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Hydrogeological Characteristics of a Karst Mountainous Catchment in the Northwest of Vietnam

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Abstract This paper presents a preliminary assessment of the hydrogeological characteristics of a karst mountainous catchment, the Suoi Muoi River catchment, in the northwest of Vietnam. The catchment is located at 600 –700 m a.s.l. and covers an area of 284 km. Exposed limestone occupies 32% of the total catchment area. Various types of assessments have been carried out, including geological and hydrogeological field surveys, cave surveys, dye-tracer tests, meteorological and surface water monitoring. Geological studies and cave surveys have identified the most important active cave/conduit systems within the catchment. Although these data are essential, they are insufficient to make a comprehensive appraisal of the hydrologic nature of the catchment under interest. An attempt was made to calculate a global water balance of the catchment, based on short-term (15 months) meteorological and streamflow records. The results show that, despite the existence of a number of substantial cavern conduit systems, the groundwater system of the catchment is governed by the fracture/fissure matrix. The cavern conduit systems only collect groundwater from the adjacent fracture matrix and/or connect topographically isolated surface watercourses. The groundwater storage of the cavern conduit systems appears to be regionally insignificant in comparison with the governed fracture matrix groundwater system.

Key words : karst hydrology, geology, lowflow

1 Introduction

Approximately twenty percent of the landmass of Vietnam is covered by tropical mountainous karst (Tuyet, 1998). Within the Suoi Muoi catchment, approximately 32% of the landmass is occupied by exposed karstified carbonate rocks, which form a landscape characterized by sinkholes, sinking streams, caves and karstic springs. Although various geological, hydrogeological and karst geological studies have been carried out in the area, very few studies have profoundly documented the karst hydrology. None of these studies has so far assessed, at a regional scale, the nature of the groundwater system of the catchment area of interest.

It is often argued that the study of karst hydrology is particularly difficult due to the lack of necessary input data and poorly developed mathematical description/theory of water flow in karst aquifers. The theory and methods developed on the basis of the Representative Elementary Volume (REV) concept are sometimes applied to karst aquifers when baseline data are limited. Under certain assumptions, various hydrological models developed for porous media have been successfully applied in karst areas, thereby rendering insight into the hydrological situation at a regional scale. There is a common conviction that the validity of such models is limited by the great complexity and

discontinuity of the karst medium. The data most commonly available for karst areas are time series records of streamflow discharge and/or spring discharge, because they are relatively cheap and easy to collect. Therefore, most studies about the functioning and hydrodynamics of karst aquifers have been based on analyzing hydrographs (depletion and/or recession; Felton and Currens, 1994; Bonacci, 1988, 1993; Eisenlohr, 1997; Bent, 1999) or on the cross-spectral analysis of time series data of streamflow and rainfall (Labat, 2000; Lacey, 1998; Larocque, 1998; Padilla, 1995).

The overall objective of this study is to identify the functioning and hydrodynamics of the karst aquifers of the Suoi Muoi River catchment based on analyzing the hydrograph of the Suoi Muoi River streamflow. A simple monthly water balance model was subsequently calculated to estimate the storage surplus/deficit of the soil layer and the underlying karst aquifer. The outcomes of the model, together with the results of geological and hydrogeological studies, cave surveys and dye-tracer experiments, yield an initial understanding on the nature of the karst groundwater system of the catchment.

2 Geological and Hydrogeological Setting

The Suoi Muoi River catchment is situated in the mountainous Da River basin, more specifically to the southwest of this river, between eastern longitudes $103^{\circ}35'5''$ and $103^{\circ}51'33''$ and northern latitudes $21^{\circ}20'03''$ and $21^{\circ}33'53''$. The catchment is located at an altitude of 600–1700 m a.s.l. and encompasses approximately 284 km² (in this study, the Suoi Muoi sinkhole was determined as the catchment outlet). The administrative and geographic center of the area is Thuan Chau Town, located northwest of Son La Town. The area 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. About 20% of the catchment area is covered with forest. The surface drainage density is 0.66 km/km².

The catchment is confined by two regional deep fault systems trending in NW-SE direction, the Son La Fault on the east and the Da River Fault on the west. Within the catchment a range of non-limestone and limestone rocks of different ages are exposed (Fig. 1). In the southwestern part the non-limestone rocks consist of Proterozoic-Ordovician quartzite/sericite schists and sandstones intercalated with thin-bedded limestone; the central part is covered by Permian basalts; late Triassic thin-bedded siltstones and shales and Jurassic-Cretaceous medium-thick bedded gravelstones, sandstones and conglomerates crop out in the northeastern part. The limestone rocks, which constitute the main geological object of this study, are confined within the two fault systems as shown in Fig. 1. The rocks are regionally dipping to the southwest.

The most perspective groundwater is located within karstified carbonate rocks outcropping in the area between the two regional deep fault systems. The karst area consists mainly of two sub-areas: the central part is composed of karst water bearing carbonate rocks of Early Permian-Carboniferous and Middle Devonian ages, the eastern part is of Middle Triassic age. The limestone rocks are cut by southeast-northwest and northeast-southwest trending faults. Many different tectonic phases and neotectonic movements have affected these rocks. The activation of the Son La Fault system has resulted in a relative subsidence of the right-side block. The neotectonic movements have led to the formation of mainly peak forest landscapes in the limestone, with residual karst peaks and towers, which emerge here and there above the dissolution-erosion valleys. Here, the groundwater occurs at great depth and the land is dry.

The movement of karst groundwater is closely controlled by these tectonic deformations. The groundwater is mainly stored in fractures, crushed zones and caves and circulates in consistence with

the hydrodynamic variation.

Between the central and eastern sub-areas exist many karst springs at the lithologic contact between the extremely karstified Triassic, the highly karstified Early Permian-Carboniferous and the semi-impervious, non-karstic formations of different ages. Karst springs also exist along the surface watercourses and at the western limit of the central sub-area near the lithologic contact between the highly karstified limestone and the semi-impervious, non-karstic rocks. Most of the karst springs are permanently active, only a few of them stop flowing during the dry season.

The Suoi Muoi River system is the main surface drainage system in the Thuan Chau area, which is underlain in great part by the above-said limestone units. A narrow area of clayey Quaternary alluvium is present along the Suoi Muoi River and its tributaries. Along the river course there exist a number of karst springs/resurgences and sinkholes, which interact with the karst groundwater aquifers.

The karst aquifers receive water, mainly by the regional groundwater flow, with additional important in-situ recharge by rainfall, surface water and exotic water from higher-lying non-karstic areas. Discharge of the groundwater takes place in the river valleys and depressions. A comprehensive discussion of the geology, including tectonic history and stratigraphy of the region, is provided by Tuyet (1998).

3 Hydrogeological Studies and Tracer Experiments

Three karstic groundwater units were identified within the catchment territory: the Middle Devonian formation, the Early Permian-Carboniferous formation and the Middle Triassic formation, all being medium–highly karstified limestone rocks. These karstic groundwater units were hypothetically defined on the basis of the geological stratification and fracture/karstification degree of the outcropping rocks. The non-limestone formations are much less permeable than the limestone formations (Xuyen, 1998; Hop, 1996). No strong evidence exists to argue whether the groundwater units are indeed hydrologically dissimilar. The study of the results of the seven existing pumping tests (Xuyen, 1998) could not help to validate the delineation of these units since the boreholes were limited to a depth of around 100 m, which is much shallower than the presumed 400–1000 m thickness of the limestone formations and is also shallower than the local karstification depth (Tuyet, 1998). A detailed study of the lineament scheme developed from satellite images (the result is not shown here) and of the geo-structural map of the area showed that the fractured and crushed zones prolong in two main directions, namely NW-SE and NE-SW. A very rough estimation, based on the density of estimated fractures at regional scale, of the groundwater conductivity is 100 times higher in the NW-SE direction in comparison with the NE-SW direction.

A river discharge monitoring survey carried out during the dry season has shown that the total discharge of the Suoi Muoi River tributaries located in the non-limestone area west of the Son La Fault contribute only 7%–10% of the total river discharge measured at the catchment outlet. Their discharge contribution can rise up to 25% of the total river discharge during storms. It is believed that this increase is mainly due to surface runoff, which is much more generated by the steeper terrain (altitude changing from 1700 m to 800 m) of the non-limestone rocks in comparison with the more flatten terrain (altitude changing from 800 m to 600 m) of the limestone rocks.

Since 1993 a number of caving-expeditions have been carried out, primarily focusing on active cavern conduits existing in the study area. It was found that the development of the cavern conduits mainly coincides with the development direction of geological faults and fractured zones (November, 1999). The cavern conduits range from a few hundred metres to a few kilometres in length. Their starting point is in most cases the end of a surface watercourse in a blind valley or in a depression.

Their endpoint is generally a resurgence located at an elevation more or less equal to that of the surface watercourses where the karst groundwater discharges. A tracer experiment was carried out in the largest cavern conduit (approximate length of 2.5 km) between the Suoi Muoi River sinkhole and resurgence. Uranine was used as tracer dye, the tracer-breakthrough curve is shown in Fig. 2. Analysis of this curve using the software QTRACER showed that the mean tracer transit time is around 28 hours and that the estimated karst conduit volume is 43,000 m³ (Vu, 2000). Another tracer experiment was carried out in a cave conduit with an approximate length of 2 km, located in the southeastern part of the catchment. The mean tracer transit time was 10.4 hours and the estimated conduit volume was 13,796 m³. Based on these results it is believed that the storage of the cavern conduits is regionally insignificant. The conduits play only the role of conveyers between surface water bodies or of galleries collecting karst groundwater from the adjacent fracture/fissure media.

Much of the sinkholes and dolines are covered with a layer of Quaternary alluvium, consisting of clay, sand and gravel. The soil thickness is up to 17 m near the Suoi Muoi sinkhole and gradually diminishes along the Suoi Muoi watercourse and its tributaries. In a borehole very close to the Suoi Muoi sinkhole, no groundwater was found at the depth of 17 m. In another borehole about 3 km upstream of the sinkhole, groundwater was found at the same level as the river water and as the groundwater level observed in a nearby cavern conduit. A number of karst springs/sinkholes can be found along the Suoi Muoi River course. They play the role of interaction between karst groundwater and surface water. The interaction can be direct or indirect through the soil cover layer. In dolines and closed karst valleys the soil thickness can be up to 3–5 m, below which a blind system of shaft/open fracture exists and therefore the surface water find the way to percolate deeper to the groundwater system.

4 Hydrograph Analysis

Hydrograph analysis has proven to be a useful technique in a variety of water-resources investigations. Quantitative analysis of streamflow recession is of considerable importance to many aspects of water resource management such as water allocation, irrigation, flow requirements for aquatic ecosystems, hydroelectricity generation, wastewater disposal and dilution of contaminant discharges. Separation of streamflow hydrographs into base-flow and surface-runoff components is used to estimate the groundwater contribution to streamflow. Hydrograph-separation techniques also have been used to quantify the groundwater component of hydrologic budgets and to aid in the estimation of recharge rates. In addition, base-flow characteristics determined by separation of hydrographs from streams draining different geologic areas have been used to show the effect of geology on base flow (Lacey, 1998; Bent, 1999).

Three USGS computer programs (RECESS, PART and HYSEP) were used in this study to analyze the streamflow record of the Suoi Muoi River. The river streamflow hydrograph, covering a period of 15 months, was constructed on the basis of the data recorded by an automatic waterlevel logger (pressure-transducer type) installed at the outlet of the catchment, i.e. the Suoi Muoi River sinkhole. A rating curve of the form $Q = a(h + b)^c$, with Q being the river discharge and h the river waterlevel, was constructed to convert the recorded waterlevel to discharge. The original data were recorded on a 10-minute basis, but they were averaged and converted to a daily basis in the hydrograph analysis.

The RECESS program (Rutledge, 1998) was used to determine the streamflow master recession curve (MRC) during times when all flow can be considered to be groundwater discharge. The program uses a repetitive interactive procedure for selecting several periods of continuous recession. Consequently it determines a best-fit equation for the rate of recession as a function of the logarithm

of flow. Finally the coefficients of this equation are used to derive the MRC, which is an equation of time as a function of the logarithm of flow. The program thus allows for the *possibility of nonlinearity* in the relation between time and the logarithm of flow. In the application to the streamflow of the Suoi Muoi River, only recession periods of at least 6 continuous recession days in rainless wintertime were selected for the determination of the MRC.

The PART program (Rutledge, 1998) was used to estimate a daily record of baseflow under the streamflow record. The program scans the record for days that fit a requirement of antecedent recession, designates baseflow to be equal to streamflow on these days, then linearly interpolates the daily record of baseflow for days that do not fit the requirement of antecedent recession. The program was applied to a long period of the Suoi Muoi River streamflow record to give an estimate of the mean rate of groundwater discharge. The calculated result was compared against the one simulated by the HYSEP program (Eaton, 1996), which operates on the principle of systematically drawing connecting lines between the low points of the streamflow hydrograph. With the streamflow data of the Suoi Muoi River catchment, the computed groundwater discharge by the two programs shows a small discrepancy (3%).

Results of the hydrograph analysis are shown in Fig. 3 and Table 1. It is calculated that the baseflow index (i.e., the ratio of groundwater discharge volume over total streamflow volume) of the Suoi Muoi catchment is 0.86. This high value of the baseflow index shows that a major portion of the streamflow of the Suoi Muoi River comes from the groundwater. According to literature, the baseflow index is a good indicator of the effects of geology on lowflows (Smakhtin, 2001) and can give an indication of the percentage of carbonate bedrock area (Bent, 1999). The high baseflow index is often associated with high primary porosity – deep permeable soils or highly fractured bedrocks (Lacey, 1998). Analysis of an hourly basis hydrograph (data not shown here) shows that the surface runoff generated by a storm terminates within 32 hours after the end of the event. The short life of the surface runoff is assumed to be due to extreme differentiation of the terrain and the heavy deforestation of the catchment. The recession index, interpreted in literature as a *representative of the residence time or the turnover time* of the groundwater (Wittenberg, 1999), is for the Suoi Muoi River catchment 55.4 days. Compared with the common values of 10–140 days found for other catchments (Nathan, 1990), the Suoi Muoi groundwater system is considerable.

An analysis of the auto-correlation of the time series streamflow record and the cross-correlation of the streamflow and rainfall was made with the catchment data (Fig. 4). One can apparently see the existence of two distinguished storages in the cross-correlation function (Fig. 4a) of the Suoi Muoi catchment: the first sharp peak at time lag $T_{lag} = 1$ day representing the quick flow storage (which could be of surface runoff or highly transmissive conduit system or both) and a series of top-flat peaks at a much longer time lag representing the slower depletion storage, the baseflow. Time response to rainfall of the Suoi Muoi streamflow is quite long, about 100 days. The quick response to rainfall at the Suoi Muoi sinkhole is 1 day. One can consider the time to centroids of the quick flow component (first peak) and baseflow component (series of topflat peaks) as the mean resident time of these components; for the Suoi Muoi catchment $T_q = 1$ day and $T_b = 50$ days, where T_q and T_b are mean resident time of quick flow and baseflow, respectively. The series of top-flat peaks of the cross-correlation function were explained by the notable periodic components occurring in the input rainfall time series. The long residence time of the groundwater, together with the high baseflow index value, suggest that the karst groundwater system of the Suoi Muoi catchment is governed by the fracture and fissure media.

5 Global Water Balance of the Catchment

Quantitative assessment of the catchment water balance can provide useful information about the seasonal variation of different hydrological fluxes. A simple monthly based water balance model for the catchment was therefore built. It accounts for rainfall input, evapotranspiration, groundwater recharge, groundwater discharge and surface runoff components. In this model, the catchment was considered as a lumped and spatially homogeneous hydrological entity with two layers. The lower layer represents the karstic groundwater aquifers and the upper represents the topsoil layer and/or the epikarst zone. The water balance for the model is described by the following equations:

– Equations for the epikarst zone:

$$\Delta S = S_{t+1} - S_t = I_{t+1} - ET_{t+1} - GWR_{t+1} - SR_{t+1} \quad (1)$$

– Equation for the karst aquifers:

$$\Delta GW = GW_{t+1} - GW_t = GWR_{t+1} - BF_{t+1} \quad (2)$$

where ΔS and ΔGW are monthly soil storage deficit and groundwater storage deficit, respectively; S_{t+1} , S_t , GW_{t+1} and GW_t are respectively monthly soil storage and groundwater storage; I_{t+1} , ET_{t+1} , GWR_{t+1} , SR_{t+1} and BF_{t+1} are respectively monthly rainfall, evapotranspiration, groundwater recharge, surface runoff and groundwater discharge; t is time.

The parameter values, necessary to calculate the monthly storage deficit, were derived from the above-described hydrograph analysis i.e. the surface runoff and groundwater discharge. The monthly groundwater recharge value was calculated by the USGS computer program RORA (Rutledge, 1998), under the assumption that the groundwater recharge areally diffuse. The evapotranspiration was determined using a reference crop evapotranspiration measured at a nearby hydrometeorological station. Result of the water balance calculation is shown in Fig. 5 and Table 1.

Table 1 Global water balance of the Suoi Muoi catchment

Month	I (mm)	ET (mm)	GWR (mm)	BF (mm)	SR (mm)	ΔS (mm)	ΔGW (mm)
Jan. 2000	1.20	71.50	6.60	12.68	0.28	-77.18	-6.07
Feb. 2000	86.30	79.40	10.54	15.16	1.80	-5.44	-4.62
Mar. 2000	21.10	100.80	28.02	16.96	2.49	-110.21	11.06
Apr. 2000	71.10	112.40	13.92	15.58	1.22	-56.44	-1.66
May 2000	287.08	71.80	50.47	23.57	11.61	153.20	26.90
Jun. 2000	167.82	60.30	60.17	48.18	13.97	33.38	11.99
Jul. 2000	248.65	64.30	185.24	115.10	28.10	-28.99	70.14
Aug. 2000	226.13	61.80	67.61	108.23	16.54	80.18	-40.62
Sep. 2000	36.30	62.40	60.58	62.45	7.08	-93.76	-1.87
Oct. 2000	105.59	56.20	78.89	59.28	10.13	-39.63	19.62
Nov. 2000	1.80	69.10	51.64	47.60	0.92	-119.86	4.04
Dec. 2000	7.50	68.30	46.63	40.22	0.95	-108.38	6.41
Jan. 2001	18.30	81.00	33.68	34.79	1.54	-97.92	-1.11
Feb. 2001	1.80	74.40	27.41	29.12	1.18	-101.19	-1.72
Mar. 2001	128.96	86.60	26.80	31.83	4.84	10.73	-5.04

During the period of January 2000–March 2001, the groundwater system received a surplus storage (deficit = 87.45 mm). This is evidenced by the higher groundwater discharge at the end of dry season of the year 2001 in comparison with the one of the preceding year (Fig. 3). In contrary, the topsoil layer received a negative deficit of storage (-561.5 mm). This could be explained by the fact that the total rainfall volume of the year 2000 is about 250 mm less than a normal year, the rainy season

started earlier and the rainfall was more intensive. Another possible explanation, which could not be tested here, is that the years before 2000 were relatively dry. Clear is that the epikarst zone plays the important role of buffering and transferring rainwater to the groundwater system. During rain events, the zone stores infiltrated rainwater and later replenishes the groundwater in dry season, which starts from September till April.

6 Conclusion

A multi-thematic analysis was carried out to identify hydrogeological characteristics of the Suoi Moi Catchment. The study showed that the karst groundwater aquifers are determined by fractured/fissured media whilst the cavern conduits, although abundant occurring in the region, act as groundwater galleries and/or conveyers. At regional scale, such a conclusion is very important with respect to later applications of the hydrological models, which have been developed on the basis of the REV concept. A simple model to estimate the catchment global water balance was developed to estimate seasonal change of the hydrological components in the catchment. It is believed that with a longer data record the model can explain better the functioning and hydrodynamics of the karst aquifers under interest.

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References

- Bent, G.C., 1999. Streamflow, baseflow, and groundwater recharge in the Housatonic River Basin, Western Massachusetts and parts of Eastern New York and Northwestern Connecticut. U.S. Geological Survey, Water-Resources Investigation Report 98-4232, 70.
- Bonacci, O., 1988. Determination of the catchment areas in karst. *IAHS Publication No.176*: 606-611.
- Bonacci, O., 1993. Karst springs hydrographs as indicators of karst aquifers. *Hydrol. Sci*, 38: 51–62.
- Eaton, G.P., 1996. Hysep: a computer program for streamflow hydrograph separation and analysis. U.S. Geological Survey, Water-Resources Investigation Report 96-4040, 46.
- Eisenlohr, L., 1997. Numerical simulation as tool for checking the interpretation of karst spring hydrographs. *J. Hydrol.*, 193: 306–315.
- Felton, G. K., Currens, J.C., 1994. Peak flow rate and recession-curve characteristics of a karst spring in the Inner Bluegrass, central Kentucky. *J. Hydrol.*, 162: 99–118.
- Hop, N.D., 1996. Report on Geological Mapping scaled 1:50000, Thuan Chau Area. Research Institute of Geology and Mineral Resources of Vietnam, Hanoi (in Vietnamese), 178.
- Labat, M., Ababou, R. and Mangin, A., 2000. Rainfall-runoff relations for karstic springs. Part I: convolution and spectral analyses. *J. Hydrol.*, 238: 123–148.
- Lacey, G.C., Grayson, R.B., 1998. Relating baseflow to catchment properties in south-eastern Australia. *J. Hydrol.*, 204: 231–250.
- Larocque, M., Mangin, A., Razack, M., and Banton, O., 1998. Contribution of correlation and spectral analyses to the regional study of a large karst aquifer (Charente, France). *J. Hydrol.*, 205: 217–231.

- Nathan, R.J., and McMahon, T.A., 1990. Evaluation of Automated Techniques for Baseflow and Recession Analyses. *Water Resour. Res.*, 26(7): 1465–1473.
- November, J., 1999. Karstgeologisch onderzoek in het gebied van Son La en Thuan Chau (NW-Vietnam). KULeuven, dissertation (unpubl.) (in Flemish), 135.
- Padilla, A., 1995. Study of hydrographs of karstic aquifers by means of correlation and cross-spectral analysis. *J. Hydrol.*, 168: 73–89.
- Rutledge, A.T., 1998. Computer programs for describing the recession of groundwater discharge and for estimating mean groundwater recharge and discharge from streamflow records – update. U.S. Geological Survey, Water-Resources Investigation Report 98-4148, 43.
- Smakhtin, V.U., 2001. Low flow hydrology: a review. *J. Hydrol.*, 240: 147–186.
- Tuyet, D., 1998. Overview on Karst of Vietnam. In: Yuan Daoxian (ed.), *Global Karst Correlation*, Final Report of International Geological Correlation Program. Beijing: Science Press, 179–191.
- Tuyet, D., 1998. Karst geology investigation of the Northwest region. Research Institute of Geology and Mineral Resources, Hanoi, 250.
- Xuyen, C.X., 1998. Report on Hydrogeological Mapping scaled 1:200000, Dien Bien Yen Bai Area. Geological Survey of Vietnam, 202.
- Wittenberg, H., 1999. Baseflow recession and recharge as nonlinear storage processes. *Hydrol. Process.*, 13: 715–726.
- Vu, T.M.N., 2000. Design of Karst Web-based Database and Hydrological Analysis for Thuan Chau – Son La Catchment, VN. Master dissertation, Free University Brussels, 88.

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Figures:

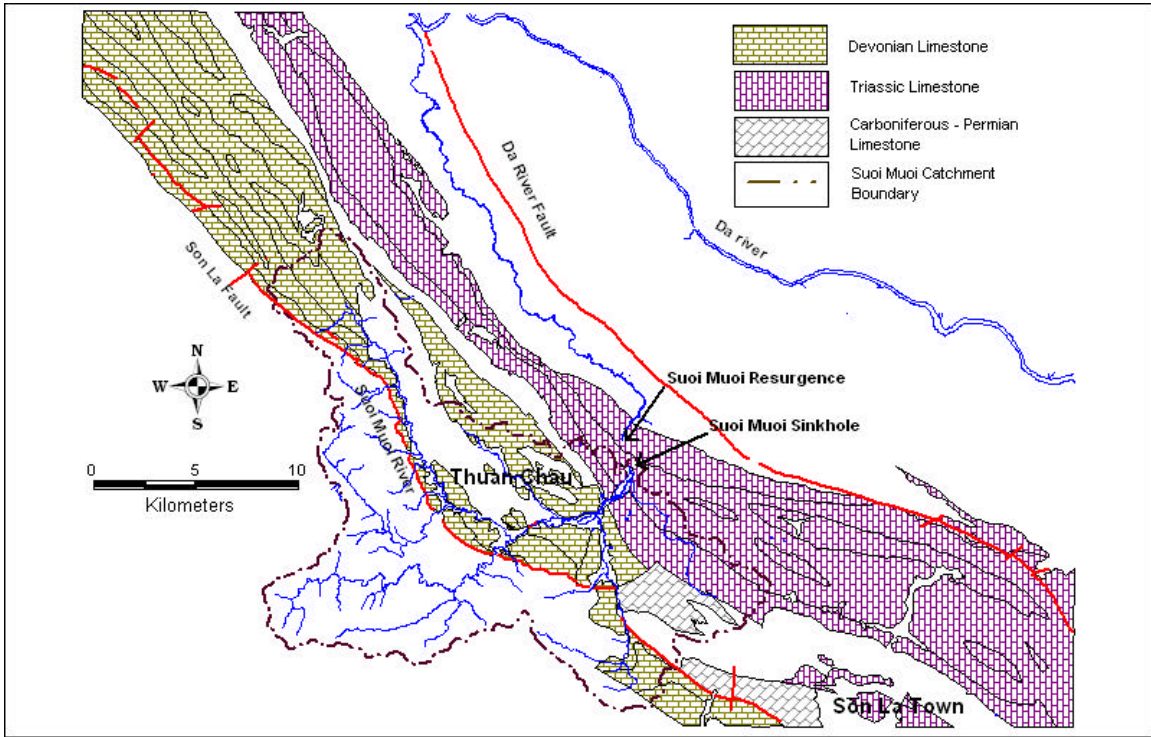


Fig 1: Geological map of Suoi Muoi Catchment

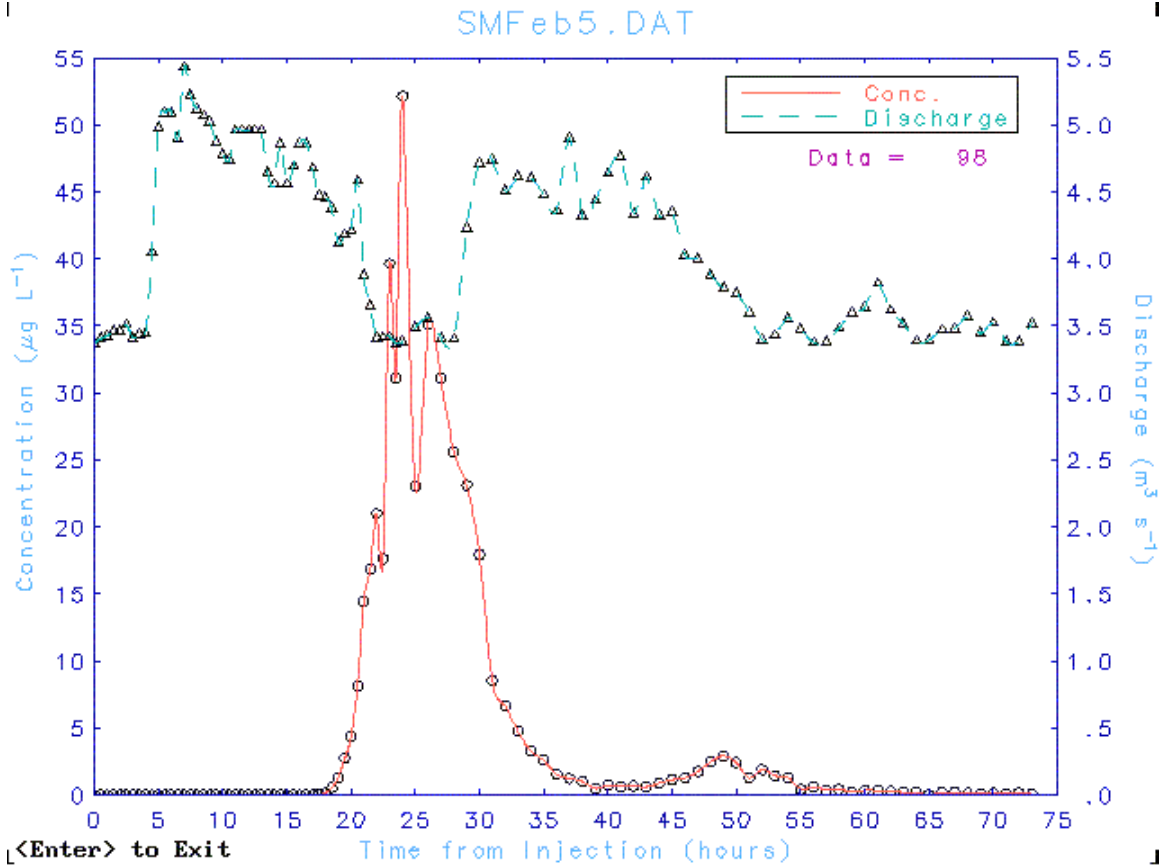


Fig 2: Tracer breakthrough curve of uranine at the Suoi Muoi River resurgence

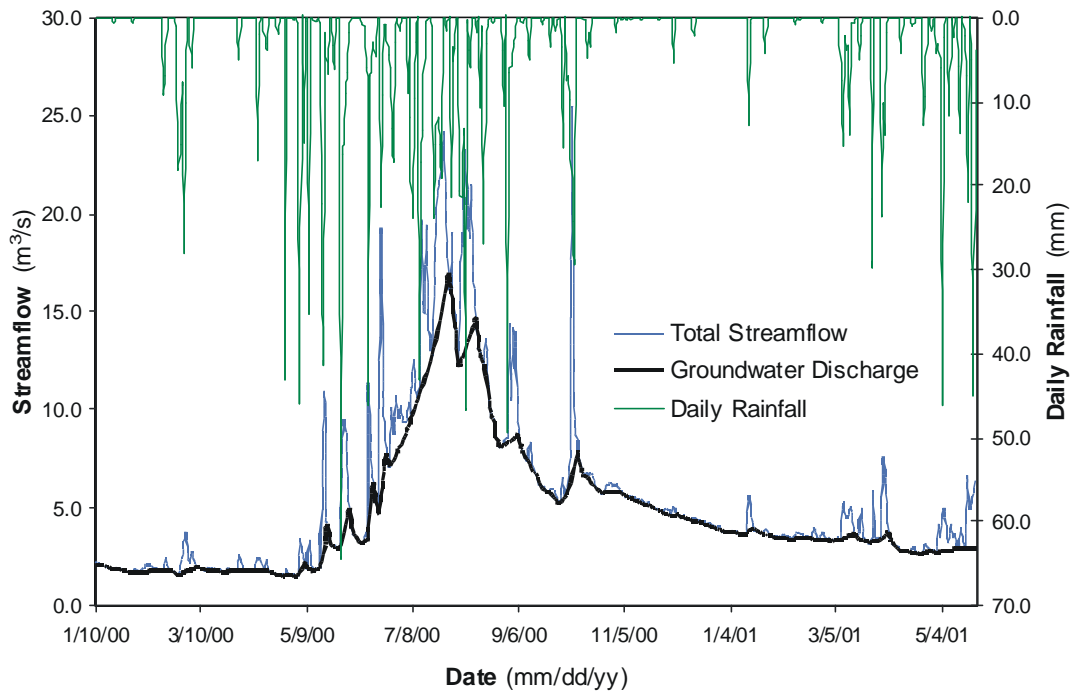


Fig 3: Total streamflow and groundwater discharge calculated by the PART program

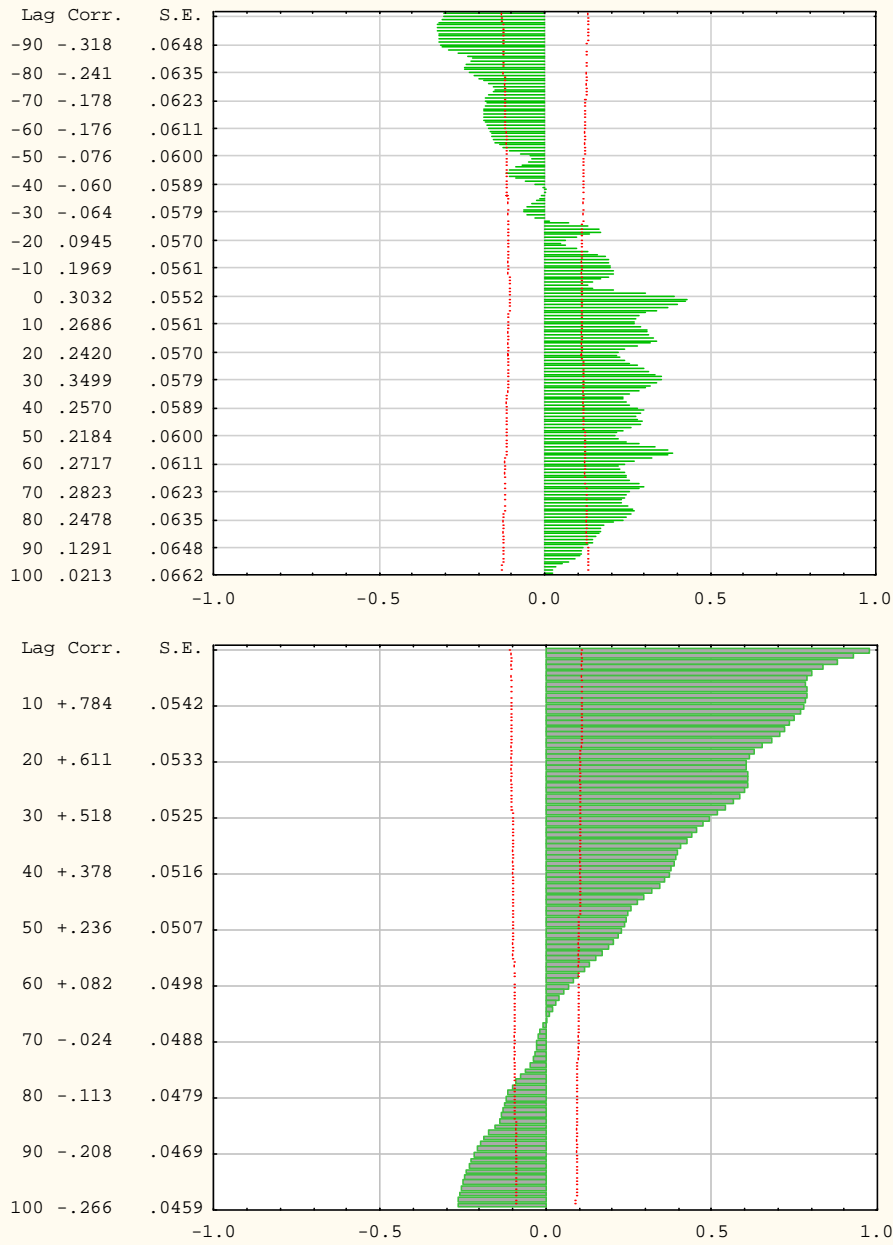


Fig 4: Cross-correlation function analysis of the Suoi Muoi sinkhole (upper) and autocorrelation function analysis of the Suoi Muoi sinkhole streamflow (lower) of the Suoi Muoi River

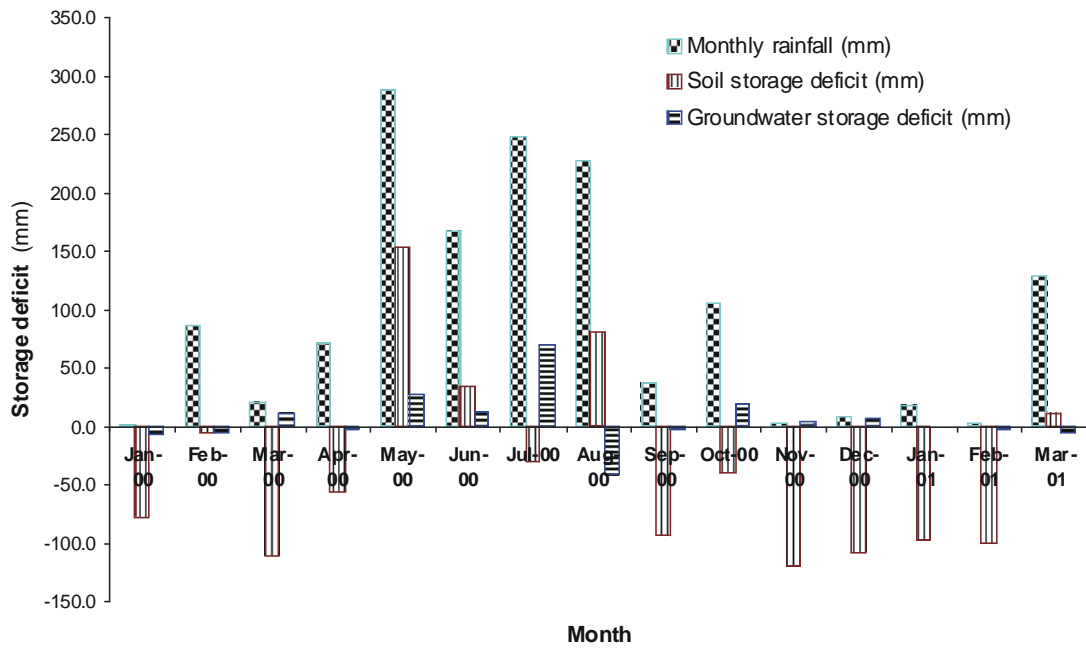


Fig 5: Monthly soil storage and groundwater storage deficit