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# EFFECT OF A STRONG RAINSTORM ON THE HYDRODYNAMICS OF THE PUERTO PRINCESA UNDERGROUND RIVER (PALAWAN, PHILIPPINES)

# UČINEK MOČNEGA NALIVA NA HIDRODINAMIKO PODZEMSKE REKE PUERTO PRINCESE (PALAWAN, FILIPINI)

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**Abstract** UDC 551.444.3:532.5(599.18

***Chiara Calligaris, José Maria Calaforra, Franco Cucchi, Paolo Forti & Luca Zini: Effect of s strong rainstorm on the hydrodynamics of the Puerto Princesa underground river (Palawan, Philippines)***

Fascinating and fragile environments as are the underground estuaries, need to be studied, understood and protected for present and future generations. Even if wide and abundant bibliography related to tides and their behaviour with respect to the external estuaries is available, none dealed with the estuary caves and the related hydrogeology. This paper aims to partially fill this gap presenting a preliminary study done at the Puerto Princesa Underground River (PPUR), in the Palawan Island (Philippines). The data was collected during the last expedition (November 2016) organised by La Venta, in which some of the authors took part. During the survey, the cave has been instrumented with in continuous diver data-logger devices (CTD) recording temperature (T), electrical conductivity (EC) and water level fluctuations. Longitudinal and vertical water hydrogeological profiles of the cave were realised with the aim of understanding the dynamics of the waters during different hydrogeological regimes in combination with salt water intrusion. In addition, a bathymetric profile was done to better identify the point where to realise the vertical logs. A significant rainstorm occurred during the expedition, lasting for approximately 12 hours resulting in 80 mm of rain, and its effects gave the re-

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***Chiara Calligaris, José Maria Calaforra, Franco Cucchi, Paolo Forti & Luca Zini: Učinek močnega naliva na hidrodinamiko podzemske reke Puerto princese (Palawan, Filipini)***

Očarljivo in občutljivo okolje, kot so podzemni estuariji, je treba preučevati, razumeti in zaščititi za sedanje in prihodnje generacije. Četudi imamo na voljo široko in bogato bibliografijo o plimovanju in delovanju plimovanja v zunanjih estuarijih, nobeno delo ne obravnava estuarskih jam in s tem povezane hidrogeologije. Namen tega članka je delno zapolniti to vrzel in predstaviti predhodno študijo na podzemni reki Puerto Princesa (PPUR) na otoku Palawan (Filipini). Podatki so bili zbrani med zadnjo ekspedicijo (novembra 2016), ki jo je organizirala La Venta, v kateri so sodelovali tudi nekateri avtorji. V raziskavi je bila jama opremljena z zveznimi merilci (CTD) temperature (T), električne prevodnosti (EC) in nihanja nivojev vode. Vzdolžni in navpični hidrogeološki vodni profili jame so bili izmerjeni, da bi razumeli dinamiko voda med različnimi hidrogeološkimi nivoji in med vdori morske vode. Poleg tega je bil opravljen tudi batimetrični profil, da bi lažje določili, kje izvesti navpične meritve. Med ekspedicijo se je zgodil močan naliv, ki je trajal približno 12 ur, padlo je 80 mm dežja, njegov učinek pa je raziskovalcem omogočil analizo hidrodinamike tekočih voda med poplavo. V običajnih vodostajih so vzdolžne meritve pokazale na dotoke sveže vode, vertikalne meritve pa so pokazale

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searchers the opportunity to analyse the hydrodynamics of the flowing waters during a flood. In normal flow conditions, the longitudinal logs highlighted the presence of freshwater inlets and the vertical logs testified to a clear stratification of the waters (freshwaters at the surface and brackish waters at the bottom). During floods, the EC and T data showed evidence of a fast substitution of the resident waters.

**Key words**: anchialine caves, sea water intrusion, hydrodynamics, karst springs, PPUR, Philippines.

jasno stratifikacijo lastnosti vode (sveža voda na površini in brakična voda na dnu). Med poplavami so podatki EC in T potrdili hitro zamenjavo vode.

**Ključne besede:** anhialine jame, vdor morske vode, hidrodinamika, kraški izviri, PPUR, Filipini.

## INTRODUCTION

Underground estuaries represent fascinating and fragile environments to be primarily understood and later protected for present and future generations. An abundant bibliography (herein citing only a short summary) is available on tides and their behaviour in the external estuaries (Dronkers & van Leussen 1988; van Rijn 2010; Dermissis 1993; Fleury *et al.* 2007; Kwokal *et al.* 2014; Lace & Mylroie 2011), but nothing is available for the estuary caves (anchialine) from the hydrogeological viewpoint. A significant number of papers focuses on the biological aspects of these particular environments where groundwater ecologists are involved (Humphreys 2009). As per Humphreys (2009), these coastal areas also offer new opportunities to develop cross-disciplinary work between hydrogeologists and groundwater ecologists. The fluxes are complex and usually require interdisciplinary efforts in order to be properly understood, as also stated by Araujo and Asp (2013).

This paper could begin to fill the void of knowledge regarding hydrogeological connections between freshwaters and brackish waters in an underground cave estuary.

This study was made possible thanks to a joint project between the Tagbalay Foundation (Philippines) and La Venta (Italy), granted by the Philippines-Italy Debt for Development Swap Program (De Vivo *et al.* 2017). The 2016 project started with the aim of completing the exploration and studies on the PPUR. During this expedition, several hydrogeological surveys were realised (3 longitudinal logs and 8 vertical logs) and 3 data-logger devices were installed at various points in the cave in order to better understand the hydrodynamics of the area analysing Temperature (T), Electrical Conductivity (EC) and water level. The focus of this paper is the preliminary hydro-dynamic results obtained from the observations performed on the data recorded during this expedition.

## STUDY AREA

The Puerto Princesa Underground River (PPUR) is one of the largest caves in the Philippines and it is the most visited show cave, with over 300,000 visitors/year (Badino *et al.* 2018). It is found in the Puerto Princesa Subterranean River National Park (PPUR NP) known for its spectacular karst landscape applied to have this site registered as a Natural World heritage site (Restificar *et al.* 2006). The cave is inhabited by huge colonies of swallows and bats, and the related underground ecosystem is one of the richest in the world. In 2004 the importance of the cave was recognised by the National Committee on Geological Sciences and it was declared a National Geologic Monument (Restificar 2004).

The underground section of the Cabuyagan River is responsible for the formation and enlargement of this through-cave, to which some small tributaries bring the waters which infiltrate at different elevations on the Mt. Saint Paul karst massif, a limestone ridge slightly higher than 1000 m a.s.l. in the Palawan Island.

The La Venta Italian association has carried out several expeditions in the area over the last 25 years so that the PPUR karst system reached a total development of over 32 km (Fig. 1). From the swallow hole (Daylight) to the South China Sea (Outflow), a gallery of about 8 km, SW-NE oriented, flushes the freshwaters to the sea. Approximately 2.5 km from the entrance (Daylight) a sump (Rockpile) is present (Fig. 1). From this point to the Outflow, the cave is navigable and the last 2 km were transformed into a show-cave accessible by boat.

Some of the scientific results and data have already been published (Forti *et al.* 1993a; Piccini & Rossi 1994;

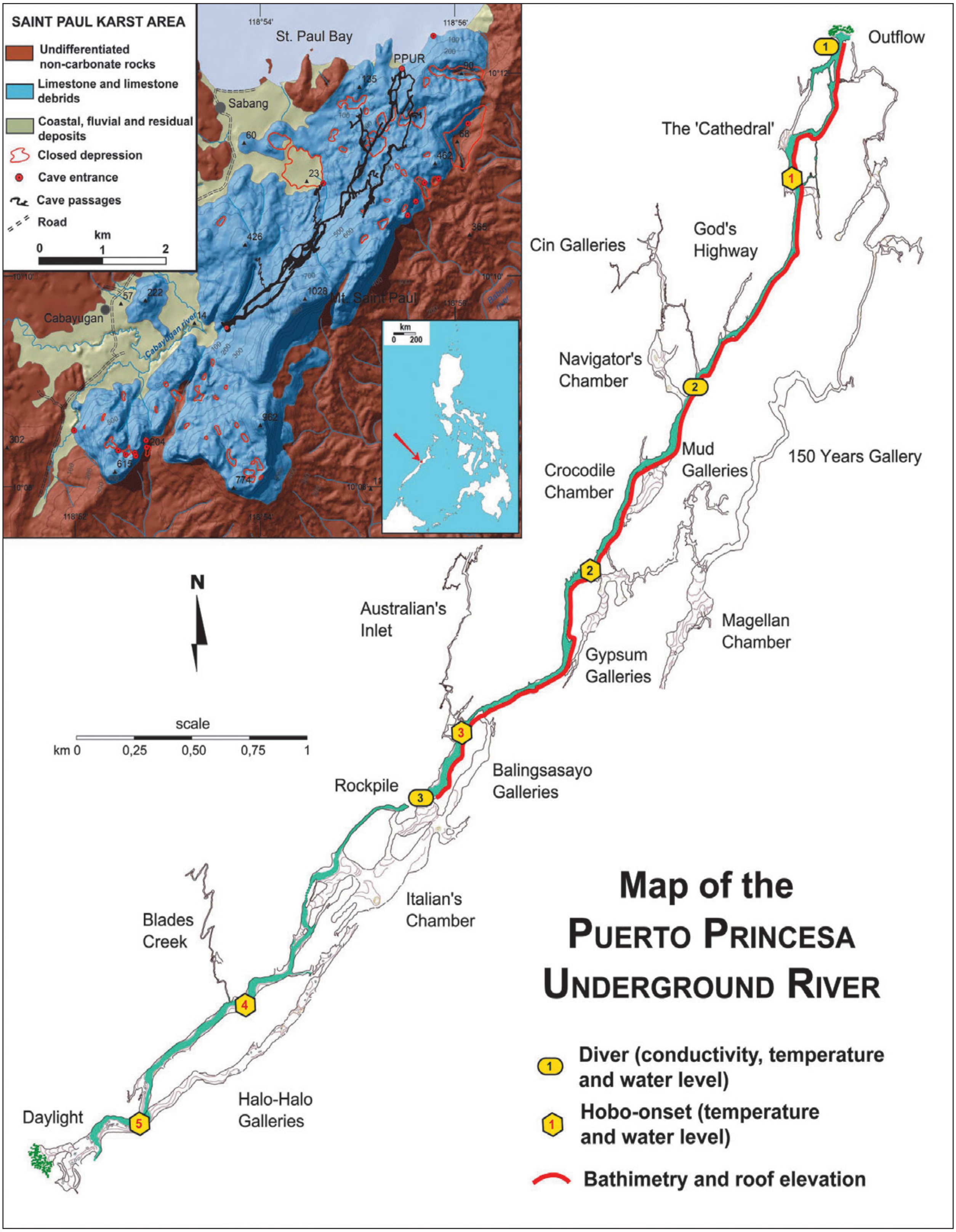

*Fig. 1: Index map, geological sketch (modified after Piccini & Iandelli 2011), present day extension of the PPUR with location of the instruments installed during the 2016 expedition (modified after De Vivo et al. 2013). The river path is seen in blue. All other cave paths are at higher elevations.*

De Vivo 2007; Piccini 2007; Piccini *et al.* 2007; Sbordoni 2007; De Vivo *et al.* 2009; Forti *et al.* 2011; Piccini & Iandelli 2011; Forti & Galli 2012; Badino 2013; De Vivo & Piccini 2013; De Vivo *et al.* 2013; De Vivo & Forti 2014a; De Vivo & Forti 2014b; Coombes *et al.* 2015; Badino *et al.* 2018; Forti *et al.* 2017).

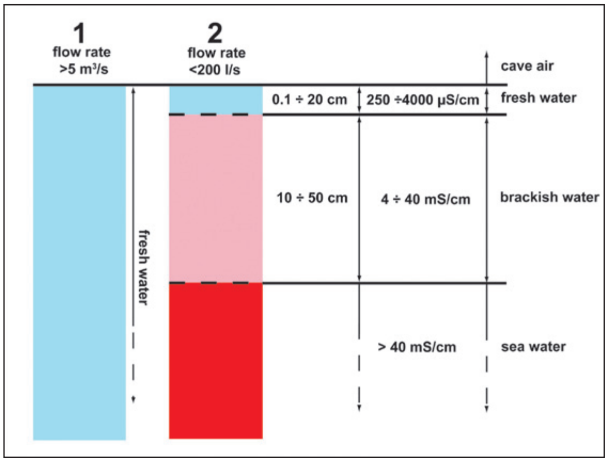

*Fig. 2: Behaviour of the water flow in the first 5.5 km of the cave in two extreme scenarios: (1) during floods, or when flow rates exceed 5.0 m³/s (occurred during the May 2000 expedition) only fresh water is present; (2) during dry periods, with fresh water supply not exceeding 0.2 m³/s (corresponding to that which occurred during the first expedition in February 1991), three water layers are present with different saline content (after Forti 2014).*

Palawan is located on the Intertropical Convergence Zone and therefore its average temperature is relatively high (~27 °C) with daily, monthly, and yearly temperature excursion rarely exceeding ±5 °C. The average year rainfall is close to 2000 mm, 95 % of which falls during the wet (monsoon) season (from May to November) with frequent heavy rainstorms.

During the dry season, the discharge is approximately 0.2 - 0.5 $m^3/s$, while during floods, it can increase up to 10 $m^3/s$ in few hours.

The study of the hydrodynamics of the underground river has been the aim of the scientific research started by Piccini and Rossi (1994) since the inception of the project and this has continued during all subsequent expeditions (De Vivo *et al.* 2013; Forti 2014) but 2016 was the first time during which the cave has been instrumented. Observations made over the proceeding 20 years allowed researches to pinpoint two distinct scenarios. When the discharge is higher than 5.0 $m^3/s$ (Forti 2014), the only water present inside the cave is fresh water (Fig. 2). Forti (2014) indicated that during high flow conditions, the tides act as a barrier and their effects occur exactly at the same time at the entrance and 5.5 km within the cave, but the entire flow is always directed toward the outflow.

On the opposite side, with a discharge below 0.2 $m^3/s$, the first 5.5 km of the cave, during the high tides, are characterised by the presence of the sea water which invades the gallery up to the sump with more than 100,000 $m^3$. In these conditions, the presence of three distinct water layers can be identified: an upper fresh water surface layer, an intermediate brackish, and a lower layer with sea water (Fig. 2). The three water layers do not mix completely and move rather independently with a laminar flow under the tide influence. The turbulence is present only at the interface between the layers. The water propagation inside the cave is induced by back and forth movements of the water masses (Fig. 3), so the flow direction of a single or of all the three water layers reverts 4 times a day (Forti *et al.* 1993b). In these conditions, the run-off time is very high: the fresh water emerging at the Rockpile sump takes over 15–20 hours to reach the Outflow (Forti 2015).

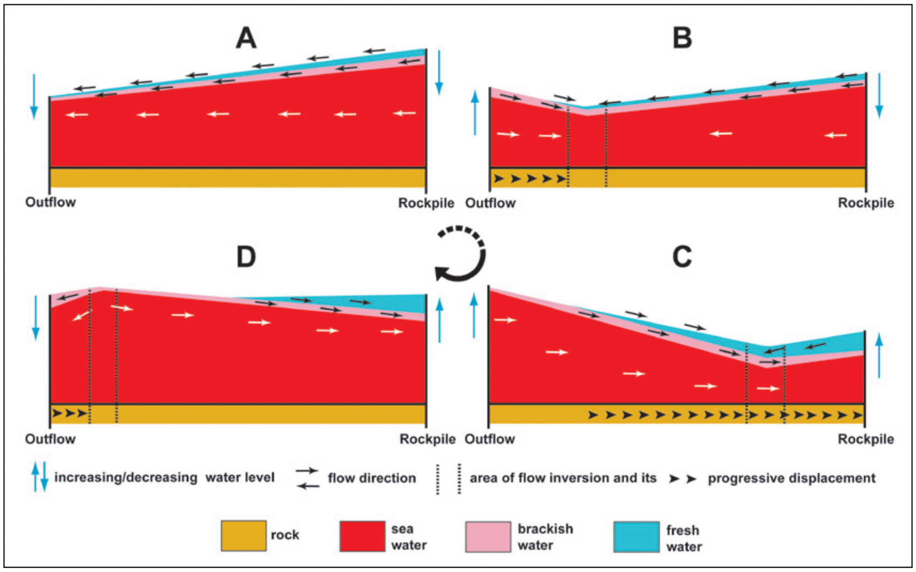

*Fig. 3: Tide induced variations in the flow directions of the three water layers existing within PPUR during extremely dry periods (less than 200 l/s of fresh water). A: period from top of high tide at Rockpile to top of low tide at the Outflow; B: period from top of low tide at Outflow to top of low tide at Rockpile; C: period from top of low tide at Rockpile to top of high tide at Outflow; D: from top of high tide at Outflow to top of high tide at Rockpile.*

## METHODS

During the 2016 expedition part of the field activities were devoted to improve the knowledge of the hydrodynamics of the PPUR. Three data-loggers CTD-Diver Eijekelkamp (pressure range 10 m, accuracy +/- 0.5 cm, resolution 0.2 cm; T range -20 °C to +80 °C, accuracy +/- 0.1 °C, resolution 0.01 °C; EC range 0 to 120 mS/cm, accuracy +/- 1%, resolution +/- 0.1%) were installed between Outflow and Rockpile (Fig. 1). The instruments record the water temperature (T), electrical conductivity (EC) of the water and the water level fluctuations. The compensation of the atmospheric pressure variability is ensured by a Baro-Diver from Eijekelkamp (pressure range 150 cm, accuracy +/- 0.5 cm, resolution 0.1 cm) installed close to CTD-Diver 1. All instruments had a recording range interval of 15 minutes. CTD3 was installed at Rockpile at an average depth of 1.24 m, CTD2 was installed at Navigator's at 2.04 m, while CTD1 was installed at the Outflow at 2.29 m.

Three T and EC longitudinal logs (on November 24, 26 and 27, Fig. 4 and Fig. 5) were recorded from Outflow to Rockpile by means of another CTD-Diver. The instrument placed 20–30 cm below the water surface had an acquisition frequency of 10 seconds (roughly corresponding to 5–10 m in length). The logs were completed dragging the data-logger behind the boat which travelled at a constant velocity. These logs represent a useful methodology (Beddows *et al.* 2007; Smith *et al.* 2008; Bonzi *et al.* 2010; Parra *et al.* 2015) to study the variations of T and EC in detail along the river course, identifying the freshwater inlets due to lateral tributaries or dripping events caused by intense rainfalls.

In order to better identify the best physical locations where to realise the vertical logs, a bathymetric profile between Outflow and Rockpile was done. The profile was performed using a H22PX- HawkEye Handheld Sonar System (4 impulses per second, operation interval between 1 and 61 m with a resolution of 10 cm).

The data-logger device used for the longitudinal logs was also used to obtain eight vertical logs at the lagoon, in correspondence with the Outflow (in and out), at the Cathedral, at Navigator and at Rockpile. These investigations took place on November 24 and on November 27 in order to understand the variations of the T and EC with depth.

## RESULTS

### LONGITUDINAL LOGS

Several dry days preceded the first T and EC longitudinal log acquired between noon and 3 p.m. on November 24 (Fig. 4). The observed pattern can be considered related to the "equilibrium state" with respect to the flow rate (over 1 $m^3/s$) of the underground river in that period.

One day after the acquisition of this log (on November 25) a strong rainstorm occurred in the PPUR area (on the coast area it rained between 3 and 5 p.m. to midnight, in the rest of the watershed, it had already started to rain that morning), causing a flood inside the cave, as evidenced by the muddy water outflowing at the Outflow on the morning of November 26 (Fig. 11). Seeing that a pluviometer was installed only on the last day of the expedition, no other rainfall data were available for that period. The local people estimate there was a rainfall of 80 mm.

The second log was taken after the end of the rainstorm (late morning of November 26). The water in the lagoon in front of the Outflow was muddy and the flow rate was still higher than that of November 24.

The third and last longitudinal log was made 48 hours later, on November 27. The water in the lagoon was quite clean but the flow rate was still high.

The longitudinal T log of November 24 demonstrates a quite constant behaviour, especially in the section between the Outflow and the Navigator. Further, inside the cave the fluctuations are in the range of 0.4 °C. The longitudinal log of November 26 has an overall pattern much more constant but cooler than the other two logs. Approximately 0.1 °C of variation in temperature, not considering the zone of fast decrease and fluctuation where the 1 °C temperature drop is clearly caused by the storm water, which was cooler than that of the Cabayugan River sinking at the Daylight.

By the 27th, there is a sudden increase in temperature, which remains lower than that of the 24th, but higher than the 26th, bearing witness to a fast recovery of the pre-storm conditions.

The longitudinal EC log acquired on November 24 is subdivided into three sectors (Fig. 5). Conductivity rapidly decreases from the Outflow to close to the Cathedral (from 1000 to 470 µS/cm), then it remains relatively stable up to Navigator's Chamber (470-450 µS/cm). A

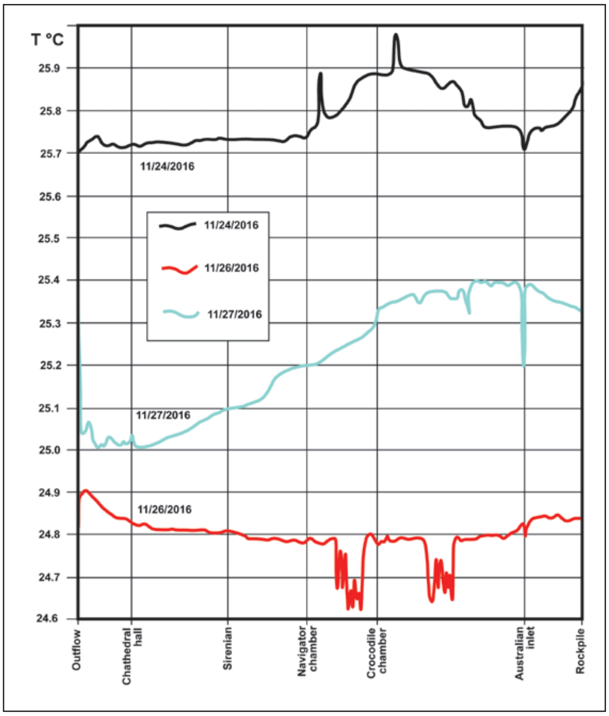

*Fig. 4: Water temperature longitudinal log in the PPUR acquired from Outflow to Rockpile on November 24 (black line), before the storm event, November 26 (red line) one day after the storm event, November 27 (blue line) two days after the storm event.*

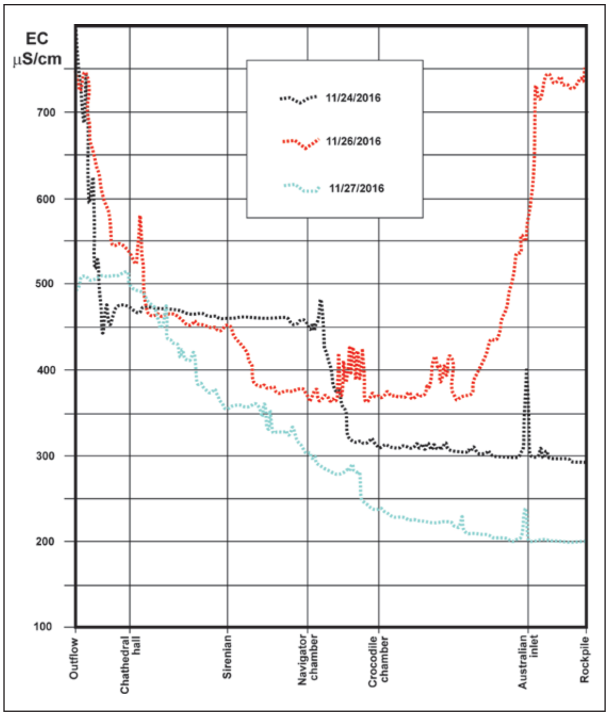

*Fig. 5: Conductivity longitudinal log in the PPUR acquired from Outflow to Rockpile on November 24 (black line), before the storm event, November 26 (red line) the day after the storm event, November 27 (blue line) two days after the storm event.*

sudden conductivity increase is in evidence two hundred meters beyond this point (480 µS/cm). Immediately after conductivity undergoes a steep short decrease (from 450 to 310 µS/cm) after which its value maintains a relatively stable rate (just a smooth progressive decrease) up the Rockpile sump (290 µS/cm): in this last sector a sharp increase in conductivity (up to 400 µS/cm) is recorded in correspondence to the junction with the Australian branch.

The log recorded on the 26th has different steps compared to that of the 24th, and it is interesting to note that there is a sharp EC increase up to 700 µS/cm between Crocodile chamber and the Australian inlet.

The log recorded on the 27th maintains lower values than the other two logs and the curve is more uniform with less spikes.

## BATHYMETRIC PROFILE

In order to better identify the best physical location where to realise the vertical logs, a bathymetric profile between Outflow and Rockpile was done. The obtained profile was compared to that acquired in 2011 with a rope-bathymeter during a previous expedition (Forti 2014). The observed differences between the two surveys (Fig. 6: the red line showing the 2016 results and the black line related to 2011) are slight and in most cases

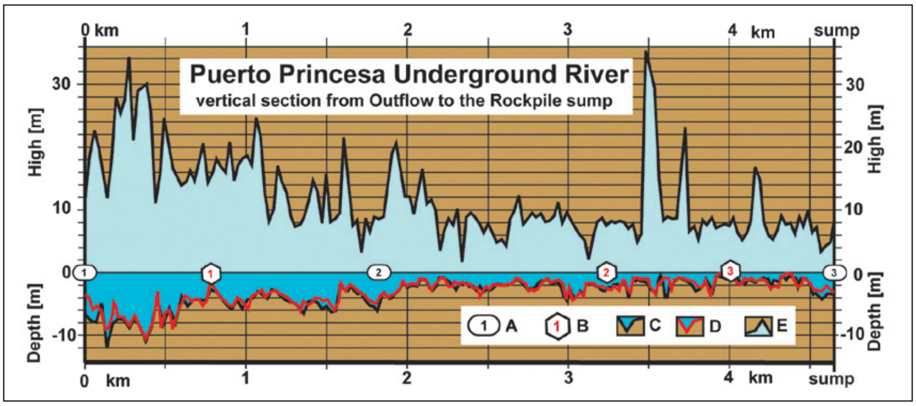

*Fig. 6: The vertical section of PPUR from Outflow (0 km) to Rockpile (sump). A: CTD-Diver location; B: Hobo-Onset location; C (black line): 2011 bathymetry (measurements each 25–30 m); D (red line): 2016 bathymetry (measurements each 30–35 m); E (black line): 2016 roof elevation (measurements each 35-40 m).*

similar to the expected value between low and high tide (on average less than one metre). The few larger differences may refer to different places where the acquisition was made. From Rockpile to Navigator's Chamber (about 2.5 km) the depth of the river does not exceed 4 m; from Navigator's to the Outflow (the last 2 km), there is a deepening of the river-bed up to 10–12 m.

## VERTICAL LOGS

On the way to the cave on November 24, the first vertical log was acquired close to the CTD1 near the Outflow (Fig. 1, Fig. 7A; Fig 10, Outflow in) at the beginning of the increasing tide. The log showed a sudden increase of temperature (from 25.76 to 27.53 °C) and conductivity (from 488 μS/cm to 33 mS/cm) in between 175 and 220 cm below the surface (Fig. 7A), marking the sharp transition between the upper level of fresh water and the lower of brackish one.

Approximately three hours later, close to high tide and on the way out from the cave, a second vertical log was made in the same place (Fig. 7B; Fig. 10, Outflow out). The measured EC was higher (from 2 to over 35 mS/cm) and the transition between fresh and brackish water occurred between 50-70 cm and was progressive, while the increase in temperature was nearly doubled (from 25.75 to 29.01 °C).

The same day, another vertical log (Fig. 8) was made upstream from Cathedral (Fig. 8) about half an hour before that represented in Fig. 7B, so that the tide situation was similar. In this case, the temperature variation was extremely scarce (from 25.64 to 25.66 °C) while the conductivity increase was less than 0.2 mS/cm (from 1.06 to 1.24 mS/cm).

On the same day, all the other vertical logs recorded deeper inside the cave found only fresh water with a very slight variation in temperature and conductivity with depth (Tab. 1 and Fig. 10).

Vertical logs made after the flood demonstrated a strong decrease in temperature and conductivity, their variation with depth becomes close to the sensitivity of the instrument during the 27th and therefore no graphs are reported.

Finally, on November 27 a vertical log was made in the external lagoon (Fig. 9, Fig. 10), which demonstrated that only the water coming out from PPUR was feeding the lagoon; its conductivity is essentially the same measured inside the Outflow (Fig. 7A), while the observed temperature trend is coherent with solar heating.

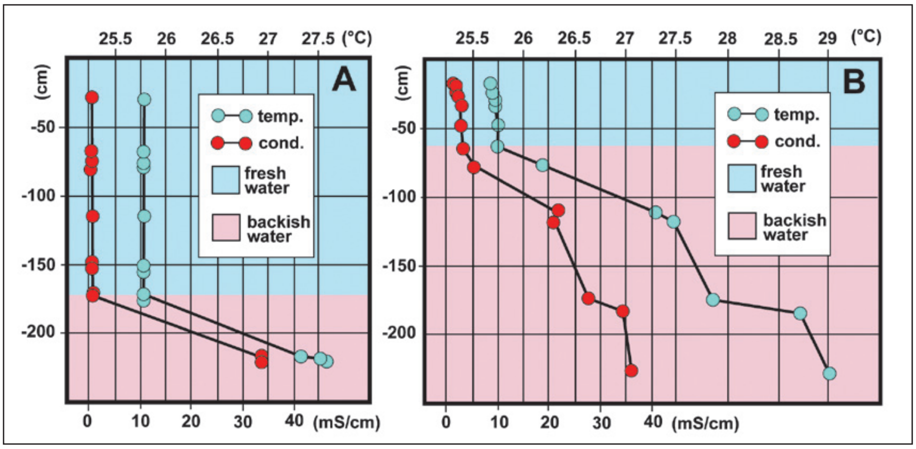

*Fig. 7: Vertical logs for water T and EC made close to the Outflow on November, 24. 7A: log made from 2.27 to 2.30 p.m.; 7B: log made at the same point but in the afternoon, from 5.14 to 5.19 p.m.*

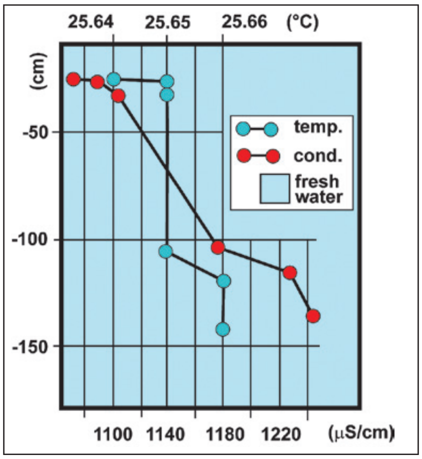

*Fig. 8: Vertical logs for T and EC made a few tens of meters upstream from Cathedral on November 24, 2016: log made at 4.46 to 4.47 p.m.*

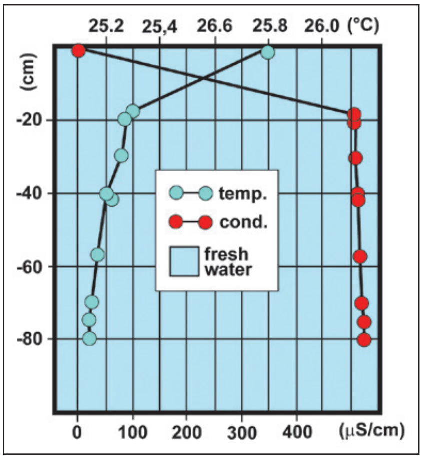

*Fig. 9: Vertical logs for temperature and conductivity made in the external lagoon on November 27, 2016, from 3.27 to 3.30 p.m.*

*Tab. 1: EC and T ranges of the vertical logs performed on November 24 and 27.*

| site | distance from entrance [m] | Air temp. [°C] | EC range [mS/cm] | T range [°C] | log depth [cm] | time |
|---|---|---|---|---|---|---|
| **2016/11/24** | | | | | | |
| Outflow in | 80 | 26.72 | **0.29 – 0.56** | **25.72 – 25.76** | 213 | 2:27 p.m. |
| Navigator's | 1800 | 26.62 | **0.30 – 0.31** | **25.89 – 25.95** | 369 | 2:50 p.m. |
| Rockpile | 4500 | 26.07 | **0.29 – 0.30** | **25.75 – 25.76** | 213 | 3:15 p.m. |
| upstream Cathedral | 580 | 25.75 | **1.06 – 1.24** | **25.64 – 25.66** | 139 | 4:46 p.m. |
| Outflow out | 80 | 25.85 | **4.67 – 36.13** | **25. 89 – 29.02** | 235 | 5:15 p.m. |
| **2016/11/27** | | | | | | |
| Rockpile | 4500 | 25.82 | **0.19 – 0.20** | **25.31 – 25.32** | 116 | 1:15 p.m. |
| Cathedral | 550 | 25.64 | **0.38 – 0.43** | **25.14 – 25.27** | 446 | 2:50 p.m. |
| Lagoon | -10 | 25.46 | **0.50 – 0.52** | **25.11 – 25.56** | 80 | 3:30 p.m. |

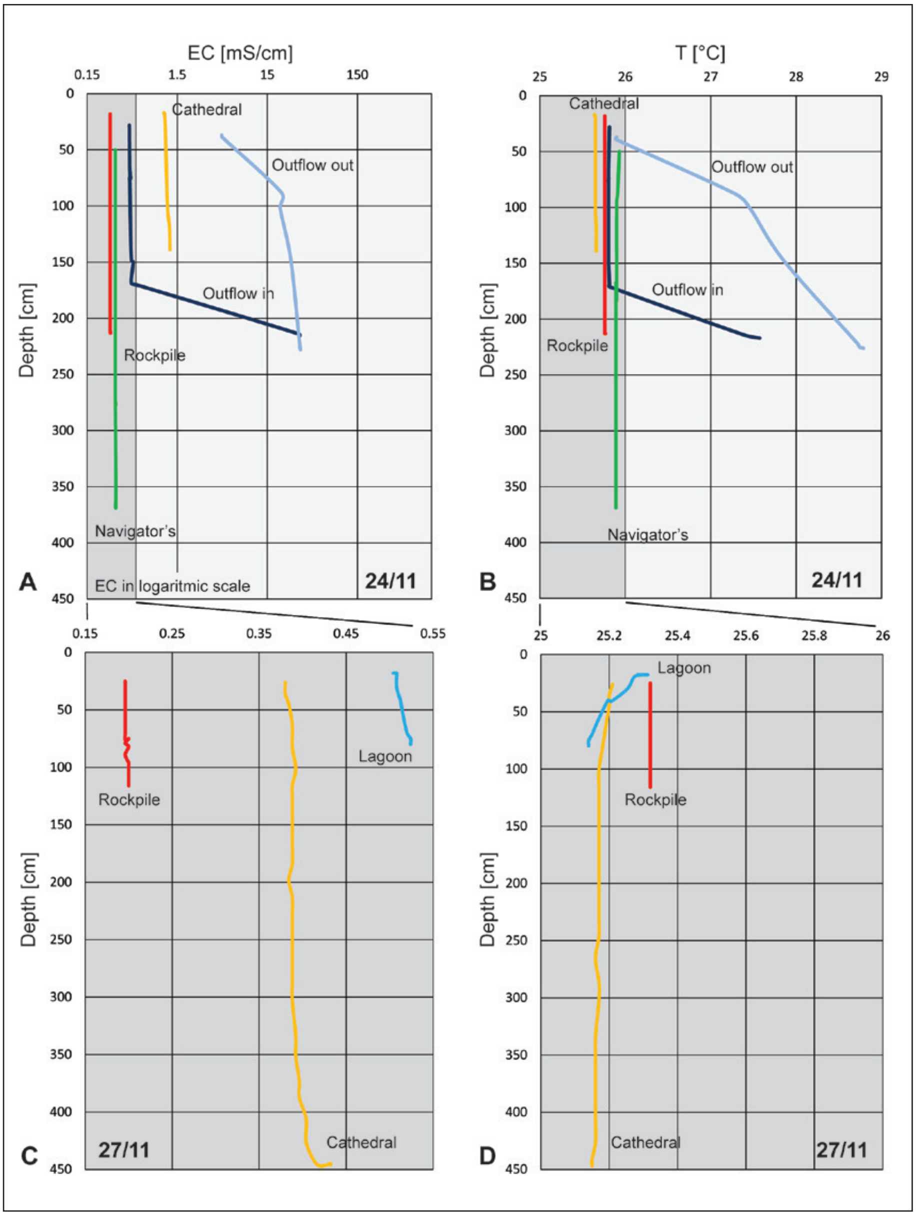

*Fig. 10: EC and T summary of the vertical logs taken on November 24 (A and B) and 27 (C and D). Different colors represent different logs. Outflow in is related to the log described in Fig. 7A and acquired from 2.27 to 2.30 p.m.; Outflow out corresponds to the log described in Figure 7B and recorded from 5.14 to 5.19 p.m. of the November 24.*

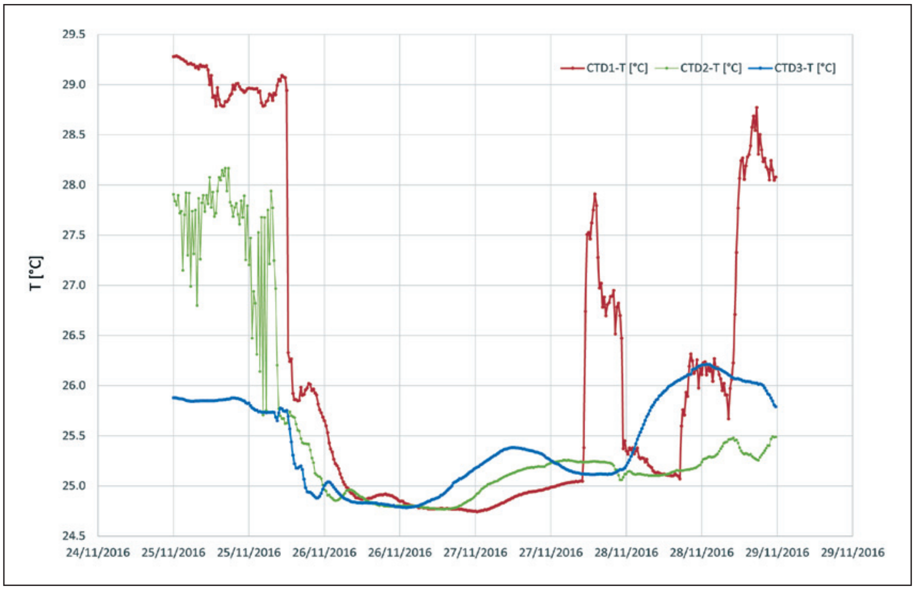

*Fig. 11: Variations of temperature at Rockpile (blue), Navigator's (green) and Outflow (red) from November 25 to November 29, 2016.*

## CTD-DIVER DATA ANALYSES

The analyses of the T graphs obtained by continuous acquisition due to the 3 CTD data-loggers installed at Rockpile (CTD3), at Navigator's (CTD2) and at the Outflow (CTD1) revealed interesting results (Fig. 11).

Before the storm event, the graph demonstrates a different behaviour in correspondence to the three monitored points. The instrument at Rockpile (CTD3) demonstrates a quite constant behaviour regarding temperature with very small fluctuations and with values of approximately 25.8 °C. At Navigator's (CTD2) the recorded data are deeply influenced by the colder waters at the Australian inlet and the heavy dripping from the ceiling (Fig. 11) and finally by the turbulence resulting from tourist boats present in the area. Before the storm

*Fig. 12: Significant dripping point from the ceiling near Australian inlet. Photo taken on November 26, 1:29 p.m. from Francesco Lo Mastro – La Venta (Photo: F. Cucchi).*

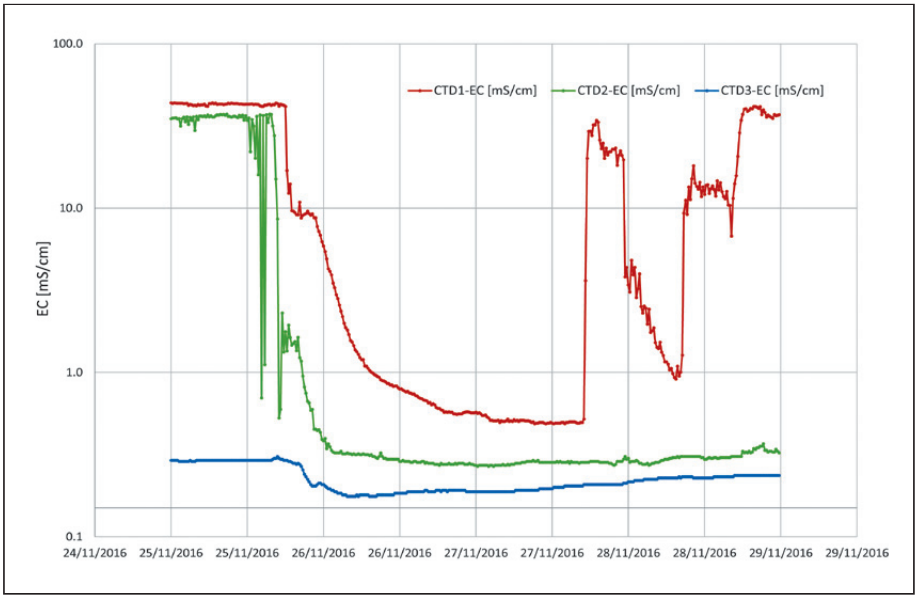

*Fig. 13: EC variations (in logarithmic scale) at Rockpile (blue), Navigator's (green) and Outflow (red) from November 25 to 29, 2016.*

event, the T values ranged between 27 and 28 °C. During the storm event there is an increase in dripping and freshwater income in correspondence of the Australian inlet. This is witnessed by an increase in the T variations which have values between 26 and 28 °C.

At the Outflow (CTD1), T is more stable but higher in value: 29 °C ±0.3 °C.

The flood signal of the Cabuyagan River swallowing at Daylight records an abrupt decrease in temperature: at CTD3 from 25.7 °C to 24.8 °C, at CTD2 from 27.9 °C to 24.8 °C and at CTD1 from 29.0 °C to 24.8 °C.

A clear signal of the brackish water ingression is recorded by CTD1 on November 27 at 17:00, with a sharp increase in water temperature.

As discussed for temperatures, is confirmed by the EC trend at the three monitored points. At CTD3 (Rockpile), the EC value is quite constant with values of 0.29 mS/cm, bearing witness to the presence of flowing freshwaters at depths of about 1.24 m from the water surface in low flow conditions. At CTD2, the average EC value is 37 mS/cm, but some abrupt decreases of up to 1.5 mS/cm are clearly present due to the freshwaters coming in from the Australian inlet, heavy dripping from the ceiling (Fig.13), and finally from turbulences resulting from tourist boats present in the area. Fluctuations are wider in due to precipitation which increases the inflows by the Australian inlet and the dripping from the ceiling.

At CTD1 the EC values are again quite stable around 41.7- 43.5 mS/cm, demonstrating the presence of brackish to salty waters.

The flood signal of the Cabuyagan River swallowing at Daylight, records an abrupt decrease in the EC: at CTD3 from 42.3 mS/cm to 0.5 mS/cm, at CTD2 from 37.2 mS/cm to 0.27 mS/cm and at CTD1 from 0.29 mS/cm to 0.18 mS/cm.

The clear signal of the brackish water ingression was recorded by CTD1 on November 27 at 17:00, when a sharp increase in the water temperature occurred. CTD2 also recorded the signal on November 27 at 22:30. CTD3 reaches the lower EC values of 0.18 mS/cm on November 26 around 05:00 and later it slowly started to increase reaching values up to 0.24 mS/cm at 00:00 of November 29.

## DISCUSSION

The available data collected as T and EC longitudinal and vertical logs and the acquired data recorded by the in situ installed CTD data-loggers are enough to define the hydrodynamics of the underground river during floods. The occurrence of a strong rainstorm just in between the field survey gave the researchers an excellent opportunity to understand some of the main hydrogeological characteristics of the PPUR.

In general, the water temperature along the system is very stable especially in its shallower part (20-30 cm from the surface), in the first two longitudinal logs (November 24 and 26), the T variation range was close to 0.3 °C, while on November 27 the total variation was about 0.4 °C. The slight variability within the same log is reasonable for several reasons, above all the extremely stable Palawan climate.

The relatively high and constant temperature drop from the first to the second log (1–1.1 °C in Fig. 4) is a direct consequence of the extremely fast hydrodynamics that characterises the underground river. This potentially avoids a fast mixing among the colder flood waters and the warmer ones stored within the system. The peak of the flood clearly reached the external lagoon only few hours after a rainstorm, as seen in the photo taken on November 26 (Fig. 14).

The apparent extremely fast homogenisation should also be magnified by the data acquisition method: the values for all the 3 longitudinal logs are related to 20–30 cm from the water air interface and therefore only the fast flowing water was tested.

The few available data from the vertical logs (Figs. 7 – 10) showed a noticeable thermic difference (2 °C and 3.5 °C, respectively) immediately after the transition from fresh water to the brackish layer in correspondence the Outflow.

This relatively large temperature difference between these two water layers may be explained by the fact that the brackish water remains in contact with the cave walls for a very long period and therefore may reach the equilibrium with the walls. Moreover, it fluctuates upstream and downstream below the fresh water layer following the tides, thus possibly coming in contact with the warmer environment of the external lagoon.

This hypothesis appears to be supported by the fact that the longitudinal log of November 26 had an overall pattern which was much more constant: about 0.1 °C of variation in temperature, not taking into consideration the zone of fast decrease and fluctuation around the Australian inlet where the 1°C temperature drop was clearly caused by the storm water which was cooler than that of the Cabayugan River sinking at the Daylight.

Seeing that no rain occurred in the previous days, the log acquired on November 24 (Figs. 4, 5) may rea-

*Fig. 14: Muddy water escaping from PPUR filled the Lagoon. Photo taken on November 26 at 11:35 a.m., after the strong rainstorm occurred November 25 (Photo: F. Cucchi).*

sonably represent a condition of thermic equilibrium within the PPUR. The overall sinusoidal pattern between Outflow and Rockpile may likely be regarded as the consequence of the variation of the external water temperature induced by daily solar radiation.

The progressive decrease of the sinusoid amplitude from Rockpile to Outflow is a consequence of the thermal interaction of flowing water with cave walls and cave atmosphere.

At any rate, a single log cannot fully explain the observed temperature variation along the underground river because of the complexity of contributions involved in the process (external fresh water flows all the day round downstream, while the water coming from the lagoon move back and forth twice a day following the tides, or at least stop the fresh water flowing downstream). Even more complex is the behaviour of the meteoric seeping waters, causing diffuse dripping along the underground river.

The third log (Figs. 4, 5) is very similar to the first one but with a progressive temperature drop towards the Outflow. The temperature begins to increase again only few tens of metres upstream from the Outflow, probably due to the effect of the contact with the cave walls, which had a rather higher temperature in the previous days due to the contact with the brackish water and also due to the solar radiation in the close external lagoon. The average temperature variation of this third log is still 0.4–0.5 °C colder than the first one, demonstrating that after 30 hours the thermal equilibrium was far from being achieved. As previously mentioned, the water behaviour can be witnessed also by the analyses of the T graphs obtained by the in continuous data acquisition of the 3 CTD data-loggers installed at Rockpile (CTD3), at Navigator's (CTD2) and at the Outflow (CTD1) (Fig. 11). In addition, from these data analyses, it is possible to deduce the arrival of the colder waters of the flood and the delays recorded at the sites which show a time difference of 1:15 h–1:30h between the arrival at CTD3 and at CTD2, and a 2–3 h delay between CTD2 and CTD1. This means that in the inner section of the cave, from Rockpile to Navigator's, the water flows three-times faster than from Navigator's to the Outflow.

Moving from temperature to Electrical Conductivity (EC), in general the values in all the three longitudinal logs (Fig. 5) correspond to a fresh/slightly brackish water, never exceeding 700–1000 µS/cm. These values are related only to the shallower part of the flowing water, 20–30 cm below the water surface. These low values suggest that even in the period before the rainstorm, the flow rate of the underground river was high enough to prevent sea water ingression into the system during the high tides. This is confirmed by the fact that only the vertical log from November 24 recorded a frankly brackish water several metres upstream from the Outflow inside the system (Fig. 7, Fig. 10, Outflow in and Outflow out). The brackish layer was absent in the vertical log recorded several tens of metres upstream from the Cathedral (Fig. 8). This fact, in accordance with the evident stop in the decrease in conductivity observed in the longitudinal log from November 24 in the same area, suggests that if only the shallower part of the flowing waters are taken into consideration, the brackish water layer ends here. Nevertheless, it is possible that some insulated brackish/salt lenses may have survived in some of the deep depressions existing along the river bottom, up to Navigator's.

Close to the Outflow, the incoming high tides cause the increase in the brackish layer and its progressive upstream migration under the fresh water, which flows in the opposite direction. This contrast induces turbulence and a partial mixing close to the interface, which is responsible for a progressive increase in the conductivity of the upper level (Fig. 7).

Another cause of turbulence with a subsequent EC increase is induced by tourist boats coming from the external lagoon (where the salinity is higher), which lasts for the entire time of the tourist activities. The presence of boats is restricted to the very first part of the cave (up to God's Highway, Fig.1) and surely has a certain impact on the increase in conductivity but it is impossible to define its amount without specific measurements.

A contribution to the salinity increase may also be due to the presence of sea water trapped within the soft bottom sediments and /or insulated lenses: close to the Outflow the gallery bottom is relatively deep (6–12 m below the water surface) and therefore the ionic diffusion from these lenses/deposits may last even long after the whole sea water has been pushed out of the system by the incoming fresh water.

The relative conductivity constancy in the Cathedral-Navigator's and Navigator's-Rockpile sectors suggests that before the rainstorm the system was in rather good hydrodynamic equilibrium: the relatively fast EC increase from Cathedral to the Outflow could be mainly due to diffusion from the brackish layer, and to a lesser extent by tourist boats and salt water layers/lenses present/trapped in the bottom.

Finally in the third sector from Navigator's to Rockpile, the low thickness of water due to the bottom depth decrease, together with the relatively high flow rate reduces the likelihood of the presence of thick bottom deposits and therefore impedes the storage of brackish water.

The log from November 26 was made about 12 hours after the rainstorm and its pattern is very similar to the first one, but shows an unexpected higher conductivity for most of its pattern: only in the short sector between Navigator's and the end of God's Highway its conductivity is practically the same as November 24.

Heavy flood turbulences have surely induced a homogenisation of the brackish layer close to the Outflow and most likely also of some insulated lenses of brackish/salt water deeper inside: this could explain the increase in conductivity from God's Highway to Outflow.

The rather constant increase in conductivity between the Rockpile sump and God's Highway (on average higher than 70 µS/cm with respect to the log from November 24), cannot be explained by the mobilisation of sea/brackish water trapped upstream, however. Moreover, the few vertical logs performed after the rainstorm confirm that all the water present in the PPUR downstream from the Rockpile are fully freshwaters.

Part of the increase in EC could be only partially due to the chemicals used in the rice fields and in other agricultural activities in the catchment area of Cabayugan River, while a part could be progressively induced by the dissolution of chemical compounds produced within the cave by the mineralisation of the abundant organic deposits (mainly bat and swiftlet guano) widespread in all the PPUR. The increase in the water level may easily reach places which are normally dry and where those strongly ionic and highly soluble substances (chlorides, sulfates, nitrates etc.) had time to develop. Moreover, an important contribute can also be provided by the storm induced increase in dripping and seeping waters in the whole karst system, which can dissolve many chemicals before reaching the main river or some of its tributaries. This hypothesis is supported by the fact that in the log from November 26 there is a noticeable and sudden increase in conductivity (up to 400 µS/cm) just at the confluence between the underground river and the creek flowing in the Australian branch: this conductivity increase was maintained from a relatively long sector of the underground river (> 0.5 km) downstream from this branch. A similar increase, even restricted to the junction area, was also present in the November 24 and 27 logs, thus demonstrating that the water coming from the Australian inlet is richer in dissolved ions than that of the underground river.

Other smaller EC increases are present in all the three logs (Fig. 5), which consistently corresponds to temperature lowering (Fig. 4), thus suggesting that they were always induced by dripping.

For this reason, the slight increase in conductivity of the sector between Cathedral and Outflow should be reconsidered: it is more likely induced by the presence of a strong, highly conductive dripping also along this final part of the karst system.

On November 27 the conductivity was reduced along all the PPUR, even if in a small portion around the Cathedral the values were still higher than those observed before the rainstorm: this may be explained by the fact that the new freshwaters did not have enough time to wash away the brackish-fresh mixed waters produced during the rainstorm.

## CONCLUSIONS

The intertidal-zone PPUR cave is one of the beauties of the natural world from geomorphological and biodiversity viewpoints. The show-cave has been studied since the 1960s and has a total length of 32 km of known conduits and galleries set at different elevations of which, a portion represents a unique environment to be studied from a hydrogeological viewpoint. During the expedition organised by La Venta in November 2016, researchers installed datalogger devices in the estuarine-cave for the first time. During the expedition, a rainstorm affected the area and the freshwaters were used by researchers as a natural tracer. The analyses of the experimental data provided the opportunity to improve upon the existing knowledge of the hydrodynamics of a karst system, adding to what is known of these specific environments. The main results obtained for the study area may be summarized as:

From the longitudinal logs related to the shallower part of the flowing waters (20–30 cm from the surface), it emerged that the temperature in the cave is quite constant and that they proved to be a proper methodology to identify the freshwater inlets such as the Australian's inlet and the dripping waters. Moreover, the progressive increase in EC from the Rockpile sump (where the values are always below 0.3 mS/cm), to the Outflow were at least partially induced by ions coming from washed guano.

The vertical logs also allowed for an analysis of the behaviour of the deep waters (up to 1.5 m, but sometimes reaching also 4 m below the water surface). The data show that there is a stratification in the waters and that mixing between fresh and sea waters can be observed only in the Outflow monitored point, close to the lagoon (see Outflow in and Outflow out, Figs.7A, 7B, 10).

The long-term monitoring EC and T data are related to data-logger devices installed at different average depths: 1.24 m (CTD3), 2.04 m (CTD2) and 2.28 m (CTD1). Placed at lower depths, the recorded data demonstrated a clear stratification of the waters with freshwaters always present at Rockpile (CTD3) and brackish waters at Navigator's (CTD2) and at the Outflow (CTD1). From the analyses of the simplified bathymetric section (Fig.4), it was seen that at Navigator there is an increase in the slope (from Rockpile to the Outflow) deepening the bottom of the cave from 4 m up to 10–12 m.

All the data shows that the storm had significant effects on the hydrodynamics of the PPUR through-cave.

The presented detailed study is the very first one realised in an underground estuary of such dimensions and it will be a benchmark to every future study on similar environments. The variations in temperature and in electrical conductivity emerged from the data analysis recorded during the short but heavy storm event, demonstrated the low inertia of the system which involve about 100,000 m$^3$ of groundwater. The great variability in the physico-chemical parameters reflects on the ecosystems present in the PPUR which are the most important and interesting. These ecosystems which live side by side, while being so different, have to quickly adapt to new environmental conditions (from salty to brackish, to fresh waters, from cold to warm, etc.) in order to survive. This is the framework that needs to be better characterized and which take advantages from joined researches in different disciplines.

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