Coastal Karst Aquifers in Mediterranean Regions. 2. A Methodology for Exploring, Exploiting and monitoring Submarine Springs

Michel Bakalowicz, P. Fleury, Bruno Jouvencel, Jean-Jacques Promé, P. Becker, Thierry Carlin, Nathalie Dörfliger, Jean-Luc Seidel, Philippe Sergent

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2. A methodology for exploring, exploiting and monitoring submarine springs.

BAKALOWICZ M.[(1)], FLEURY P.[(2)], JOUVENCEL B.[(3)], PROMÉ J.J.[(4)], BECKER P.[(5)], CARLIN T.[(5)], DÖRFLIGER N.[(6)], SEIDEL J.L.[(1)], SERGENT P.[(7)].

[1] *CNRS, Hydrosciences, cc MSE, UM II 34095 MONTPELLIER CEDEX 5 (France)*
[2] *Doctorante, Université Paris 6, Nymphea Water, Les Dauphins, 520 av. de Jouques, 13685 AUBAGNE CEDEX (France)*
[3] *LIRMM Montpellier, rue Ada, UM II, 34095 MONTPELLIER CEDEX 5 (France)*
[4] *Hytec 501 rue de la Croix de Lavit, 34197 MONTPELLIER CEDEX 5 (France)*
[5] *Nymphea Water, Les Dauphins, 520 av. de Jouques, 13685 AUBAGNE CEDEX (France)*
[6] *BRGM Service Eau, Unité RMD, 1039 rue de Pinville, 34000 MONTPELLIER (France)*
[7] *Gradient, CETMEF, 2, boulevard Gambetta, BP 60 039, 60 321 COMPIÈGNE CEDEX (France)*

Abstract. In coastal regions, the study of karst aquifers and the ground water resource exploitation require a specific methodology and exploration and monitoring techniques. Two directions are investigated, leading to new technological and methodological developments. The first investigation axis deals with the exploration of fresh water plumes from submarine karst springs. An Autonomous Underwater Vehicle (AUV) is being developed and tested in order to collect all data (salinity, temperature and depth) along its trajectory. The submarine discharge may be estimated by modelling. The second axis deals with the water works for collecting the submarine fresh water discharge. The capture system is designed for monitoring the spring discharge, salinity, temperature, radon concentration and turbidity. The data time series will be analysed in order to determine the aquifer functioning. Discharge data will be used for simulating the spring flow in function of rain series. The prototypes are presently being developed and tested.

INTRODUCTION

The study of karst aquifers in coastal regions, particularly around the Mediterranean sea, and the ground water resource exploitation require the use of specific exploration and monitoring techniques, in complement of those usually used. The pinpoint is the monitoring of the submarine outlets in order 1) to know the order of magnitude of the flow rate, i.e. the significance of the discharge compared to the total estimated discharge of the karst system, 2) to know the range of flow rate variation, i.e. the practical interest for its possible exploitation, and 3) to make a permanent monitoring of the flow rate, temperature and salinity for surveying the possible effects of on-shore exploitation and of sea water intrusion in the aquifer.

Two complementary directions are presently investigated which are leading to new technological and methodological developments. The first investigation axis is focused on the estimate of the submarine spring flow rate. It is the necessary exploration phase of the coastal karst aquifers, which should determine the following exploration and exploitation steps. It deals with the exploration of the fresh water plumes from submarine karst springs. The second axis deals with the monitoring of the submarine spring and the water works for collecting the submarine fresh water. The prototypes are presently being developed and tested.

Exploring submarine karst springs with an Autonomous Underwater Vehicle

In the necessary exploration phase of the coastal karst aquifers, the submarine springs must be characterised by their location, the outflow conditions and the order of magnitude of the submarine ground water discharge. A preliminary field survey is most of time the best way to determine the existence and the approximate location of submarine karst springs from local population. The outflow conditions may be concentrated at a unique spring or dispersed through several outlets or diffused through low permeability sediments coating the karst. That information as well as the order of magnitude of the outflow are essential for the following exploration and exploitation steps. The spring could be or not of great interest for monitoring and for a possible exploitation.

In preliminary investigations (Doerfliger *et al.*, 2001), it appears that the flow rate of a submarine spring is very difficult to estimate. The literature copiously refers to many flow rate estimates, done directly by fishermen and divers, or indirectly from remote sensing or chemical data. Most of time the flow rate values are unlikely, too high compared to what shows the hydrological balance. In reality the flow rate must be evaluated from the whole fresh water plume. The only way is 1) the survey of the plume in its 3 dimensions, and 2) the modelling of the plume as flow, temperature and salinity fields for different discharge conditions.

Two surveys of the plume were attempted. Measurements of temperature and electrical conductivity or salinity were done for nods of a 5x5 to 10x10 m grid at different depths, from a boat. The experiment could not be repeated because it requires a too long time, 3 days, during which the flow conditions must be permanent and the climate conditions excellent, with no wind and no change in the sea level. Moreover the dimension of the grid should be improved for better results.

Consequently, we looked for a more efficient way of exploring the fresh water plume. An Autonomous Underwater Vehicle (AUV) previously developed has been tested in order to collect all data (salinity, temperature and depth) along its trajectory.

THE AUTONOMOUS UNDERWATER VEHICLE (AUV)

The AUV prototype is being developed par LIRMM laboratory in co-operation with Hytec Company which should build and commercialise the AUV with the attached methodology. The first results are presented, after a description of the device and the operating processes.

Mechanical description

The AUV TAIPAN (Vaganay *et al.*, 1998) is 1.8 m long and has a 15 cm diameter, for a total dry weight of about 30 kg. Its hull is completely watertight and trimmed at about 0.3 kg positive buoyancy. The aluminium interface between the nose (made of hostaform) and the main carbon fibre body holds the bow diving plane (actuated by a servo-motor), the pressure sensor, the UHF and GPS antennas and the 10-pin underwater connector used to connect the onboard electronics with the outside. The head (nose, interface) and all the electronic boards can be detached from the main body and all pop out as one. Water tightness is ensured by an O-ring and 6 screw nuts. A DC motor rotates the propeller via a gear wheel located outside the hull. The power electronics is located above the motor, next to the servo-motors used to actuate the rudder and the stern plane. The servo-motors command the rotation angles of axes through the hull. These angles are transmitted to the control surface axes via wire ropes. A fairing with fixed surfaces is located in front of the rudder and the stern plane. Behind the three-bladed propeller is a set of 4 fixed surfaces slightly twisted to stabilise the vehicle.

Sensor suite

At this point, TAIPAN's sensor suite is limited to the sensors required for heading and depth control as well as positioning at the surface. Roll, pitch, and yaw are measured by an electronic compass module including a three-axis magnetometer and a two-axis inclinometer (TCM2, Precision Navigation Inc.). Depth is measured by means of a piezoresistive sensor chip housed in a fluid-filled cylindrical cavity and isolated from the water by a stainless steel diaphragm and body (NPI Series, Lucas NovaSensor). Yaw rate and pitch rate are measured by two piezoelectric vibrating gyrometers (Gyrostar, Murata). Finally the position of the vehicle can be determined at the surface by means of a Differential GPS receiver (Lassen SK8, Trimble). Speed is determined based on a priori calibration between the voltage sent to the motor and the effective vehicle speed.

Hardware

The vehicle (fig. 1) is powered by a 48V/8Amph NiMH battery. TAIPAN's electronics comprises a Transputer board based on an INMOS T805, a power/relay board, DC/DC power boards, a power distribution board, a GPS board, and a UHF radio board. All actuators and sensors are interfaced to the T805 board where I/Os, A/D conversions, and RS232 serial communications are performed. The transputer board can be connected to the shore PC by plugging the tether in the underwater connector. The power/relay board includes various DC/DC converters and internal reed switches activated from the outside by a hand-held magnet to turn the electronics on and off.

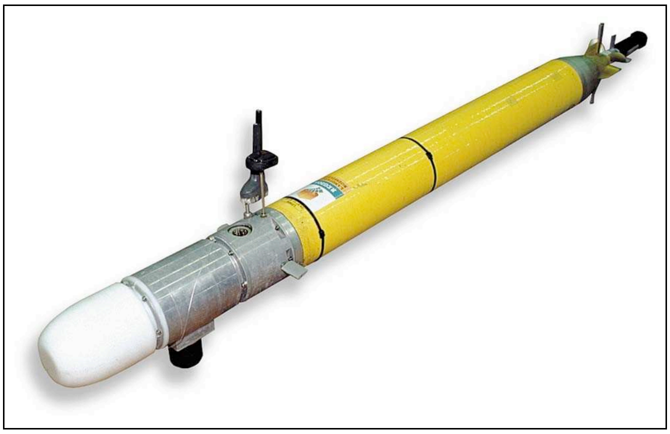

Figure 1. The TAIPAN AUV

Software

TAIPAN's software is written in parallel C, which in addition to C includes Transputer specific functions for data exchange between processors, and real-time management. The T805 board sequences the actions to be undertaken according to the mission file (setpoint, waypoint, track following, GPS reset). It also ensures the 0.2 s sampling where sensors are read and filtered, position is dead-reckoned, control laws are computed, data is logged, and security is checked. At the beginning and the end of a mission this board runs communication routines with the shore PC to respectively input the mission file and initialisation parameters and to output the logged data.

Simulation

A hydrodynamic simulator of TAIPAN has been developed in MATLAB. This simulator is of course not accurate enough to predict what the exact behaviour of the vehicle will be during a given mission, but it allowed to test control laws before real implementation in the vehicle. TAIPAN can also run its own software on its simulated dynamics and simulated sensors, thus allowing easier software debugging. This is performed by running in real-time the C parallel software on TAIPAN's transputer and the MATLAB simulator, and having the two environments communicate via the vehicle's tether. The minor changes of the parallel C software for this hybrid execution mode concern the sensor readings which are no longer obtained by the T805 board but received from the PC (simulated sensors), and the actuator commands which are also sent from the T805 board to the PC (input of the dynamic model).

Mission Programming

A graphical user interface (fig. 2) developed in MATLAB allows to :

program simulations,

test the vehicle before running a mission (sensors, actuators),

program the trajectory to be executed by Taipan,

visualize measured data after completion of the mission.

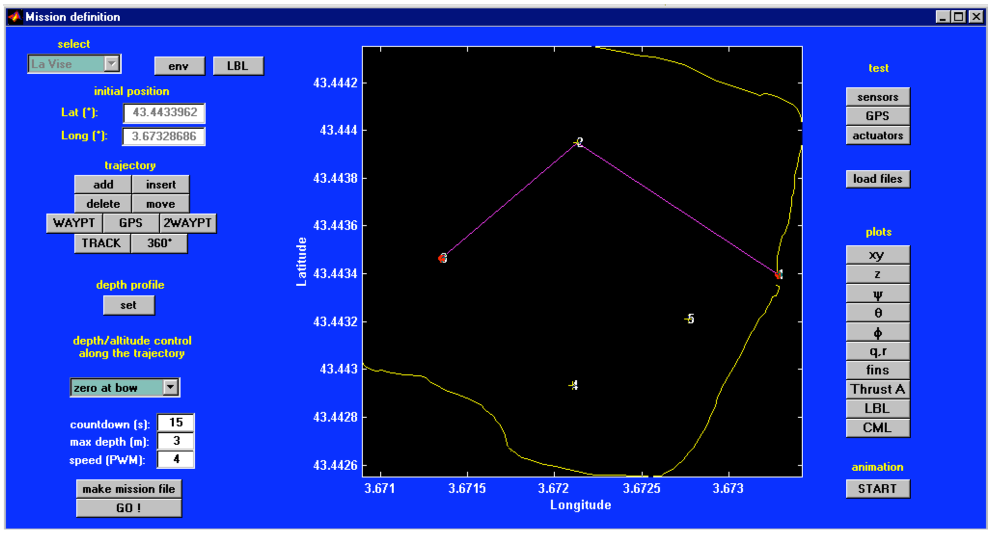

Figure 2. Mission programming interface

When the vehicle is connected to the PC by its tether, the interface allows to directly act on the actuators (fins and thruster) by manipulation of sliders. It can show real-time plots of sensor measurements (roll, pitch, yaw, depth, yaw rate, pitch rate) and display DGPS fixes as they arrive.

A map representing the shore as well as the area in which the vehicle will manoeuvre is represented. Heading and depth setpoints can be programmed by simply clicking in the map. The vehicle trajectory can also be defined by a series of waypoints with their associated latitudes and longitudes. The waypoints are clicked in the map with the mouse and the desired depth can be defined for each leg as well as the desired depth control law. A depth yoyo motion between two limits can also be programmed. The desired speed along the mission, the maximum authorised depth and the countdown duration are also entered in editable areas. Once the mission is completely defined, it is automatically transformed into an ASCII file by pushing a button.

Differential GPS

Several differential stations broadcast RTCM SC-104 differential corrections in VHF on the French coasts of the English Channel, the Atlantic and the Mediterranean. The differential stations of interest for experiments carried out near Montpellier are located at Cap Béar (about 140 km South West) and at Porquerolles (about 210 km East South East). The corrections could, however, not be received directly in the AUV because the differential receiver's VHF antenna was too long.

Therefore, they are received on shore and relayed to the vehicle via a UHF radio link. The vehicle is then only fitted with a small UHF antenna and the bi-directional radio link is only used one way to transmit differential corrections from the shore to the vehicle (Jouvencel *et al.*, 1998).

The DGPS setup (fig. 3) is divided into onshore and onboard equipment connected by the UHF radio link as showed in next figure. Onshore, the differential correction receiver (MLR DF300) receives the corrections transmitted by the remote differential station in VHF at 100 bits/s and outputs them in RTCM SC-104 format on a serial port at 1200 bits/s. This serial data is buffered in the UHF radio and transmitted by packets of 128 bytes at 1200 bits/s. The onboard equipment includes the UHF radio board and its 15 cm long whip antenna, as well as the GPS board (Lassen SK8) and its small active micro-patch antenna. The GPS antenna is fixed on top of a mast without pressure housing and can be set to raise between 5 and 15cm above the hull before launching. One of the serial ports of the GPS board is connected to the transputer board and is used to receive system configuration commands and transmit DGPS fixes. The second serial port is connected to the UHF board and receives the corrections transmitted from the shore.

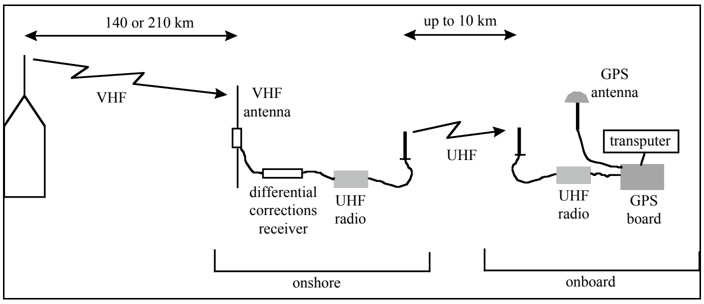

Figure 3. Schematic representation of the DGPS setup

The Lassen-SK8 GPS board can be configured to output standard precision GPS fixes only, DGPS fixes only or to output GPS fixes in case DGPS corrections are not available for all in-view satellites. For our operations, we configured the board to output DGPS fixes only.

Launch and recovery procedure

Pushing the GO button downloads the mission file in the vehicle computer via the tether and prepares the vehicle for the launch. The user is then prompted to press a key to turn the power on for the actuators and to press another key to start the countdown. Once the countdown is started, the tether is removed and the vehicle set clear for an autonomous dive from the surface which starts at the end of the countdown.

Note that the tether is 5m long so that if the boat is not too high above the sea level, the vehicle can be held by a diver in the water during the programming of the mission, the download of the mission and the execution of the countdown. Otherwise, a longer countdown has to be used to give enough time to bring the vehicle from the boat deck into the water.

After completion of the mission Taipan goes back to the surface and waits. The vehicle is recovered and reconnected to the PC by its tether. Data is transferred from Taipan to the PC and various push buttons can be pressed in order to visualize GPS fixes and dead-reckoned track, commanded and measured heading and depth, pitch, roll, pitch rate, yaw rate, and fin deflection. Finally, the behavior of the vehicle in the horizontal and vertical planes is represented by a side and top view animation of TAIPAN based on the measured data during the mission.

The first results

The vehicle control results are shown by figures 4 and 5, and GPS navigation results by figures 6 to 9.

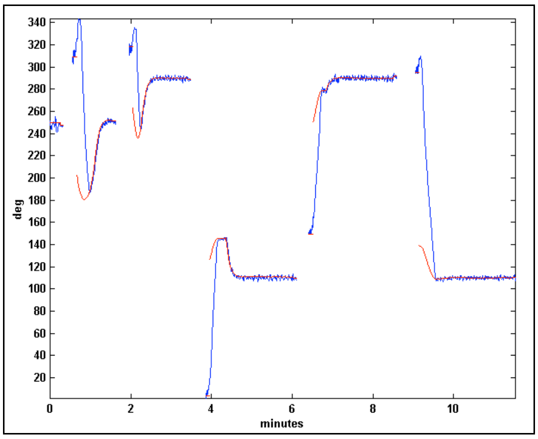

Figure 4. Heading control

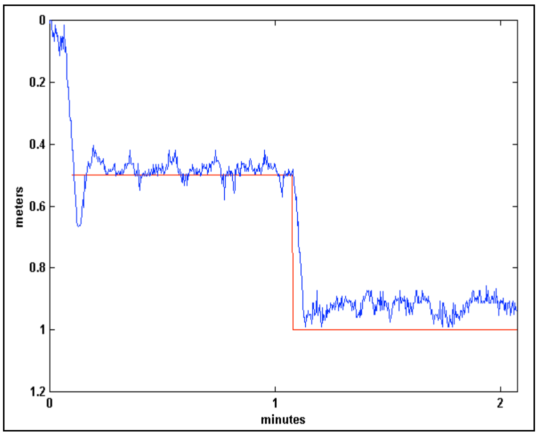

Figure 5. Depth control

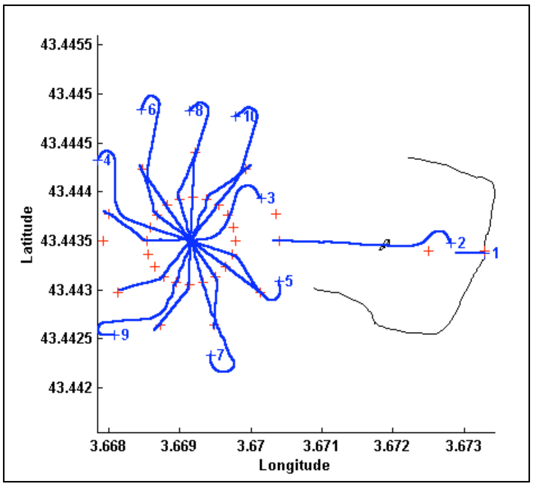

Figure 6. Thau lagoon, 2.5 km (0^h33), 10 DGPS fixes (Baccou and Jouvencel, 2002)

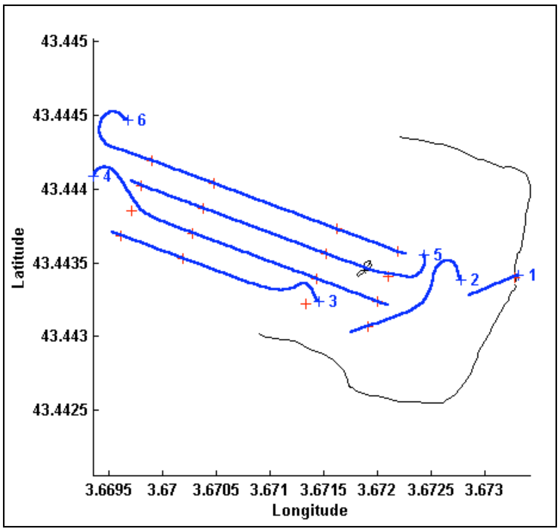

Figure 7. Thau lagoon. 1.2 km, 6 DGPS fixes

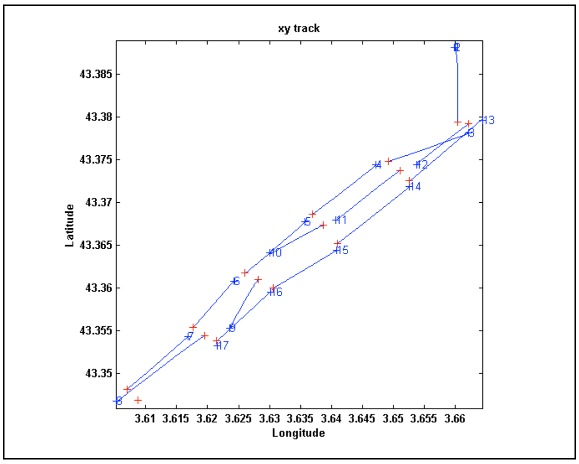

Figure 8. Mediterranean sea (Sète/Marseillan). 17.4 km (2^{h}29), 17 GPS fixes (S/A removed)

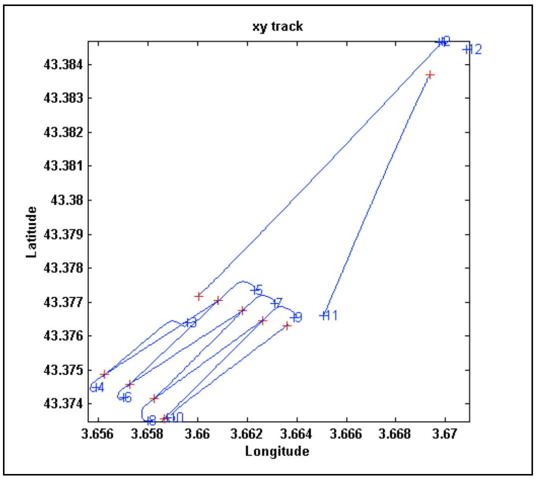

Figure 9. Mediterranean sea (Sète/Marseillan). 6.5 km (1^{h}01), 12 GPS fixes (S/A removed)

THE MODELLING OF FLOW AND TEMPERATURE FIELDS

Thanks to the quasi perfect symmetry of revolution of the bathymetry around the Vise spring, the currents and temperature fields are computed with two-dimensional models based on the finite elements method. The 2D model for currents solves the Navier-Stokes equations with variations of density due to temperature and the 2D model for temperature solves the convection-diffusion transport equation. The Vise spring is taken into account as a constant warm flow input of 20 ° C (293 K) and of given stationary volume flow. It is located in the crater centre. The ambient fluid has a temperature of 12 ° C (285 K) in conditions of the measurements campaign of March 1999.

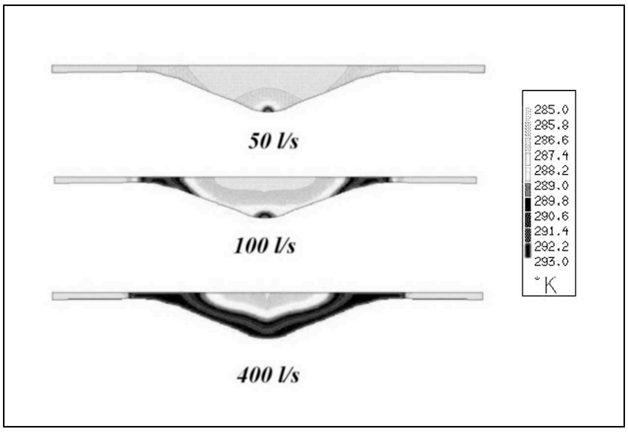

Figure 10. Temperature map for different flows of Vise spring.

The computations are performed with flows varying from 20 l/s to 1000 l/s. Temperature maps are shown in figure 10 for three different flow rates: 50 l/s, 100 l/s and 400 l/s. Computations prove that a cold water bubble stays above the crater centre whereas heat is convected towards the crater edges. The temperature of the spring is observed on these edges from a 100 l/s flow. The thickness of the warm fluid layer located near the crater bottoms increases with the flow.

Since the variations of temperature measured at the surface do not exceed 2 ° C, we conclude that the flow of the Vise spring is inferior to 50 l/s. These first computations must be completed by a sensitivity analysis, the introduction of salinity and three-dimensional models.

THE SPRING CAPTURE AND MONITORING DEVICE

The capture device is being developed and experienced by Nymphea Water (Geocean group). It will allow the monitoring of the spring discharge, salinity, temperature, radon concentration and turbidity. The selected equipment is prepared for a spring located at 36 m below the sea level and 2 km from the coast line. As well as for the continental karst springs, the data time series will be analysed in order to determine the aquifer functioning and the eventual relationship with other outlets of the system. That approach will give the necessary information and data for simulating the spring flow in function of rain series; the model is presently successfully tested on several Mediterranean karst systems. Thanks this capture work temperature, salinity and discharge time variations will be monitored during the exploitation of the aquifer from boreholes on shore or even to exploit the aquifer directly at the submarine spring, with or without a desalinisation process on line. The prototypes are presently being developed and tested.

Catchment systems. History

Submarine springs were very well known since antiquity with first reports dated B.C. (Before Christ) (Doerpinghaus, 2001). Strabo, the Roman geographer (63 BC to 21 AD) described how a spring was captured on Aradus island 4 km from the coast of Latakia and close to Syria: « In times of war the inhabitants get their water from a canal near the town. This canal is fed by a large spring; and, from a specially designed collecting boat, the inhabitants lower a wide-mouthed funnel made of lead that widens from the top down and is attached to a leather pipe made from animal skin; it fills up, forcing the water through the pipe to the surface. »

Fresh water was also trapped with primitive techniques e.g. tubes driven down spring outlets or amphorae turned upside down to catch the flow. All attempts were discontinued until the 1970's when a dam that remains in operation to this day helped separate spring and seawater at Analvos Kiveri, Greece.

A second dam with a fresh water flow leading out to sea was built in Port Miou France. It was designed to prevent seawater's entry into ducts (Potié et al, 2002) and proved efficient for a while but the salinity was considered too high and operation was discontinued. Two additional springs were also captured in Italy (Stephanon, 1973) with fresh water flowing above sea level.

The system developed by Nymphea Water

No attempt was made post 1970's until Nymphea Water, a French company and Geocean subsidiary had another try. This capture device was tested on an Italian spring approximately 1 km off Cape Mortola and close to the French border. The 36 m deep Jurassic limestone spring is the outflow of a well-developed karst. However, It was not the only karst aquifer outflow in the area and some extra outlets were spotted a few meters away although their discharge rates were considered negligible compared to the spring described here.

The first capture system

The system developed by Nymphea Water relies on differences in density between spring water and seawater. As a result, the spring outlet was topped with an oversized chimney separating the ascending spring flow from seawater, but this did not modify flows within the karst aquifer in any way. In the top part a semi-spherical dome was filled with spring water (fig. 11). Brackish water was pumped off the top of this dome and delivered to the ship. The whole test was a success and the water stored on-board ship had a low salinity. The system was maintained for several months.

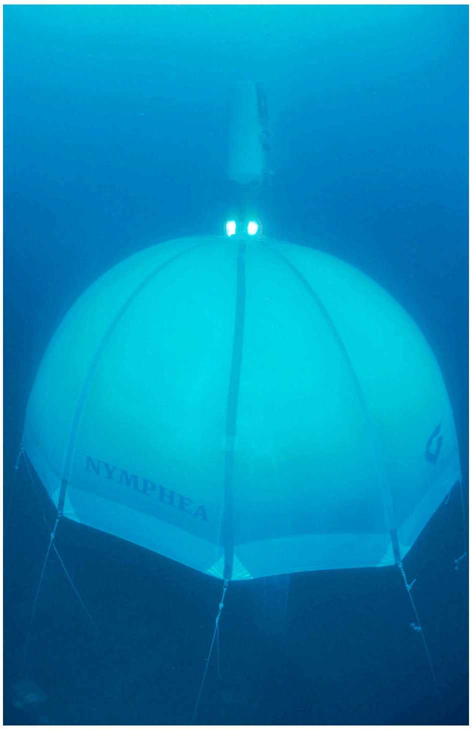

Figure 11. Submarine spring capture device by Geocean (1999).

Extensive study

Since then, Nymphea Water system has been improved and developed, and a second experience with a production version is scheduled for the first quarter of 2003. Contrarily to the first one, it is made of solid materials for enhanced reliability in time without being affected by poor weather conditions (swells, currents etc.). The system is a secure cylinder enclosing the spring, and its base was designed to follow the seabed contour. The chimney is topped with a half-sphere and pipe bent to arrive to a vertical plateau prior to opening into the sea. A pick-up point is provided on top of the half-sphere to secure a removable pipe opening up to the surface.

Driving fresh water fresh up to the surface by density excepted, this system also serves scientific purposes; it will help measure a number of hydrological parameters at the main source and extensively study this spring within the aquifer. Data shall be recorded hourly in a watertight box at the spring itself.

Two probes shall be provided inside the chimney; the first will measure conductivity, salinity and temperature and the second radon concentration. An electromagnetic flowmeter will measure the flow rate with a tolerance expressed as a percentage in the fresh water pipe. While the spring water physical and chemical parameters are recorded, a hydrological and geological study shall be undertaken to define the watershed; weather data have been recorded on a daily basis since the summer of 2002. Once they have been monitored over at least one hydrological year, these data will help in determining a conceptual, operative and rain-flow model.

As regards the application of these data, various simulations will be developed with the VENSIM software that has been specifically designed for transfers of the black box type. It was tested on several karst springs in the Mediterranean region with highly satisfactory results. Below is shown the comparison of the observed and modelled discharge time series of Fontaine de Vaucluse (France) over 380 time pitches (fig. 12).

The rain-flow model will be a significant decision and managing tool once the spring capture system will be in operation.

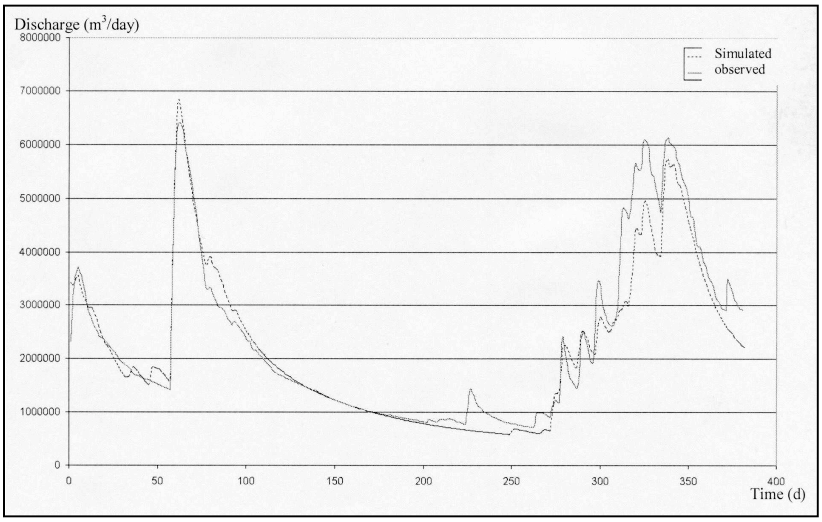

Figure 12. Observed and simulated discharge of Fontaine de Vaucluse with the VENSIM software

CONCLUSION

Presently a comprehensive methodology has been proposed for investigating, surveying and capturing submarine karst springs. The technology parts are still under development and in the testing phase. However the proposed techniques look very efficient and the first results are very attractive.

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