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Modeling Wind-Driven Circulation and Chlorophyll Concentration in Lake Valencia

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ABSTRACT

The goal of this research is to describe circulations patterns and chlorophyll concentration in Lake Valencia. The hydrodynamics of episodic events are simulated with a shallow-water model, coupled with an advection-diffusion equation. This model uses a MacCormack-TVD numerical scheme to solve the continuity and momentum equations simultaneously while the advection-diffusion equations determine the time dependent pollution dispersion, in particular the chlorophyll concentration. An analysis of chlorophyll concentration is completely developed and validated with satellite images of Lake Valencia. Although the use of shallow water models is a fairly standard in the study of lake circulation and chlorophyll concentration, its application to Lake Valencia is new. Therefore, the circulation and chlorophyll patterns developed in this numerical study represent an original contribution.

Keywords: Lake circulation model; Shallow water model; Advection-diffusion equation; MacCormack-TVD numerical scheme; Saint Venant equation; Chlorophyll concentration.

NOMENCLATURE

$b(x,y)$	bathymetry
$C(x,y,t)$	variable concentration
D	dispersion coefficient
f	coriolis parameter
g	gravity
$H(x,y,t)$	depth
$s_{f(.)}$	the slopes of the power lines dependent Manning roughness coefficient
Δt	simulation time step
$u(x,y)$	fluid velocity in direction x
$v(x,y)$	fluid velocity in direction y
Δx	spatial step in x
Δy	spatial step in y
$\eta(x,y,t)$	elevation
ρ	density
$\tau_{s(.)}$	wind shear stresses on the lake surface
ε	viscosity parameter
Δ	laplacian

1. INTRODUCTION

An increasing environmental awareness and the need to predict and improve the water quality in lakes and coastal seas has led to significant developments in wind-driven circulation and pollution transport modeling.

Hydrodynamic and pollutant transport modeling in closed water bodies requires a detailed knowledge of the transport processes existing within the body. Essential elements for life and productivity such as oxygen, heat and nutrients are transported and dispersed through these processes. These processes cause the dilution of pollutants though mixing with the ambient water resulting in their reduced impact on near shore areas. In the vicinity of Lake Valencia are industrial areas, where synthetic waste that ends up being deposited in the lake are generated.

These wastes often have high levels of phosphate and enzymes that speed playback chlorophyll. Consequently, resulting in the consumption of large amounts of oxygen and killing fish; process known as eutrophication.

The Lake Valencia is the second lake in importance of the Bolivarian Republic of Venezuela and is the biggest freshwater body of the country. Its basin is endorheic type and is located in the north central region of Venezuela, between Aragua and Carabobo states, has an area of about 391 km^2 and a maximum depth of 42.5 meters, draining water into the lake tributaries sixteen of which four are contaminated, see Fig. 1. This lake is the most important hydrographic phenomenon of the country: its length, width and maximum depth are 30 kilometers, 20 kilometers and 40 meters, respectively, which justified our two-dimensional simulation using a numerical model based on the Saint Venant equations, more information can be found in Garc´ıa and Kahawita (1986). The induced circulation can be hydraulically or wind-driven. Our work assumes that circulation in Lake Valencia is essentially wind-driven. The Lake Valencia basin is one of the most densely populated country with about 2.760.000 inhabitants in 0.3% of the country. Associated with this population density are all economic activities in the basin, which include heavy industrial activity with 30% of the country, where most paper factories, paint, batteries, food processing and metal processing industries; followed by agriculture, accounting for 3% of agricultural lands in Venezuela and where about 50% of these employees are agrochemicals.

Fig. 1. Venezuela map with zoom of Lake Valencia.

There have been some studies on the amount and types of pollutants found in Lake Valencia. Some of these studies have focused on deter-mining cadmium concentrations in water-soluble fractions, together with carbonates and total particles of different sizes in a soil of the basin of Lake Valencia. Garc´ıa and Sosa (1994) notes that lacustrine soils located in the Valencia Lake basin have significant concentrations of total cadmium, while Gonz´alez *et al*. (2010) concluded in their work that there are no significant differences between the size of the soil particles and the total content of cadmium concentration. Meanwhile, Xu and Jaff´e (2008) examined bulk geochemical parameters and organic matter biomarkers in a short, high resolution gravity core in Lake Valencia, to reconstruct anthropogenic impacts on the lake conditions.

In addition, there are several studies on Lake Valencia, particularly on the biological, physical and chemical properties of its waters at various observation's stations. We can cite as the most representative of these studies, William Lewis Jr. in the decades of the 70's and 80's, Infante *et al*. (1979), Lewis (1983a), Lewis (1983b), Levine and Lewis (1985), and the extensive report conducted by Lin (1982), which states the need for numerical modeling studies in order to better understand the complex processes occurring in the lake. These studies indicate that Lake Valencia is thermal, and possibly biological and chemically stratified. Abrupt changes in this stratification could explain the massive fish kill and changes in chemical composition of its water. The Ministry of Popular Power for the Environment of the Bolivarian Republic of Venezuela, since 1981, maintains a recovery program of Lake Valencia. As part of this program, in 2009 a campaign of sampling surface sediments of lakes in 41 seasons was performed following a sampling scheme in grid (2 × 1 km) using criteria that relate the current lake, areas of deeper, more pollution and near the mouths of tributaries and tributary areas, being determined the spatial distribution of phosphorus in the surface sediments of Lake Valencia, as well as the differences in function or grain size fractions, see Su´arez *et al*. (2013). These observations suggest that a rigorous numerical simulation of Lake Valencia should be done using three-dimensional models. The absence of information and data to feed the models has greatly limited its use. Recently there has been a unique three-dimensional numerical simulation reported by Torres *et al*. (2006). They analyze some configurations of movement, dispersal tracers and stratification effects, but their results are not conclusive. Other one-dimensional numerical simulations have been reported to determine side profiles of biological-chemical components or temperature, see for example the work done by Levine and Lewis (1987). Circulation models of Lake Valencia obtained by two-dimensional simulations using shallow water equations have not been reported as far as we have information.

The content of this paper is distributed in six sections. The first section is this introduction with the review of previous works. Then, the second section describes the Saint Venant equations the initial and boundary condition that modeling wind-driven circulation in Lake Valencia. The numerical model and the corresponding scheme description with applications in the basin are presented in the section three followed by the implementation of advection-diffusion equation and a data analysis in the section four. Finally, results and discussion, along with the appropriate conclusions are shown in the fifth and sixth sections, respectively.

2. SAINT VENANT EQUATIONS

The Saint Venant or shallow water equations model the propagation of disturbances in water and other incompressible fluids. The underlying assumption is that the depth of the fluid is small compared to the wavelength of the disturbance. Lake Valencia keeps this condition, so the use of Saint Venant equations provide a reasonable model for this situation.

The equations are derived from the principles of conservation of mass and conservation of momentum. The independent variables are the time, t, and two spatial coordinates, x and y. The dependent variables are the fluid height or depth, H, and the two-dimensional fluid velocity field, u and v. The force that acting on the fluid is gravity, represented by the gravitational constant, g. The partial differential equations are:

$$\frac{\partial \eta}{\partial t}+\frac{\partial Hu}{\partial x}+\frac{\partial Hv}{\partial y}=0,$$

$$\frac{\partial Hu}{\partial t}+\frac{\partial Hu^2}{\partial x}+\frac{g}{h}\frac{\partial H^2}{\partial x}+\frac{\partial Hvu}{\partial y}$$

$$=-gH\left(-\frac{\partial Z_f}{\partial x}-Sf_x\right)-\tau_{sx}+fv+\varepsilon\Delta(Hu), \qquad (1)$$

$$\frac{\partial Hv}{\partial t}+\frac{\partial Huv}{\partial x}+\frac{\partial Hv^2}{\partial y}+\frac{g}{2}\frac{\partial H^2}{\partial y}$$

$$=-gH\left(-\frac{\partial Z_f}{\partial x}-Sf_x\right)-\tau_{sy}-fu+\varepsilon\Delta(Hv).$$

where the depth $H = H(x,y,t)$ is defined as $H = \eta + b$, where $b = b(x,y)$ is measured bathymetry positive downward from the geoid and $\eta = \eta(x,y,t)$ is the elevation of the free surface relative to the geoid. The source terms in turn contains the following expressions: g is gravity, f is the Coriolis parameter, Z_f is the bottom elevation, $\tau_s(.)$ is the wind shear stresses on the lake surface, ρ is the density, ε is a viscosity parameter, Δ is the Laplacian and $s_{f(.)}$ are the slopes of the power lines dependent Manning roughness coefficient, more information can be found in Garc´ıa and Kahawita (1986) and Tsanis and Saied (2007).

The differential equations that arise must be treated with an appropriate set of initial and boundary conditions. The initial conditions are the speeds u and v, and the depth H throughout the calculation field for the initial time point (t=0): $(t=0):\ u(x,y,0)=u_0(x,y),$ $v(x,y,0)=v_0(x,y),\quad H(x,y,0)=H_0(x,y).$

Usually these values are known a priori, or it is necessary to estimate physically realistic values based on experience. In this paper, it is assumed that the flow velocities are initially zero and the bathymetry data is taken as the initial depth.

The boundary conditions, in this investigation, are closed and define the calculation field where the water surface is in contact with the ground. This type of boundary condition is sometimes called waterproof condition. In this research, the viscosity parameter is not null, which makes our formulation of the Saint Venant equations slightly parabolic. Consequently, it becomes necessary to change or supplement the boundary condition of impermeability to zero speed, sometimes referred to as non-slip condition. That is, $(u,v) = 0$, and additionally $(u,v)\ .\ n = 0$. The combination of the equations, initial conditions and boundary conditions described produce a mathematically well-posed problem, which was discretized using the finite difference method developed by Garc´ıa and Kahawita (1986).

3. NUMERICAL MODEL

The main program consists of two models; hydrodynamic model and pollutant transport model. Hydrodynamic and pollutant transport modeling in closed water bodies require a detailed knowledge of the transport processes that exist within the body. Hydrodynamic or circulation model is bidimensional and employs the conventional horizontal depth-averaged model and the pollutant transport model is a depth-averaged model for the advection-diffusion equation. Below is presented a description of both models.

3.1 Hydrodynamic Model

We call hydrodynamic model, to the two-dimensional numerical model used in this paper to solve the Saint Venant equations, which is an adaptation of the finite difference scheme for fractional steps developed by Robert W. MacCormack in the early 70s. This algorithm is based on the type fractional step which allows subdividing a finite difference operator into a series of simple operators. This reduces the volume of the calculation, whilst reaching second order accuracy in time and space.

The resulting numerical scheme is explicit, which avoids the cost of evaluating the Jacobean, but imposes constraints on the time step to ensure stability. Also, this hydrodynamic model is $O(\Delta t)$ + $O(\Delta x)$ and has no dispersive effects. The study of the linearized hydrodynamic model provides the following stability condition:

$$\Delta t \le \min\left[\left(\frac{1}{\Delta x^2+\Delta y^2}\right)^{-1/2}(gH)^{-1/2}\right], \qquad (2)$$

where Δx, Δy and Δt are the dimensions of the blocks of the mesh and the simulation time step, respectively. The consistency and stability of the scheme guarantees convergence. The implementation of the numerical scheme described by Garc´ıa and Kahawita (1986), was conducted at the Institute of Fluid Mechanics at the Universidad Central de Venezuela (UCV) and has given rise to a hydrodynamic code which has been used in this research to study the static circulation of Lake Valencia.

3.2 Pollutant Transport Model

The two-dimensional depth-averaged advection-diffusion equation representing the fate of a conservative pollutant can be expressed as:

$$\frac{\partial C}{\partial t}+\frac{\partial (Cu)}{\partial x}+\frac{\partial (Cv)}{\partial y}=\frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D\frac{\partial C}{\partial y}\right) \quad (3)$$

where D is the dispersion coefficient; u, v are the depth mean velocities in the x and y directions, respectively, and C is the variable concentration, see Pearson and Barber (1996). This equation can be interpreted from a particle tracking perspective. If C is considered as a probability density function, the Eq. (3) is identical to the Fokker-Planck equation. The boundary conditions completing the model are: (a) solid boundaries - zero normal flux,

(b) free transmission boundaries - uniform flux, and

(c) pollution sources - pollutant concentration is known, see Tsanis and Saied (2007). The stability condition for this model is given as follows:

$$\max\left(\left|u\frac{\Delta t}{\Delta x}\right|,\left|v\frac{\Delta t}{\Delta y}\right|\right)<1. \quad (4)$$

The Fokker-Planck equations takes place under the action of both advection and diffusion each time step. In order to translate the particles due to pure advection, it is necessary to introduce the velocities calculated by the hydrodynamic model. The method used for the approximation of the concentration at the faces of the grid cells is the centered finite difference. Any particles which cross a solid boundary are immediately reflected back into the flow domain thus maintaining mass conservation. The method is conservative, preserve and conditionally stable although the time step should be limited order to obtain an accurate representation of the advective transport.

4. DATA ANALYSIS

There are four types of data used in this research: (i) the geometry, (ii) the meshing, (iii) the bathymetry and (iv) the wind direction.

The geometry of the problem is presented in Fig. 2(a) which is a schematic representation of Lake Valencia, Venezuela. The meshes used are uniform and formed by square blocks as shown Fig. 2(b). The dimensions of the blocks used in the simulation can range from 1 kilometer to several hundred meters. It has been found these quantities are sufficient for the circulation study. The simulation of large bodies of water by the shallow-water equations is well known, see Miller (2007). In the specific case of this investigation, several models were developed to generate interpolation bathymetry data associated with different mesh sizes. This information is available in graphical form for digitization in several references, see Infante *et al*. (1979), Lin (1982), Min. del Ambiente (1995). Fig. 3 shows one form of the bathymetry used in this work. This bathymetry is generated by linear interpolation on the simulation grid.

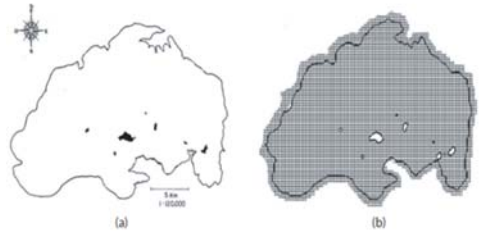

Fig. 2. (a) Schematic representation of Lake Valencia and (b) Lake Valencia simulation mesh of 95 × 65 blocks where Δx = Δy ≈ 300m.

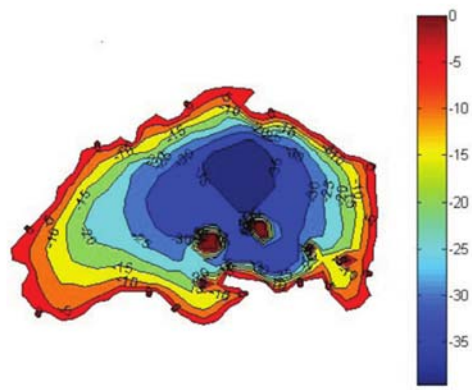

Fig. 3. Lake Valencia bathymetry measured in meters.

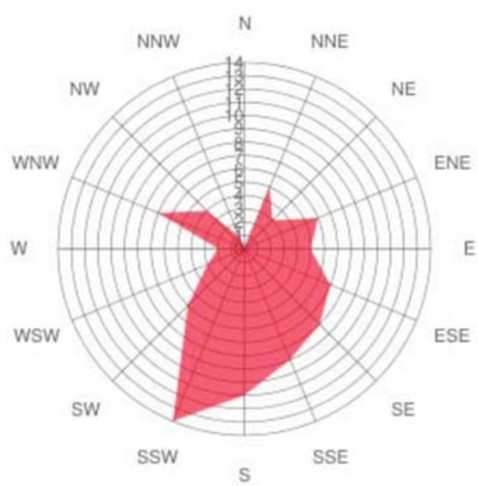

Fig. 4. Rose wind measured in km/h.

The Saint Venant equations require certain parameters which were compiled from average values reported in the literature, see Miller (2007), except for the wind speeds and directions. We use records pertaining to the Base Mariscal Sucre (Boca de Rio). For simplicity, as a first approach to the simulation of the movement of Lake Valencia, this paper took a weighted average of the collected information. In each simulation, a single constant speed and wind direction around the lake was assigned.

A good distribution of these quantities is given by the wind rose shown in Fig. 4. This speed in this wind rose is given in km/h and the wind direction is given in terms of the cardinal coordinates. This graph indicates that the direction of the winds in Lake Valencia may vary from the north-west (NW) to the north-north-east (NE), and may take either direction between the range containing the south direction (S). The wind speed falls within 0-15 km/h. The wind rose has not statistical information, but we can infer that the average magnitude of the wind speed should be approximately 10-11 km/h, which represents about 3 m/s. This speed has been used in the simulation discussed in the following section. In addition, for purposes of the simulation, to be discussed below, it is assumed that the wind is south-south-west direction. This direction is similar to that reported by Torres *et al*. (2006) which partly justifies its use.

5. RESULTS AND DISCUSSION

The simulations are stopped when the kinetic energy of the lake reaches a steady-state and the velocity distribution associated with that state has called static circulation, see Blaisdell ***et al.*** (1991). Figure 5 shows the kinetic energy curves versus time for different values of the wind speed. This figure shown that the kinetic energy of the lake always reaches a steady state, assuming that the wind speed is constant. The stability level of kinetic energy is directly proportional to the magnitude of the wind speed. The numerical test for the hydrodynamic model of Lake Valencia found that the time step does not significantly affect neither the total kinetic energy of flow nor the time required to reach the steady state as long as the stability criteria is satisfied. To study the effect of the wind speed on the time to steady state, several runs were made to obtain the stationary state.

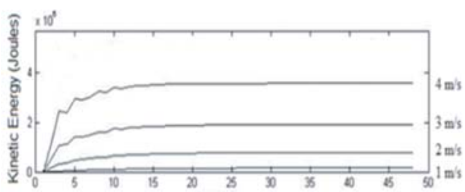

Fig. 5. Kinetic energy vs. Time.

Figures 6 and 7 are a representation of the static circulation and the velocity field for Lake Valencia obtained numerically by the shallow-water simulation. It is assumed that the wind speed and direction is 3 m/s from south-south-west to north-north-east of the lake throughout the simulation.

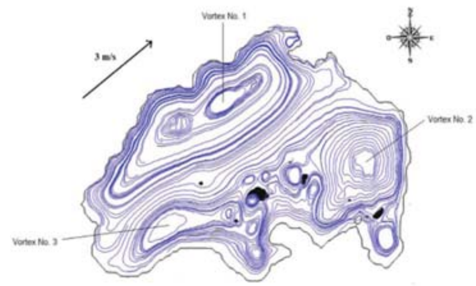

Fig. 6. Static circulation of Lake Valencia.

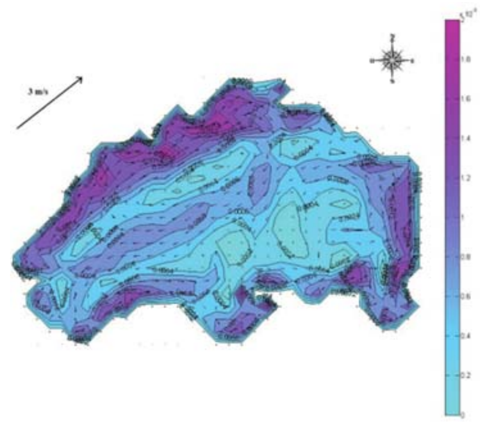

Fig. 7. Magnitude and velocity field of the flow in the static circulation of Lake Valencia.

Figure 6 shows, from another perspective, the structure of static circulation of Lake Valencia under the conditions described above. The formation of eddies or vortices in endorheic lakes, whose streams are defined by the wind, is a normal phenomenon. However, it is not always easy to predict the number of vortices that can be generated. In this graph there are three major vortices, all adjacent to a transverse current, flowing north-east to south-west through the interior of the lake. Vortex No. 1 is the largest, and is determined by the current of the north-west and crosses the internal current inside the lake. Vortex No. 2 appears to be generated artificially by Tacarigua's island, which is a large island in Lake Valencia. Vortex No. 3 is generated naturally by currents to the east and south-east coast of the lake, along with the large current flowing transversely inside. This vortex encompasses a small island that, by its size, cannot generate vortices in the environment. This observation seems to indicate that the inclusion of tiny islands, of which there are approximately twenty-two, would have little effect on static circulation configurations of Lake Valencia. Our results agree with those reported by Torres *et al*. (2006), especially with regard to the strong currents generated along the coast, parallel or partially parallel to the wind direction. The result presented in Torres *et al*. (2006) does not show the existence of vortices, constituting the main discrepancy with our results.

The analysis of Fig. 7 will be made taking into account the magnitude and direction of the currents. From the point of view of magnitude, it is observed that the scale values corresponding to high velocities are distributed almost throughout the coastal region of the lake, except the north-east and south-west. This behavior of the magnitudes of the current velocities is physically consistent with the wind direction. In shallow-water models for lakes, higher currents near the coast or shores occur when there are no other sources of current, which is the case we are simulating. The magnitudes of low current velocities, associated with the colors at the bottom of the scale, are located inside the lake and coastal parts previously excluding. This behavior is also physically consistent, since the wind must move a large water column due to a greater depth. Around the northeast coast, the low speeds are almost perpendicular to the wind direction. The low speeds around the south-west coast are determined by the current flowing in the opposite direction to the wind inside the lake, which is best shown in Fig. 7. Standard speeds that are present in this figure are scaled (i.e., calculated from a coarser mesh), however, major vortexes remain.

In the vicinity of Lake Valencia are industrial areas, where synthetic waste that ends up being deposited in the lake are generated. These wastes often have high levels of phosphate and enzymes that speed playback chlorophyll. Consequently, resulting in the consumption of large amounts of oxygen and killing fish; process known as eutrophication.

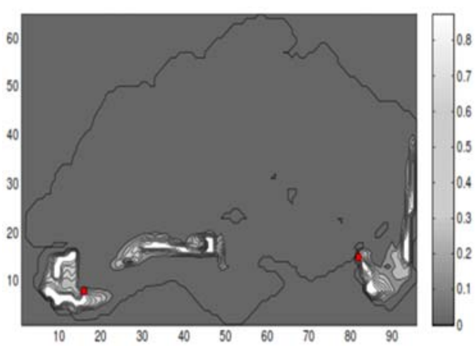

Fig. 8. (a) Pollutant distribution in Lake Valencia by the numerical scheme.

Chlorophyll concentration optically measurable because the chlorophyll pigment is a photoreceptor capable of transforming the energy to sunlight into chemical energy. This typically has two absorption peaks in the visible spectrum, one in the vicinity of the light blue and the other in the red area of the spectrum. These bands reflect the more nourished part corresponding to the green color. Thus, it can be easily detected by their behavior in the light or reflectance. The reflectance can be found and observed through satellite imagery. An image of the satellite Landsat 8 is considered a spatial resolution of 240 meters in the month of March 2014. The suitable index for the reflectance of chlorophyll is the vegetation. This index is NDV I and is obtained from the following operation between bands:

$$NVDI = \frac{Band4 - Band3}{Band4 + Band3}, \tag{5}$$

where *Band 3* represent the red band and Band 4 the infrared band.

Figure 8 shows the chlorophyll distribution after releasing the chlorophyll in two sources points, one at the south-west and other in the south-east of the lake, represented in Fig. 8 by rectangles. This figure shows the concentration of chlorophyll after releasing a conservative source continuously. Firstly, it is in the early time steps model the transport of particles in the lake (advection). Secondly, beginning to be seen the spread of the contaminant in the various regions of the lake (diffusion), as shown in Fig. 8. This image is obtained in the simulation generated by the advection-diffusion equations, (3). Comparing the image in Fig. 8 with the satellite image, Fig. 9, obtained in March 10, 2014, a great similarity is observed in the results. Satellite images considered, due to the average wind direction during the month coincides with that used for calculating the static current flow shown above. For this reason, our results are consistent.

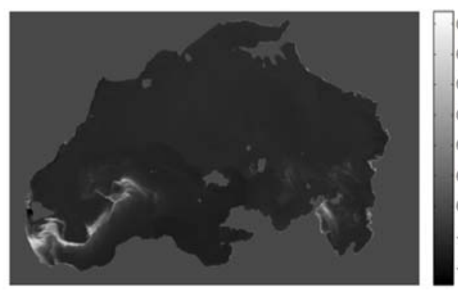

Fig. 9. (a) Satellite image.

6. CONCLUSION

It has been presented for the first time, a study of static circulation of Lake Valencia based on a two-dimensional hydrodynamic model. It is partially shown the results associated with wind settings mostly used in other research. Under constant wind directions, the kinetic energy of Lake Valencia, reaches a stable value in a few hours of simulation. The stability energy allows talking about static circulations. The static circulations obtained are physically consistent. The circulation obtained, overlap with those reported in the three-dimensional case near the boundary. A comparative study between two and three dimensional hydrodynamic models will be necessary. It is desirable to do field measurements in Lake Valencia, which allows properly adjust for any hydrodynamic model used for their study. The effect of several rivers flowing into Lake Valencia is a topic of study that has not been addressed in any simulation model. The study of the circulation generated by position dependent wind speeds is a topic of current research. Due to the large number of islands and the importance of the streams at the edges, would be advisable to repeat this study with a hydrodynamic model using adaptive mesh to the geometry of the lake. The method is conservative and useful from the qualitative point of view as means of assessing pollution transport trends, in particular chlorophyll concentration, and perhaps to assist in contingency planning.

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