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SIMPLE MODEL OF DISSOLVED OXYGEN CONSUMPTION IN A BAY WITHIN HIGH ORGANIC LOADING: AN APPLIED REMEDIATION TOOL

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Abstract. San Vicente Bay is a coastal shallow embayment in Central Chile with multiple uses, one of which is receiving wastewater from industrial fisheries, steel mill effluents, and domestic sewage. A simulation model was developed and applied to dissolved oxygen consumption by organic residues released into this embayment. Three compartments were established as function of: depth, circulation and outfall location. The model compartments had different volumes, and their oxygen saturation value was used as baseline. The parameters: (a) BOD_5 of the industrial and urban effluents, (b) oxygen demand by organic sediments, (c) respiration, (d) photosynthesis and (e) re-aeration were included in the model. Iteration results of the model showed severe alterations in Compartment 1, with a decrease of 65% in the oxygen below saturation. Compartment 2 showed a small decline (10%) and compartment 3 did not show apparent changes in oxygen values. Measures recommended for remediation were to decrease the BOD_5 loading by 30% in the affected sector. Iteration of the model for 200 h following recommendations derived from the preceding results produced an increase in saturation of 60% (5 ml O_2 L^{-1}), which suggested an improvement of the environmental conditions.

Keywords: bay pollution, Central Chile, environmental remediation, fisheries waste, organic residues, water quality

Abbreviations: V: volume of the compartment; c: oxygen saturation for temperature and salinity (Lm^{-3}) for the compartment ($_n$); Q: inflows ($_e$) or arrow/outflows ($_s$) or arrow for the compartment ($_n$); S: Oxygen sources and sinks within the compartment; Uw: wind velocity at 10 m above the water surface (m s^{-1}); k_L: reaeration constant, ms^{-1}; A: surface and bottom areas of compartments (m^2), ($_n$) = compartment; k_1: deoxygenating constant, 1/day; BOD_5: biochemical oxygen demand; SB: sediment oxygen demand [ml O_2 m^{-2} s^{-1}]

1. Introduction

Waters of the SE Pacific coast are characterized by high biological productivity, resulting in a high commercial activity related to pelagic fisheries. The fishery industries in Peru and Chile use 80 to 90% of the pelagic landings to produce fish meal and oil. The few coastal bays existing on this Pacific coast are centers of high fishing activity, harboring fishing fleets and serving as industrial processing centers. All of the fishing ports produce effluents from these industries. There is a high degree of environmental impact, based on the high content of organic waste in these effluents, which varies according to local regulations and recent remediation efforts. Fishing operations docks, are localized on embayments, where the waste water of fish landed, and industrial processes of oil and fish mills production were discharged without any treatment to the coastal seawater. The fishing industrial effluent produces several impacts on marine environments which often result in a benthic defaunation. However few benthic species, mainly those resistant to low oxygen conditions, manage to survive in impacted areas (Carrasco *et al.*, 1989). Examples of these conditions have been found in areas near Ilo, Chimbote and Callao in Peru. Also in Iquique, Mejillones, Caldera, Coquimbo, Talcahuano, San Vicente, Coronel and Lota in Chile (Rudolph *et al.*, 2002; Ahumada *et al.*, 2004).

In the year 2000, the Chilean fishery industry landed 3.5×10^6 TM of fish, of which 80% was converted into fish meal and fish oil. Out of this total a 30% was landed in San Vicente (SERNAPESCA, 2001). In 2003, the Chilean fishery industry landed 2.3×10^6 TM of fish and 85% was converted to fish meal and fish oil. From the total Chilean landed, about 34% was landed at San Vicente. Although there has been a decline in fishery activities, due to catch restrictions imposed by the Chilean in 1999 when the landed were up to 5.5×10^6 TM of fish (SERNAPESCA, 2000). The surplus production of fish industry and the increased waste water, produced a reducing conditions of many bay bottom sediments, accompanied by hypoxia, which persisted and impacted more severely over time due to larger amounts of deposited organic waste.

1.1. BACKGROUND OF THE STUDY AREA

San Vicente Bay is located on the central Chilean coastline at $36°44'15''$ S; $73°09'10''$ W. The mouth of the bay is oriented to the NE and is 4.5 km in width. Its average depth is 17.3 m, and it has a surface area of 19.3 km^2; it's volume is approximately $3{,}351 \times 10^8$ m^3 (Ahumada *et al.*, 1989). Using an average current velocity of 5 cm/s, the residence time of the water in the bay is approximately 48 h (i.e., worst case). About 25% of the total Chilean fish landings occur at San Vicente Bay, with a total landing of about 117,500 tons per month (SERNAPESCA, 2000). Wastewater is released directly into the bay at 13 outfall points (8 of which are industrial wastewaters associated with a steel factory, 4 with industrial fisheries and 1 with domestic wastewater). The fishery industry waste has a total discharge rate of 66.6 L s^{-1} representing 3,600 mg L^{-1} BOD$_5$ for 6.5 h daily (Ahumada, 1995). The fishery discharges include landing wastewater and residual wastewater from production processes, calculated to be 320 L s^{-1} for 12 h daily. This information was obtained from measurements obtained during environmental monitoring programs from 1991 to 1992, and from 1996 to 1997. Compiled data from year's 1991–1996 provided definitions of critical pollutants from the fishery industry and oxygen demands of residual waters. The oxygen behavior in the bay was based on

TABLE I
Total mean discharged by fishery industries at the fishery dock sector, San Vicente Bay (Ahumada, 1995)

Critical parameters	Effluent concentration
Chemical oxygen demand (COD)	10,554 ± 310 mL O_2 L^{-1}
BOD_5	5,737 ± 420 mL O_2 L^{-1}
Total oil and grease*	2,269 ± 106 mg L^{-1}
Suspended solids	5,874 ± 560 mg L^{-1}
Ammonium ion	15 ± 2 μM
Phosphate	123 ± 4 μM

* Low density of oil-grease residues produce a surface film which impedes re-aeration.

studies from previous years (Rudolph *et al.*, 2002). The model took into account outfalls from 10 industries that have the characteristics listed in Table I.

Wastes from fishery plants have low toxicity, and their negative impact is mainly from organic matter loading, with consequent dissolved oxygen depletion in the receiving water (Rudolph, 1995). This situation becomes critical during the summer, when maximum landings coincide with upwelling of oxygen-poor water from the continental shelf (Ahumada *et al.*, 2004), and its intrusion into inner bay waters on the N and central Chilean coast (Ahumada *et al.*, 2000). Other inputs of organic matter include municipal wastewater discharged to the bay through a 1.4 m diameter outfall.

Total inflow of fisheries industrial waste water was estimated to be 23.5×10^3 $m^3 day^{-1}$ and with a load of 500 TM O_2 day^{-1} BOD_5 (Ahumada *et al.*, 1989). Minor discharges originate from an industrial complex (steel, chemical and metal-mechanics industries) located at the head of the bay, which produces effluents with low organic loading that are not comparable to fishery effluents.

1.2. ENVIRONMENTAL FEATURES OF THE WATER COLUMN AND SEDIMENTS

The water column was found to be uniform in salinity and temperature (Table II) and underwent little change during the year. The vertical dissolved oxygen showed a seasonal pattern and a heterogeneous spatial distribution. The seasonal behavior showed lower concentration levels in summer compared to winter. Localized areas (Compartment E1) showed sub-saturated dissolved oxygen conditions throughout the year (Figure 1).

The bay shows sedimentation zones near the Fishery dock and outside of Pt. Liles. At this location, the amount of organic matter found in sediments showed an average of 10% (Arcos *et al.*, 1992). These sediment samples had a black appearance, malodorous and highly reducing clayed-mud content. Elevated organic material content from these zones produced a high rate of oxygen consumption. The central part of the bay was characterized by having predominantly coarse sand

TABLE II
Hydrographic characteristics of San Vicente Bay

Variable	Surface water	Subsurface water
Depth (m)	0–10	21–45
Temperature (°C)	14.5–13.5	11.5–13.0
Salinity (PSU)	33.80–34.55	34.40–34.55
Dissolved oxygen (mL O_2 L^{-1})	Near saturation*	<3 mL O_2 L^{-1}

*With the exception of the fisheries dock, and sectors near the head of the bay where subsurface samples showed permanent values of under-saturation.
(*Source*: Ahumada, 1995)

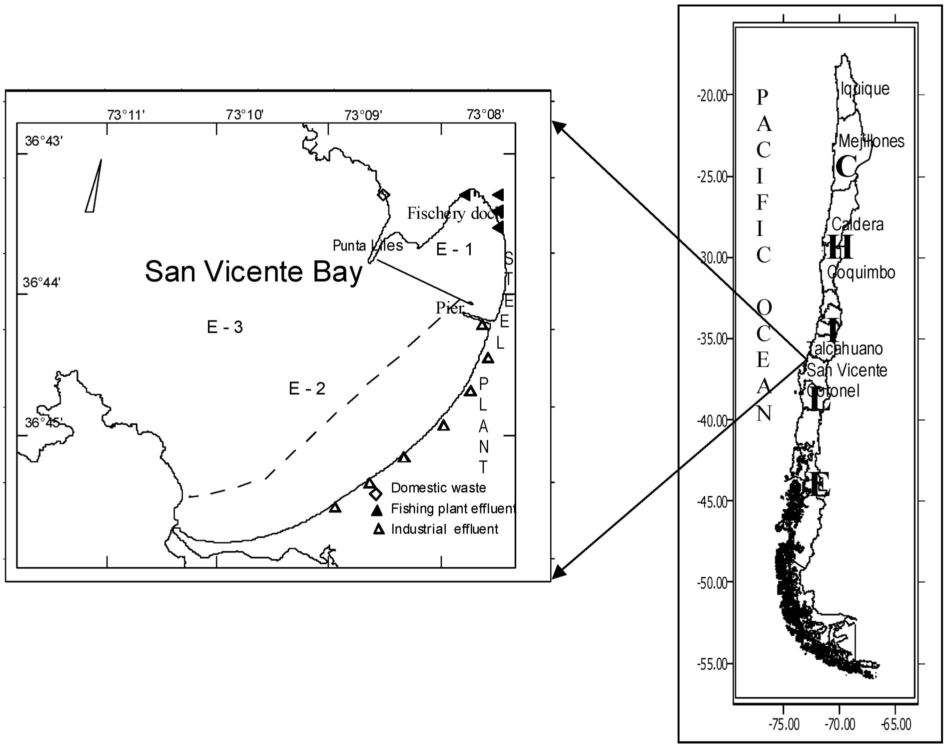

Figure 1. Map of San Vicente Bay showing outfall points for liquid industrial wastes. Symbols indicating different discharge points into the Bay are showed in the legend map.

(250–500 μm particles) bordered by lateral areas with fine sand (125 μm particles) (Ahumada, 1992).

1.3. HYDRODYNAMIC FEATURES

Two-layer stratification was observed in the bay during the summer. The surface layer showed counter-clockwise rotation, related to the dominance of the S-SW winds, which have a maximum velocity of 14 m $\sec^{-1}$ (Ahumada *et al.*, 1989). Subsurface waters follow the same circulation pattern. In the winter season dominant winds are from the N and NW with maximum velocity of 16 m $\sec^{-1}$ (Ahumada, op cit) and with intermittent calm periods of one or two days. However during winter, when the wind changed dominance, the superficial pattern of waters remains, although in weak counter-clockwise current circulation current

1.4. MODELING DISSOLVED OXYGEN

A simulation model was used in the present study to attempt; an interpretation of the natural process which may have took place at these impacted periods on the bay and integrated the information obtained. The approach of a one box model consist in a building budget of energy and matter, to described the marine environment in order to know the impact of changes of dissolved oxygen content. Basically it should be considered: (i) the source of the dissolved oxygen in the marine environment, (ii) determination of the water movement through the modeling box, (iii) Detect the principal processes which consumed oxygen in the seawater ecosystem (high organic material input from the fisheries industries (BOD_5), Sediment Oxygen Demand, Photosynthesis/Respiration rate). A multi-box model was used because it has been reported that the distribution of oxygen in San Vicente Bay is horizontally heterogeneous (Rudolph *et al.*, 2002). Three boxes model (Figure 2) allowed the characterization of the dynamic of waters, the input of organic matter and the heterogeneous pattern of distribution of dissolved oxygen. It was assumed that the water column inside each box was completely mixed and homogeneous. The organic matter input was considered instantaneous, dispersed, and homogeneously mixed throughout each box (Chapra, 1997). It was not possible to define spatial variations within the compartments, and seasonal variations were determined only using mean values.

Compartment 1. (V_1), Fishery dock, included the area between the steel plant pier and Point Liles. Dominated by discharges of liquid industrial residues from fishery activities (Q_{ip}) and interchanges with flows from compartment 2 (Q_{12} and Q_{21}) occurred.

Compartment 2. (V_2) represented surface water of the bay up to 15 m depth. This compartment included the discharge of sewage at Pt. Liles (Q_{as2}) and residual industrial liquids from steel, metal-machine, and chemical industries at the head of the bay (Q_{cap2}). An algorithm for surface re-aeration was included and an area of interchange with water from the open sea was established (Q_{s2} and Q_{e2}).

Compartment 3. (V_3) represented the deepest layer with the slowest water circulation affected by sewage (Q_{as3}) and by processes of vertical interchange. It had an interchange of flows to and from the open sea (Q_{e3} and Q_{s3}).

Model assumptions and set-up (Thomann and Mueller, 1987):

- The water in the residues from steel, metal-machine, and chemical industries (Q_{cap}, Q_{ip}, Q_{as}) were assumed negligible did not introduce changes capable of affecting the mass balance of the volume of the bay.
- Water volume was assumed in equilibrium based on small differences (<2 m) in tidal extremes and bay size.
- Modeling was based on the summer season.
- The *residence time* variable was incorporated into the model based on inflow – outflows through the open sea (given by Q_{e} and Q_{s}).

The residence times were calculated for each compartment based on current velocities and areas of interchange.

The estimated residence times were:

Compartment 1 = 50 h; Compartment 2 = 21.3 h; and Compartment 3 = 53.2 h.

The dynamics of oxygen in the water could be expressed by the mass conservation law and the modeling of dissolved oxygen was expressed by the following relation (WQRRS, 1978) (Equation (1)):

$$V\frac{dc}{dt} = Q_e c_e - Q_s c \pm V \cdot S \tag{1}$$

where V is volume of the compartment; c is concentration of dissolved oxygen in the compartment; Q_e is flows entering into the compartment; Q_s is flows leaving the compartment; S is Oxygen sources and sinks within the compartment.

The matrix form for each compartment following:

Equation (1)

$$= \begin{bmatrix} V_1 & 0 & 0 \\ 0 & V_2 & 0 \\ 0 & 0 & V_3 \end{bmatrix} \begin{Bmatrix} \dot{c}_1 \\ \dot{c}_2 \\ \dot{c}_3 \end{Bmatrix} = \begin{bmatrix} -Q_{12} & Q_{21} & 0 \\ Q_{12} & -Q_{21} - Qs_2 & 0 \\ 0 & 0 & -Qs_3 \end{bmatrix} \begin{Bmatrix} c_1 \\ c_2 \\ c_3 \end{Bmatrix} + \begin{Bmatrix} p_1 \\ p_2 \\ p_3 \end{Bmatrix}$$

$$\text{or } [V]\{\dot{c}\} = [S]\{c\} + \{P\} \tag{2}$$

where the vector $\{P\}$ represents the ecological impact on the oxygen content, which may occur in each compartment.

The initial oxygen content in the surface water of the model depended on the oxygen saturation value of sea water. Changes of this value are driven by loss / gain of oxygen by different processes as follows:

Compartment 1

(1) Re-aeration, oxygen exchange with the atmosphere. Reduction of exchange rate was due to surface oil and grease and was estimated to be about 25% at the surface of the compartment.

(2) Loss of oxygen by oxidation of waste organics emitted by the fisheries sector.
(3) Oxygen demand by the bottom sediments.

Then:

$$p_1 = \underbrace{\left[\underbrace{\frac{0.728 \cdot Uw^{1/2} - 0.317 \cdot Uw + 0.0372 \cdot Uw^2}{86400}}_{k_L} \cdot \frac{3A_1}{4}(c_1 * - c_1)\right]}_{(1)} - \underbrace{[(1 - e^{-k_{ip}t})\mathrm{BOD}_{ip}]}_{(2)} - \underbrace{[\mathrm{SB} \cdot A_1]}_{(3)}$$

where Uw is wind velocity at 10 m above the water surface, ms^{-1}; k_L is reaeration constant, ms^{-1}; $k_\mathrm{a} = k_L A_1/V$; $k_{\mathrm{a}(^\circ\mathrm{T})} = k_{\mathrm{a}(20\,^\circ\mathrm{C})}(1.024)^{\mathrm{T}-20}$, $k_{L(^\circ\mathrm{T})} = k_{\mathrm{a}(^\circ\mathrm{T})}V/A$; A_1 is surface and bottom areas of Compartment 1, m^2; c_1 is oxygen saturation concentration for Compartment 1 [L m^{-3}]; k_1 is deoxygenating constant, 1/day; k_1 is 0.35[1/day] = $1.46 * 10^{-2}$ [1/h] at 20 °C; $k_{1(T^\circ)} = k_{1(20^\circ\mathrm{C})}(1.04)^{T-20}$. BOD$_5$ ip: biochemical oxygen demand (liquid residues from fishery industry, [L O$_2$ h^{-1}]); SB: sediment oxygen demand [L O$_2$ m^{-2}s^{-1}].

Compartment 2

(1) Flow of water entering (Q$_{\mathrm{e}2}$) from the open sea, saturated with dissolved oxygen.
(2) Re-aeration from the surface.
(3) Losses of oxygen related to the discharges of wastewaters

Then:

$$p_2 = \underbrace{[Qe_2 \cdot c_2^*]}_{(1)} + \underbrace{\left[\frac{0.728 \cdot Uw^{1/2} - 0.317 \cdot Uw + 0.0372 \cdot Uw^2}{86400} A_2(c_2^* - c_2)\right]}_{(2)} - \underbrace{[(1 - e^{-K_1 t})\mathrm{BOD}_{\mathrm{as2}} + (1 - e^{-K_1 t})\mathrm{BOD}_{\mathrm{cap2}}]}_{(3)}$$

where $Q_{\mathrm{e}2}$ is flow entering from the open sea to Compartment 2 [m^3 s^{-1}]; c_2 is oxygen saturation for temperature and salinity of Compartment 2 [mL O$_2$ L^{-1} or L O$_2$m^{-3}]; A_2 is area of Compartment 2 [m^2]; BOD$_{5\mathrm{as}2}$: biochemical oxygen demand due to sewage discharge into Compartment 2 (15% of the total [L O$_2$h^{-1}]). BOD$_{5\mathrm{cap}2}$: biochemical oxygen demand due to liquid industrial waste discharged into Compartment 2 (15% of total [L O$_2$h^{-1}]).

Compartment 3

(1) Flow of water entering Q_{e3} from the open sea, oxygen saturated.
(2) Losses of oxygen due to sewage discharge and liquid industrial wastes from steel, metal-machine, and chemical industries.

Then:

$$p_3 = \underbrace{\lfloor Qe_3 \cdot c_3^* \rfloor}_{(1)} - \underbrace{[(1 - e^{-k_1 t})\mathrm{DBO}_{\mathrm{as}3} + (1 - e^{-k_1 t})\mathrm{DBO}_{\mathrm{cap}3}]}_{(2)}$$

where $\mathrm{BOD}_{5\mathrm{as}3}$ is biochemical oxygen demands due to sewage discharged into Compartment 3 (85% of total [L $\mathrm{O_2h^{-1}}$]); $\mathrm{BOD}_{5\mathrm{cap}3}$ is biochemical oxygen demands due to of liquid industrial waste discharged into Compartment 3 (85% of total [L $\mathrm{O_2h^{-1}}$]).

To integrate Equation (2) with time, the following numerical approximation was introduced for each compartment:

$$c_{t+\Delta t} = c_t + \frac{\Delta t}{2}(\dot{c}_t + \dot{c}_{t+\Delta t})$$

at any point t, c_t and c_t' are known. Thus the preceding expression produces:

$$c_{t+\Delta t} = B + \frac{\Delta t}{2}\dot{c}_{t+\Delta t}$$

where

$$B = c_t + \frac{\Delta t}{2}\dot{c}_t \tag{3}$$

In matrix form, Equation (3) remained as:

$$\{c\} = \{B\} - \Delta t/2\{\dot{c}\} \tag{4}$$

Substituting Equation (4) in Equation (2) produced:

$$\begin{aligned} &[V]\{\dot{c}\} = [S]\{B\} - \Delta t/2[S]\{\dot{c}\} + \{P\} \\ \text{or}\quad &[S^*]\{\dot{c}\} = \{P^*\} \end{aligned} \tag{5}$$

where

$$[S^*] = [V] + \Delta t/2[S]$$
$$[P^*] = [S]\{B\} + \{P\}$$

For the solution of Equation (5) the following iterative process was followed:

1 Form vector $\{B\}$ from the initial conditions or the recently presented solution.
2 Form $[S^*]$ and $[P^*]$ with known values for $[V]$, $[S]$, and $[P]$.
3 Resolve $\{c'\}$ for time $t + \Delta t$.
4 Calculate $\{c\}$ by substitution into the equation.

1.5. EXPERIMENTAL DATA INPUT

The model was validated using empirical data obtained during cruises carried out in San Vicente Bay. Water column parameters were collected (temperature, salinity, dissolved O_2, surface oil and grease) along with sediment samples (organic matter and sedimentary oxygen demand). Cruises were carried out from June to December 1996 and January to June 1997, sampling was done at six hydrographic stations. Temperature, salinity, and density were obtained using a Neil Brown CTD probe. Dissolved oxygen was analyzed using the Winkler method and methods for BOD_5, COD, and oil and grease followed standard methods (Clesceri *et al.*, 1999). Sedimentary organic material was assayed by ignition (Byer *et al.*, 1978). The means for the parameters modeled for each compartment were calculated using discrete data obtained on different cruises, at depths and stations located within each compartment. Discrete concentrations were integrated to calculate weighted mean dissolved oxygen. A mean value for oil, grease, and organic matter in surface sediments was computed from different samples taken at 32 stations using 3 replicates per station.

2. Results

The model was iterated for 200 h, assuming an unaltered, non-oxygenated system, with baseline values equal to saturation value.

Compartment 1 or Puerto Pesquero. The dissolved oxygen decreased exponentially from 6.75 ml O_2 L^{-1} (saturation) to 3.21 ml O_2 L^{-1} over the 200 h of simulation. This compartment was strongly impacted by the input of organic material additionally influenced by the discharge from fishing plants. There was a loss of 48% of dissolved oxygen in this period from the entire compartment.

Compartment 2 or Surface Compartment. This compartment was adjacent and connected to the Fishing dock area. The concentration of dissolved oxygen in the compartment decreased from 6.75 ml O_2 L^{-1} (saturation) to 6.05 ml O_2 L^{-1}. The oxygen loss was minimal, considering that this compartment corresponds to adjacent and surface water.

Compartment 3 or Deep Sector. This compartment had an almost negligible variation in dissolved oxygen concentration. The saturation value of 6.75 ml O_2 L^{-1}

TABLE III

Mean values obtained in the field for parameters estimated in the model

Parameters	Compartment 1	Compartment 2	Compartment 3
Dissolved oxygen (ml L^{-1})	3.3 ± 0.1	6.1 ± 0.4	6.35 ± 0.7
Oil and grease (mg L^{-1})	36.5 ± 21.7	21.2 ± 17.3	18.7 ± 12.7
Type of sediments	Clay		Coarse & medium sand
Organic matter* (%)	19.4 ± 2.2		0.80 ± 0.01–1.17 ± 0.55
Sediment oxygen demand (ml O_2 m^{-2} s^{-1})	0.074	0	Considered negligible
Reaeration coefficient (m/s)	$6.45 * 10^{-5}$	$6.45 * 10^{-5}$	0
Water flow (m^3s^{-1})	63.28	587.75	586.95

^{*,1} See environmental features of the water column and sediments.

^{*,2} Surface sediments.

dropped to 6.50 ml O_2 L^{-1} over the 200 h modeling period. Environmental impact was minimized since the organic loading was indirect, and came from the advection and sedimentation from the other compartments.

2.1. Experimental data

The mean value for temperature was 11.56° + 0.62 °C with a coefficient of variation of 5.36%. The mean value for salinity in the bay was 34.02 + 0.42 PSU with a coefficient of variation of 1.2%. The oxygen saturation value for the water was 6.75 ml O_2 L^{-1}. The results from the experimental determinations for of oxygen values in the field are listed in Table III.

3. Discussion

In the 200 h simulation period carried out using a model representing 5 times the residence time of the water in the bay, it was found that the oxygen consumption curves tended to stabilize within each of the compartments (Figure 3).

Compartment 1, which experienced the greatest impact on dissolved oxygen in the water, reached such a low value (3.21 ml O_2 L^{-1}) that it could be critical for the survival of pelagic organisms (Theede *et al.*, 1969), detriments to benthic finfish, shellfish and benthic macro- faunal health (Díaz and Rosenberg, 1995). The decrease was explained by the loading conditions of the dissolved oxygen sector. The compartment had an enclosed, small, and shallow volume, which had little assimilation capacity for oxidation of waste organic material. This change in the water quality could be attributable to fishery activities. Compartment 1 has been described as having little or no benthic macro fauna (Carrasco and Carbajal, 1995).

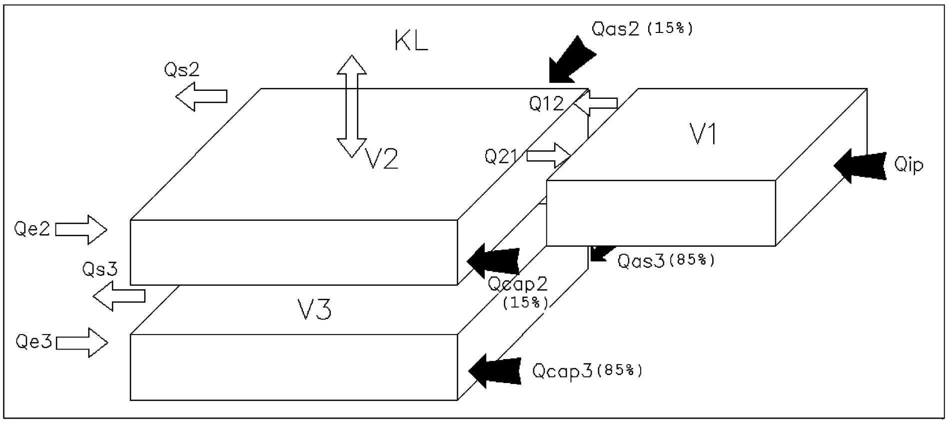

Figure 2. Diagram representing the model compartments and fluxes for San Vicente Bay.

Based on these results, accepting the oxygen value of saturation as a baseline and the dissolved oxygen level criteria (Rudolph *et al.*, 2002), we can assess the water quality of the compartments. It was determined that the impact occurred with a BOD_5 loading of 31,000 ml O_2, and the model was used to establish a mitigation of the impact according to three criteria: (a) decrease in the BOD_5 loading by waste treatment, (b) elimination of the sources by relocating the discharge of residual waters from industrial processes outside of the embayment, and (c) elimination of discharge from fish landings by processing of these waters.

The loading value was used to propose alternatives of remediation and the final point of the iterations corresponded to the stabilization of the oxygen value in the curve.

Data obtained included final concentration and a value for stabilization.

CASE I

Here BOD_5 is reduced by 50% as means for impact mitigation. This is possible either by reducing the number of sources or reducing the volume of discharge. This reduces the consumption from 6.45 ml O_2 L^{-1} (saturation) to 5.32 ml O_2 L^{-1}. A decrease of 17.52% based on water quality criteria (Table III) would provide some improvement of water quality, with a stabilization time of 60 days.

CASE II

Elimination of processed wastewater (i.e. $BOD_5 = 40\%$) from wastewater discharge to Compartment 1, could produce a smaller remediation than case i. In this case, if discharged water is subjected to treatment, the impact of discharged water could be reduced by about 5% of the oxygen saturation value.

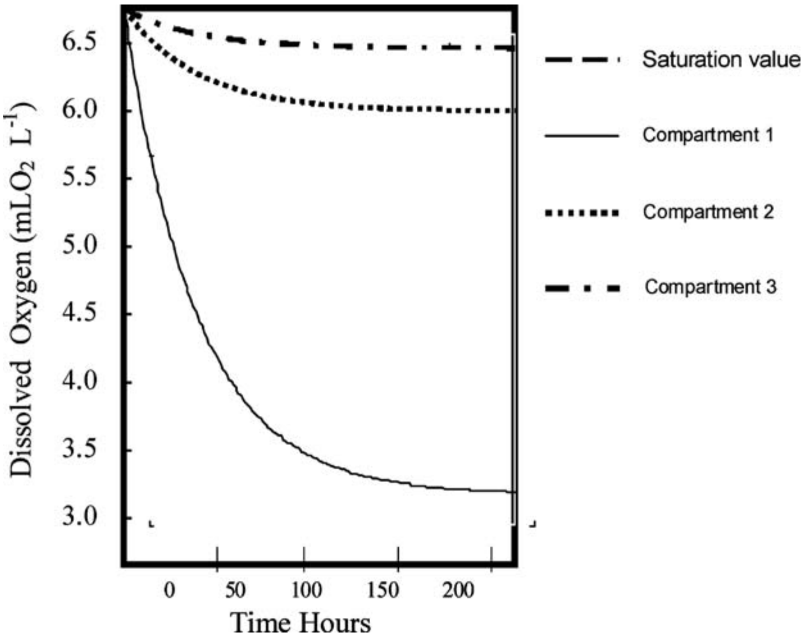

Figure 3. Simulated evolution of dissolved oxygen in surface water (Compartments 1, 2 and 3) after 200 h of wastewater discharge.

CASE III

Here the number of sources is reduced while maintaining the current discharge load into the bay. It is concluded that the number of sources must be reduced by eight, both for fishery discharge and wastewaters from processing plants to obtain the same impact as in Case ii, with a lower stabilization time.

Figure 3 summarizes the behavior of each of the compartments of the model. Compartment 1 evolves over time, showing a rapid decline in dissolved oxygen in the water with stabilization at 3 ml O_2 L^{-1} after 200 hourly iterations. This compartment receives the highest load of organic residues from the fishery industry. The weighted averages of dissolved oxygen content for all compartments (Table III) are consistent with the results of the model for each Compartment.

Compartment 2 showed an important improvement of oxygen concentration over compartments. After the 200 h simulation, a loss of 7% in oxygen content was observed. This compartment represented surface water, and was subject to atmospheric exchange. The loss of oxygen may be explained by the higher demand due to particulate material from compartment 1 and/or due to the presence of surface oil and grease residues which impede re-aeration. The experimental means and profiles showed a minimized impact due to dilution, given the volume of the compartment.

Compartment 3 maintained values near saturation, given that it is uncoupled from the rest of the system. The bottom sediments include coarse, medium, and fine sands. Its water is oxygenated and sub superficial, receiving little impact from Compartments 1 and 2. The decrease in its average content of dissolved oxygen was about 3%. This was a high energy compartment where one of the main forcing functions included currents generated by the topography of the adjacent continental shelf.

4. Conclusions

The implementation of a model to dissolved oxygen dynamics in Chilean bay allowed evaluating the impact produced in defined sectors of its basin, and the extension of the impacts to other sectors. Also the procedure allowed determination of the deterioration of environmental quality of the water.

Comparison between the empirical mean of dissolved oxygen and the simulated value suggested by the model validates its application and establishes trends in dissolved oxygen. Modeling of the problem and mitigation programs are a function of the oxygen demand in discharged wastewaters and the dynamics of the basin. Thus, the modeling may help assess the loading and define a program for environmental recuperation considering the impact of the receiving water body.

San Vicente Bay experiences problems with dissolved oxygen concentration in the fishery dock (fishery industry) sector depicted by Compartment 1 of the model. The water of this sector represents about seven percent of the total bay volume and 12% of its surface. This area has the worst pollution conditions and the lowest dissolved oxygen concentration, impeding the development of marine life in the sector.

By decreasing the BOD_5 loading by 30% of the present discharge, the model shows an increase in oxygen concentration of about 60% (5 ml O_2 L^{-1}), which would improve habitat conditions for marine life in the area.

The modeling carried out for San Vicente Bay is a simple and useful tool to choose the criteria for remediation of the organic waste load in the embayment. The environmental impact of other sources could be easily incorporated in this model. This model is also open to improvement by incorporating additional factors and variables.

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