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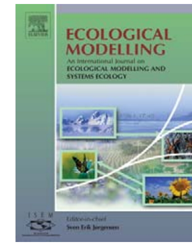

An integrated model for the Orbetello lagoon ecosystem

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ABSTRACT

This paper describes the evolution in time and space of the submersed vegetation in the Orbetello lagoon. This model was developed for the local Lagoon Management Office to predict the development of both macroalgae and macrophytes and test effect of the harvesting decisions. Based on a previous model describing the interactions between nitrogen and the submersed vegetation [Giusti, E., Marsili-Libelli, S., 2005. Modelling the interactions between nutrients and the submersed vegetation in the Orbetello lagoon, Ecol. Model. 184, 141–161], this paper presents several further major improvements introducing the dynamics of phosphorus as a second nutrient, extending the generality of the model to all nutrient conditions and providing a better fit of the observed behaviours, a cellular automaton to describe the dynamics of wigeongrass (*Ruppia maritima*) and a hydrodynamic model for the water movements. The three models are now synchronized and run in the same context with the Manning friction coefficients acting as a feedback link from the hydrodynamic model to the vegetation dynamics. Another important feature is the wind module, generating synthetic wind time-series required as an input to the hydrodynamic model to produce long-term simulations. The integrated model has been implemented as a stand-alone executable code which can be used as a decision support system. Three-year simulations show the expansion of the existing *Ruppia* prairies in accordance with the observations.

1. Introduction

The Orbetello lagoon, schematically shown in Fig. 1, is composed of two communicating coastal basins, with a combined surface of approximately 27 km^2, an average depth of 1 m and is connected to the Tyrrhenian Sea through one inlet at each end of the western lagoon and one at the south end of the eastern lagoon. Given the insufficient tidal head, forced pumping is provided at the three ports at critical times over the year, mainly in spring and summer, in order to secure a minimum water exchange with the sea. Two water-quality monitoring stations, indicated by the two circles in Fig. 1, transmit hourly physico-chemical data to the Orbetello Lagoon Managerial Office headquarters.

The main problem in the Orbetello lagoon is the control of the submersed vegetation, given the critical coexistence between macroalgae and rooted macrophytes (wigeongrass, *Ruppia maritima*). Macroalgae, though of epiphytic origin, float in dense mats and absorb a large quantity of nutrients, eventually producing sudden blooms followed by dystrophic crises. On the other hand macrophytes, being rooted to the bottom play a key role in determining the oxidised or reduced state of the sediments, which is the primary factor controlling nutrient cycling. Selective harvesting is therefore the key problem in the lagoon management and a decision support tool is required to forecast the location and extent of "hot spots", where pre-emptive harvesting may be implemented. In particular, the need arises to monitor and forecast expansion of the wigeongrass prairies over the lagoon.

In the context of a decision support system, this model provides the necessary long-range prediction capability required to answer the typical "*what–if*" question asked by the man-

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Nomenclature

A_x	cell cross-section along the E–W direction (m^2)
A_y	cell cross-section along the N–S direction (m^2)
c_d	surface shear coefficient for the wind force
$F(p)$	spline smoothing objective function
g	acceleration of gravity ($m\,s^{-2}$)
G	germination function, as a fraction of seedling
h	water depth (m)
M	flux along the x (E–W) direction ($m\,s^{-1}$)
n	Manning friction coefficient ($m^{1/3}\,s^{-1}$)
N	flux along the y (N–S) direction ($m\,s^{-1}$)
p	spline smoothing parameter
P_s	wigeongrass seed production rate ($g\,m^{-2}\,day^{-1}$)
$R_{i,j}$	wigeongrass density in the (i, j) cell ($g\,m^{-2}$)
$S_{i,j}$	wigeongrass seeds concentration in the (i, j) cell ($g\,m^{-2}$)
$u_{i,j}$	water velocity in the E–W direction ($cm\,s^{-1}$)
v	wind cross-correlation coefficient
$v_{i,j}$	water velocity in the N–S direction ($cm\,s^{-1}$)
$V_{i,j}$	water volume of the (i, j) cell (m^3)
w_E	wind speed in the east basin (m/s)
w_W	wind speed in the west basin (m/s)
w_x	wind speed in the x direction ($m\,s^{-1}$)
w_y	wind speed in the y direction ($m\,s^{-1}$)
z	bottom elevation with respect to a reference altitude (m)
α_E	wind angle in the east basin (°)
α_W	wind angle in the west basin (°)
σ_E^α	wind angle standard deviation in the east basin (°)
σ_W^α	wind angle standard deviation in the west basin (°)
σ_E^w	wind speed standard deviation in the east basin (°)
σ_W^w	wind speed standard deviation in the west basin (°)
ρ	water density ($kg\,m^{-3}$)
ρ_a	air density ($kg\,m^{-3}$)
Φ	maximum water shear velocity for seed deposition ($cm\,s^{-1}$)
Ψ	data roughness used in data smoothing

ager. Previously, simulation of the lagoon behaviour was accomplished in an elaborate and unsatisfactory way: the hydrodynamic field was generated by a separate platform, either the first version of Swamp (Covelli et al., 2002) or the MIKE21 commercial platform (DHI, Horshølm, DK). The resulting water velocities were then used in the ecological model (Giusti and Marsili-Libelli, 2005) to provide the required advection–diffusion terms. This procedure, apart from being very cumbersome, had two major pitfalls: (1) the hydrodynamic fields were generated under the assumption of monthly constant wind for the whole simulation; (2) the rooted vegetation had no influence on the hydraulics, in terms of varying friction.

To overcome these difficulties this integrated model was conceived, with an internal feedback path from the rooted vegetation growth to the hydraulics. Further, the rooted vegetation dynamics has been significantly enhanced by complementing the basic growth mechanisms with a set of rules governing the spatial spread of the meadows. The resulting model has also a finer resolution with respect to the previous versions (Covelli et al., 2002; Giusti and Marsili-Libelli, 2005) both in time and space, and has been used to forecast the expansion of the rooted macrophytes over a time horizon of several years, with good agreement with the reported observations.

2. Modelling the lagoon ecosystem

To take into account the facts just outlined, a comprehensive hydraulic–ecological model was produced by integrating two pre-existing modules: the hydrodynamic model Swamp (Covelli et al., 2002) and the ecological model LaguSoft (Giusti and Marsili-Libelli, 2005), which were previously used separately. Both models now use a regular 100 m × 100 m grid and operate as two interlocked modules. The Swamp module generates the velocity fields induced by the wind and the pumping scheme at the three inlets. The velocity field is then used in the ecological module LaguSoft, where each cell implements the kinetics of nutrients and their interactions with the submersed vegetation. The cell dynamics runs on an hourly basis to keep track of the circadian cycles, whereas the advection/diffusion model has a daily time-base, enough to account for mass transfer among adjacent cells. The velocity field is also passed to the wigeongrass module, which computes the growth of wigeongrass through seed dispersal and burial. In turn, the wigeongrass density determines the Manning friction coefficients which act as feedback elements to the velocity computation for the following day. This combined model represents a considerable advance with respect to previous ecological models (Marsili-Libelli and Giusti, 2004; Giusti and Marsili-Libelli, 2005) in which the wigeongrass dynamics consisted of a growth–decay balance modulated by several environmental factors, but lacked the feedback path through water flow. Previous instances of integration between hydraulics and eutrophication models have been published (e.g. Umgiesser et al., 2003) and in the model presented here specific feedback links between hydraulics and ecology are represented by:

1. Vegetation-dependent Manning friction coefficients, which are modelled as a function of the wigeongrass density, as suggested by Stephan and Gutknecht (2002), Järvelä (2004) and Thompson et al. (2004), with a feedback on the velocity fields.
2. Seed dispersal and germination, which are modelled with a fuzzy cellular automaton (Balzter et al., 1997; Chen et al., 2002; Gronewold and Sonnenschein, 1998; Marsili-Libelli and Giusti, 2004), taking into account, among other factors, the water velocity through the Manning friction coefficient.

The structure of the integrated model is shown in Fig. 2, where the outer loop is iterated once per day, given the slow growth of the rooted plants with respect to hydraulic