Characteristics and Affecting Factors of Sinkhole Development in Cho Don Area, Bac Kan Province, Vietnam

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Abstract. Cho Don district, Bac Kan province, Vietnam is an area where mineral resources are very concentrated. The most potential minerals in the areas are iron, lead, zinc ores and construction materials with large reserves. The mines that have been explored and have large mineral reserves are mines in Bang Lung town's surrounding area with reserve of about 5,032 thousand tons of ores. Na Tum mine in Cho Don district, Bac Kan province started to operate in April 2007, but since December 2007 up to now a number of large and very large sinkholes have been being developed and most likely shall be developed in future. Na Tum mine dewatering had been considered as a main induced sinkhole formation driving factor. Other necessary and sufficient conditions of sinkhole development and natural factors which accelerate sinkhole formation triggering mechanism have been studied and identified in this paper. The results are essentially important for future comprehensive detailed engineering geological, hydrogeological and geotechnical engineering investigation plan which is required for sinkhole geotechnical quantitative analysis, based on which both management and engineering measures to prevent the future sinkhole development, to provide sinkhole warning, to remediation of sinkholes, to carry out the local resident resettlement etc. can be developed. This is an important part of sustainable social-economical development and environmental protection in term of induced geohazards related to mining activities.

1. Introduction
Vietnam is a country with diverse and abundant mineral resources with nearly 5,000 mines and ore spots of about 60 different minerals. Mining and processing of mineral resources have an important position in the national economy as it had contributed about 9.6%-10.6% of total GDP since the year of 2000 [1]. However, the exploitation and processing of mineral resources have been leading to different geological hazards that may cause serious human and property loss consequences.

Geohazards are defined as events caused by geological, geomorphological, hydro-meteorological processes or their combination, that are potential dangerous or present a threat to lives, property, infrastructure and the environment [2]. Geological hazards are also defined as incidents due to geological conditions or geological processes that threaten life, property and natural environment or human environment [3]. The view of ‘geohazards’ is deliberately very broad and includes all earth surface processes with the potential to cause loss or harm to the community or the environment [4]. Therefore, identification induced geohazard formation conditions and driving factors plays an important role in ensuring environmental sustainability in mineral resources exploitation.

Cho Don district (Bac Kan province, Vietnam) is a district with concentrated mineral resources. The most potential minerals in the areas are iron, lead, zinc and construction materials with large reserves.
The mines that have been explored and have large mineral reserves are mines in Bang Lung town with about 5,032 thousand tons of ore [5]. Na Tum mine in Ngoc Phai commune and Bang Lung town, Cho Don district, Bac Kan province (Figure 1) started to operate in April 2007, but sinkholes have been being occurred in some areas around the mine since December 2007 up to the present.

Figure 1. Study area map.

Based on the classification of six sinkhole types (dissolution, collapse, dropout, buried, caprock and suffusion sinkholes) by Lowe and Waltham (2002) [6] dependently upon the mechanism of sinkhole formation, most of sinkholes in the study area are collapse sinkholes, and some are dropout sinkholes. As it was stated by Waltham and Fookes (2003) [7] that subsidence (collapse) sinkholes occur with very low frequencies in natural undisturbed karstic environment (one new collapse sinkhole occurs in 11 km$^2$ in a year). Collapse sinkholes formed entirely within soil profile area mainly induced by engineered works including groundwater level decline by groundwater abstraction or mine dewatering [8]. Therefore, the occurrence of collapse sinkholes in the study area would mostly be directly caused by Na Tum zinc-lead ore mine dewatering.

Groundwater withdrawal did result in sinkhole development in many places in the world. Foose (1953) [9] showed that the Annville stone company pumped groundwater of a rate of 19,080 m$^3$/day for many years before May 1949 in the Hershey valley, part of the Great Valley, Harrisburg, Pennsylvania, however no sinkholes occurred. When the mine began pumping 35,430 m$^3$/day in May 1949, the groundwater level drastically was lowered over an area of more than 25 km$^2$, subsequently most valley springs and many wells were dried up, and about 100 sinkholes were developed in the area.

In December 1962 a three-storeyed crusher plant of a gold mine at Westdriefontein, west of Johannesburg, South Africa collapsed into a catastrophic sinkhole causing a loss of twenty-nine lives. The frequency of the sinkhole occurrence in the Transvaal dolomite formation in the area increased very greatly within the years of 1958-1962 corresponding with a period a greater groundwater pumping for underground mining which led to a substantial lowering of the groundwater level as much as 120 m [10].

Land surface collapses in clays and sands of the Talbot formation overlying the Santee karstic limestone aquifer have occurred in the Jamestown area of Berkeley County, South Carolina since the summer of 1975 due to large groundwater level decline of more than 114 m in the Santee aquifer because of groundwater pumpage of 136,275 m$^3$/day since the summer of 1975 [11]. The land surface collapses have caused not only property damage, but also human injury because of sudden occurrence of collapses.

Sinclair (1982) [12] described that pumping at the section 21 well field of Tampa (Florida, United State) municipal well fields with a rate of 18,925 m$^3$/day since February 1963 and at a rate of 53,000 m$^3$/day since April 1964, then by May 1964 there were 64 new sinkholes occurred within 1.61 km radius of the section 21 well field. The South Pasco well field of Tampa municipal well fields began pumping in 1973, then more than 30 small sinkholes were identified in 1974 [12].
In accordance to Newton (1986) [13], the 1981 investigation of sinkhole occurrence in the eastern United States had identified 6,000 sinkholes in 850 sites in 19 States, the costs of damage of which and of sinkhole occurrence protective measures for some limited sites was about 170 million dollars. The author had much emphasized on groundwater pumping and on the water table declining which resulted in various mechanisms of sinkhole development by citing many researchers' findings.

In the Bapsfontein area in South Africa, some 28 sinkholes were also triggered by fast lowering of the groundwater level prior to 2003, and on the Far West Rand many sinkholes triggered by dewatering have reached diameter up to 125 m and depth up to 50 meters [14].

Therefore, the occurrence of collapse sinkholes in Cho Don area would mostly be directly triggered by groundwater dewatering Na Tum zinc-lead ore mine regardless a strict standard abidance of the environmental protection assessment of the mining had been followed. As the law on environmental protection No. 55/2014/QH13 approved by Vietnam National Assembly on the 23rd of June 2014 [15] any mineral excavation project is required to assess risk of hazards which may be resulted during the project implementation and to propose appropriate hazard risk preventing measures. The remaining of the paper presents the status of the collapse sinkhole development in the area, the natural conditions, the factors affecting the sinkhole development and triggering factors directly leading to the sinkhole occurrence. The results would be essential and important for predicting further sinkhole risk, for developing sinkhole remediation design, for taking future sinkhole preventing measures in Na Tum mining activities. The results are also helpful lessons for other relevant mining projects to have sustainable mineral exploitation in term of induced geohazards.

![Figure 2. Location map of Na Tum lead-zinc mine and areas of sinkholes.](image)

**2. The development of sinkholes in the study area**

Lead-zinc ore Na Tum mine was investigated by Thai Nguyen mineral company and started to be excavated in April 2007. The ore body was reached at depth of 20 m at the end of the year of 2007. The
pit quarry has a funnel-shaped configuration with open surface area of about 1000 m$^2$ with slope from 45 degrees to 60 degrees. Dewatering is needed to be carried out 4-5 days continuously by pumping with a rate of about 35,000 m$^3$/day, and then at a rate of about 17,500 m$^3$/day for maintaining a required low water level for ore excavation work.

From the end of 2007, there have been frequently developed sinkholes in Na Tum mine's surrounding areas [16]. Four areas of sinkhole development had been observed around Na Tum mine: 1) Na Bua - Phieng Lieng area, 2) provincial road number 254 area, 3) Tan village area, and 4) Lac village area (Figure 2).

2.1. Na Bua - Phieng Lieng Area of Sinkholes
The earliest and most frequent sinkholes occurred in Na Bua - Phieng Lieng area. The first sinkhole occurred on the 12th December 2007 had a diameter of about 8 m and a depth of about 2 m. Following the first sinkhole, a series of sinkholes (10 sinkholes) occurred in January 2008, the diameters of which are from 4 m to 20 m and the depths from 1.5 m to 5 m (Figures 3 and 4). The sinkholes in this area are from 1,000 m to 2,500 m from the center of Na Tum mine to the North (Figure 2).

2.2. Provincial road 254 area of sinkholes:
A 12 m-diameter and 15-m depth sinkhole occurred in the evening the 2nd January 2016 on the provincial road 254 in Bang Lung town, Cho Don district (Figure 5). Fortunately, there was no either human injury nor property loss. The sinkhole had been remediated by earth filling in the next couple days. However, the road collapse occurred again at the same location on the 6th of January 2016 in a larger area causing damage to some nearby private houses. This area of sinkholes is 1,000 m from the center of Na Tum mine to the North-East (Figure 2).

Figure 3. Sinkhole occured on the 5th of January 2008 in Na Bua - Phieng Lieng area (http://news.vnay.com.vn).

Figure 4. Sinkhole occurred on the January 2016 in Na Bua - Phieng Lieng area (photo taken on Dec. 2018).
2.3. Tan Village Area of Sinkholes
Sinkholes in this area occurred relatively longer time from the start of the exploitation of Na Tum mine. Some small sinkholes occurred in 2016 and 2017. However, several larger sinkholes occurred during the 26th and 27th November 2018 (Figure 6). A very large sinkhole with a diameter of about 14 m and a depth of about 16 m occurred there causing collapse of large trees and discharge the whole stream water into it (Figure 7). Besides, there were two other sinkholes nearby with a diameter of about 5 m and a depth of about 3 m. An especially deep sinkhole, 30 m in depth and 6 m in diameter (Figure 8), occurred few days later on the 2nd December 2018. The sinkholes in this area are about 700 m from the center of Na Tum mine to the South West (Figure 2).

2.4. Lac Village Area of Sinkholes
Many sinkholes (34 sinkholes) occurred from the 10th to the 23rd August 2017 in a rice field in Lac village, Bang Lang commune, Cho Don district (Figures 9 and 10). The sinkholes are small in diameters and depths. The sinkholes in this area are from 2,000 m to 3,000 m from the center of Na Tum mine to the South (Figure 2).

3. The Study Area’s Conditions

3.1. Relief
Cho Don district is a mountainous district in the North of Vietnam having two popular terrain types [17] mountainous terrain in the North and valley terrain in the South of Bang Lung Town. The highest mountain in the North East has elevation of 446 MSL (Mean sea level) and the lowest valley in the South has elevation of less than 285 MSL.

3.2. Geological Conditions
The study area is entirely located in Lo Gam structural block (Tran Tuan Anh et al. 2011) which is bounded with Tong Ba-Phu Ngù structural block in the South East (Figure 11). Faults in the area are mainly North East-South West or nearly South North. From Vietnam 200,000 map of geology and minerals [18] the following geological formations are existing in the area.

Figure 5. Sinkhole on provincial road 254 on the 3rd January 2016 (TTXVN-https://bnews.vn).
Figure 6. Sinkhole in Tan village (https://dantocmiennui.vn).

Figure 7. 14m-diameter and 16m-depth sinkhole under remediation by earth filling (photo taken Dec. 2018).

Figure 8. Sinkhole in Tan village (https://vnexpress.net).

Figure 9. Sinkhole in Lac village (https://www.nhandan.com.vn).

Figure 10. Sinkhole in Lac village (https://www.nhandan.com.vn).
Figure 11. The study area’s geological map.
3.2.1. Phu Ngu Formation (O₃-S₃pn):
The formation is divided into the following three strata:
- Stratum 1 (O₃-S₃pn₁): mainly consists of shale, siltstone, sandstone with thin layers of cervicitis shale or calcareous siltstone, tuff. Thickness 1100-1200 m.
- Middle stratum (O₃-S₃pn₂): mainly consists of dark shale, silicate shale, siltstone, sandstone, tuff with lenses of limestone, calcareous siltstone. Thickness 300 m.
- Stratum 3 (O₃-S₃pn₃): consists of quartz sandstone, quartzite sandstone, hornfels (biotite-andalusite-cordierite). Thickness 1000 m.

3.2.2. Lower Devon-Middle Eifeli, Lower Coc Xo Formation
This formation is divided into the following two strata:
- Upper stratum (D₁-D₂ecx₁): The lower part consists of continuous quartz-sericite shale, sericite shale and sandstone, and quartzite sandstone. The upper part consists of sericite shale with clear foliation, in some places in unclear band shape, and thin lenses of limestone. The thickness is 200 m - 500 m.
- Middle stratum (D₁-D₂ecx₂) which mainly consists of bedded calcified limestone fossil Favosites, which is interbedded with thin layers or lenses of quartzite sandstone and sericite shale. The thickness is 300 m - 400 m.

3.2.3. Khao Loc Formation - Lower Stratum 1 (D₁-2kl₁)
This formation is available in the South West of Bang Lung town and consists of sericite shale, quartzite sandstone interbedded with thin layers of limestone. The thickness is 500 m - 600 m.

3.2.4. Undivided Quaternary Formation (Q)
The Quaternary formation is distributed only in Khau Cum valley and in a small area in the South East of the study area. It consists of pebbles, gravels, sands, and silt or clay. The thickness is less than 10 m.

The geological map of the study area is presented on Figure 3 in which a cross section line AB through the areas of sinkhole development and Na Tum mine in the direction from downstream to upstream is also shown.

3.3. Weathering Crust
In the study area, there are the following 2 types of weathering crust developed on different geological formations:
- Ferrosialite weathering crust is developed on Phu Ngu and Mia Le sedimentary and metamorphic sedimentary formation rich on alumosilicat. The weathering section has fully all zones weathering from weak to complete degree of weathering. The mineral composition in the fully weathered zone is mainly montmorillonite and limonite. With the depth increase, the proportion of these minerals decreases and eventually only in small quantity in the cracks of the bedrock.
- Terra rossa weathering crust is developed on Mia Le carbonate sedimentary formation. This weathering crust type is composed mainly of clay and weathered humus from carbonate formation and adjacent terrigenous sedimentary formation.

3.4. Hydrogeology
In the study area, there are existing two aquifers: a upper unconsolidated aquifer which is either Quaternary formation (pebbles, gravels, sands and silts) in valley area or weathering product crust of Coc Xo formation in other than valley areas, and a lower fractured aquifer composed of Coc Xo terrigenous or and carbonate formation.

The upper unconsolidated aquifer has average thickness of about 10 m and the water depth varying from 2 m up to 3 m, which changes by seasons.

The fractured aquifer has thickness less than 100 m for terrigenous formation and less than 150 m for carbonate formation [16]. The aquifer transmissivity varies from very small values up to 30 m²/day for
terrigenous aquifer, to 300-500 m³/day for carbonate aquifer. Groundwater level fluctuates strongly by seasons and are often lower than that of the above unconsolidated aquifer.

3.5. Precipitation
Precipitation is a major meteorological factor which has most relevant influence on geohazards, including sinkholes.

Figure 12. Minimal, average and maximal monthly rainfall.

Although Cho Don study area belongs to the B2 Vietnam climate zone, and has average annual rainfall of 1,804 mm [19], but Cho Don has average annual rainfall of 2,136 mm which is much higher than the average of the B2 Vietnam climate zone. The dry season is from October of the previous year to April of the following year, and a rainy season from May to September. The months with heavy rainfall are June, July and August, with average rainfall from 224.4 mm/month to 456.6 mm/month [20]. The lowest rainfall is in November, December, January, February and March, with average rainfall from 0.5 mm/month to 18.7 mm/month. The total rainfall from May to September is equal to 75-80% of the total annual rainfall. The minimal, average and maximal monthly rainfall in 2013-2017-year period are shown in Figure 12.

3.6. Hydrology
The largest stream in the study area is Khau Cum which originates from the Southern side of Khau Tham range and flows through Phieng Lieng valley, Na Tum mine, Na Bop mine and then discharges into Day river. The stream maximal and minimal flow rates are 71,521 l/s and 221 l/s, respectively. The stream is a steep slope and a high meandering with a very sharply fluctuating flow rate and water level.

4. Factors Affecting the Sinkhole Development in the Study Area
Since the sinkholes continuously develop in the study area, both mass information media and political systems from central level to provincial level from year to year repeat the phenomena and request an answer for the sinkhole development causing reasons and demand necessary measures for stopping the sinkhole development. On the February 2017 the provincial authority pronounced the following preliminary sinkhole formation reasons initially identified by the Geophysical Division [21]:

- In the condition of the existence of open underground cavities (the ceiling is a weak neither unsaturated or saturated consolidated formation) and saturated fractured zone in combination of other favorable factors sinkholes may be developed.
- The groundwater abstraction in the residential areas and dewatering of the mines in the area are one of the factors causing sinkhole development in Bang Lung town and its adjacent areas.
- Besides, one of the sinkhole triggering factors is the traffic on the provincial roads 255B and 254 and on other local vehicle roads: large-load vehicles create resonance dynamic vibration causing the
ceiling layer of the formation being shaken, gradually being cracked and fallen, and to some level land subsidence and ground surface shrinkage develop.

Based on the analysis of geological, hydrogeological, hydrological, precipitation conditions, and the dewatering Na Tum mine, the combination of the specific factors leading to the sinkhole development in the area are discussed as follows:

- Sinkholes happened in the Khau Cum valley area with Quaternary sediments, thickness of about 6 m -10 m overlying the upper stratum of the lower Coc Xo formation ($D_1-D_{secx_1}$) composed of shale interbedded with calcareous shale with a thickness of up to 230 m. This is a common classic factor for sinkhole development. However, even the areas underlain by carbonate bedrock are most sensitive to sinkhole risk (Prasad et al. 2017), in accordance with Waltham (2008) sinkhole formation is rare in natural karst landscapes, and may mainly be induced by human activity (Waltham 2008) such as groundwater abstraction and dewatering of mines.

- The sinkholes developed in the study area are mostly within unconsolidated Quaternary formation or bedrock weathering crust are distributed in the zones of faults or not too far from the faults (large sinkholes on the provincial road 254 is just on a Northwest-Southeast fault, the Lac village area of sinkholes is located right in the Northeast-Southwest fault, the giant sinkhole in Tan village lies close to the Northwest-Southeast fault, some sinkholes in the South of the Na Bua - Phiang Lieng in Ngoc Phai commune are close to the Northeast-Southwest fault). In the area of the faults or adjacent to the faults, the rock and soil may be strongly broken so that have high permeability which is a favorable condition for soil suffusion (subsurface erosion). The drilling survey data in the area have shown that cavities are existing in the fractured aquifer in different depths, from the depth of 25 m up to the depth of 70 m which are usually filled with silts, sands and gravels. Besides, the aquifer formation is very much fractured in the areas of faults.

The above argument is in accordance to Newton (1986) who had pointed out the role of subsurface erosion caused by groundwater flow through unobstructed faults, joints, fractures or other openings filled with unconsolidated sediments in creating and enlarging cavities which directly cause sinkholes in the Eastern United States. Also, Prasad et al. (2017) had carried out an analysis which showed that faults in South Western part of the Cuddapah basin, India are favorable conditions for sinkhole occurrence due to the secondary permeability features (faults) as all the sinkholes were produced along a fault zone, which serves as a boundary between two different formations.

- The sinkholes started to be formed since the end of 2007 after the Na Tum mine launched into operation in April 2007, when the mine excavation reached a depth of 20 m into the upper 10 m the ore bedrock, the mine pit quarry had a 10 m-column water. During the dewatering the mine, the water level in the bedrock aquifer in the Na Bua - Phiang Lieng area of sinkholes in the upstream of the mine quickly lowered (Figure 13) which had led to a strong vertical seepage from the upper unconsolidated aquifer so suffusion actively takes place.

![Figure 13. Groundwater level drawdown due to Na Tum mine dewatering.](image-url)
This is the reason why in December 2007 and January 2008 a series of sinkholes was developed in this area. In fact, the dewatering required a continuous water pumping with a rate of 35,000 m$^3$/day during the first 4-5 days, and after a pumping rate of about 17,500 m$^3$/day is required for maintaining needed water level for ore excavation. During the mine excavation, i.e., the dewatering, dozens of household water wells in Tan village, Bang Lung town (about 300 m from Na Tum mine) had been dried up, even 75-m deep water supply wells in the area could not be able abstract enough volume of water for domestic needs of Bang Lung town as usually as before. Since the second year of Na Tum mine excavation the dewatering caused groundwater level in the fractured aquifer decrease in around 20 m. At the present time the groundwater level drawdown is around 55 m. From the groundwater well hydraulic fundamentals, the groundwater level drawdown at any time counted from the beginning of groundwater dewatering when the pumping is long enough, would reach equilibrium and is proportional to the natural logarithm of the distance from the center of the mine pit quarry under dewatering [22]. Figure 13 illustrates the groundwater level depth in the second year of Na Tum mine excavation in 2008 and at the present, which shows that very large water level drawdown occurred over very long distance of several thousands meters. The water level in the fractured aquifer are schematically drawn on the cross section through the areas of sinkholes and Na Tum mine in Figure 14.

![Figure 14](image_url)

**Figure 14.** Schematic geological cross section AB through areas of sinkholes and Na Tum mine.

- The time of sinkhole occurrence is mostly the end of the previous year or the beginning of the following year, i.e., at the middle of dry season (sinkhole 1 formed on the 28th December 2007; sinkhole 2 on the 5th January 2008; sinkhole 3 on the 8th January 2008, sinkhole 4, 5, 6 on the 15th January 2008, sinkhole 7 on the 3rd January 2016). The sinkhole incidence time could be related to the sinkhole development condition as follows: In the rainy season, the water level in the bedrock aquifer increases and reduces the difference the pressure between the bedrock aquifer and the above unconsolidated aquifer, which reduced the suffusion process as well as increase the pressure on the bottom of the unconsolidated aquifer, contributing to reducing the risk of sinkhole occurrence. The condition of drying during dry season and wetting during rainy season would decrease the soil strength parameters, i.e., friction angle and cohesion.

The above-described factor leading to formation of sinkholes had been stated by Sinclair (1982) [12] for the case of sinkhole development in 1963-1964 in the Tampa area, Florida. The groundwater level in fractured Floridan aquifer had been decreased due to groundwater pumping in the municipal groundwater well fields in the North of Tampa city which led to more seasonal declines in the subsurface aquifer due to increased leakage to the Floridan aquifer thanks to the sharply increased difference in water levels in the two aquifers. Sudden decline in the artesian pressure, the induced decline in the water table of the above overburden aquifer, and the increased downward leakage combined to trigger the
collapse of cavities in the fractured aquifer, the sizes of which had become critical with respect to the bearing strength of the overlying overburden soil layer.

Newton (1986) [13] while studying induced sinkhole development in the Eastern United States due to the groundwater level decline had pointed out the following mechanisms of sinkhole development: 1) loss of buoyant support to roofs of cavities or caverns in bedrock, 2) increase in the velocity of movement of ground water, 3) increase in the amplitude of water-level fluctuations, and (4) movement of water from the land surface to openings in underlying bedrock.

Khanlari et al. (2012) [23] described the following respectively natural and man-made sinkhole development triggering factors in the West of Iran as the presence of solution sinkholes and caves in the limestone, the establishment of turbulent groundwater flow in the interface between the above porous soil and the below bedrock during groundwater pumping, which led to washing out the fine materials in the interface into the cavities in the bedrock and small cavities form and expand at the soil-bedrock interface, and finally the roof of the cavity would be under tensile stress and becomes unstable and collapses when the cavity is large enough.

Regarding the sinkhole occurrence in Lac village in the middle rainy season from the 18th July 2017 to the 22nd July 2017, the following factor would be interesting. The year of 2016 is a drought year having total rainfall of 1,770 mm which is only 66% of the following year of 2017 with rainfall of 2,664 mm which is about 1.25 times of the average annual rainfall. Furthermore, there was a significant rainfall event during July and August 2017 during which monthly rainfall were 431 mm and 656 mm, respectively. Heavy rainfall results in large surface runoff and stream flow that are favorable conditions in soil erosion and sand transport in stream and greater subsurface soil suffusion which are triggering sinkhole development. Prasad et al. (2017) [24] pointed out that the area which is dried up due to prolonged drought thanks to over exploitation of groundwater, is subject to subsequently heavy rainfall would have sudden recharge and raise in groundwater level leading to shrinkage of ground along the weak zones such faults or strongly fractured rock. This sinkhole formation factor had been demonstrated by Newton (1986) [13] providing a fact that in Missouri 13 catastrophic sinkholes occurred during a 2-month period in 1973 having precipitation 3 to 6 times higher than normal, in Montgomery County 12 sinkholes during a 3-month period having precipitation greater than average. This factor of sinkhole development was also pointed out by Prasad et al. (2017) [24] in their study of factors controlling the occurrence of sinkholes in Chintakommadinne area, Cuddapah Basin, South India: the heavy rainfall (248 mm) during the month of November 2015 subsequently resulted in flooding which caused sudden large recharge leading to shrinkage of ground along the weak zones controlled by a major fault. Similarly, Maria Elena Martinotti et al. (2017) [25] by rank analysis of hourly rainfall had shown that perturbed meteorological conditions over Italy resulted in torrential precipitation with cumulative rainfall of more than 500 mm in the 6-day period from the 1st to the 6th September 2014, which is the rainfall driven sinkhole factor in Gargano karst area, southern Italy. Heavy rainfall following a severe drought period would cause an active ingress of surface water into subsurface aquifer to lead to subsurface downwards erosion which enlarges the void to substantial size enough for the subsurface roof to collapse to form sinkhole as Jennings et al. (1965) [10] described the mechanism of sinkhole formation.

The initial undisturbed condition without sinkhole development, the dewatering of Na Tum mine leading to vertical water flow and subsurface erosion and the sinkhole occurrence in the study area are illustrated in Figure 15(a), 15(b) and 15(c), respectively.

5. Concluding Remarks
The sinkhole development in the study area is a very dangerous hazard causing a long-term social anxiety and economic damage for local residents, common properties and Na Tum mine company. The number of sinkholes is large and the sinkholes are mostly with diameters of from 4 m to 8 m, which are in the upper range of medium and lower range of large sizes as classified by Buttrick and Van Schalkwyk (1995) [26]. Most of the sinkholes are distributed in farming land. There were two very large sinkholes with diameter is greater than 15 m) one of which occurred right on the provincial important road, ad the other just on a area of rural residential houses. The history of sinkhole development in the study area
does emphasize a high risk of sinkhole development in future since the mine dewatering is undergone and no land and surface water management and preventing engineering measures have been taken since the beginning of the sinkhole formation.

The factors and mechanism of sinkhole development in the study area are diverse which cover almost all factors triggering sinkhole as follows:

**Figure 15.** Sinkhole development scheme in study area.
- Presence of subsurface unconsolidated roof of Quaternary or weathering crust with thickness up to 10 m where sinkholes may be developed;
- The underlying bedrock has fractures in form of joints and fissures formed under tectonic activity and weathering and cavities which serve a compartment for accepting soil material flow from above due to subsurface erosion (suffusion);
- With time the enlargement of the void space under the subsurface unconsolidated roof reaches such sizes that enough for collapse of the above lying soil layer;
- The dewatering of Na Tum mine had caused water level in the bedrock formation decline to several tens meters over a large distance of several thousand meters around the mine, which led to unsaturated bedrock under a unconfined aquifer of Quaternary formation or weathering products through which a free soil erosion occurs under free vertical water flow from the unconfined aquifer;
- Rainfall in the rainy seasons constantly supplies water to the surface streams and unconfined aquifer to maintain subsurface erosion, and heavy rainfall after long severe droughts may lead to an active ingress of surface water to the unconfined aquifer causing more severe subsurface erosion, which may soon after the rainy season started result in sinkhole development;
- The farming activity may at some level accelerate the ingress of surface water into the subsurface aquifer and weaken the strength of the top of the subsurface soil layer to resist the soil collapse.

Future comprehensive detailed engineering geological, hydrogeological and geotechnical engineering investigation is required for sinkhole geotechnical quantitative analysis, based on which both management and engineering measures to prevent the future sinkhole development, to compile sinkhole warning and risk map, to remediation of sinkholes, to carry out the local resident resettlement etc. This is an important part of sustainable social-economical development and environmental protection in term of induced geohazards related to mining activities. From this sinkhole development case study which is directly related to the dewatering of Na Tum mine pit quarry, an important lesson would be drawn that a comprehensive geological, hydrogeological and geotechnical investigation is required to be carried out over a large relevant area surrounding any mine which is subject to dewatering to forecast and predict risk of sinkhole incidence for the area having carbonate and highly fractured formations. This is an important part of sustainable social-economical development and environmental protection in term of induced geohazards related to mineral resources exploitation activities.

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