area to define the karst morphology changes and to develop 3D representation and visualization. A detailed visualization of the karst terrain and its surface changes were represented using 3D virtual reality tool to substantiate the impact of surface mining in the Bukit Merah. Topographical characteristics of limestone hills, mountainous areas and flat areas were presented in 3D prospective. The results show the simulation topographical analysis results have confirmed that there were changes in elevation over the period from 1981 to 2004 especially in the limestone hill area as detected by the digital elevation model. It showed a dramatic variation in elevation has increased over a time interval. This means there has occurred an interference with the terrain attributed to human intervention or natural causes during the time interval. The result shows that the digital terrain model (DTM) derived time-series of steriopair aerial photography is able to delineate the changes in karst topography.

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## 1. Introduction

The description of karst terrain is either qualitative or quantitative. However, qualitative methods have been criticized for their subjectivity, as well as for the fact that little correlation or hypothesis-testing can be done from qualitative descriptions of karst terrains. Williams (1972) noted the uncertainty of analyzing the degree of similarity between different areas. Since the 1970s, there has been an increased focus on quantitative methods and techniques. Jennings (1985) also commented that morphologically similar landforms were given different descriptive names. As a result, many names had been given to similar karst landforms, leading to much confusion in studying a particular feature (Williams, 1972).

Morphometry can be defined as the measurement and mathematical analysis of the configuration of the Earth's surface and of the shape and dimensions of its landforms. Application of morphometric techniques to karst landforms provides an objective and quantitative system of karst landform description and analysis (Bates and Jackson, 1987). Morphometric techniques have been applied to a variety of karst regions and were proven effective in placing many karst landforms, especially depressions, in perspective (Williams, 1972; Day, 1983; Troester et al., 1984; Magdalene and Alexander, 1995). Morphometric techniques allow more precise measurements of the shape of landforms, and quantitative data generated can be used for mathematical and statistical analysis. The output of such analysis can then lead to objective comparison of karst terrains, as well as be used for statistical modeling, the creation of process-response models, and terrain simulations. Day (2004) noted the role of morphometry while studying geomorphic form and processes, where "explicit linkages" between landforms and landscape assemblages, and the various karst processes, were revealed.

The quantification of the character of landscapes and landforms using morphometric techniques has allowed thorough inter-regional comparisons to be carried out, providing a clearer picture about the global diversity of karst. With recent advances in technology and the ability to quantitatively study karst terrain, it is possible to use computers to produce increasingly sophisticated karst terrain models. Ahnert (1994) used the polygon model to simulate karst landform development, and utilized the software Surfer to create three-dimensional surfaces for visualization purposes. However, many programs are not very versatile in terms of their use in different morphometric applications. This task is increasingly being carried out using GIS which analyzes the morphometry of an area and carry out measurements such as area, length and perimeter. Ultimately, GIS, like the other morphometric techniques, is a useful tool for better understanding of karst terrain. It requires sound geomorphic expert knowledge to conduct tests and generate models in a computer's virtual setting. GIS can also calculate spatial distribution, pattern and densities as well as conducts proximity and other spatial analysis. It can perform three-dimensional simulation and analyses by calculating profile, aspect and slope and measuring volumes. GIS, on the other hand, provides rapid access, integration and analysis of spatially referenced data stored in large numerical databases. It also displays the results graphically in maps and charts. New morphometric techniques are also essential to simplify the complicated task of studying karst landscapes and their features. It is often necessary, as Ahnert (1994) stressed, to model on ideal, homogeneous landscapes, and then test the model in more complex situations. Morphometric models should test the influence of both bedrock characteristics and climate on karst development.

Other morphometric techniques have been used to correlate data and identify patterns, which would have to be described. While morphometric analyses have become increasingly complicated, the description of karst landscapes has become less qualitative, and has embraced the use of science, mathematics, and technology. DEM and DTM have been useful tools in recognizing geological and geomorphological features (Grover, 2002) where they have provided additional information beyond that available from two-dimensional imageries alone (Davis and Mason, 2000). This is beneficial to humans, who analyze data more comfortably in three dimensions than in the two dimensions, which are usually available in multispectral imageries (Rimal et al., 2001). Terrain plays a fundamental role in modulating earth surface and atmospheric processes. This linkage is so strong that an understanding of the nature of terrain can directly confer understanding of the nature of these processes, in both subjective and analytical terms. It is therefore natural to place representations of terrain, in the form of digital elevation models (DTMs) (Hutchinson, 2007).

There is a need to represent geographic area in a virtual setting to allow for the visualization of distant terrain, assessment of the visual impact of different planning schemes, recreation of the ancient settlements, as well as for military applications particularly for the flight simulation training. Brodlie and El-Khalili (2002) discussed the latter as a high degree of human–computer interaction, where users intimately react with the virtual landscape for example, crashing into the virtual hillside. While virtual reality can be considered to be the creation of a complex three-dimensional computer-generated landscape with which users can readily interact, the combination of virtual reality technology with GIS greatly enhances the resources available to researchers. Faust (1995) described the ideal VRGIS as not only consisting of a realistic depiction of geographic areas in a computer-generated environment where full user interaction is permitted, but also consisting of standard GIS capabilities, such as spatial analysis, querying, and calculations. Therefore, in a true VRGIS, as Haklay (2001) put it, the system database remains a traditional GIS, while virtual reality is used to augment the cartographic capabilities of the GIS.

With particular regard to karst geomorphology, it is possible to create a virtual environment using Triangulated Irregular Networks (TINs) and aerial photographs or satellite images. This is possible in the 3D Analyst extension of the desktop GIS software Arc View and ArcGIS, which allows the creation of three-dimensional scenes, where users may freely roam, rotate, and move through a three-dimensional environment, albeit with a lower degree of human–computer interaction than in military applications (Lyew-Ayee, 2004). Due to the extreme ruggedness of most karst terrain, the ability to visualize and move through such areas in a virtual setting can, by itself, be quite appealing. The virtual landscapes can be particularly useful before setting out on field excursions, as well as in recreating past field trips (Lyew-Ayee, 2004).

The current study demonstrates the viability of using integrated morphological tools including geostatistical analysis and Volumetric Surface Movement Spatiotemporal Data

Model (VSMSDM) to create karst terrain surface movements in the Virtual Geographical Information Systems (VGIS) based on a reliable aerial photo grammetry – derived DTM and remotely sensed data.

## 2. Study area

Gunung Rapat is a village within the district of Bukit Merah, located in the state of Perak, which is around 200 km north of the Malaysian capital city, Kuala Lumpur Fig. 1. The study area is located approximately between the northeast corner (4° 47′ 3.11″, 101° 10′ 10.63″) and the east corner (4° 2′ 31.95″, 100° 51′ 9.59′). Bukit Merah is considered one of the richest tin-mining areas in the world and one of the most famous Karst areas in Malaysia (Al-Kouri1 et al., 2014). Its mines were discovered in 1870 by British mining companies. Geologically, the Bukit Merah is underlined by limestone dated Devonian to Permian (Suntharalingam, 1968). Karst in the Bukit Merah reflects a typical tropical karst with scattered steep-sided limestone hills protruding throughout the flat-lying valley. Only about 23% of the limestone occurs as hills, while the rest is over laid by the alluvium. Since it is sandwiched between two granitic highlands.

## 3. Data collection and preparation

The data used in this study comprise of remotely sensed imageries and relevant ancillary data as listed in Table 1. Details of the data collected are described in subsequent sections. The imageries acquired by SPOT 5 and LandSat 5 satellites over the study area, were collected from the Malaysian Centre for Remote Sensing (MACRES); Spot5 images on March 27, 2005 while LandSat 5 images in 1991, 1998 and 2000. Aerial photography of the study area and its surrounding, acquired in 1981 and 2004, were collected from the Department of Survey and Mapping (JUPEM). The images provided information on karst surface features and facilitated the process of field investigations, especially when identifying surface features across large landscapes. A total of four images covering the study area have been selected carefully. The approximate image overlap is 70%. These images were acquired using a Leica RC 30 Aerial Camera Systems of focal length 153.28 at a 1:1000 nominal scale. The photo negatives were scanned with a photogrammetric precision scanner of resolution of 24 µm resulting in an approximate ground pixel resolution of 0.24 m and later were converted from tagged interchange format (TIFF) to 8 bit per pixel RGB jpeg-images that are suitable for processing. Soil and land use maps (2000) of the study area were provided by the Department of Agriculture, Malaysia.

### 3.1. Data pre-processing

Satellite digital image data sets contain a number of distortions which must be corrected at the ground receiving station during production of the image file. Prior to implementation of the automatic edge detection processing to map lineaments,

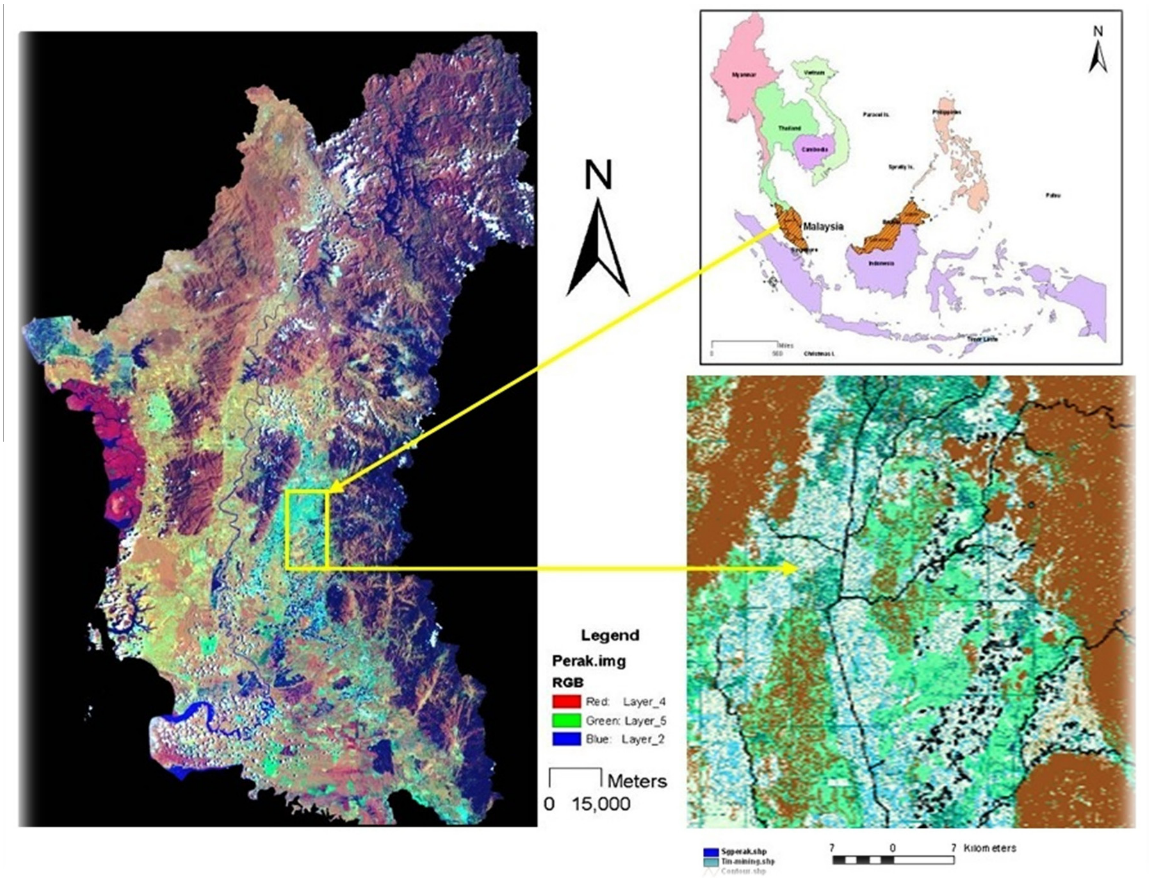

**Figure 1** Study area location.

**Table 1** Data type in the study area.

| Type | Year | Source |
|---|---|---|
| Landsat | 1991, 1998 and 2000 | MACRES |
| Aerial photography | 1981 and 2004 | JUPEM |
| Land use map | 2000 | Department of Agriculture |
| Planning map | 2005 | Town plan Department Ipoh |
| Digital topographical map | 1991 | JUPEM |

Landsat TM data were enhanced and then geometrically corrected. Digital images collected from airborne or space borne sensors often contain systematic and unsystematic geometric errors. Systematic errors, especially sensor distortion, are corrected using ephemeris of the platform and these are known also as internal errors. Other errors are being corrected by matching image coordinates of physical features on the image to the geographic coordinates of the same features on a map or acquired from Global Positioning system (GPS).

Geometric errors are corrected using sensor characteristics and ephemeris data include scan skew, mirror-scan velocity variance, panoramic distortion, platform velocity, and perspective geometry. Errors that can rectify using GCP's include the roll, pitch, and yaw of the platform and/or the altitude variance.

Also, image enhancement techniques are used to produce the best representation of the initial scene for clear visual presentation of the image and so improve its information content to the interpreter.

### *3.2. The DTM generation for the study area*

Contour lines data collected from JUPEM were not complete, which may lead to errors in analyzing the topographical variation and visualization. In order to overcome this problem, the DTM has been extracted automatically from stereo pair's aerial photos for the years 2004 and 1981. The DTM generated from the photo pairs were then mosaicked. The black and

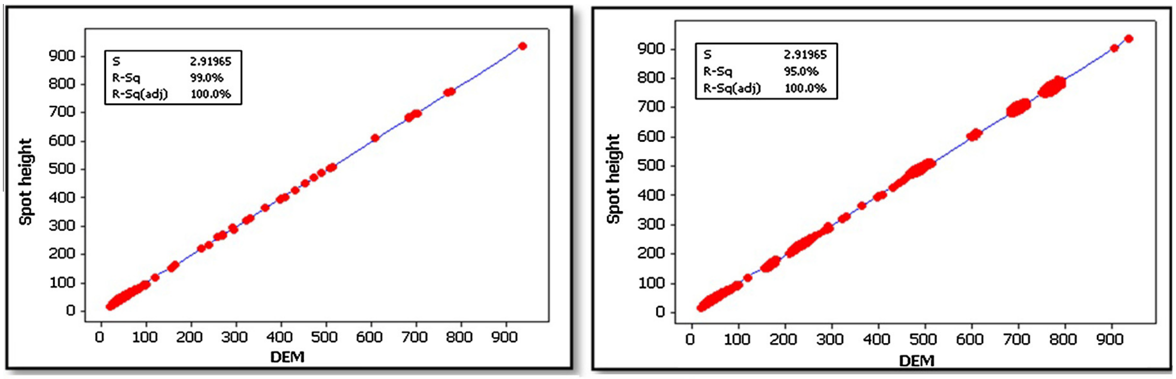

**Figure 2** Linear regression – DTM and spot heights for Bukit Merah (2004 and 1981).

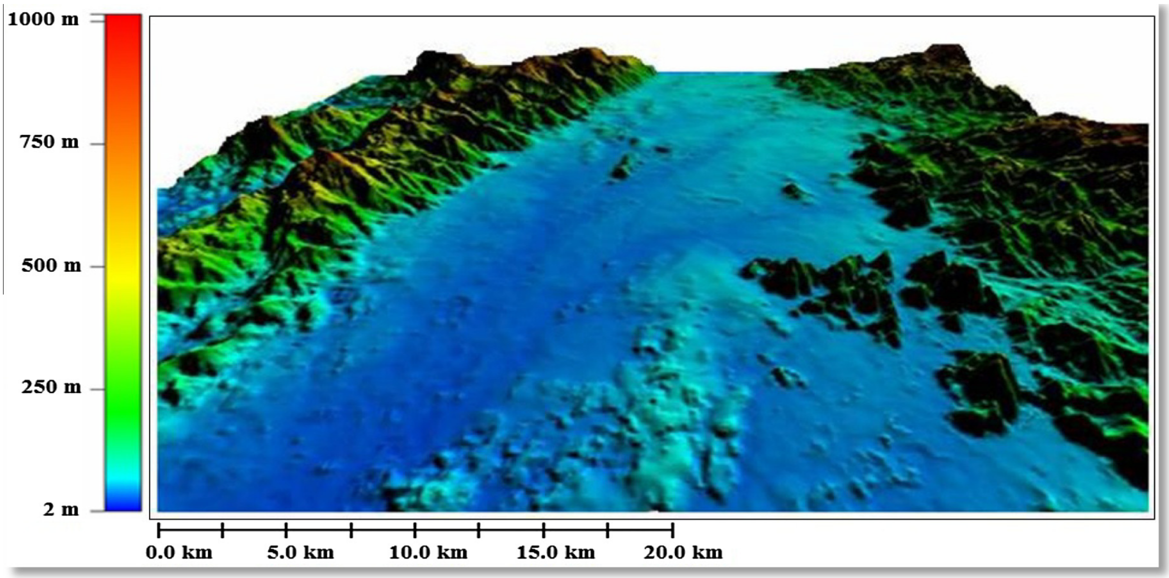

**Figure 3** 3D visualization of the terrain in Bukit Merah.

white and color aerial photographs and stereo model images were generated by first resampling the original images along epipolar lines to aid stereo viewing by the operator and to assist in the image matching process during automatic DTM generation. The epipolar lines indicate where the epipolar plane intersects the two images and the images of the ground point. Given two over-lapping images and a ground point, the epipolar plane is therefore a plane containing the ground point and two camera stations.

DTM were derived using the SOCET TEM generation software from stereo-pairs of both Black–White and color images. This software uses image-matching techniques to locate conjugate points in the images and then determine the heights based on the image orientation data. The DTMs were generated for all areas of mining at a spatial resolution of 0.85 m. Given the reliability of the GCPs used, an absolute accuracy of 99% in relative height differences in stereo models was achieved.

Ortho-images were then generated from the orientated Black–White and color images and the DTMs resampled at ground distance of 0.85 m to annotated grid spacing of 30 m. For 2004, the ortho-images and DTMs were mosaicked producing image maps that were annotated appropriately for use in the field. The main benefit of generating DTMs and associated ortho-images was that the extent and height of Bukit Merah karst could be mapped and compared for the years 1981 and 2004.

TINs were created using the 3D Analyst extension. Like grids, they are a surface representation derived from irregularly spaced sample points, each with X and Y coordinates, as well as an attribute, Z, which in this case would represent elevation at that particular point. The TINs were created from XYZ points generated from aerial photographs and spot heights data available for the study area. These spot heights were entered as mass points to ensure an accurate representation of the terrain after triangulation. Once the TINs were created, cross-sectional profiles were produced, and their surface area characteristics were determined using an option found in the 3D Analyst extension. This is one of the criteria for determining the surface roughness of a terrain confirmed by Day (2004), whereby the ratio between the surface area and the flat planar area of the terrain is determined. ‘Rough’ areas would have higher ratios than ‘smoother’ terrain. The actual surface area is determined by calculating the area of each triangle that makes up the TIN; the flat planar area describes the area of the boundary polygon. The two first-order derivatives of elevation – slope (the rate of change of elevation over horizontal space, measured in degrees, ranging from 0° to 90°) and aspect (the compass direction or orientation of a slope, measured in compass bearings, from 0° to 360°, or expressed as cardinal directions), were easily calculated from the DTM in ArcGIS using the Spatial Analyst extension.

**Table 2** Topographic description of study sites.

| Limestone hills name | Height (m) | Base area (km$^2$) | Alluvial plain (m) |
|---|---|---|---|
| Gunung Rapat | 318 | 4.6 | 50–60 |
| Gunung Lanno | 407 | 2.5 | 50–55 |
| Gunung Terendum | 200 | 2.1 | 55–60 |

### 3.3. DTM accuracy assessment

The validation for the digital terrain model (DTM) analysis were carried out to assess the accuracy of the digital terrain

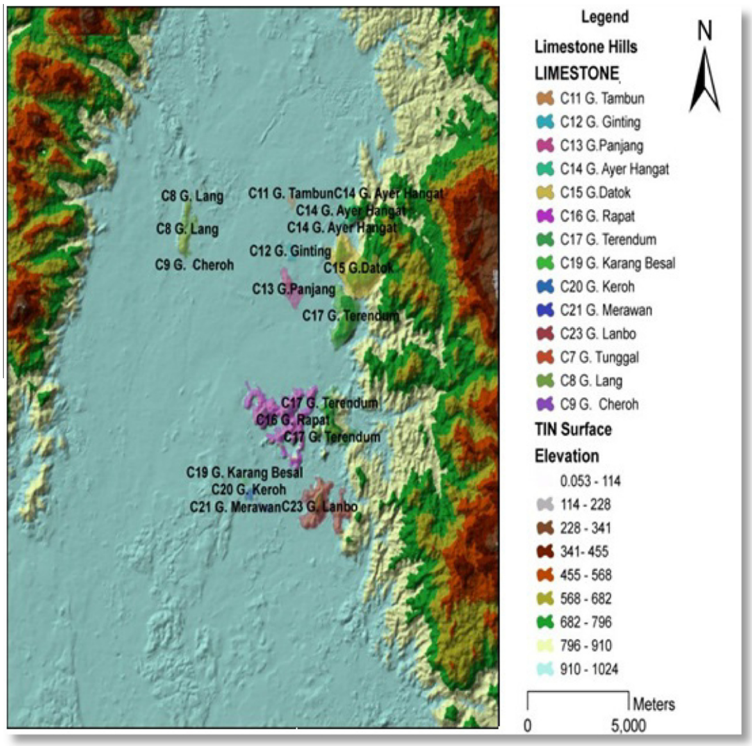

**Figure 4** Limestone hills distribution overlaid on of TIN surface.

data model. This has also helped in the evaluation of topographic parameters used for karst surface movement modeling and analyses of the variation. The quantitative assessment for accuracy of DTM was made compared to GCPs extracted from existing digital vector topographical map published by JUPEM in 2003, including contour lines with 5 m intervals and spot height elevation data. Contour lines and spot height points were derived from aerial photos of the study area captured on 2003. The data at a scale of 1:3000, were projected in WGS 1984-ellpsiod with horizontal accuracy of 1.5 m and vertical accuracy of Z ± 2.5 m. Randomly sampled Spot heights consisting of 147 and 195 points captured for 2004 and 1981 respectively were correlated to corresponding points derived from DTM (Fig. 2).

The linear regression analysis has revealed strong correlation between DTM generated points and spot heights reference data for the study area. The R2 of 0.99 and 0.95 were obtained for 1981 and 2004 respectively. *T*-tests, performed on the linear regression data, showed this correlation to be highly significant for the study areas. It was also observed that the slope value of the regression line was close to 1. A formal analysis of the distribution of DTM errors has confirmed that the errors were normally distributed within 95% confidence limits. The DTM error (m) of the 147 points in the study area had a mean of 4.83 m with standard deviation of 6.927 m.

## 4. Results and discussion

### 4.1. 3D visualization of Bukit Merah

The need for detail visualization of the Karst terrain and its surface changes necessitates the use of 3D virtual reality tool to substantiate the impact of surface mining in the Bukit

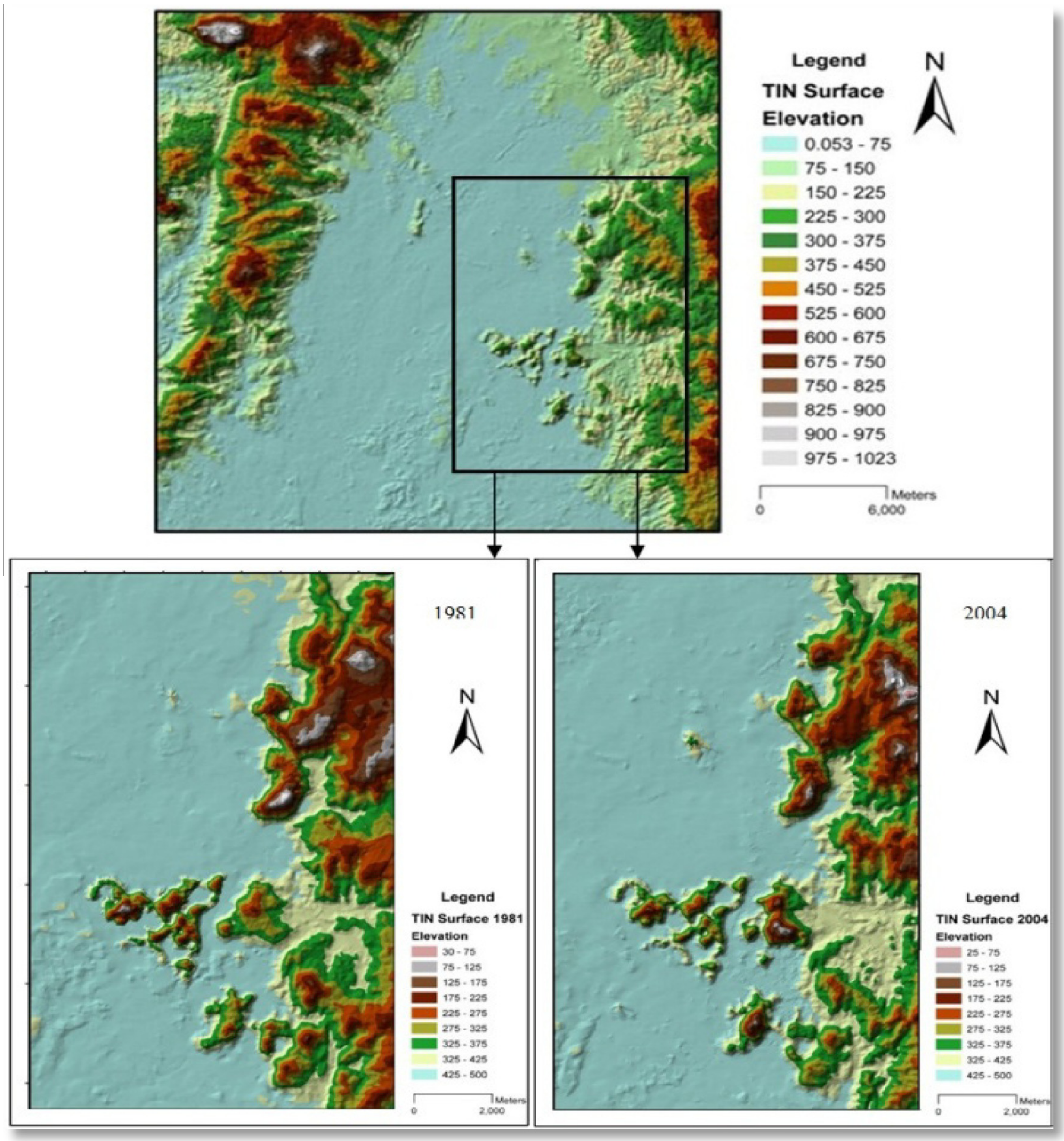

**Figure 5** Digital elevation surfaces from TIN of Kinta for 1981 and 2004.

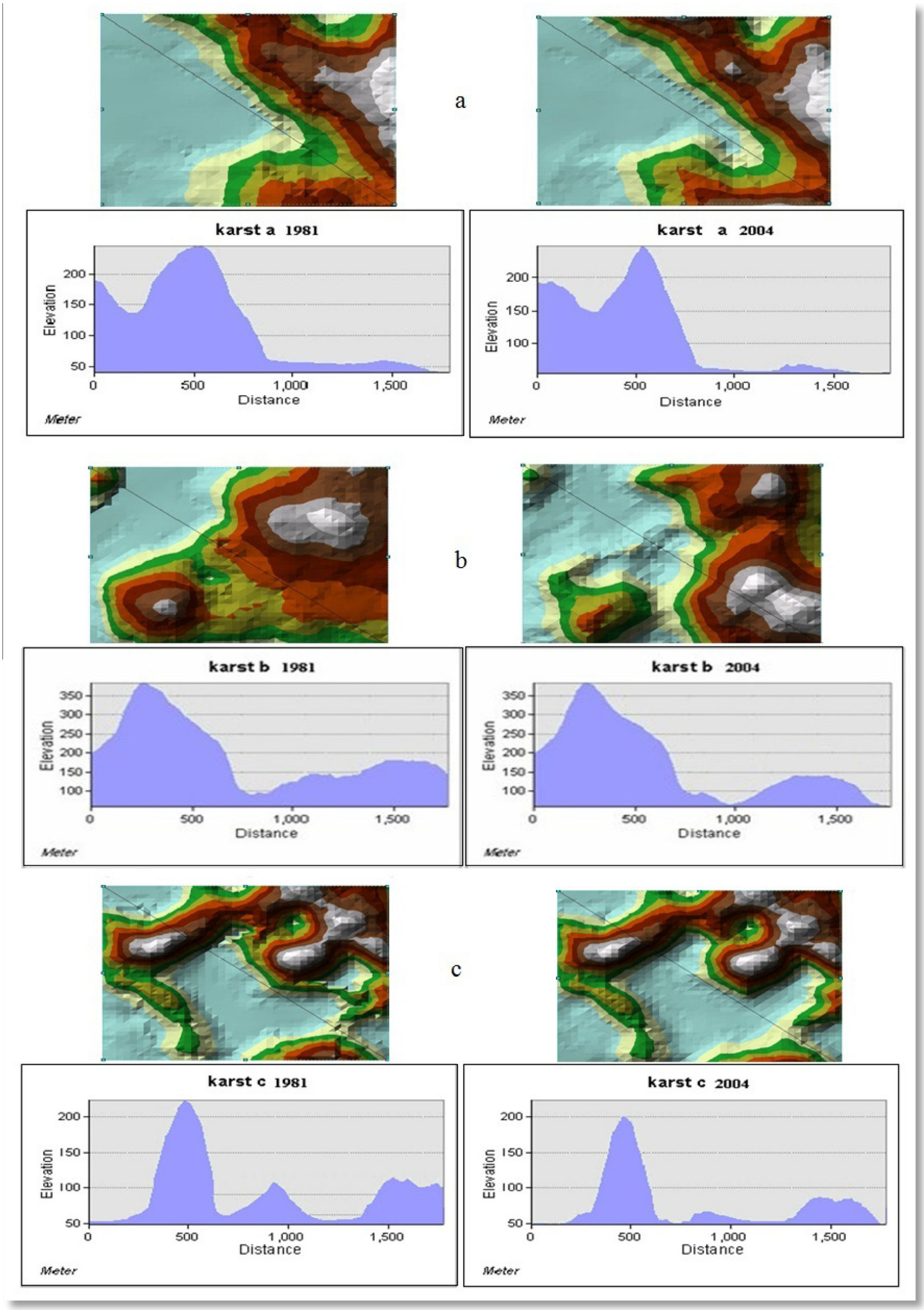

**Figure 6** Limestone karst profiles generated from TIN – 1981 and 2004 (a: Rapat, b: Terendum and c: Lanbo).

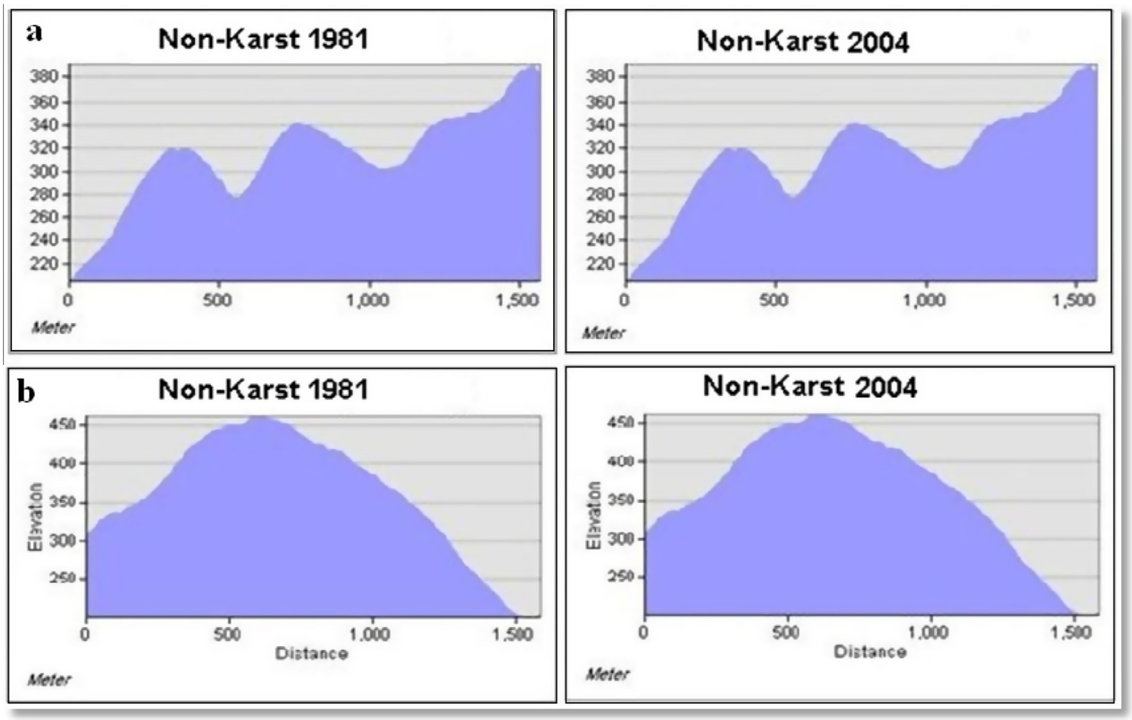

**Figure 7** Granite (non-karst) profiles for the period 1981–2004.

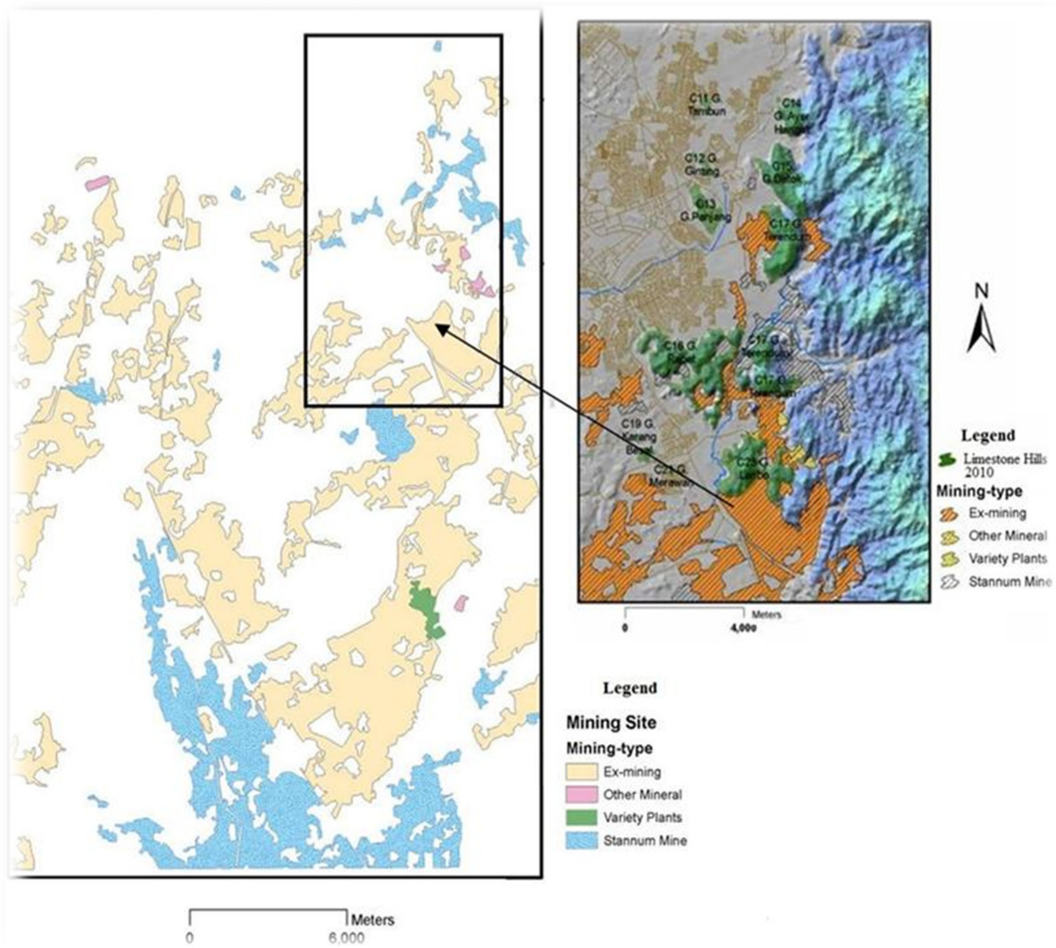

**Figure 8** Mining activities (Quarries) in Bukit Merah area.

**Figure 9** (a) Three dimension quarry operations have inflicted limestone hills and (b) satellite image shows quarries operation in Bukit Merah.

Merah. Topographical characteristics of limestone hills, mountainous areas and flat areas were presented in 3D prospective as shown in Fig. 3 in the GIS environment. The Karst Mountains of tropical regions, like that at Bukit Merah, are distinguished by their steep walled mountains separated by broad flat valleys or plains. These towers like features looming above, with rocky overhanging cliffs, are riddled with caves typical of humid-tropical limestone terrain.

The limestone hills of Bukit Merah has gone through tropical karstification over decades to form steep sided cockpit towers protruding from the plain. The 3D perspective of the Kinta terrain can be viewed from different angles and altitudes, providing a photo-realistic depiction of the landscape and change in the geological environment due to surface mining. In addition, a virtual fly-through animation tool was also developed and has enabled a viewer to interact with the terrain and view different perspectives of the landscape to attain a more comprehensive understanding.

### *4.2. Limestone hills topographic analysis*

The field an investigation has shown that the massive limestone hills are characterized by slopes of steep sided hills called karst towers. This represents the mature stage of chemical weathering reflected by isolated small to large mogote within the alluvial plain of the Bukit Merah. Its characteristic peak is about 407 m and its base is approximately 2500 square meters as depicted in Fig. 4. The limestone in Ipoh covers a substantial 21% of the total limestone hills in Perak. This is another reason why Kinta, Ipoh was selected for the study area. The output statistics of differences in sinkhole densities and percent distribution among areas of carbonate rocks. These variations could be due to the heterogeneity and different combinations of limestone and dolomite.

Three limestone hills had been selected for the study Gunung Rapat, Gunung Lanno and Gunung Terendum. Table 2 shows some topography descriptions of these hills. Which cover some 20% of the total limestone area of Ipoh; Gunung Rapat is the most famous limestone hill in the Bukit Merah. It is located near Ipoh town in the north east and it has a spectacular shape representing an advanced stage tower karst formation with attractive features, appealing to many visitors. It is the largest hill in Kinta at 318 m and covers 4.6 km$^2$ base areas. Its alluvial plain is about 60 m above mean sean level (AMSL). The limestone is characterized by steep to vertical walls and rounded crest and caves of which, the most important types are the foothill or notch caves. Such caves are very accessible and have been housing various temples of Buddhism and Hinduism.

Gunung Lanno is located about 10 km to the south east of Ipoh. Its terrain characteristic resembles that of mogote with the highest peak at 407 m AMSL and has an area base of approximately 2500 square meters. There is also a large water filled polje in the north east of the hill. Notch caves at about 6.4 m above the plain level are common features besides the presence of a few foothill caves at various heights.

Gunung Terendum Selatan is located to the south of Gunung Terendum. Its peak and base area are respectively 200 m ASML and 200 square meters. In general the Kinta topography comprises granitic mountain ranges at the east and west fringes of the valley. The valley itself is a wide extensive plain comprising of quaternary alluvium cover, which is low-lying land and underlain by limestone and subordinate schist. The area is predominantly hilly especially at the fringes, which has elevation between 160 m and 1023 m. The middle of Kinta is flat, located in the valley and it is exists the highest peak in the valley. The solubility of limestone has generally caused most hills lower than the surroundings.

Aerial photos stereo pairs of Bukit Merah taken in 1981 and 2004 were used to generate the TIN surfaces as shown in Fig. 5. This was because existing elevation records from JUPEM were difficult to analyze due to missing points and did not gave a clear picture of the topography changes. The comparison of karst extent between the two years has revealed substantial movement over the 23 years period. This was due to geological changes of the limestone and granite landscapes.

Changes in the heights of the three karst sites were also studied in more detail using TIN profiles generated for 1981 and 2004 as shown in Fig. 6a–c. These changes in limestone hills elevation and morphologies in the three study sites were found to be directly effected by erosion arising from human

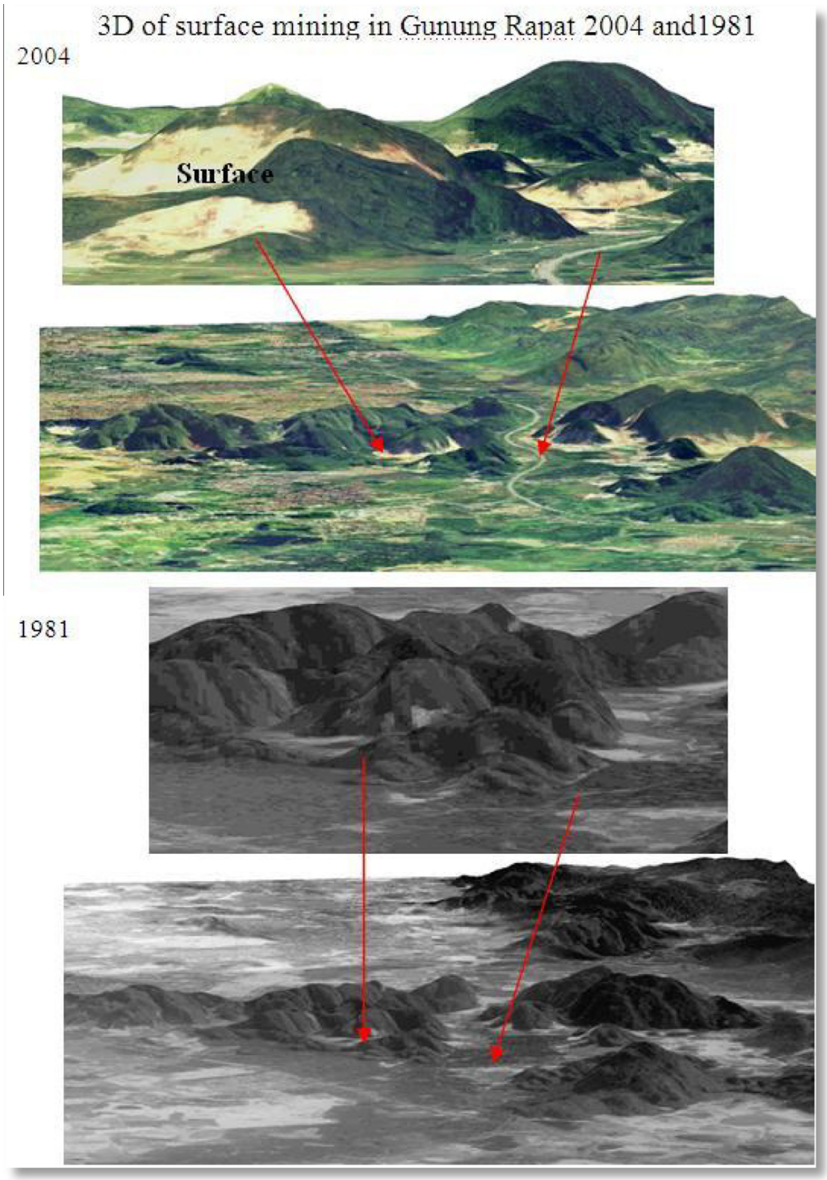

Figure 10 3D visualization of karst features in Gunung Rapat of 1981 and 2004.

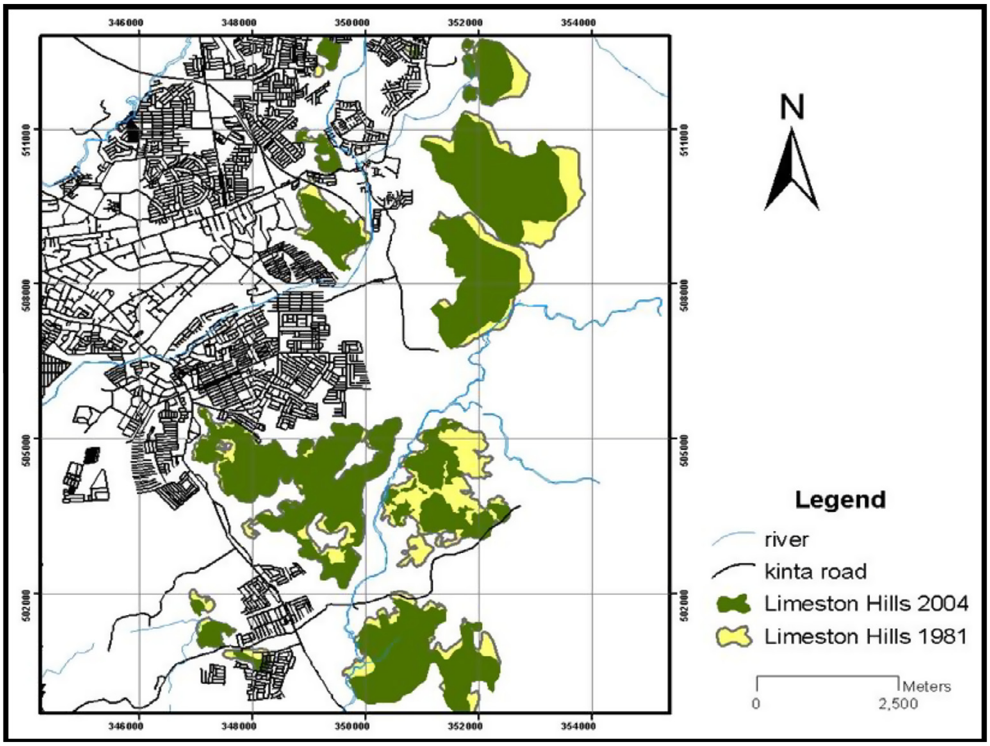

**Figure 11** Size Limestone hills changed from 1981 to 2004.

interventions, humid dissolution and mining activities operations. Terrain quantification of the granite landscapes during the period from 1981 to 2004 showed no significant change as indicated in Fig. 7a and b, due to reduced surface mining operations.

The study demonstrated the viability of using time-series of aerial photography for monitoring and understanding the long-term response of the geological substratum to environmental impacts in the Bukit Merah.

### *4.3. Limestone mining and quarry activities and conservation*

The study area has many mining and quarry activities. The open pit cut of limestone has accelerated the dissolution and chemical weathering processes of the limestone itself. This explains the increasing number of sinkholes in the Bukit Merah. Geologically, the study area is susceptible to subsidence and collapse leading to localized earthquake. Mine subsidence is a movement of ground surfaces as a result of the collapse or failure of underground mine work.

Fig. 8 depicts a typical surface effect of mine subsidence. It is important to note that mine subsidence can occur as a result of mining at any depth. From the results of the total surface area analysis, it was found that subsidence has increased with depth of mining. This is due to structural damage caused by subsidence sinkholes that occurred in areas underlain by underground mines.

The quarry operations have inflicted unsightly scars on the limestone hills, which sometimes are conspicuous to travelers along the North–South Road for instance in Gunung Rapat as shown in Fig. 9(a), despite quarrying activities continued to operate close to roads and highways, which were constructed subsequent to existing quarries as shown in Fig. 9 (b). As such, safety of the public using public roads is now of concern. The infringement of residential buildings and structures/factories to existing quarry sites and operations has resulted in issues related to public and worker safety.

Fig. 10 shows the 3D prospective of Gunung Rapat using DTM data sets of 1981 and 2004. It shows clearly the surface mining scars viewed at different angles, perspectives and scales. The analyst would then have the complete information of this feature enabling more accurate identification of it.

From the result it was found that the area of limestone hills has been reduced substantially form 1981 to 2004 as shown in Fig. 11 due to human interferences. The changing rate and hazard of limestone hills have made it obligatory that conservation and geo-conservation for some limestone hills in the future, such as Gunung Rapat, which has been ranked as a heritage site. Studies have been carried out for its karst features and scientific importance. Given this scenario the geological value and flora population of the limestone hills especially at certain locations have to be protected and conserved. Hence, no quarrying, blasting or agricultural activities should be permitted in these hills to prevent further degradation and reduction in size.

## 5. Conclusion and recommendations

Bukit Merah village has been deteriorating dramatically due to changes that had occurred in the past and continues because of the close relationship between the fast rates of extensive dimensional expansion of surface mining and quarrying. This study demonstrated the viability of using time-series of aerial photography for monitoring and understanding the long-term response of the geological substratum to environmental impacts in the Bukit Merah. Aerial stereo pair photos of

1981 and 2004 were used to generate a reliable DTM, which has been used to produce the TIN profiles of selected karst sites in the study area. This has shown substantial changes in their morphologies from 1981 to 2004 to define the karst morphology changes and to develop 3D visualization of Bukit Merah. The spatial and temporal digital terrain model has confirmed that there were changes in elevation in the two data sets acquired in 1981 and 2004 especially in the limestone hills area as detected by the digital elevation model. Given the current degradation scenario of the limestone resources in Bukit Merah, and its associated environmental impacts, Bukit Merah is facing the threat of destruction through on-going quarrying activities.

Based on that, it could be concluded that:

- The differences of sinkhole densities and percent distribution among areas of carbonate rocks could be due to the heterogeneity and different combinations of limestone and dolomite.
- There was geological changes of the limestone and granite landscapes between 1981 and 2004. This conculsion was baesed on the comparison of karst extent during that period which has revealed a substantial movement over 23 years period.
- Erosions arising from human interventions, humid dissolution and mining activities operations are the major causes of changes in limestone hills elevation and morphologies between 1981 and 2004.
- No significant change in the granite landscapes due to reduced surface mining operations in such areas.
- Subsidence increases with depth of mining. This is due to structural damage caused by subsidence sinkholes that occurred in areas underlain by underground mines.
- The quarry operations have inflicted unsightly scars on the limestone hills, which sometimes are conspicuous to travelers along the North–South Road for instance in Gunung Rapat.
- The infringement of residential buildings and structures/factories to existing quarry sites and operations has resulted in issues related to public and worker safety.

Based on these conclusions, it is recommended to:

- Conserve karst limestone hills, considering their heritage values and potential hazards arising from the current accelerated infrastructure development.
- Have quarry operations far away from main roads since the existing query have inflicted unsightly scars on the limestone hills, which sometimes are conspicuous to travelers along main roads in the area.
- Take more care about public and worker safety since the infringement of residential buildings and structures/factories to existing quarry sites and operations has resulted in issues related to people safety.
- Use the 3D perspective in future studies to provide a photo-realistic depiction of the landscape and change in the geological environment due to surface mining.
- Use time-series of aerial photography in future studies for monitoring and understanding the long-term response of the geological substratum to environmental impacts.

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