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Assessment of Wind-Induced Sediment Resuspension Zones in the Patzcuaro Lake Using Empirical Equations

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors designed the study, performed the statistical analysis, wrote the protocol, wrote the first draft of the manuscript, managed the analyses of the study and managed the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

Aims: An analysis to determine sediment resuspension zones in the Patzcuaro lake (Mexico) through empirical equations is carried out.
Place and Duration of Study: The study was carried out at the Patzcuaro Lake in Michoacán, Mexico. The last stage of the project was finished during January 2019.
Methodology: The site wind force is considered as the main cause inducing the resuspension. Wind data recorded at two near stations (Chupícuaro and Pacanda) were processed and the main wind directions, in terms of intensity and duration, were obtained. Additionally, wind-induced wave values and the initial depth for the resuspension phenomenon were computed. Finally, bathymetry maps are plotted to indicate the zones where sediment resuspension occurs in the lake for the

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minimum water depth scenario concurrent with maximum winds and a sufficiently long duration to generate resuspension.

Results: Towards the north zone a larger particles motion is observed in the lakes riviera, form 5 m depth to the shore. In the middle part of the lake a larger incidence of the resuspension phenomenon is exhibited, since it is developed for all the considered depth levels. In the south part the resuspension is almost absent; only a spot between the Tecuén and Janitzio Islands show resuspension.

Conclusion: The empirical equations are a useful alternative to evaluate the quality of shallow lakes in terms of sediment resuspension.

Keywords: Resuspension; sediments; empirical equations; Patzcuaro Lake.

1. INTRODUCTION

The resuspension of deposited particles at river, estuaries or lakebeds is a phenomenon usually triggered by friction forces over the surface due to the water movement. In [1] a summary of references where the background and recent information on sediment resuspension as the consequence of hydrodynamic processes can be found (e.g., [2,3,4,5,6]). On rivers and estuaries this flow is frequently influenced by the gravity. In lakes or dam reservoirs the main force to move the flow is wind [7]. Sediment resuspension has been recognized as one of the most important factors with regard to eutrophication [8]. In shallow lakes the inorganic sediment particles and algae are constantly moving as a response to the resuspension and sedimentation cycle. The wave activity very often causes the resuspension (wave effects induced by wind can cause disturbances that are able to reach the bottom of the water column [9]); however, sometimes the fishes looking for food at the lakebed can move the particles causing sediment resuspension. The Patzcuaro lake is a shallow water body located at Michoacán State in Mexico, where the weather is template and humid. The potential resuspension in the lake is feasible due to the lake morphology and the magnitude and direction of the governing winds at the site.

An approach based on empirical equations can be effective in small lakes with shallow waters [10], as is the case of the Patzcuaro Lake. For larger bodies of water or consideration of many variables, measured values have been contrasted in the literature with methodologies derived from advance techniques to include water temperatures using thermistor chain, the use of optical backscatter sensors for the measurement of turbidity, a surrogate for suspended sediment concentration, and also the use of meteorological data [11]. The use of empirical equations is a valuable alternative reported in the literature; for instance, [12] established empirical formulations of sediment entrainment and resuspension processes, which were parameterized by laboratory data and field studies in Lake Michigan.

To investigate the sediments resuspension at lakes is important, since it can cause problems in the water bodies which exhibit this phenomenon. Among the more relevant problems in the lake that resuspension may cause, it can be mentioned: 1) an increase in the turbidity and a decrease of light penetration at the water column, which reduces the depth at which algae and submerged littoral vegetation can developed, 2) a significant decrease of dissolved oxygen and a corresponding increase in the Biochemical Oxygen Demand (BOD), which directly affects the fishing activity, 3) the cumulated nutrients at the lakebed are frequently transported inside the water column, leading to an increasing algae development and, 4) the resuspension process, together with the wave effects, create a sediment layer which makes difficult the growing of the aquatic plants roots. More detailed effects of the sediment resuspension in lakes, from an environmental standpoint, are available in the literature. For instance, [13] describes how wind-induced wave disturbance resuspension (but also resuspension due to currents, turbulent fluctuations and bioturbation) may lead to an impact in the water quality characteristics such as turbidity, light conditions, and concentrations of suspended solids and nutrients; moreover, the increase in turbidity may favor the larger development of phytoplankton in comparison to macrophytes, the predator-prey interactions contributing to the trophic state of a lake may also be affected by an increase in the turbidity levels; resuspension also enhances the cycling of phosphorus and switches between phosphorus and nitrogen limitation may be induced, among other issues.

The main objective of the present study is to assess the wind-induced sediment resuspension at the Patzcuaro lake by using empirical equations, so that possible resuspension zones under critical physical conditions can be located and visualized. Results could be useful for engineering and environmental purposes.

2. METHODOLOGY

In the present study the main variables to assess sediment resuspension are first characterized (in quantitative terms) and then used for the computing. With available information from records and/or the literature, the wind at the site is determined, then the fetch and bathymetry are also determined, and finally the mathematical expressions to estimate the resuspension are described. Results are given in the next section.

2.1 Wind

The height and period of the waves are a direct function of the wind velocity; consequently, a wrong estimate of the wind velocity would lead to large errors in the assessment of the wave parameters; wind conditions for a given direction and constant duration, able to mobilize the lakebed material, should be taken into account [14]. The wind characteristics at the site are estimated from recorded data in the nearest of the lake at a 10 m height over the lake (U_{10}). A conversion factor denominated as U_A, is used to adjust the land wind velocity to water surface wind velocity, and is given by Equation 1 [15].

$$U_A = 0.71U_{10}^{1.23} \tag{1}$$

A total of 24,772 wind data were analyzed for two stations; data were recorded each 20 minutes from June 2003 to December 2004. For the wind data, the Mexican Institute of Water Technology (IMTA, by its acronym in Spanish), through the Department of Hydrological Technology, installed two climatological stations [16]. The stations are located in the municipality of Chupícuaro and the Pacanda Island, and are shown in Fig. 1, together with the Patzcuaro Lake.

A statistical analysis was performed with the wind data to compute the weighted average as the mean value for several directions. In Tables 1 and 2, for Pacanda island and Chupícuaro stations, respectively, the considered directions, magnitude and frequency of the most frequent (mean) and governing (maximum) winds are listed.

Fig. 1. Location of the wind stations considered in the study (from Google Maps)

Table 1. Most frequent and maximum winds in the Pacanda island station

	Wind velocity (m/s)							
Directions	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
%	39,14	13,23	2,93	7,80	11,15	2,99	2,76	20,01
Mean wind	2,08	1,06	1,27	2,02	2,13	1,41	1,12	2,95
Maximum wind	2,16	2,34	3,12	4,07	4,25	3,20	2,66	4,50

In Table 1 it can be observed that the mean and maximum predominant winds occur in the north direction with a 39% of observations, and a velocity over the 2 m/s. The maximum value was recorded in the northwest direction (4.5 m/s) with an incidence of 20%.

The winds at Chupícuaro station exhibited a larger incidence percentage in the south direction (29%), being the mean value equal to 0.66 m/s and the maximum equal to 1.36 m/s for the general average. The largest value occurred also in the northwest direction, with a value of 4.37 m/s and an incidence percentage of almost 20%.

In order to adjust the wind velocities reported in Tables 1 and 2 so that they can be useful for the present study, it should be considered that the sediments resuspension occurs when the wind lasts over 3600 seconds in the same direction [15]. Therefore, an analysis of the average winds selecting the maximum significant values (for one-hour duration) in the same direction for each station was required, so that a map with such average values could be plotted; they are listed in Table 3.

In Table 3, values in bold numbers correspond to intermittent and scarce winds, which occurred rarely and did not impact significantly the results; nonetheless, an analysis for these cases was performed, because resuspension could exist due to these winds for the corresponding direction, although it would be for a very short period of time (one hour, once in a year, approximately).

With the carried-out analyses, it was found that a wind of 10.8 m/s in the north direction has a larger incidence in the lake during a year, besides its magnitude and duration is usually larger than in any other direction. This value will be considered to compute the sediment resuspension in the present study, since it represents a condition under which the resuspension phenomenon is likely to occur. By using Equation 1 the final considered wind velocity was 12.2 m/s.

2.2 Fetch

The fetch represents the distance in which the wind flows freely (without obstacles) over a water body and leads to an optimal development of wave activity. The expression by [17] was employed to determine the fetch and is given by Equation 2 below.

$$F = \frac{\sum_{i=1}^{15} xi(\cos\alpha)^2}{13.5} \tag{2}$$

Where, F is the effective fetch, xi denotes the distance from a given point in the lake to the shore, and α represents the wind angle direction in azimuth.

Table 2. Most frequent and maximum winds in Chupícuaro station

	Wind velocity (m/s)							
Directions	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
%	6,30	4,84	4,32	18,54	29,97	6,70	9,54	19,80
Mean wind	1,45	1,69	0,80	0,55	0,66	0,88	1,54	2,35
Maximum wind	3,26	4,25	2,52	1,43	1,36	2,75	3,67	4,37

Table 3. Winds with maximum duration and intensity at the studied Site (m/s)

	N	**NE**	**S**	**SW**	**E**	**W**	**NW**	**SE**
Pacanda	10.8	7.01	7.17	6.10	**4.52**	**10.55**	**4.15**	**11.40**
Chupicuaro			1.91	1.81	4.40			

**Blank spaces correspond to directions with not significant values*

2.3 Bathymetry

From the level records provided from the Patzcuaro Fishing Agency, from 1978 to 2004, the minimum observed level of the lake in that period was obtained. It corresponds to October 2001, when the recorded value was 2035.08 meters above sea level (MASL).

In Table 4 a summary of the observed elevations is listed; values in bold and italics correspond to maximum and minimum recorded values in the available time window, respectively.

With the minimum available recorded level, the bathymetric plot was obtained (where bathymetry can be understood as a survey of the lakebed), by adjusting the level curves to visualize the minimum and maximum depths in the lake for this scenario and is shown in Fig. 2.

2.4 Sediments Resuspension

The sediments resuspension occurs when the wind-induced waves move the lake matter. The intensity of this phenomenon is determined by the wind velocity transmitted to the wave and the water depth in the lake. The maximum horizontal wind velocity generated by the waves decreases exponentially as a function of depth.

To compute the sediments resuspension empirical equations were used (Equation 3, [10]), which give the wave length as function of wind velocity and fetch; once the wave lengths are computed, the criterion that only those waves which reach the lakebed generates resuspension is established, in order to define relevant values as per Equations 4 and 5 [10] explained below.

$$L_w = 1.56\left[0.77W \tanh\left[0.077\left(\frac{9.8F}{W^2}\right)^{0.25}\right]\right]^2 \quad (3)$$

where L_w is the wave length in m, W is the wind velocity in m/s and F denotes the fetch in m.

The wave length is increased almost linearly with increasing wind velocities, while the fetch increment is non-lineal.

The resuspension is site-dependent (i.e., it behaves different from body water to body water), since it depends on the sediment type, the size and the depth of the lake, among other variables. Considering some practical trends and the literature [10], the resuspension happens when the wave length is at least two times the depth D, i.e., when

$$L_w = 2D \quad (4)$$

$$D = \frac{L_w}{2} \quad (5)$$

where D is given in m. Substituting Equation 3 in Equation 5 and solving for D,

$$D = 2 * 1.56\left[0.77W \tanh\left[0.077\left(\frac{9.8F}{W^2}\right)^{0.25}\right]\right]^2 \quad (6)$$

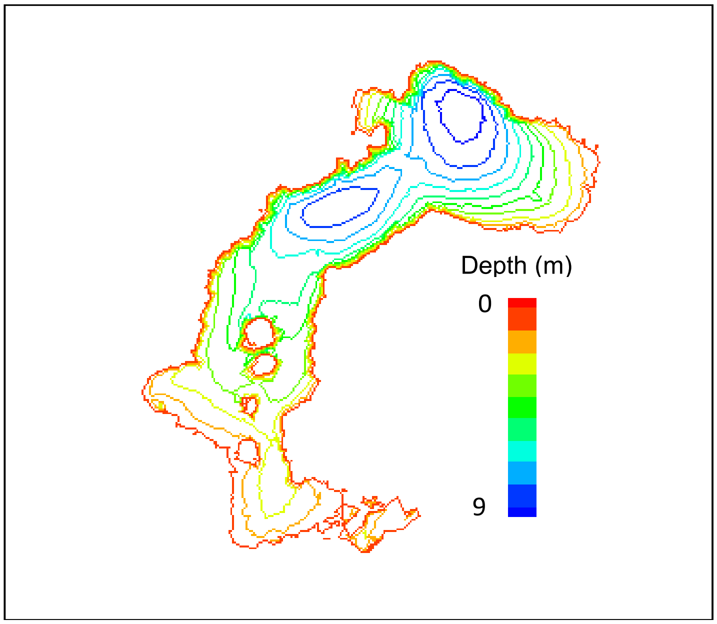

Fig. 2. Bathymetry of the Patzcuaro Lake considering the minimum water level

Table 4. Summary of the observed maximum and minimum levels (MASL)

Years		**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dic**	**MAX, MIN**
1978-1991	MAX.	2039	2039	2039	2039	2039	2039	2039	2039	2039	2039	2039	**2039**	**2039**
	MIN.	2037	2037	2037	2036	2036	*2036*	2036	2036	2037	2037	2037	2037	*2036*
1992-1999	MAX.	2037	2037	2037	2037	2036	2036	2037	2037	**2037**	2037	2037	2037	**2037**
	MIN.	2036	2036	2036	2036	2036	*2036*	2036	2036	2036	2036	2036	2036	*2036*
2000-2004	MAX.	2037	2036	2036	**2037**	2036	2036	2036	2036	2037	2037	2037	2037	**2037**
	MIN.	2036	2036	2036	2035	2035	2035	2035	2036	2036	*2035*	2036	2036	*2035*
													MAX	**2039**
													MIN	*2035*

Table 5. Computed depth values required to generate sediment resuspension

	Wind velocity m/s														
Fetch distance in m	0,50	1,00	2,00	3,00	4,00	5,00	6,00	***6,10***	7,00	8,00	9,00	10,00	11,00	12,00	13,00
500	0,06	0,15	0,34	0,53	0,72	0,91	1,10	***1,12***	1,29	1,48	1,68	1,87	2,06	2,25	2,44
1000	0,07	0,19	0,45	0,72	0,99	1,26	1,53	***1,56***	1,80	2,07	2,34	2,61	2,88	3,15	3,43
2000	0,09	0,24	0,60	0,97	1,35	1,73	2,11	***2,14***	2,49	2,87	3,25	3,64	4,02	4,40	4,79
2230	***0,09***	***0,25***	***0,62***	***1,01***	***1,41***	***1,81***	***2,21***	***2,25***	***2,62***	***3,02***	***3,42***	***3,83***	***4,23***	***4,64***	***5,04***
3000	0,09	0,27	0,69	1,14	1,60	2,07	2,53	***2,58***	3,00	3,46	3,93	4,40	4,87	5,34	5,81
4000	0,10	0,29	0,77	1,28	1,81	2,34	2,88	***2,93***	3,41	3,95	4,49	5,03	5,57	6,11	6,65
5000	0,10	0,31	0,83	1,40	1,98	2,57	3,17	***3,23***	3,77	4,37	4,97	5,58	6,18	6,78	7,39
6000	0,10	0,32	0,88	1,50	2,13	2,78	3,43	***3,49***	4,08	4,74	5,40	6,06	6,72	7,38	8,04
7000	0,10	0,33	0,92	1,58	2,26	2,96	3,66	***3,73***	4,37	5,08	5,79	6,50	7,21	7,93	8,64
8000	0,10	0,34	0,96	1,66	2,39	3,13	3,87	***3,95***	4,63	5,38	6,14	6,90	7,66	8,43	9,19
9000	0,11	0,35	1,00	1,73	2,49	3,28	4,07	***4,15***	4,86	5,67	6,47	7,27	8,08	8,89	9,70
10000	0,11	0,36	1,03	1,79	2,60	3,42	4,25	***4,33***	5,09	5,93	6,78	7,62	8,47	9,32	10,18
20000	0,11	0,40	1,23	2,24	3,32	4,44	5,59	***5,70***	6,75	7,92	9,11	10,29	11,48	12,68	13,88

Equation 5 can be used to compute the required depth to generate resuspension as a function of wind velocity and fetch. The following table (Table 5) shows the computed depth values for the listed wind velocities and fetch distances.

The highlighted row and column in Table 5 represents computed depths with the empirical equation for the given values of fetch and wind velocity. Analogous values were obtained for each analyzed direction.

3. RESULTS AND DISCUSSION

In this section the final results are given for a critical scenario. First the computed fetch is shown; then the resuspension is shown as well; finally, a brief discussion is given.

The contour map in Fig. 3 depicts the fetch values in the Patzcuaro Lake computed for a wind velocity of 12.2 m/s in the north direction (the adjusted velocity at the water surface, as explained in Section 2.1, and which corresponds to a critical scenario leading to resuspension).

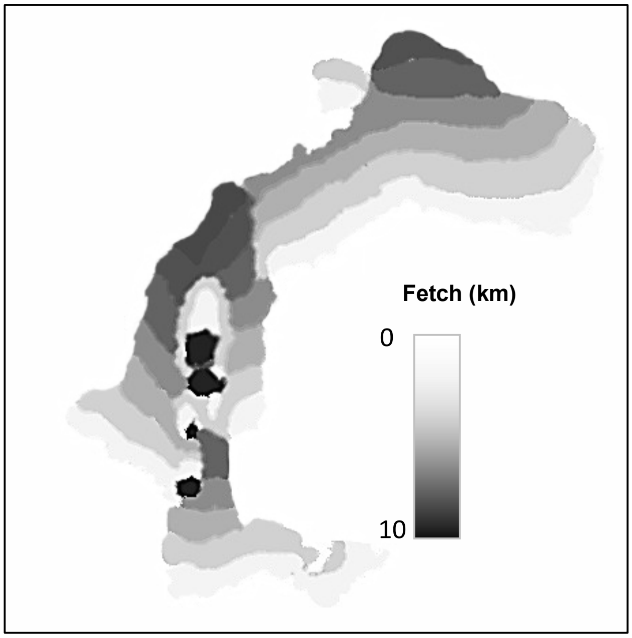

Fig. 3. Fetch of north-oriented winds in the Patzcuaro Lake

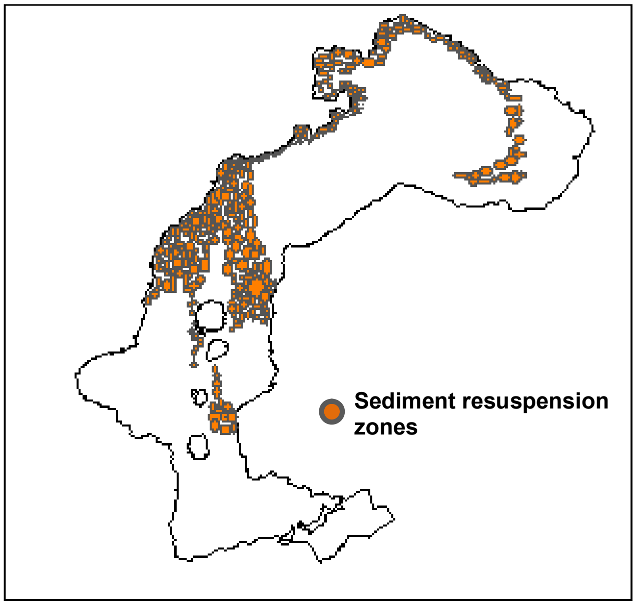

Fig. 4. Sediments resuspension in the Patzcuaro Lake

The sediments resuspension for the most critical scenario in the Patzcuaro Lake occurs over approximately 24 km^2 (i.e, almost in a third of the whole lake area which is 88.9 km^2) and is spread over different parts as shown in Fig. 4. Towards the north zone larger particles motion is observed in the lakes riviera, form 5 m depth to the shore. In the middle part of the lake a larger incidence of the resuspension phenomenon is exhibited, since it is developed for all the considered depth levels. In the south part the resuspension is almost absent; only a spot between the Tecuén and Janitzio Islands show resuspension (Fig. 4), where due to the wind, acting jointly with the large fetch distances (Fig. 3), the matter at the lakebed is moved up.

4. CONCLUSION

It is concluded that the empirical equations are a practical tool to assess the sediments resuspension zones in lakes (or reservoirs), although their use is restricted to small lakes with shallow waters, since only the predominant wind velocity at the site, the lake depths and the distance of wind action (fetch) are evaluated. Comparison with actual measurements of the lake resuspension (when available) is recommended for future research.

The adequacy of the empirical approach was shown for the case of the Patzcuaro Lake, where the sediments resuspension zones were plotted and clearly identified. It was found that larger particles motion zones are located in the middle part of the lake, and to a lesser extent in the north part, while only a limited spot between two islands in the lake exhibited resuspension of sediments in the south.

It is also concluded that the empirical equations approach is relatively straightforward to implement, but available information on the site wind velocities and orientations, as well as detailed bathymetry are required. The obtained results can be useful to characterize the water quality for ecological [18], engineering and environmental purposes [13].

The results from the empirical equations could be altered if the existence of fishes and littoral vegetation is considered. The equations show general trends of the sediment resuspension, but the places where particles motion is expected can be identified. Further research including other variables and techniques, and larger water bodies, is recommended for future studies.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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