

Estimation of underground rivers in a tropical karst area by way of a multi-thematic study

by

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Abstract This paper presents results of the estimation of underground rivers connecting the sinkholes and the resurgence of the Nam La blind river in the tropical, highly karstified limestone area of NW Vietnam. In the Nam La catchment, the Nam La River disappears underground in several sinkholes near the outlet of the catchment. A hypothesis is that the Nam La river resurges at a large cavern spring 4.5 km east of the catchment outlet. A multi-thematic study is carried out to prove possible connection between the sinkholes and the resurgence, including geostructural - tectonic analysis, cave structure analysis, hydrograph analyses and tracer experiments. Those underground rivers are used to better understand flooding records of the study area. The maximum water ponding volume in nearby dolines was estimated and shown to play an important role in the flooding mitigation of the catchment outlet area.

Introduction

Karst areas fascinate hydrogeologists because of their beautiful landscape and their complicated hydrological flow systems. Two notions of particular concern regarding karst areas, especially for blind karst valleys, are: (i) the surface and groundwater interact directly through abundant occurrence of sinkholes and shafts; (ii) the surface drainage system is blinded, i.e. water abruptly sinks underground and passes through open conduits called swallow holes or it may infiltrate through a soil mantle to a dendritic karst system. The water flows through the karst systems, i.e. a system of enlarged joints, bedding planes and conduits, before it resurges at a distance from the sinkholes. Karst systems in most cases flush very rapidly; whatever enters the system moves rapidly and completely through the system (Kresic et al., 1992). Depending upon the conveying capacity of the karst system with respect to a particular rainfall event, closed valleys can often suffer from flooding or water stagnancy near a sinkhole area. This phenomenon is the most problematic hydrologic problem in the study area, and hence the understanding of the flow regime, both surface and underground, is required.

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Tracer experiments have been widely used in the practice of karst hydrology to ascertain the connection between sinkhole(s) and resurgence(s), via underground cavern conduits. In the implementation of the tracer methodology, it is often forgotten to interpret a failed test, when a tracer is injected in a sinkhole but it is not recovered in the resurgence. The failure of a tracer test obviously results from many factors, and the test itself does not mean that there is no underground connection between the two points. A proper interpretation can therefore only be given when other integrative studies indicate a similar result. However, in many cases these integrative studies bring useful information, which allows even failed tracer tests to be well interpreted.

The main objective of this study is to contribute scientific evidences to possible underground rivers connecting sinkholes and a resurgence in a closed karstic catchment in NW Vietnam. Independent analyses are made on basis of streamflow hydrograph, cave mappings, geosstructural, and geotectonic data; each yielding an interpretation of possible connections of the points under consideration. The results are then compared to each other to identify the most likely connections, which are finally tested by tracer experiments. A simple water balance calculation is made to reveal that during extensive rainy periods, when the streamflow is very high, the river water is temporarily ponded in nearby dolines.

Hydrogeological setting

The Nam La catchment is located in a high mountain plateau at an elevation of 560 to 1700 m a.s.l and encompasses an area of 460 km². The catchment is characterized by a humid subtropical climate with extensive summer rainfall; the yearly mean temperature is 21.1°C and the mean total yearly precipitation is 1450 mm. The catchment can be lithologically divided into two regions: (i) the northern part (Fig. 1) occupies one third of the catchment area and is characterized by a steep landmass of carbonate limestone rocks, from Carboniferous-Permian to Triassic age and (ii) the southern part consists of less steep non-limestone rocks aged from Proterozoic to Ordovician. Due to the activation of the Chieng Den fault and the Da River fault, the limestone rocks in the North, especially those of Middle Triassic age are relatively subsided with respect to the older non-limestone rocks in the South. The carbonate rocks are highly fractured and karstified. The dissolution cavern conduits create underground passages for the groundwater, while the role of the fractured/fissured limestone media is mainly in storing groundwater. The rocks are regionally dipping in NW and SE direction and form local NW-SE trending anticlines and synclines. Faults develop mainly in NW-SE and NE-SW directions, they act as tectonic boundaries of the geological formations or cross the regional geological structural orientation. Those geological elements facilitate favorable pathways and drive the underground water to discharge or to resurge along the Nam La River course.

The only surface network system is the Nam La River, which drains the entire catchment and disappears underground in several sinkholes near the Cao Pha Pass (Fig. 1). Along the river course there are a number of sinkholes and resurgences through which the surface water and karst groundwater interaction occurs. The sinkholes near the Cao Pha Pass constitute the outlet of the Nam La catchment and are determined by the geotectonic structure (Dinh, 2001). Those sinkholes are grouped by location and by their drainage capacity: Ban Ai, Bom Bay and Cao Pha sinkholes, at respectively an elevation

of 572, 550 and 560 m a.s.l.. The Bom Bay sinkholes are located in a depression at a relatively lower elevation than the Nam La River. The depression turns, during the rainy season, into a ponding lake. Most of the sinkholes have been partly blocked by sediments, rolling stones and straw. Consequently, inundation often occurs after rainstorms in the Nam La River valley upstream of the sinkholes. The largest flooding calamity of the last century was in 1991 when the inundated area extended upstream up to Son La Town, with 600,000 residents, at 7 km distance from the sinkholes. The flooding resulted in a terrible loss of human lives and properties.

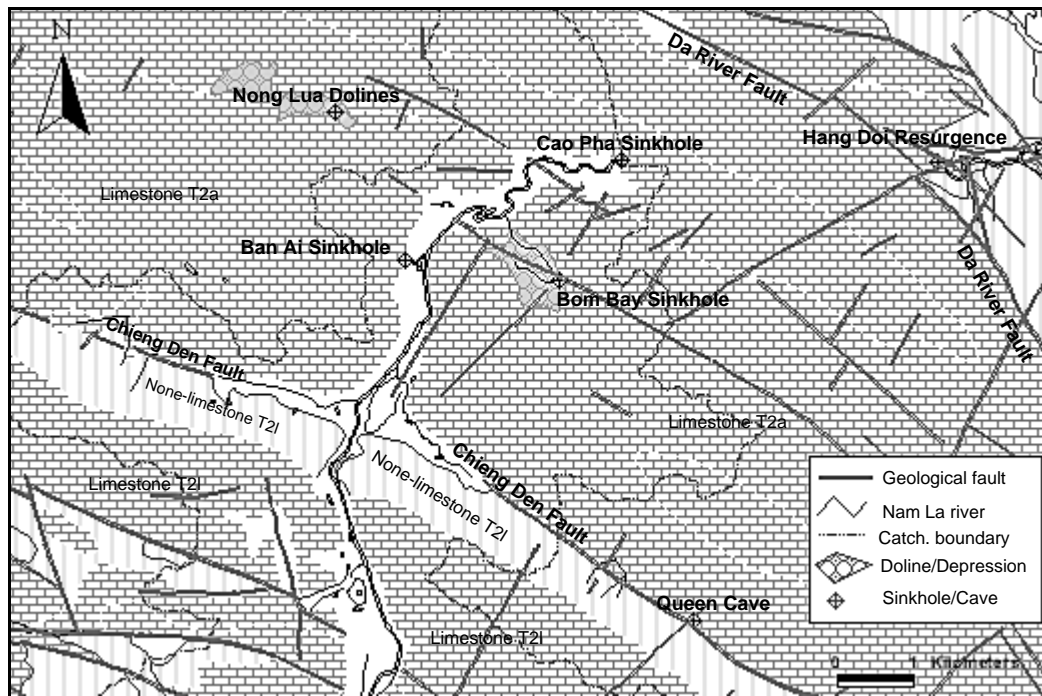


Figure 1. Geological sketch of the Cao Pha Pass area.

A huge spring, the Hang Doi cave, at 136 m a.s.l and located 4.5 km East of the Cao Pha sinkholes, is hypothesized by local residents as the resurgence of the sinkholes (Fig. 2). The only evidence to support this hypothesis is that no other resurgence is found within a radius of 10 km around the sinkholes. So far, there has not been any scientific prove of the hypothesized connection between the sinkholes and the resurgence.

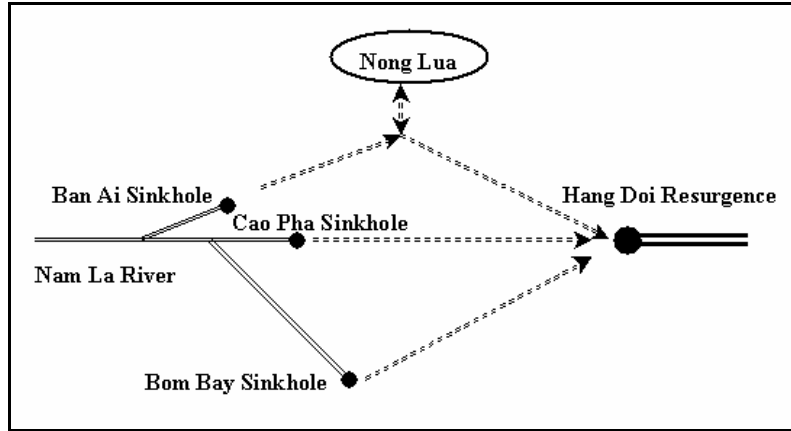


Figure 2. Schematization of the Nam La sinkholes and the resurgence.

Streamflow cross-correlation and cross-spectral analysis

Time series analyses, as developed by Jenkins and Watts (1968) have been applied in hydrology by Yevjevich (1972), Spolia and Chander (1973), Long and Derickson (1999) and others. These works have been oriented essentially towards forecasting, completion of data, and estimation of parameters of stochastic models. Methods for the description and the functioning of karstic aquifers appear in Mangin (1984), Padilla et al. (1995) and Larocque et al. (1998). These works are based on the theory of linear systems and transform an input series into an output series. Hence hydrologic parameters are lumped into the derived impulse response function, which is then used to interpret the functioning of the system under consideration, e.g. system memory, and response time distribution. Commonly the input series of such models is the precipitation while the output series is often the streamflow at catchment outlet. Following here this approach, the total streamflow before the sinkholes is taken as the input series and the discharge of the resurgence as the output series (Fig. 3). They are subject to a cross-correlation and cross-spectral analysis to detect possible connections between the sinkholes and the resurgence.

The cross-correlation analysis, made in this study, is in the time domain. If x_t (x_1, x_2, \dots, x_n) and y_t (y_1, y_2, \dots, y_n) are two discretized chronological series, \bar{x} and \bar{y} the means of the series x_t and y_t , and n the total number of data pairs, then the cross-correlation function is described as:

$$r_{+k} = r_{xy}(k) = \frac{C_{xy}(k)}{\sigma_x \sigma_y} \quad (1)$$

$$r_{-k} = r_{yx}(k) = \frac{C_{yx}(k)}{\sigma_x \sigma_y} \quad (2)$$

Where k is the time lag ranging from 0 to the cutting point m , and

$$C_{xy}(k) = \frac{1}{n} \sum_{t=1}^{n-k} (x_t - \bar{x})(y_{t+k} - \bar{y}) \quad (3)$$

$$C_{yx}(k) = \frac{1}{n} \sum_{t=1}^{n-k} (y_t - \bar{y})(x_{t+k} - \bar{x}) \quad (4)$$

$$\sigma_x = \sqrt{\frac{1}{n} \sum_{t=1}^n (x_t - \bar{x})^2} \quad (5)$$

$$\sigma_y = \sqrt{\frac{1}{n} \sum_{t=1}^n (y_t - \bar{y})^2} \quad (6)$$

Note that the cross-correlation function is not symmetrical [$r_{xy}(k) \neq r_{yx}(k)$], i.e. if $r_{xy}(k) > 0$ for $k > 0$, the input series x_t influences the output series y_t , while if $r_{xy}(k) > 0$ for $k < 0$, the output influences the input. The delay time, defined as the time lag between $k = 0$ and the occurrence of the maximum $r_{xy}(k)$, gives an estimation of the peak impulse response time of the system.

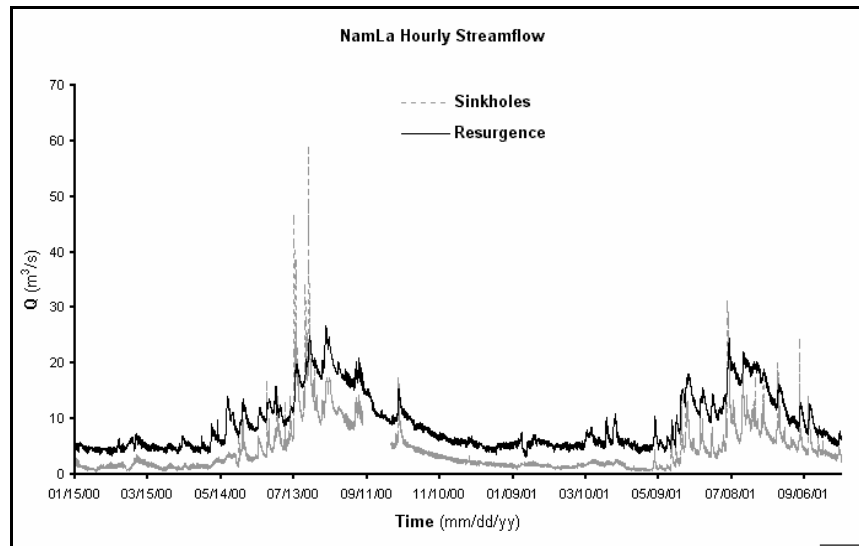


Figure 3. Streamflow hydrographs of the Nam La sinkholes and the resurgence.

The data for the analysis are hourly streamflow hydrographs for the period 1st October 2000 till 8th October 2001, as presented in Fig. 3. Two automatic reading loggers recorded the data, one capturing the total discharge upstream of the sinkholes and the other the discharge of the resurgence. The data series were smoothed by a Tukey filter (Jenkins and Watts, 1968) to overcome bias in the determination of the cross-correlation function. The result of the analysis is shown in Fig. 4.

The resulting cross-correlation function (Fig. 4a) diminishes slowly with increasing time lag and reaches a zero value at a time lag of 69 days, implying that the duration of the impulse response of the system is quite long. It is therefore concluded that the influence on the output of an input event, which enters the system, takes as long as 69 days. The maximum $r_{xy}(k)$ of 0.92 at a time lag of 13.6 h implies that (i) there is a strong correlation between the discharge at sinkholes and the resurgence and (ii) the most visible influence of an input event on the system should be observed after 13.6 h. The only peaked value (for time lag > 0) of the function is likely an indication that no other flow

component significantly influences the system. The influence can also be visualized by a cross-amplitude function as a result of a Fast Fourier Transform (FFT) in the frequency domain. The transformation allows to decompose a complex time series with cyclical components into a few underlying sinusoidal (sine and cosine) functions of particular wavelengths. The low frequency components of the streamflow time series provide an appropriate metaphor for the smoothly changing baseflow, while the high frequency components can be associated with the quickly changing surface runoff. The cross-amplitude function can be interpreted as a measure of covariance between the respective frequency components in the two series. Thus, the spectrum analysis of the in- and output streamflow series can provide information on the functioning of the system. The resulting cross-amplitude function shows that the low frequency (< 0.025) components in the input and output series have a high covariance (Fig. 4b). It is also observed that the value of the cross-amplitude function decreases slowly between the frequencies 0.025 and 0.33, and reaches practically a zero value for frequencies of 0.33 and higher. This indicates that the low-flow components (low frequencies) of the input series have a response in the output series, whilst the rapidly changing flow components (for instance the streamflow peaks during extensive rainy periods) are filtered and attenuated by the underground system. It is therefore hypothesized that the response of the high-flow components during extensive rainy periods could be dampened by the internal storage of the system, or by a surface ponding. Since the input series is the total streamflow of all sinkholes, it is very hard to make conclusions on the connection(s) of the individual sinkhole(s) and the resurgence, but at least one such connection must exist.

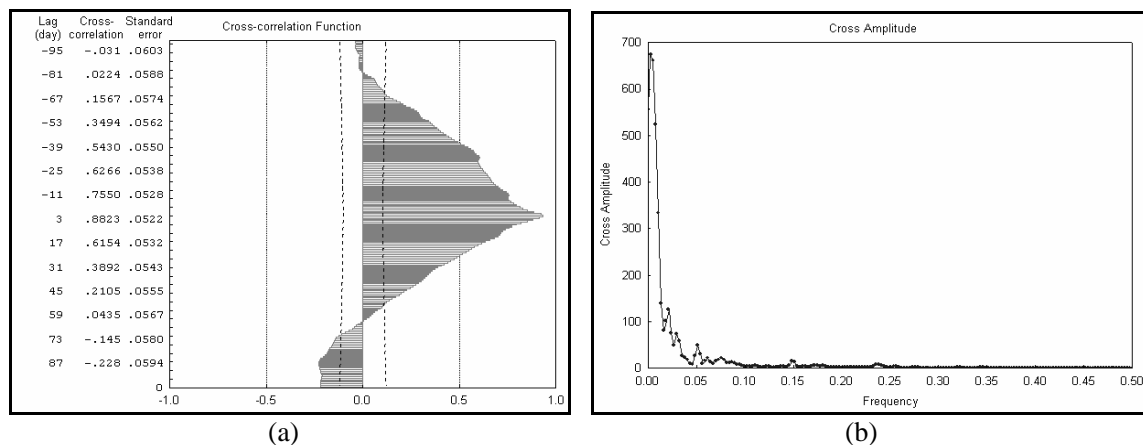


Figure 4. Cross-correlation function (a) and cross-amplitude function (b) of the streamflow of the Nam La sinkholes and the resurgence.

The ponding of streamflow in dolines and depression

A number of discharge monitoring campaigns along the Nam La River were carried out. They showed that approximately half of the river discharge disappears in the Ban Ai sinkhole, one seventh in the Bom Bay sinkholes and one eighth in the Cao Pha sinkholes, the rest is lost in the river section between Ban Ai and Cao Pha. It is noted that the total inflow of all sinkholes is smaller than the outflow of the resurgence, except at some moments of peak discharge, when the inflow exceeds the outflow (Fig. 3). It is also

noticed that the streamflow peaks of the resurgence appear to be constrained to maximum 20 to 25 m³/s. The hypotheses for these observations are that during periods of high discharge the river water could (i) pond in a surface storage, for instance in nearby dolines; (ii) internally be stored in an underground reservoir before resurging at the Hang Doi cave. While both cases are possible, only the first can be tested here with the available data.

Two nearby dolines, situated in the Nong Lua village, approximately 2.5 km NW of the Ban Ai sinkholes (Fig. 1), are found to be 30 m lower in elevation in comparison with the Ban Ai sinkholes. A number of caves are found at the bottom of these dolines, with entrances, which are partly or fully blocked by rocks, soil debris and tree branches. During extensive rainy periods, groundwater emerges above the cave entrance and ponds in the dolines for a few days. The time, when the groundwater starts to emerge in the dolines, is observed to coincide with moments when peak discharges fill the Ban Ai sinkhole. Ponding in the dolines also occurs when the total inflow of the sinkholes is larger than 25 m³/s and exceeds the outflow at the resurgence at the Hang Doi cave. It is therefore concluded that the water ponding in the Nong Lua dolines results from the streamflow, which disappears in the Ban Ai sinkhole. Furthermore, the conveying capacity of the underground river system between Nong Lua and the resurgence seems to be limited to a magnitude of 20 to 25 m³/s. This deduction is also supported by a cave structure study shown later in this paper.

In order to find out how the high flooding level is related to the ponding in the Nong Lua dolines, the difference of the total inflow and outflow, during the period 12 till 15 July 2000 and caused by a total rainfall of 80 mm, is calculated as about 1.4 10⁶ m³. This volume of surplus water was filled in the dolines and the Bom Bay depression. A digital elevation model (DEM), with a spatial resolution of 20m, developed on basis of the topographic map of scale 1:50,000 and using the method described by (Turcotte, 2001), was used as a baseline data for the filling process. The water filling is an iterative process with the constraints: (i) the minimum water depth filled in the Bom Bay depression is 2 m (taking into account the field observation that during high stream discharge periods, this depth of water is ponding in the depression but no groundwater rose in the dolines) and its maximum elevation is 1 m lower than that of the Ban Ai sinkhole (accounting for the estimated streamflow head loss downstream to Bom Bay) and (ii) the maximum elevation of the water column filled in the dolines is 2 m lower than that of the Bom Bay depression (accounting for the estimated minimum head difference between the water column in the depression and that in the dolines). These conditions also warranted that the difference of the stream water level in the Ban Ai sinkhole and the possible highest elevation of the water column filled in the dolines is 3 m, an estimated minimum head loss for water flowing through the underground conduit from the Ban Ai sinkhole to the Nong Lua dolines. The GIS ARC/INFO 8.01 package was used to calculate the water volume ponded in the dolines/depression given an initial trial water column of 2.1 m in the Bom Bay depression. For each subsequent level an increment of 0.1 m of water column was used. The iteration process was continued until a reasonable match with the surplus water volume was obtained. The filling definitively showed that during the period of interest the highest ponding water level is 13 m above the bottom of the Nong Lua dolines, which is approximately equal to the flooding traces left on the rock walls in the doline. The estimated maximum water ponding volume of

A relatively comprehensive study on the cave structure and development in the study area revealed that most of the caves developed in different geological stages, resulting in the multi-step cave profile as seen today (Dinh, 2001). This is illustrated in the typical cave development profile of the Queen cave (Fig. 5a); the two fault systems, one in NW-SE and the other in SW-NE direction, drive the cave development and hence the groundwater follows the same directions. The stepping down (or shaft) segments of the cave resulted from the crossing of the two fault systems. The change of cave development from the NW-SE to SW-NE direction is due to the fact that the SW-NE fault system occurred after the NW-SE system. Such a typical cave development pattern explains why the beginning and end of a cavern conduit can link surface watercourses located at largely different levels, as in the study area.

Because of limited cave expedition data, the connection between the Bom Bay sinkholes and the Hang Doi resurgence, as well as between Ban Ai and Nong Lua, cannot be completely visualized (Fig. 6). However, if the first part of the cave develops in the direction of the resurgence then it is regarded as an indication for a possible existence of a connection. In case of the Nong Lua cave (Fig. 5b), an inflow conduit is located at 463 m a.s.l, 79m below the ground surface, and the main outflow conduit is at 435 m a.s.l, 107 m below the ground surface. The streamflow disappearing in the Ban Ai sinkhole is at 572 m a.s.l, and likely steps down, along an about 2.5 km path, to the Nong Lua inflow conduit. Consequently, it drops down along the cave shaft, at the bottom of the doline, to the main outflow conduit, which is thought to lead to the main resurgence at Hang Doi. The conveying capacity of the Nong Lua main outflow conduit is likely limited to 20 – 25 m³/s, which means that whenever the inflow exceeds this capacity, the groundwater rises in the shaft and emerges above the cave entrance, resulting in the flooding of the Nong Lua dolines.

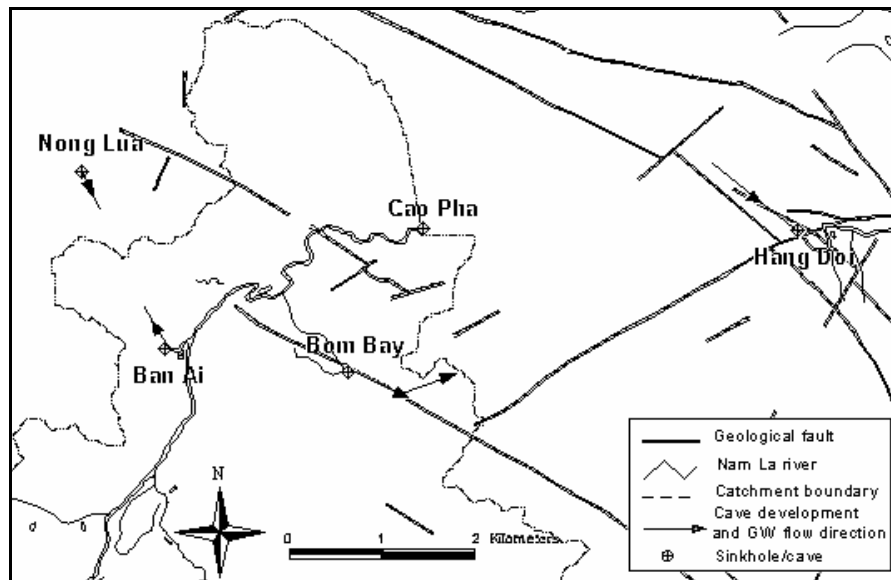


Figure 6. Plan of cave development and groundwater flow direction in Nam La study area.

Finally, a schematization of the underground river system is shown in Fig. 2, with the following assessment:

- The Nam La streamflow follows three major underground rivers: (i) from Ban Ai to Nong La and further to Hang Doi; (ii) from Cao Pha to Hang Doi and (iii) from Bom Bay to Hang Doi; all emerge in Hang Doi resurgence.
- The functioning of these rivers is dependent on the discharge regime. If the Nam La streamflow is less than $25 \text{ m}^3/\text{s}$ the Ban Ai – Nong Lua – Hang Doi underground river is the major drainage path, while the Cao Pha – Hang Doi and the Bom Bay – Hang Doi are in that case of minor importance. However, if the streamflow exceeds $25 \text{ m}^3/\text{s}$ then the latter flow paths become more important.
- The Nong Lua dolines play an important role in temporally storing the Nam La streamflow during extensive rainy periods. It is therefore recommended that the dolines should be under protection.

Verification of the estimated groundwater rivers by tracer experiments

Two tracer experiments were carried out by the end of a rainy season to verify the above described flow paths. The first tracer test was executed with 2 kg of Sulforhodamine B ($\text{C}_{27}\text{H}_{29}\text{N}_2\text{NaO}_7\text{S}_2$) and injected in the Ban Ai sinkhole, the second tracer test was executed half an hour later with 2 kg of Uranine ($\text{C}_{20}\text{H}_{10}\text{Na}_2\text{O}_5$), injected in the Cao Pha sinkhole. For both tracer tests sampling was done during four days at the Hang Doi resurgence. The Quantech Digital Filter Fluorometer FM109510-33 was used to detect the chemicals present in the samples. The earliest detected arrival of the Uranine is 19 hours after the chemical was injected. The concentration of the chemical in the samples is so low that a real break-through curve is hardly detectable, most likely the peak occurred 29 hours after the tracer was injected. For the first tracer test none of the samples detected the Sulforhodamine B tracer. On basis of the cross-correlation and cross-spectral analysis (Fig. 4a and 4b), it is very likely that the underground river system has a huge storage. Therefore, it is assumed that the used volume of tracer was not sufficient to be detected at the resurgence.

Conclusions

Various analyses were done to ascertain the existence of a system of underground river(s) between sinkholes and resurgence. Although a tracer test is one of the tools giving the clearest evidence of a connection between two points of interest, it is not practically applicable in all circumstances. In that case, other methods could be integrated in the study as alternatives to show the existence of the connection. The integrative approach, followed in this study, yielded useful information, which cannot be obtained by the tracer experiments alone. The result of the hydrograph analysis shown in this paper could for instance assist in properly scheduling a tracer test sampling campaign in terms of sampling interval and duration. The study on the geotectonic activities and relationship to the cave development is resulting in a more in-depth interpretation of the tracer test result. The lesson learnt from this work is that a multi-thematic approach is advised in order to obtain a satisfactory interpretation of the hydrological functioning of an underground complex karst river system.

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