A Hydrodynamics model to help prevent hypoxia of the fauna and flora in Polynesian's Bays

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ABSTRACT

Inspired by the study conducted in the Orbetello lagoon (Italy), we developed a versatile hydrodynamics model which can be used to help prevent hypoxia of the fauna and flora in the bays of French Polynesia. The model represents the first phase of a multi-step strategy. This first step allows us to determine five critical points where to perform a seasonal measurement campaign of the water level and currents. The measurements, which represent the second phase of the project, will permit to define the most effective strategy to optimize the hydrodynamics flow by the mean of water pumps, bottom dragging or reef drilling.

{**CITATION**: ALESSIO GUARINO. A hydrodynamics model to help prevent hypoxia of the fauna and flora in Polynesian's Bays. American Journal of Research Communication, 2018, 6(1): 20-33} www.usa-journals.com, ISSN: 2325-4076.

INTRODUCTION

The knowledge of water circulation and oxygen concentration in bays and lagoons is very important. Indeed, bays and lagoons play an important role in the reproductive cycle and growth of fish, crustaceans and shellfish. However, they are increasingly under the influence of human activity. The influence of man is mainly represented by coastal developments such

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as ports or embankments. Even alterations carried out within the island do not remain without effects particularly when an area is deforested or during the excavations. The leaching of these areas by the rain brings a considerable amount of sediment in lagoons and bays. The terrigenous input is a stressor for marine wildlife. Knowing the water circulation in bays and lagoons is then essential to know and understand how this water will be discharged to the open sea [1-7].

Inspired by the studies conducted in the Orbetello lagoon [5], we developed a versatile hydrodynamics numerical model adapted to the configuration of French Polynesian's bays. The model represents the first phase of a 3-step strategy conceived to increase water circulation and thus prevent the risk of hypoxia of the fauna and flora.

Given the multitude of configurations of lagoons and bays, we propose, at first, the study of water circulation in a bay with standard features: Paopao Bay (Moorea). Thanks to currentologi measurements performed by J. Hench in 2004, a theoretical approach of the water and oxygen circulation in PaoPao's bay is already possible [5]. The purpose of this study is to model the flow of water and the oxygen concentration in the Bay of Paopao according to different environmental conditions. The results will determine the essential characteristics of the hydrodynamic flow in the bay, which allow us to determine 5 critical point of the bays. A seasonal measurement campaign of the water level and currents in these points, phase two of the project, will permit to define the most effective strategy to optimize the hydrodynamics flow by the mean of water pumps, bottom dragging or reef drilling (final phase of the project).

PAOPAO'S BAY

The main axis of the lagoon is approximately north-south and is open to ocean at the Avaroa opening, Figure 1. The lagoon shows a depth of 30 m, while the reef flats are typically located at 2 m depth. The reef contains a geometrical constriction. The south end of the lagoon is surrounded by mountains on the east, south and west. An inspection by scuba divers revealed a relatively flat clay substrate in the deep lagoon (> 20 m) but with corals along the edge of the lagoon [8].

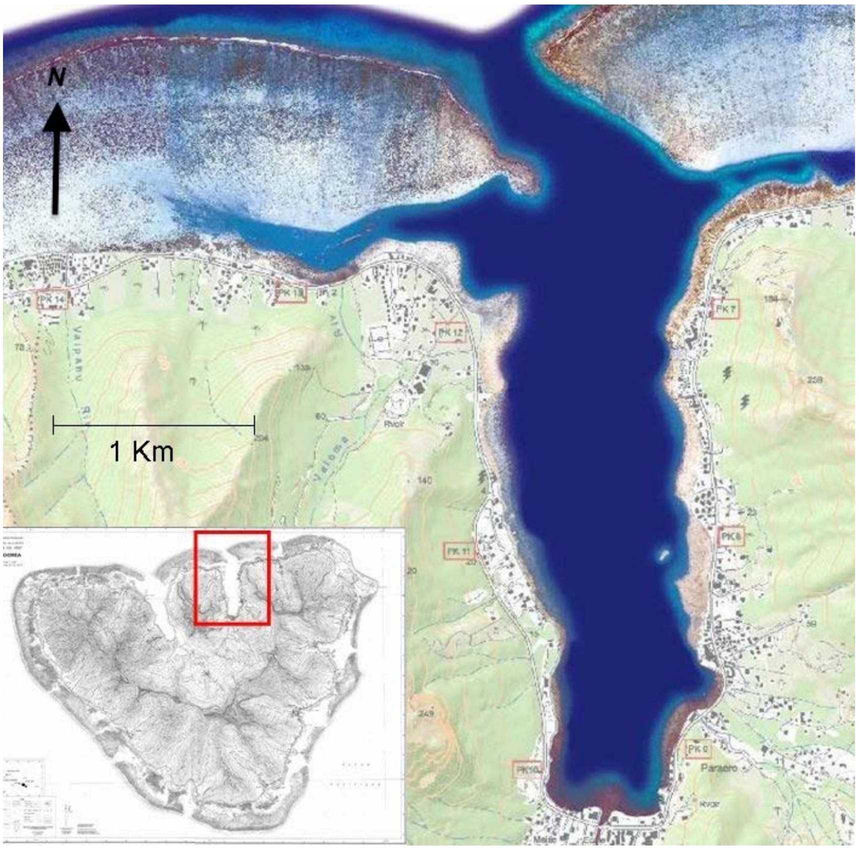

Figure 1. Topography of Paopao's bay, Moorea Island, French Polynesia [8].

THE MODEL

Circulation and hydrological measurements have been performed in the Bay of Paopao in 2004 by J. Hench [4]. The positions of measurement points are shown in Figure 2. The salinity along the section formed by the measuring stations in Figure 2 are shown in Figure 3. The measurements show that the variation of salinity in the water column is small (maximum amplitude of 0.5 psu) and therefore the application of a two-dimensional model is sufficient [6,14-16]. Salinity variations are due to significant rainfall, which usually take place early in the day.

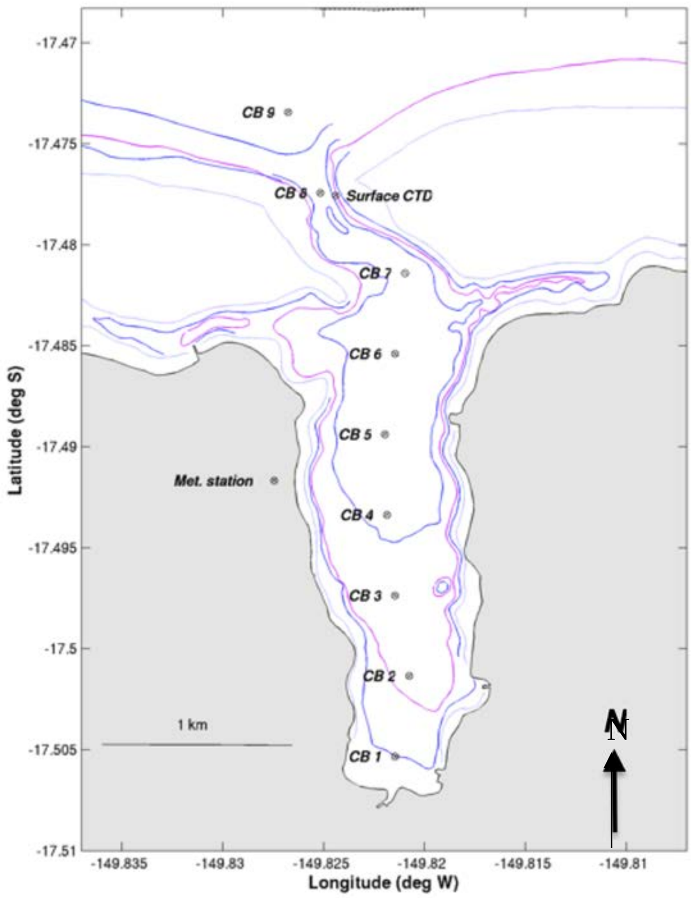

Figure 2. Position of the points of measurement (CB1, CB2, …,CB9) performed in the bay of Paopao by J. Hench in 2004 [1].

The two-dimensional hydrodynamic model that we developed for this study is based on an algorithm with finite differences [7-9]. Our model allows to determinate, at any point of the bay $\vec{x}$ and at any time t, the current velocity $\vec{v}(\vec{x},t)$, the oxygen concentration $C(\vec{x},t)$ and the water depth $w(\vec{x},t)$ relative to the mean ocean level $m(\vec{x})$, Figure 4. We adapted the finite difference scheme on a case study of the lagoon circulation by discretizing two equations.

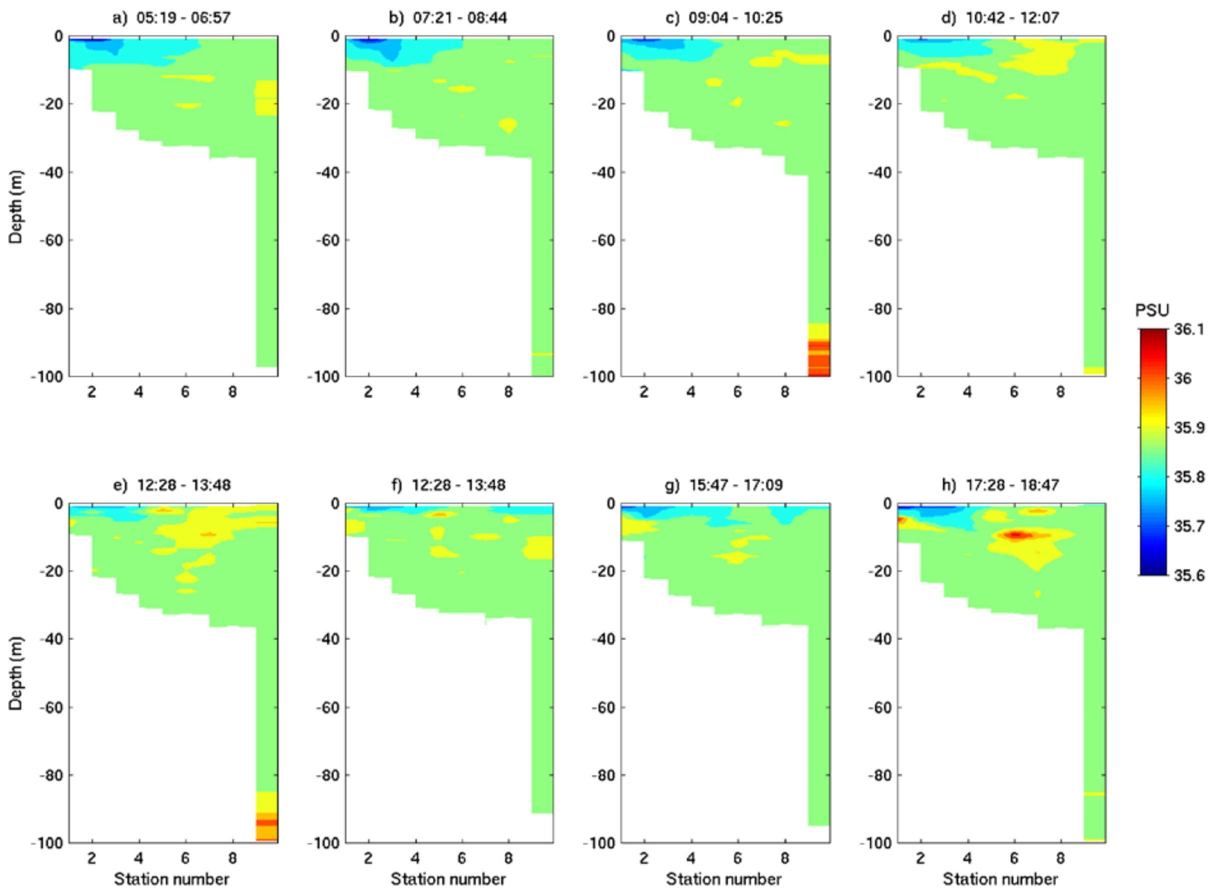

Figure 3. Salinity measured at the points showed on Figure 2.

In order to calculate the water circulation, we used the transport and diffusion equation:

$$\frac{\partial w(\vec{x},t)}{\partial t} = D\nabla^2[w(\vec{x},t)] \qquad \text{eq. 1}$$

for all the submerged points, i.e. for the points for which $w(\vec{x},t) > z(\vec{x})$. Here, $z(\vec{x})$ represents the distance of the sea bottom with respect to the mean sea level $m(\vec{x})$ and D the diffusion coefficient, Figure 4. In order to estimate the oxygen concentration $C(\vec{x},t)$ into the water, we used the transport equation of a passive scalar :

$$\frac{\partial\, w(\vec{x},t)C(\vec{x},t)}{\partial t} = -\vec{\nabla}\left[\vec{v}(\vec{x},t)\; w(\vec{x},t)\; C(\vec{x},t)\right]. \qquad \text{eq. 2}$$

In our model, the oxygen concentration is conserved, indeed, we neglect the dissipation due to consumption by the flora and fauna of the lagoon and the degassing into the atmosphere [15]. Simulations are performed by imposing at the surface of the water outside the bay a sinusoidal movement $m + a \sin(\omega t)$. Here, a represents the amplitude of the wave and ω the wave angular frequency. The latter, is not a physical parameter in our model because we did not consider the inertial term in equation (2). Finally, we assume that the concentration of oxygen in the ocean is constant.

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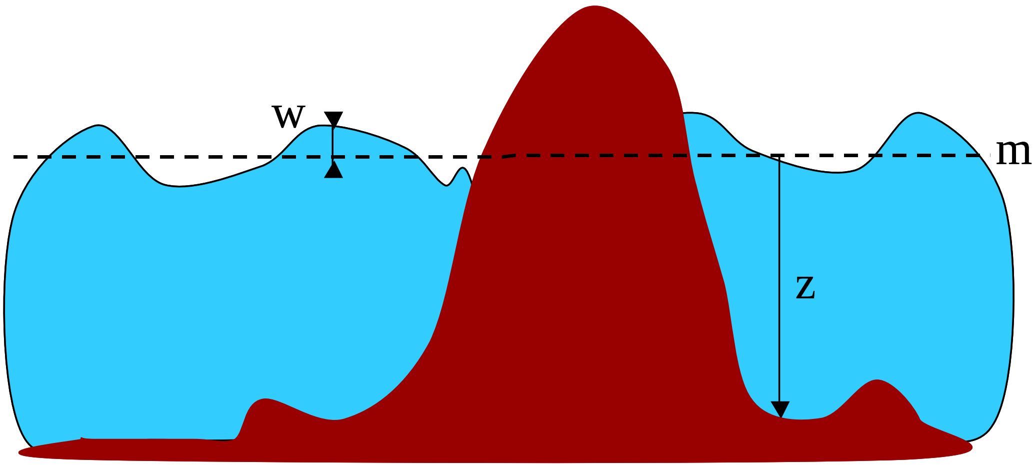

Figure 4. Definition of the geometrical parameters of the simulation : $m(\vec{x})$**,** $w(\vec{x},t)$ **and** $z(\vec{x})$ **, respectively : the mean sea level, the heigh of the water with respect to the rest level and the depth of the water with respect to the mean sea level.**

Bay bathymetry and boundary conditions, Figure 5, were obtained through the database of the “service de l’urbanisme” of the French Polynesia government [13]. The mesh used in the simulations is 768x768. The lateral size of each cell corresponds to about 4.5 m, which is more than satisfactory for the purpose of our study.

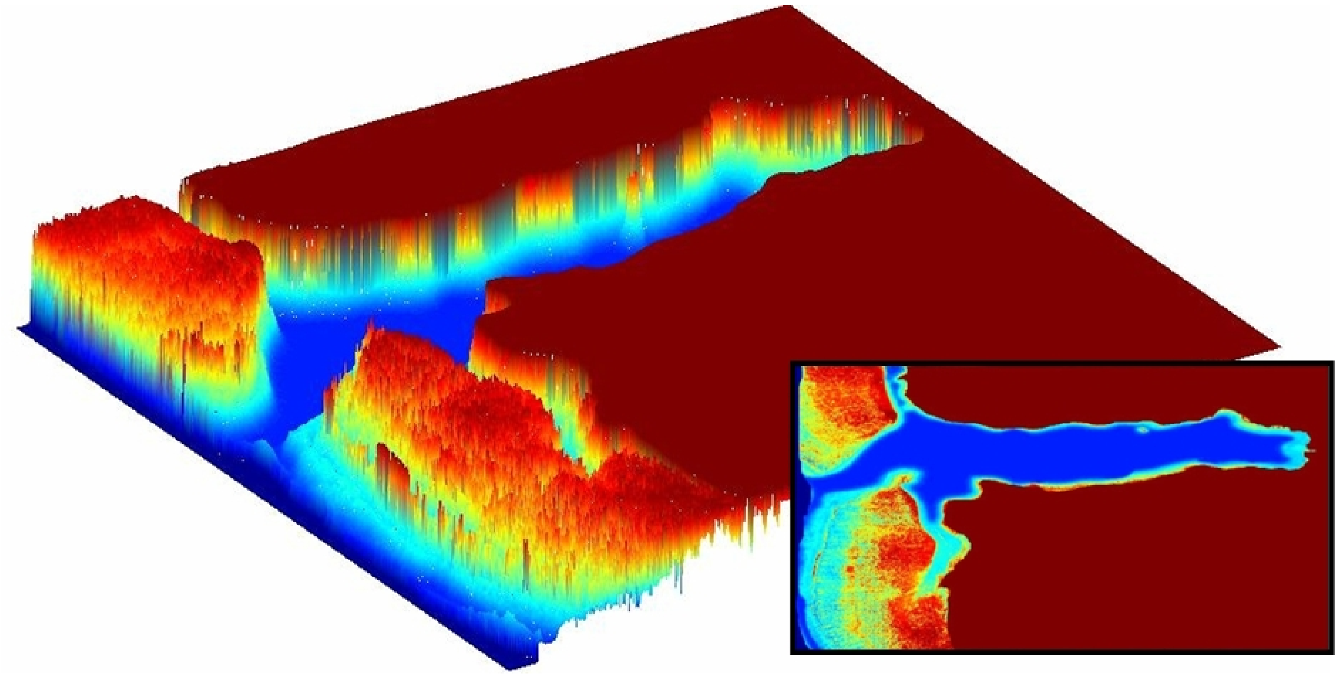

Figure 5 : The schematization of the bay used in the simulation.

RESULTS

The water circulation in the bay strongly depends on the condition imposed beyond the coral reef lagoon (ocean), in particular, the oxygen distribution and velocities in the lagoon strongly depend on the average level *m* of the ocean.

If sea level does not allow the ocean water pass over the reef, Figure 6, the ocean-lagoon water exchange occurs mainly through the pass (Avaroa opening). The bay's internal water circulation is very low. This limits the oxygen concentration in the bay. The oxygen transported by ocean water is concentrated on the outer reef, at the Avaroa pass and at the bay's entrance Figure 6a). The distribution of oxygen at the entrance of the bay is asymmetric, the concentration being higher on the west side, Figure 6a.

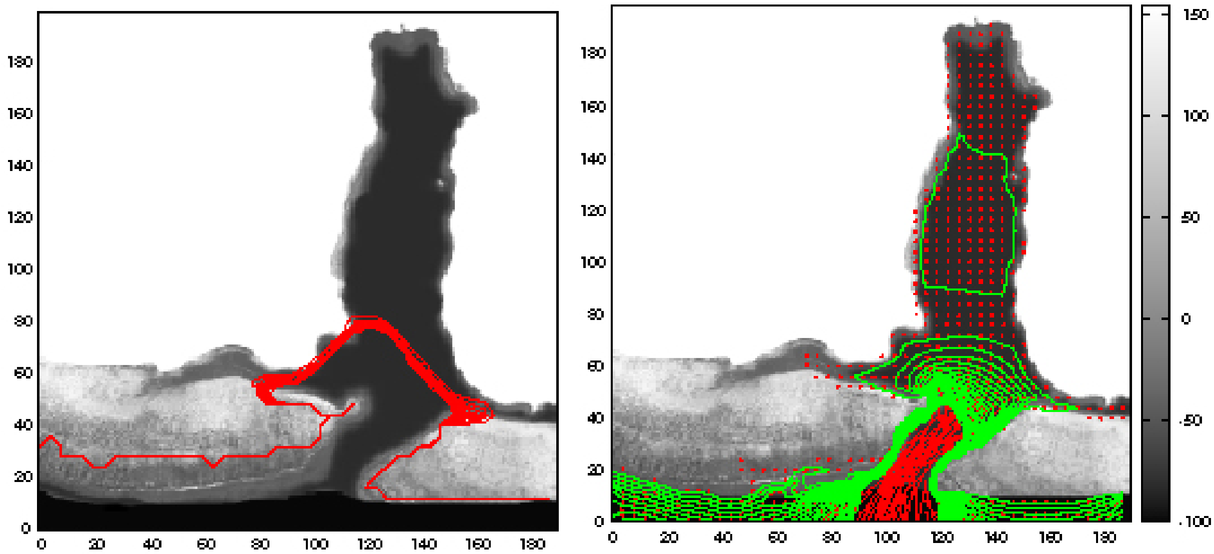

Figure 6 : The oxygen concentration a) and water velocity b) in case were the sea level m does not allow ocean water to pass over the reef. The red lines in a) and green in b) represent, respectively, the contours of oxygen and currents level. The units of axes are arbitrary.

Increasing the mean ocean level *m*, we observe that the ocean-lagoon water exchange is also done through the reef. If the reef is submerged only by the wave crests (i.e. mean sea level *m* is of the same order as the height of the reef), Figure 7, we note that the oxygen distribution at the bay's entrance become symmetrical with respect to the bay axis and enters a few hundred meters into the bay. In contrast, the concentration of oxygen remains high on the reef that faces the ocean and it is practically zero on the lagoon side. The reef to the west of the pass is lower than the one on the east side, because of this, the current in the in west (internal) side of the pass is much stronger that on the east side, where the water velocity is much lower.

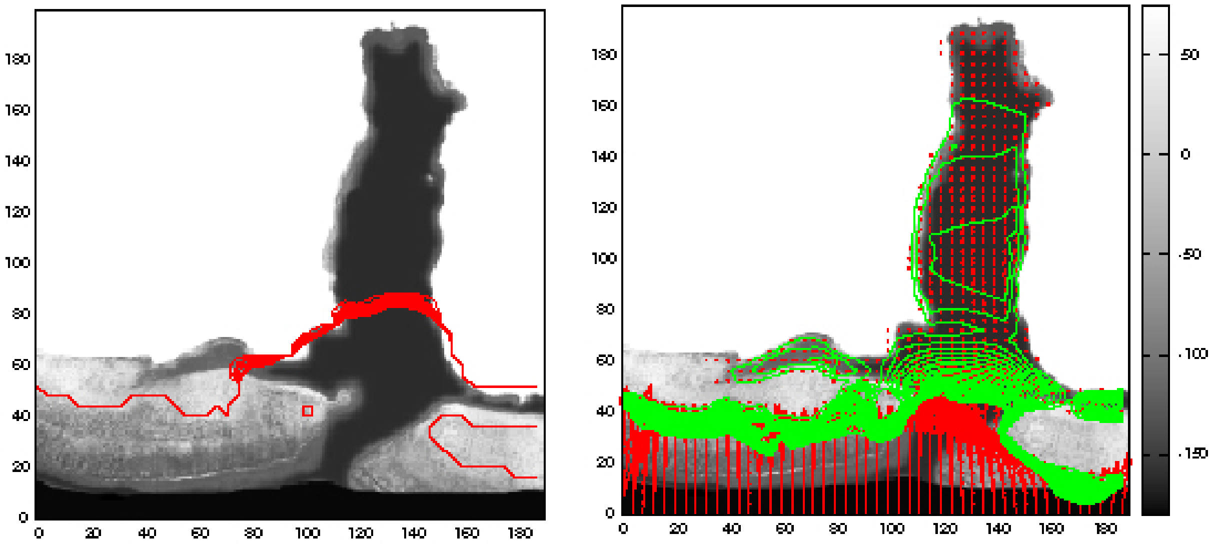

Figure 7 : The oxygen concentration a) and water velocity b) in case were the sea level m is about the same level than the coral reef. The red lines in a) and green in b) represent, respectively, the contours of oxygen and currents level. The units of axes are arbitrary.

If the mean ocean level *m* allows waves to easily pass over the coral reef (*m* > reef height), Figure 8, one can observe a strong water flow across the lagoon. However, inside the bay the current remains fairly limited. The water entering into the lagoon over the reef is discharged through the pass. Therefore, in these case there is an outward current at the pass. Because of this outward current, part of the oxygen that enters into the lagoon, escapes through the pass and returns into the ocean. The lower is the water that passes over the reef the lower is the oxygen penetrating into the. Because of the asymmetry of the reef, the outward west current in the Avaroa pass is stronger than on the east side, Figure 8a), in contrary to the case where the average level of the ocean is lower than the height of the reef.

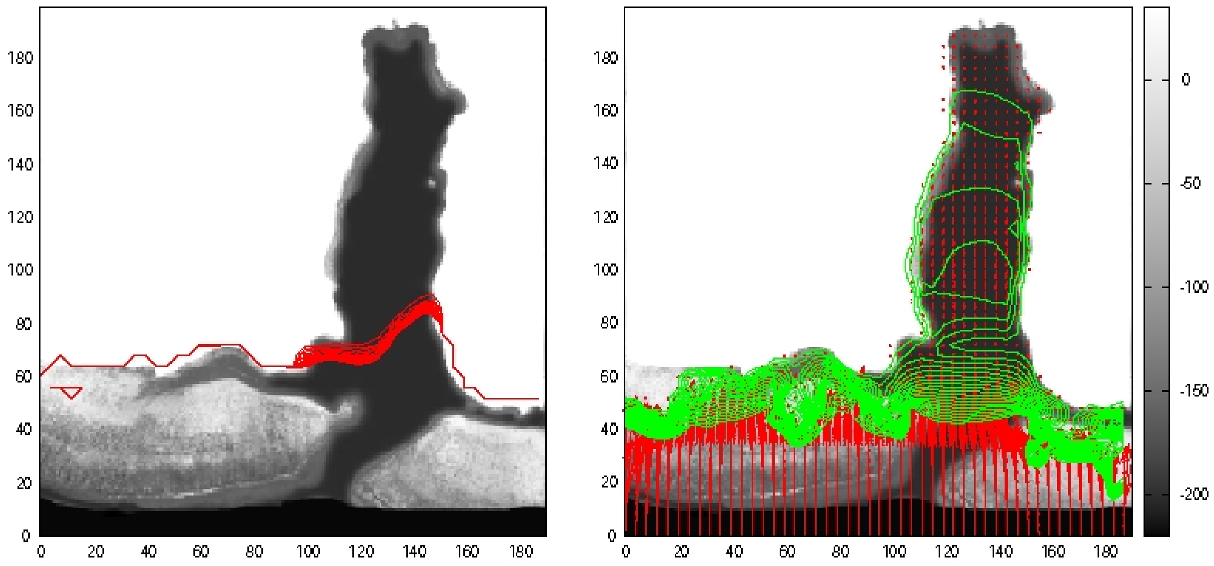

Figure 8 : The oxygen concentration a) and water velocity b) in the case were the sea level m Allows the ocean water to pass over the reef. The red lines in a) and green in b) represent, rispettivamente, the contours of oxygen level and currents. The units of axes are arbitrary.

These results are consistent with experimental measurements effected by J. Hench in 2004 [8]. As in our model, the currents observed in the bay are weak, slightly variables and they are stronger near the pass.

DISCUSSION

We developed a 2D numerical model, based on the finite-difference method to study the circulation in the Bay of Paopao. The water circulation in the bay is heavly dependent on the mean sea level *m* and on the waves amplitude *h*. Circulation within the bay increases proportionally to the average level of the ocean *m*. In contrast, the oxygen concentration decreases as the sea level *m* allows ocean water to easily pass over the reef and thus to create an outward current through the pass. We also observe that the oxygen concentration of the reef lagoon depends strongly on the average level of the ocean, while in the outer reef oxygenation is independent of ocean conditions. This is consistent with observations that show that the flora and fauna of the ocean side of the reef is much more developed than the inner side.

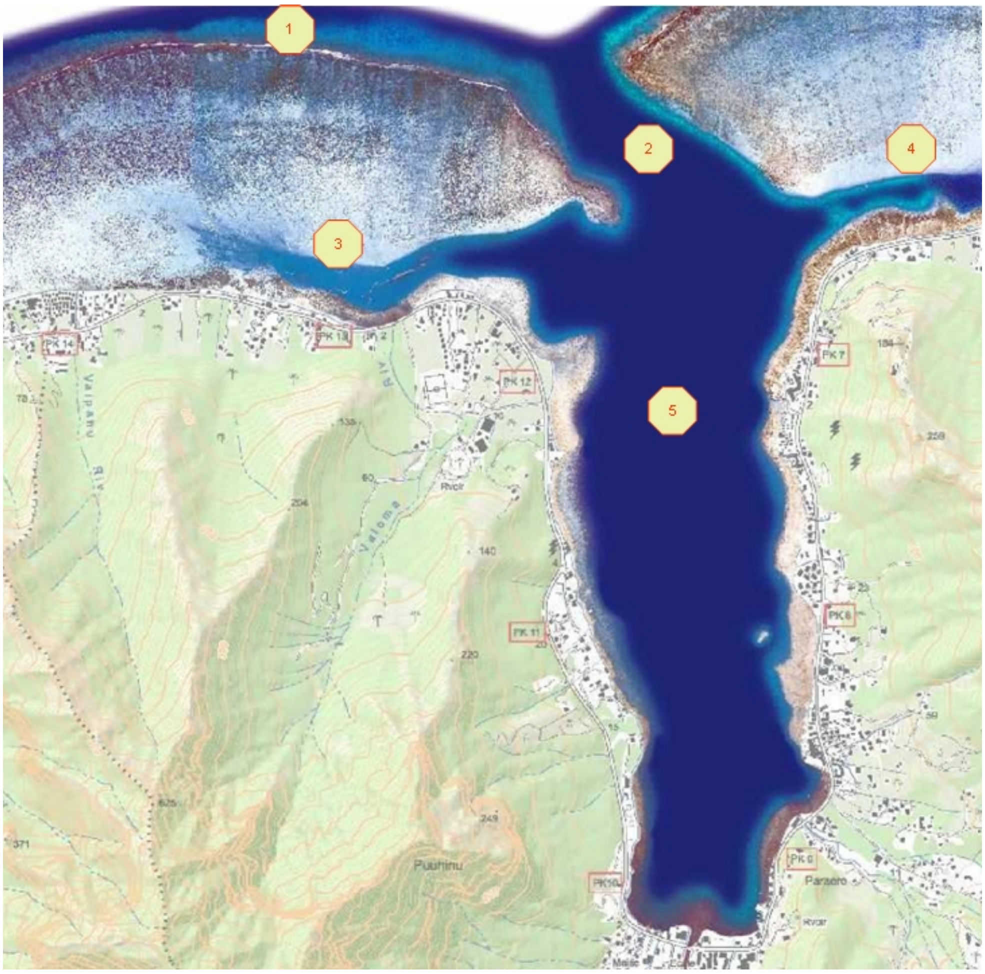

Figure 9: The proposed five measurement points.

In a second study phase, we propose to develop an effective strategy to force the water flow (pumps, dredging channels, reef drilling, etc.) in order to obtain a better water circulation and water oxygenation. For this purpose, it is essential to study the statistics of the conditions under which the bay is submitted. It is therefore necessary to conduct a measurement campaign in the bay. In order to optimize the measurement campaign, we propose to measure the water level and currents on the 5 points shown in Figure 9. The first proposed measurement point is on the ocean side, this is important to have a statistic of the swell which the bay is submitted. The second measurement point is at the center of the pass, this point is necessary to know the incoming or outgoing nature of the current. The third and fourth points of measurement give information on flow created by the reef-ocean interaction and the currents due to the lagoon surrounding the pass, which has not be taken into account in our simulation. These points lie on the sides of the pass lagoon. To get a statistics on the current inside the bay, we also propose a measuring point situated in the inner Bay: point 5 in Figure 9. This measurement campaign should be at least 1 year long, so that seasonal variations are taken into account. These measures would allow us to simulate the circulation in the bay in a more realistic way and therefore to develop the most effective strategy in order to optimize the flow hydrodynamics by the mean of water pomp installation, bottom dragging or reef drilling.

Our model is easily adaptable to the water circulation and oxygen transport study of other bays. A bathymetric map of the bay in question is all one need in order to run our simulation. It is therefore possible to generalize its use to all lagoon systems that have circulation and transport problems.

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