Sensitivity Analysis of VELFEEM –Venice Lagoon Finite Element Ecological Model- to the Macro-Nutrient Input Regime

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Abstract: A sensitivity analysis of VELFEEM, the Finite Element Ecological Model for the lagoon of Venice, has been performed in order to test the responses of the model to changes in external input regimes. The model is obtained by internally coupling a hydrodynamic model, an energetic model, and an ecological model. The hydrodynamics are simulated using SHYFEM, a barotropic bi-dimensional model based on a finite element discretization of the spatial domain, which allows for a very good spatial resolution of the lagoon morphology while keeping at a low level the computational demand. Using a standard heat fluxes formulation, the energetic module computes the water temperature of each element starting from meteorological daily measurement. The ecological processes are simulated by the evolution of nine state variables, namely by phytoplankton, zooplankton, nutrients (ammonia, nitrate and phosphate) organic detritus (organic nitrogen organic phosphorous and CBOD) and dissolved oxygen. In a previous work, the role played by physical forcings in the definition of the water quality level has already been investigated, and the conclusion was that a proper parameterisation of these processes would increase the accuracy of our model prediction. Here we aim to see whether the same consideration could be extended at the macronutrient input regime. Assuming that the total amount of macronutrients and of freshwater entering the basin is the same in our scenarios, we vary the river input regime comparing an idealised scenario with a realistic scenario. The sensitivity to the variation in input regime and variations in the macro nutrient exchange with the sea has been investigated, by comparing model predictions of spatial and temporal evolution of major state variables and of an aggregate index of water quality (TRIX). In the idealised scenario the water discharge is represented by an idealised function and the concentration in macronutrient is constant during the whole year, and it is the same for each river, during the one-year simulation. In the real scenario we use monthly data field of river flow and the concentration values sampled at each river.

Keywords: ecological modelling, water quality, Venice Lagoon

1. INTRODUCTION

The lagoon of Venice is the largest Italian lagoon. It is located in the Northern western coast of the Adriatic Sea, it is a shallow basin with the average depth of 1 meter, and a surface area of around 550 Km^2.

The evolution of the lagoon, a transitional environment between land and sea, is influenced by the surrounding-interacting systems, by the internal ecological processes, and by the human impacts that act on the lagoon system both directly and indirectly, mediated by the main land and open sea. Therefore a complete representation of the eco-dynamics of the Lagoon of Venice should include those main interacting processes, or, at least parameterise them.

The lagoon exchange with the sea is 385 million of cubic meter per day on average, and receives, on average 33 m^3/s of water from the drainage basin through the 9 main rivers. The drainage basin covers 1,870 Km^2 of relatively densely populated area, with its 1,500,000 inhabitants, where intensive agriculture and important industrial activities are located.

In addition, internal islands, such as Venice itself, Murano and Burano, do not have proper sewage treatment systems and the sludge is directly dumped into the lagoon after going through a very coarse first step of the biological degradation.

Therefore the lagoon, that is naturally a eutrophic-mesotrophic environment, has reached the eutrophic- distrophic conditions in the last decades. This trend was inverted lately by the growing awareness in environmental issues that have triggered the reduction of the loadings from the drainage basin, acting at both the production level and at the nutrient abatement level, increasing the efficiency of the processes.

The Lagoon of Venice is a well-studied environment, and several research programs have been developed in the last decades, in order to understand the peculiar dynamics of the ecosystem and in order to evaluate the effects of human activities.

The lagoon– per se- is a sensitive site and specific regulations, aimed to maintain and improve the ecosystem health, have been recently introduced in the national legislation devoted to Venice

This approach aims to set the MPL (maximum permissible load) considering both the external constrains and the self-purifying processes in the ecosystem in order to reach a global water quality target (WQT).

Water-quality integrated models can be useful tools in the definition of feasible WQT and MPL and this paper illustrates one of the steps of the creation of such an integrated tool.

The objective of the work presented here is to improve a previous release of VELFEEM (Venice Lagoon Finite Element Ecological Model) presented in Melaku Canu et al. (2001), and to analyse the sensitivity of model output to changes in the nutrients loadings regime. In a previous work (Melaku Canu et al. 2002) the model has already been shown to be sensitive to physical forcing variations - such as the wind and tide regimes.

2. THE INTEGRATED MODEL

The model is an advective-diffusion two-dimensional ecological model made by coupling a finite element hydrodynamic model SHYFEM (Umgiesser & Bergamasco, 1993, Umgiesser, 1997) that resolves the water balances, with the ecological model EUTRO-WASP (Water Quality Simulation Analysis), and a heat flux module (Umgiesser et al., 2001).

This system simulates the evolution of 9 ecological state variables, namely, zooplankton, phytoplankton, ammonia, nitrate, phosphate,organic nitrogen, organic phosphorous, carbonaceous biochemical oxygen demand, and dissolved oxygen,- which interact together in the four bio-geo-chemical cycles of nitrogen, phosphorous, oxygen and carbon.

At each time step, the values of the variables in the 2D domain, and also the value of an aggregate index of water quality, TRIX, (Vollenveider et al. 1997) are given.

The integration of the two models described in detail in Umgiesser et al., 2001, uses the splitting operator technique. The global temporal variation of any state variable is split into the sum of two contributions - a physical term, and a biological-reactive term - resolved within two independent modules (Fig. 1). The hydrodynamic module first resolves the momentum and continuity equation to update the current velocities and water levels. The physical (temperature and salinity) and bio-chemical scalars are then advected and diffused. Once this advection step has been handled the new loadings and forcing terms are set-up and then EUTRO is called for the bio-chemical reactions.

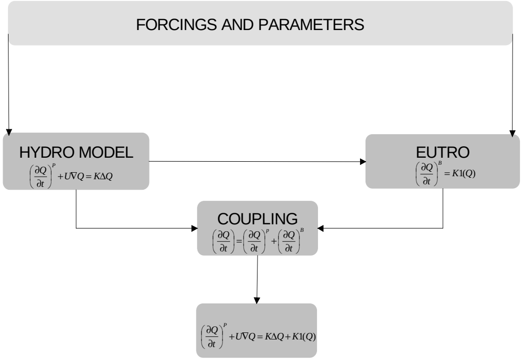

Figure 1. Overall structure of the integrated model

2.1 The hydrodynamic model FEM

The hydrodynamic module solves the two dimensional barotropic shallow water equations using a semi-implicit algorithm. The spatial discretization of the equations is done on a triangular finite element grid (Fig. 1). These linear finite elements give enough flexibility to describe the complex geometry and bathymetry of the Venice Lagoon.

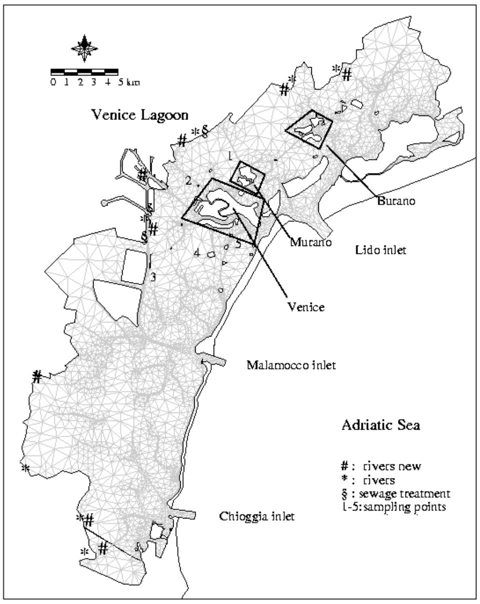

Figure 2. The Venice Lagoon: grid, sampling points, input points.

The model equations are:

$$\frac{d\eta}{dt}+\frac{dU}{dx}+\frac{dV}{dy}=0 \qquad (1)$$

$$\frac{dU}{dt}+g\cdot\frac{d\eta}{dx}+R\cdot U+X=0 \qquad (2)$$

$$\frac{dV}{dt}+g\cdot\frac{d\eta}{dy}+R\cdot V+Y=0 \qquad (3)$$

$$U=\int_{-h}^{\varsigma} u\,dz \qquad (4)$$

$$V=\int_{-h}^{\varsigma} v\,dz \qquad (5)$$

where η is the water level, u,v the horizontal velocities in x and y direction, while U and V are the vertically-integrated velocities, g is the gravitational acceleration, H=h+η the total water depth, h the undisturbed water depth, t is time and R is the friction coefficient. The terms X and Y include all other terms like the wind stress the non-linear terms. Evaporation is assumed to equal the precipitation, and therefore they are not explicitly computed.

The wind stress uses a constant drag coefficient, and the friction coefficient is determined through the Strickler formula.

Water levels are described by linear form functions defined on the nodes (intersections) of the grid while the velocities are described by constant form functions over one element, which corresponds to the definition of the velocities on the centre of the elements.

The model also treats shallow water flats, subjected to dry and flooding periods. It takes the shallow water flats out of the algebraic system during the dry period and adds them again, once the surrounding water level is higher than the water inside the dry element. This specific implementation conserves the mass in each element.

The transport and diffusion of a dissolved substance is done through an explicit up-wind algorithm that is mass conserving. The dissolved substance is represented by linear form functions with the variables defined on each node. The variables used in the model are the temperature, salinity and all the state variables of the ecological module EUTRO.

2.2 The ecological model

The ecological model has been extracted from the original code, the EUTRO code of WASP, (Ambrose et al. 1993), adapted to our case study and then improved (Melaku Canu, 2000). Now it simulates the evolution of the 9 state variables, ammonia *NH3*, nitrate *NOX*, phosphate *OPO4*, phytoplankton *Phy*, zooplankton *Zoo*, organic nitrogen *ON*, organic phosphorous *OP*, carbonaceous bio-geo-chemical oxygen demand *CBOD*, and dissolved oxygen *DO*. (Fig. 2)

The evolution of state variables simulates the biogeochemical cycles of nitrogen, phosphorous, oxygen and carbon. Phytoplankton here is considered as a pool of primary producers and is driven by the nutrient concentration and by the dynamics of grazers. It is described (equation 1 in table 1), by the growth term, GP1, the death term, DP1, and by the grazing, GRZ. In GP1 the optimal growth, K1C, is multiplied by dimensionless factors, which simulate limitation to growth due to sub-optimal levels of light intensity, temperature, and nutrient concentration. The limiting factors are computed following the standard formulations: the Michaelis Menten –Monod for nutrient limitation, the Steele formulation for the limitation due to light intensity, and an exponential relation for temperature.

The evolution of the zooplankton (eq. 2 Table 1) is described by the grazing term -using the Holling type II relationship between phytoplankton and zooplankton concentration- and by the mortality term, which is described by a first order kinetic.

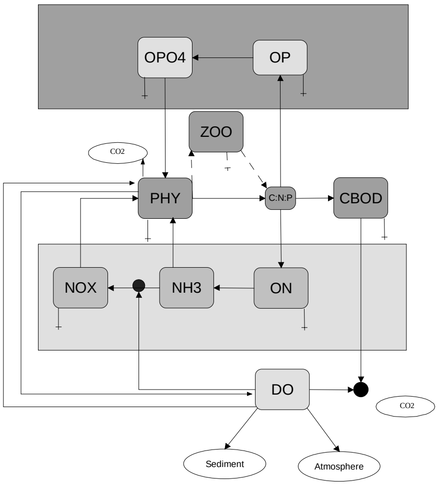

Figure 2. Ecological model state variables and fluxes

3. MODEL SETUP AND DEFINITION OF SCENARIOS

The model is run for one year: four simulations are made under 2 different scenarios, obtained by varying external conditions. Using a time step of five minutes, each simulation took around 4 days of computer time on a medium power workstation.

Boundary concentration values (Bergamasco and Zago, 1999), and river input (Zonta et al., 2001) of freshwater, nutrients and organic materials are input from external data files.

External data files are provided also for experimental values of meteorological parameters, such as light intensity, clouds cover, humidity, which are used for computation of water temperature and irradiance level. Thermal loadings from the industrial sites are input in the model following Cedolini et al., 1997. The tide is given by experimental value of sea levels measured at the Lido inlet in 1987.

As for biological submodel, we have used parameter values from literature on previous modelling works about the Venice Lagoon. As for physical submodel calibration has been performed versus tidal gauges

Likely, there still is space for improving the capability of the model to reproduce quantitatively real evolution. However a formal calibration of a model of this complexity and of this computational demand is very difficult, and as not been performed as yet. Instead, after some empirical calibration, we have focused on the comparison between model predictions under different scenarios of forcings. The assumption is that the emerging indication are robust, at least qualitatively, in respect of minor modification in some parameter values.

We run two simulations using the nutrient loading values provided by the DRAIN project. This amounts to 3996 tonns/year for total nitrogen, and 228 tonns/year for total phosphorous. This is the most updated estimate available. (Zonta et al., 2001).

In the simulation called "*real*", we use monthly data of river flow and the concentration values sampled at each river, as reported in Zonta et al., (2001), maintaining the space and time variability.

In the simulation called "*sim*", the total loadings from the drainage basin are input assuming a constant macronutrient concentration in the whole river network. Accordingly, the load of nutrient input by each river varies in dependence on the water load of the river. This approximation is not infrequent in modelling watershead/basin interaction, because often there is no information on the nutrient concentration of the different rivers, while measurements of fresh water volume are more frequently performed.

We adopt this very approximation in previous papers (Melaku Canu et al., 2001, Melaku Canu et al., 2002) which appeared before the results from DRAIN Project were delivered. In those papers, and in the '*sim*' scenario, estimates on river flows were as in Bernardi et al. (1993). In order to simulate seasonality, these average values are multiplied by a sinusoidal function.

The inputs over the whole basin, in the two simulations, are compared in figure 3.

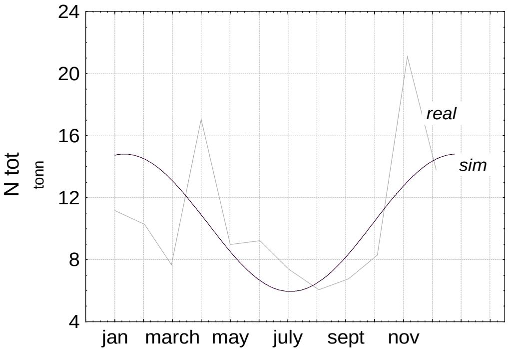

Figure 3. Total river input of N in the two simulations (*real* and *sim*)

4. CONCLUSIONS

A full discussion of model results is here omitted out of space limitation.

Analysis of model performances, in terms of ecological consistency and numerical stability can be found in the above quoted papers.

The model, however, is capable to capture the major features of nutrients and plankton evolution, and reproduces satisfactorily space and time variability of these variables.

Figure 4 illustrates a comparison of spatial distribution of yearly averaged values of Dissolved Inorganic Nitrogen (DIN), under the two scenarios mentioned above. As it can be seen, model results are very sensitive to changes in the repartition of the total N load, which is the same in the two simulations. Indeed substantial differences in spatial distributions are easily found even when inspecting yearly average quantities, as in figure 4.

This differences are so high that depending on which scenario is considered, different policy options may be suggested in planning environmental protection of the Lagoon.

The results clearly indicate that:

1. It is important to have a correct parameterisation of space and time evolution of river inputs, and therefore it is important to monitor nutrient concentration in river input, and not only freshwater volumes;
2. Space variability is very important;
3. Both results emerge because we use a coupled model, capable of describing both the nutrient cycles and the transport processes. A simpler 0D biological model, could not give the same indication. Therefore integrated models do are important tools in analysing and understanding complex systems.

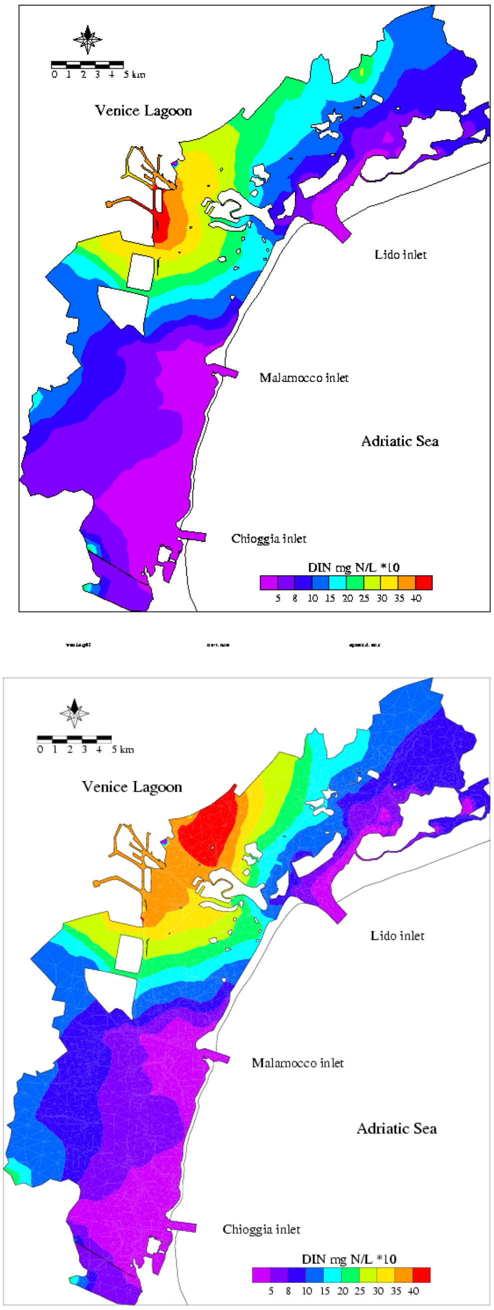

Figure 4. Comparison of spatial distribution of yaerly averaged value of DIN in the two scenarios: a) scenario *sim*; b) scenario *real*

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Mass balances			
			General Reactor Equation
$Q(PHY) = (GP1 - DP1 - GRZ) * PHY$	1		phytoplankcton Phy [mg C/L]
$Q(ZOO) = (GZ - DZ) * ZOO$	2		zooplankton Z: mg C/L]
$Q(NH3) = (N_{alg1} + ON1 - N_{alg2} - N1)$	3		ammonia NH3 [mg N/L]
$Q(NOX) = (N1 - NO_{alg} - NIT1)$	4		nitrate Nox [mg N/L]
$Q(ON) = (ON_{alg} - ON1)$	5		Organic nitrogen ON [mg N/L]
$Q(OPO4) = (OP_{alg1} + OP1 - OP_{alg2})$	6		Inorganic phosphorous OPO4 [mg P/L]
$Q(OP) = (OP_{alg3} - OP1)$	7		Organic phosphorous OP [mg P/L]
$Q(CBOD) = (C1 - OX - (\frac{5}{4} * \frac{32}{14} * NIT1))$	8		Carbonaceous biogeochemical oxygen demand CBOD mg O_2/L
$Q(O) = DO1 + DO2 + DO3 - (OC * RES) - \left(\frac{64}{14} * N1\right) - OX - SOD$	9		Dissolve oxygen DO [mg O_2/L]

Where

Functional expressions		Description
$GP1 = L_{nut} * L_{light} * K1C * K1T^{(T-T_0)}$	10	phytoplankton growth rate with nutrient and light limitation
$DP1=RES + K1D$	11	phytoplankton respiration and death rate
$GPP=GP1*PHY$	12	phytoplankton growth
$DPP=DP1* PHY$	13	phytoplankton death
$GRZ = KGRZ * \frac{PHY}{PHY + KPZ} * ZOO$	14	grazing rate coefficient
$GZ=EFF*GRZ$	15	zooplankton growth rate
$DZ=KDZ*ZOO$	16	zooplankton death rate
$PHSNK = (1 - EFF) * GRZ * PHY$	17	grazing inefficiency on phytoplankton
$N_{alg1} = NC*DPP*(1-FON)$	18	source of ammonia from algal death
$N_{alg2}=PN*NC*GPP$	19	sink of ammonia for algal growth
$NO_{alg} = (1. - PN)*NC*GPP$	20	sink of nitrate for algal growth
$ON_{alg} = NC*(DPP*FON+ PHSNK +DZ)$	21	source of organic nitrogen from phytoplankton and zooplankton death
$N1 = KC_{nit} * KT_{nit}^{(T-T_0)} * NH3 * \frac{DO}{K_{nit} + DO}$	22	Nitrification
$NIT1 = KC_{denit} KT_{denit}^{(T-T_0)} * NOX * \frac{K_{denit}}{K_{denit} + DO}$	23	denitrification
$ON1 = KNC_{\min} * KNT_{\min}^{(T-T_0)} * ON$	24	mineralization of ON
$OP1 = KPC_{\min} * KPT_{\min}^{(T-T_0)} * OP$	25	mineralization of OP
$OP_{alg1}=PC*DPP*(1. - FOP)$	26	source of inorganic phosphorous from algal death,
$OP_{alg2}=PC*GPP$	27	sink of inorganic phosphorous for algal growth
$OP_{alg3}=PC*(DPP*FOP+PHSNK +DZ)$	28	source of organic phosphorous from phytoplankton and zooplankton death
$OX = KDC * KDT^{(T-T_0)} * CBOD * \frac{DO}{KBOD + DO}$	29	oxidation of CBOD
$C1=OC*(DPP+PHSNK+DZ)$	30	source of CBOD from phytoplankton and zooplankton death
$DO1=KA*(O_{sat} - DO)$	31	reareation term
$DO2=PN*GP1* PHY *OC$	32	dissolved oxygen produced by phytoplankton using NH3
$DO3 = (1 - PN) * GP1 * PHY * 32 * \left(\frac{1}{12} + 1.5 * \frac{NC}{14}\right)$	33	growth of phytoplankton using NOX
$PN = \frac{NH3 * NOX}{(KN + NH3) * (KN + NOX)} + \frac{NH3 * KN}{(NH3 + NOX) * (KN + NOX)}$	34	ammonia preference
$RES = K1RC * K1RT^{(T-T_0)}$	35	algal respiration
$SOD = (\frac{SOD1}{H} * SODT^{(T-T_0)})$	36	sediment oxygen demand
L_{nut}=min(X1,X2) or mult(X1,X2)	37	minimum or multiplicative nutrient limitation for phytoplankton growth
$X1 = \frac{(NH3 + NOX)}{KN + NH3 + NOX}$	38	nitrogen limitation for phytoplankton growth
$X2 = \frac{OPO4}{KP + OPO4}$	39	phosphorous limitation for phytoplankton growth
$L_{light} = \frac{I_0}{I_s} * e^{-(KE*H)} * e^{(1-\frac{I_0}{I_s}*e^{(-KE*H)})}$	40	light limitation for phytoplankton growth
$KA=F(WIND,VEL,T,T_{air},H)$	41	re-areation coefficient (Covar…., O'Connor….)

With

Variables		
T	[°C]	water temperature
T_{air}	[°C]	air temperature
O_{sat}	[mg/L]	DO concentration value at saturation
I_0	[lux/day]	incident light intensity at the surface
H	[m]	depth
VOL	[m^3]	volume
VEL	[m/sec]	current speed
WIND	[m/sec]	wind speed