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# An ecohydrology model of the Guadiana Estuary (South Portugal)

Eric Wolanski<sup>a,\*</sup>, Luís Chicharo<sup>b</sup>, M. Alexandra Chicharo<sup>b</sup>, Pedro Morais<sup>b</sup>

<sup>a</sup> Australian Institute of Marine Science, PMB No. 3, Townsville MC, Queensland 4810, Australia

<sup>b</sup> Centro de Ciências do Mar, Faculdade de Ciências do Mar e do Ambiente, Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

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### Abstract

A 1-D ecohydrology model is proposed that integrates physical, chemical and biological processes in the Guadiana Estuary during low flow conditions and that predicts the ecosystem health as determined by the following variables: river discharge, nutrients, suspended particulate matter, phytoplankton, zooplankton, bivalves, zooplanktivorous fish and carnivorous/omnivorous fish. Low flow conditions prevail now that the Alqueva dam has been constructed. The ecological sub-model is based on the non-linear Lotka–Volterra equation. The model is successful in capturing the observations of along-river changes in these variables. It suggests that both bottom-up and top-down ecological processes control the Guadiana Estuary ecosystem health. A number of sensitivity tests show that the model is robust and can be used to predict – within likely error bounds provided by the sensitivity tests – the consequences on the estuary ecosystem health of human activities throughout the river catchment, such as the irrigation farming downstream of the Alqueva dam, reclamation of the salt marshes by urban developments, and flow regulation by the Alqueva dam. Remedial measures are thus necessary.

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Keywords: ecohydrology; marine ecology; flushing; modelling; dam; flow regulation; Portugal; Alqueva dam; Guadiana Estuary

### 1. Introduction

Throughout human history, the coastal plains and Lowland River valleys have usually been the most populated areas over the world (Wolanski et al., 2004). At present, about 60% of the world's population lives along the estuaries and the coast (Lindeboom, 2002). This is degrading estuarine and coastal waters through pollution, eutrophication, increased turbidity, overfishing, and habitat destruction. The pollutant supply does not just include nutrients; it also includes mud from eroded soil, heavy metals, radionuclides, hydrocarbons, and a number of chemicals including new synthetic products.

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The impact on estuaries is commonly still ignored when dams and irrigation farming are proposed on rivers. In addition, estuaries are often regarded as sites for future development and expansion, and have been increasingly canalized and dyked for flood protection, and their wetlands infilled for residential areas.

All these factors impact on the biodiversity and productiv-ity and, hence, the overall health of estuaries and the ecosys-tem services they provide to humans (Nixon, 2003; Erzini, 2005). They increasingly lead humans away from the possibil-ity of ecologically sustainable development of the coastal zone. Integrated coastal zone management plans are drawn up worldwide (e.g., Haward, 1996; Billé and Mermet, 2002; Tagliani et al., 2003; Pickaver et al., 2004; Lau, 2005). How-ever, in the presence of significant river input, most are bound to fail because they commonly deal only with local, coastal is-sues, and do not consider the whole river catchment as the fun-damental planning unit. It is as if the land, the river, the estuary, and the sea were not part of the same system. When

<sup>1.1.</sup> The need for an ecohydrology estuarine model

<sup>\*</sup> Corresponding author.

*E-mail address:* e.wolanski@aims.gov.au (E. Wolanski).
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115 dealing with estuaries and coastal waters, in most countries land-use managers, water-resources managers, and coastal and fisheries managers do not cooperate effectively due to administrative, economic and political constraints, and the absence of a forum where their ideas and approaches are shared and discussed (Wolanski et al., 2004). To help alleviate this problem, UNESCO - IHP has launched the ecohydrology program. In this program, the concept of ecohydrology is introduced as a holistic approach to the management of rivers, estuaries and coastal zones within entire river catchments, by adopting science-based solutions to management issues that restore or enhance natural processes as well as the use of tech-nological solutions (Zalewski, 2002).

128 This science-based management requires the use of a holis-129 tic model to quantify the human impact on the ecosystem 130 health of estuaries and to enable the exchange of information 131 between oceanographers, biologists, ecologists, engineers, so-132 ciologists, economists and water-resources managers at local 133 and national governmental levels, and the community.

135 1.2. The science behind the model

137 The model is process-based. The dominant physical, chem-138 ical, biological and human-related processes in an estuary are

assumed to follow those described by Wolanski et al. (2004) and are sketched in Fig. 1. These processes are briefly summarised below.

The ecological health of estuaries is determined by the interaction between organisms and variations in salinity, currents, waves, suspended particulate matter (SPM), bed sediments, temperature, air exposure, hypoxia, wetland contaminants and biodiversity. Like the health of a living organism, the health of an estuary or a coastal water body, cannot be measured by one single variable, indeed a number of variables are important (Balls, 1994). Well-flushed estuaries are intrinsically more robust than poorly flushed systems. As a result, environmental degradation is most often apparent during periods of reduced freshwater inflows, e.g. during drought or when human activities reduce the freshwater flow. Therefore, this ecohydrology model focuses on low flow conditions when vertically well-mixed conditions often prevail.

Once riverine-derived suspended particulate matter enters the estuary, it can be trapped within an estuarine turbidity maximum (ETM) zone (Fig. 1). The ETM is commonly located in the very low salinity reaches of an estuary. The maximum, depth-averaged, suspended solid concentration (SSC) at high water within an estuary can be predicted semi-empirically as a function of the tidal intrusion and the tidal range (Uncles et al., 2002).



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229 Sediment particles and aggregates within the ETM can give 230 rise to marked changes in water quality. Fine particles can 231 adsorb metal ions and organic macro-molecules from solution 232 to such an extent that some metals can be completely removed 233 from solution within a strong ETM (Salomons and Forstner, 234 1984; Ackroyd et al., 1986). Once nutrients enter an estuary, 235 non-conservative behaviour can be pronounced. Key processes 236 responsible for this non-conservative behaviour include burial 237 in sediment reservoirs and desorption processes particularly if 238 the sediment is nutrient-rich. Nutrients are generally mainly in 239 particulate form (i.e. absorbed to the mud particles in suspen-240 sion) in freshwater and can be released in solution in saline 241 water.

The salt marshes of Western Europe generally produce more than 1 kg m<sup>-2</sup> yr<sup>-1</sup> of above-ground dry matter (Boorman et al., 1994a,b; Lefeuvre, 1996). Salt marshes export some of this organic matter. Salt marshes and their tidal creeks are also an important nursery ground, and a refuge, for larvae and post-larvae of bivalve, carnivorous/omnivorous fish and zooplankton.

249 The estuary is modelled as a converter of living phyto-250 plankton to detrital particles; it is also a conveyor of detrital 251 matter to the sea. Fishes help transfer energy and matter 252 from estuarine plants to upper trophic levels. The great bulk 253 of the organic matter produced (sometimes 90%) is processed 254 through the detrital system. Zooplankton, planktivorous fish, 255 interstitial micro and meiofauna, surface deposit-feeding mol-256 luscs, fishes and polychaeta, and filter-feeding invertebrates 257 consume a much greater proportion of the primary production 258 of the phytoplankton and benthic microalgae. Annual plant 259 growth and decay provide continuing large quantities of organic detritus. In addition, there is often a considerable input 260 261 of detritus from river inflow. Detrital particles and their asso-262 ciated microorganisms provide the basic food source for 263 primary consumers such as zooplankton, most benthic 264 invertebrates and some fishes. The first trophic level in the 265 estuarine ecosystem is therefore best described as a mixed tro-266 phic level of detritus consumers, which in varying degrees are 267 herbivores, omnivores or primary carnivores (Knox, 1986).

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- 269 *1.3. Study area* 270

The Guadiana River is one of the largest in the south of the
Iberian Peninsula, crossing extensive rural areas and includes
the Iberian Pyritic Belt (Gonzalez, 1995).

The fluvial regime is characterised by low flows during summer and episodic runoff periods in winter with the resulting discharge of sediments into the estuary and coastal zone. The estuary is 60 km long, it has a maximum width of 550 m and the maximum depth varies between 5 and 17 m. The tidal regime of the estuary is meso-tidal, with an average amplitude of 2 m (Michel, 1980).

281The estuary has an important nursery function for several282fish species, such as the anchovy *Engraulis encrasicolus* sensu283lato and several Sparidae, and crustacean species such as the284brown shrimp *Crangon crangon*. Moreover, the outwelling285from the estuary to the coastal area promotes the development

of the food web and influences the fisheries (Chícharo et al., 286 2002; Erzini, 2005). 287

Several pollution sources exist in the Guadiana Estuary 288 area, mainly resulting from urbanisation, agriculture (fertil-289 izers, pesticides, and herbicides), cattle breeding and olive 290 291 oil production. The freshwater flow reaching the estuary is at present regulated by more than 100 dams, including the 292 293 Algueva dam whose construction was completed in 2002 294 and that forms the largest reservoir in Europe (Alveirinho 295 et al., 2004).

1	.4.	Aims

This study aimed to develop an ecohydrology model to be 299 300 applied to the low flow conditions in the Guadiana Estuary. It describes such a model designed specifically for vertically 301 302 well-mixed estuaries. The ecological sub-model is also simple, 303 though still realistic. It incorporates the seven state variables: 304 nutrients, suspended particulate matter, phytoplankton, zoo-305 plankton, bivalves, zooplanktivorous fish and carnivorous/om-306 nivorous fish in the estuary and it predicts the ecosystem health. 307 308

#### 2. Material and methods

### 2.1. Field data

313 Estuarine physical, chemical and biological data were 314 obtained from the papers of M. Chicharo et al. and P. Morais 315 et al. in this issue and from Pinto (2000), and Esteves et al. 316 (2000). Data from river inflow were obtained online from 317 Water National Institute (INAG), National System of Hydro-318 logical Resources (http://snirh.inag.pt/) from the hydrometric 319 station Pulo do Lobo (lat. 37°48' N, long. 7°38' W), located 320 a few kilometres above the last point of tidal influence 321 (Mértola). 322

### 2.2. The estuarine ecohydrology model

325 The prototype is the Guadiana Estuary at low flow 326 conditions – because such low flow conditions prevail now 327 that the Alqueva dam exists. For a freshwater flow  $Q_{\rm f} <$ 328  $50 \text{ m}^3 \text{ s}^{-1}$ , the Guadiana Estuary is vertically fairly well-329 mixed in salinity (Fortunato et al., 2002). In a vertically 330 well-mixed estuary, the distribution of salinity S is determined 331 from the solution of the 1-D advection-diffusion equation 332 (Fischer et al., 1979):

$$\partial(SA)/\partial t + \partial(QS)/\partial x = \partial(EA \,\partial S/\partial x)/\partial x$$
 (1) 334

where t is the time, Q is the flow rate (driven by tides and 336 river flows), E is the longitudinal eddy diffusion coefficient, 337 and A is the cross-sectional area. Eq. (1) is solved for a series 338 of cells of volume V distributed along the length of the estuary from the tidal limit to the mouth. The time step dt is set 340 to 1 day, thereby averaging over the tides. The open boundaries are located at the tidal limit and at the mouth. At the 342

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Fig. 2. Observed and predicted along-channel distributions of salinity in the Guadiana Estuary around the times of (square) high tide and (circle) low tide for salinity of (a)  $2 \text{ m}^3 \text{ s}^{-1}$  and (b)  $50 \text{ m}^3 \text{ s}^{-1}$ . Cell # 1 is located at the tidal limit, 60 km upstream of cell # 20 that is located at the mouth. 360

361 tidal limit, the model assumes that the salinity S = 0 and it 362 also assumes that  $Q_{\rm f}$  is known. At the mouth, the salinity 363 is assumed to be 35. Turbulent diffusion is due to tides, 364 wind, and freshwater runoffs and is parameterised by the pa-365 rameter E. In the model, this is determined by mixing coef-366 ficients that quantify the fraction of water in a cell that is 367 exchanged with adjoining cells during the time step (1 368 day). This parameter is varied until the solution fits well 369 with the observations. This is shown in Fig. 2 for the case 370 of the Guadiana Estuary for two values of the freshwater dis-371 charge  $Q_{\rm f}$  (2 and 5 m<sup>3</sup> s<sup>-1</sup>).

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372 The model enables one to readily calculate the flushing time 373 of the estuary. To do that, in the model the freshwater discharge 374 is set to be a constant and the estuary is initially filled with uni-375 form seawater salinity at t = 0. The system is then allowed to 376 evolve, and in the model salt is progressively expelled from 377 the upper reaches of the estuary until a steady state solution is 378 reached. This is shown in Fig. 3 for a freshwater discharge 379  $(Q_{\rm f})$  of, respectively, 2 and 50 m<sup>3</sup> s<sup>-1</sup>. It is apparent that for 380  $Q_{\rm f} = 50 \text{ m}^3 \text{ s}^{-1}$  the residence time is about 5 days, and that for 381  $Q_{\rm f} = 2 \,{\rm m}^3 \,{\rm s}^{-1}$  the residence time varies between 14 days in 382 the lower reaches and 37 days in the upper reaches of the estuary. 383 For a non-conservative constituent such as nutrients, plank-384 ton, detritus, fish, and bivalve, Eq. (1) is modified by including 385 a sink-source term  $\Delta C$  (Thomann, 1980), where C is the 386 concentration:

 $\partial(CA)/\partial t + \partial(QC)/\partial x = \partial(EA \,\partial C/\partial x)/\partial x + \Delta C$  (2)

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where  $\Delta C$  is derived from the ecological sub-model described below.

The ecological sub-model is based on the non-linear Lotka–Volterra equation. It is based on a finite-element model with the same cells as those used in the salinity model. A number of modeling equations are possible. In the absence of excretion and death not due to predation, the predator–prey relationship is often calculated by the non-linear equations (Brauer and Castillo-Chavez, 2001; Kot, 2001).

$$\partial X/\partial t = \beta X(1 - X/X_{o})H(Y, Y_{o1})$$
(3)

and

$$\partial Y / \partial t = -\beta X (1 - X / X_{\rm o}) H(Y, Y_{\rm o1}) \tag{4}$$

where *X* is the predator biomass (X = CV) where *C* is the predator concentration, *Y* is the prey biomass,  $\beta$  is the predator growth rate,  $X_0$  is the predator saturation biomass,  $Y_{01}$  is the prey starvation biomass, i.e. the biomass at which the predator is unable or unwilling to spend energy to find this prey. *H* is the Heavyside function, i.e. H = 0 if  $Y < Y_{01}$ , and H = 1 if  $Y > Y_{01}$ . Eq. (2) also applies if *Y* is a nutrient. Provided starvation does not occur, the solution is an S-shaped curve whereby *X* initially increases exponentially in time. The growth rate is



Fig. 3. Estimation of the residence time from the time series of salinity distribution in the estuary following intrusion of freshwater for (a)  $2 \text{ m}^3 \text{ s}^{-1}$  and (b)  $50 \text{ m}^3 \text{ s}^{-1}$ .

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457 zero at  $X = X_0$ . Because X and Y are related by Eqs. (3) and 458 (4), Y decreases toward a minimum value.

In the model, freshwater phytoplankton and bacterioplankton in the river are subject to salt stress when freshwater mixes
with saltwater; and the freshwater microbial populations die in
this zone (Flameling and Kromkamp, 1994; Goosen et al.,
1995). In the model, the salinity also limits the seaward distribution of saline water plankton, invertebrates (e.g. bivalves)
and fishes.

466 In an estuary, changes in salinity constitute a major stress 467 that can lead to death. There are other stressors, for instance, 468 small values of the dissolved oxygen concentration. A death-469 excretion rate  $\delta$  must then be added to Eq. (3) that becomes:

471 
$$\partial X/\partial t = \beta X(1 - X/X_{o})H(Y, Y_{o1}) - \delta X$$
 (5)

472 473 The solution of this equation is also an S-shaped curve, the 474 maximum value, however, is smaller than in the absence of 475 this death-excretion rate, that is  $X = X_0(1 - \delta/\beta)$ . To remain re-476 alistic the solution requires  $\beta > \delta$ , i.e. that the growth rate is 477 larger than the death-excretion rate.

478 In an estuary, fringing wetlands (mainly salt marshes and 479 riparian ecotones, together with the tidal creeks that drain 480 them) can be an important source of detritus and nutrients, 481 as well as a nursery for juveniles and sub-adults as well as 482 a refuge. This is particularly the case for bivalves. Mathemat-483 ically, this is expressed by adding a source of X to the right-484 hand side of Eq. (5). The final equation becomes:

 $\begin{array}{l} 485\\ 486 \end{array} \quad \partial X/\partial t = \beta X(1-X/X_{\rm o})H(Y,Y_{\rm o1}) - \delta X + \alpha \end{array}$ 

 $\frac{487}{488}$  where  $\alpha$  is the import rate from wetlands.

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489The ecosystem model represents mathematically through490Eq. (5) the interactions summarised in Fig. 4 between nutrients

concentration (N), suspended sediment concentration (SSC), 514 phytoplankton concentration (P), zooplankton concentration 515 (Z), bivalve concentration (B), detritus concentration (D), zoo-516 planktivorous fish concentration (ZF), and carnivorous/omniv-517 orous fish concentration (CF). All dying matter becomes 518 519 detritus. Settling is not included in the model, because the animals (e.g. zooplankton) are mobile and can swim in the water. 520 521 The model is equally complex at the lowest and highest tro-522 phic levels, which increases the model robustness (Jorgensen 523 and Bendoricchio, 2001). Thus the ecosystem model equations are: 524

$$\partial N/\partial t = -\beta_{NP}P(1-P/P_o)H(N,N_{o1}) + \alpha_N + \gamma_{SSCN}SSC$$
 (7) 528  
529

Phytoplankton (P)

$$\frac{\partial P}{\partial t} = \beta_{\rm NP} P(1 - P/P_{\rm o}) H(N, N_{\rm o1}) - \beta_{\rm PZ} Z(1 - Z/Z_{\rm o}) H(P, P_{\rm o1})$$

$$-\beta_{\rm PP} B(1 - B/B_{\rm o}) H(P, P_{\rm o1})$$

$$533$$

$$-\beta_{\rm PCF} CF(1 - CF/CF_{\rm o})H(P,P_{\rm o1}) + \alpha_{\rm P} - \delta_{\rm P}P \qquad (8) \qquad 534 \\ 535$$

Zooplankton (Z)

$$\frac{\partial Z}{\partial t} = \beta_{\rm PZ} Z (1 - Z/Z_{\rm o}) H(P, P_{\rm o1}) + \beta_{\rm DZ} Z (1 - Z/Z_{\rm o}) H(D, D_{\rm o1})$$

$$-\beta_{\rm ZZF} Z F (1 - Z F/Z F_{\rm o}) H(Z, Z_{\rm o1})$$

$$-\beta_{\rm ZCF} C F (1 - C F/C F_{\rm o}) H(Z, Z_{\rm o1}) + \alpha_{\rm Z} - \delta_{\rm Z} Z$$

$$(9)$$

$$541$$

Bivalves (B)

(6)

$$\frac{\partial B}{\partial t} = \beta_{\text{PB}} B (1 - B/B_{\text{o}}) H(P, P_{\text{o}1}) + \beta_{\text{DB}} B (1 - B/B_{\text{o}}) H(D, D_{\text{o}1}) - \beta_{\text{BCF}} \text{CF} (1 - \text{CF}/\text{CF}_{\text{o}}) H(B, B_{\text{o}1}) + \alpha_{\text{B}} - \delta_{\text{B}} B$$
(10)



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571	Carnivorous/omnivorous fish (CF)	
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573	$\partial CF / \partial t = \beta_{BCF} CF (1 - CF / CF_o) H(B, B_{o1})$	
574	$+\beta_{PCF}CF(1-CF/CF_{o})H(P,P_{o1})$	
575	$+\beta CE(1 CE/CE)H(7.7)$	
576	$+\rho_{\text{ZCF}} C \Gamma (1 - C \Gamma / C \Gamma_0) \Pi (\Sigma, \Sigma_{01})$	
577	$+\beta_{\rm DCF}{\rm CF}(1-{\rm CF}/{\rm CF_o})H(D,D_{\rm o1})$	
578	$+ lpha_{ m CF} - \delta_{ m CF}  m CF$	(11)
579		
580	Zoonlanktivoroug fish (ZE)	
581	Zoopiankiivorous jisn (ZF)	
582	$\partial ZE / \partial_{4} \rho ZE (1 ZE / ZE ) U(ZZ)$	
583	$0\Sigma F / 0l = \rho_{ZZF} \Sigma F (1 - \Sigma F / \Sigma \Gamma_0) \Pi (\Sigma, Z_{o1})$	
584	$+\beta_{\rm DZF} ZF(1-ZF/ZF_{\rm o})H(D,D_{\rm o1})+\alpha_{\rm ZF}-\delta_{\rm ZF} ZF$	(12)
585		
586	Detritus (D)	
587		
588	$\partial D/\partial t = -\beta_{\rm pp} B(1 - B/B) H(D D_{\rm s})$	
589	$\partial D / \partial i = \rho_{\text{DB}} D (1 - D / D_0) H (D, D_0)$	
590	$-\beta_{\text{DZF}}\text{ZF}(1-\text{ZF}/\text{ZF}_{o})H(D,D_{o1})$	
591	$-\beta_{\rm DCF} {\rm CF}(1-{\rm CF}/{\rm CF_o})H(D,D_{\rm o1})$	

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In these equations the subscripts denote either constituent 596 597 or the interaction between two constituents. For instance, 598  $\delta_{ZF}$  is the death-excretion rate of ZF, and  $\beta_{DZF}$  is the growth rate of ZF from detritus, i.e. the rate of mass transfer rate 599 600 from detritus to ZF.

 $+\delta_7 Z + \delta_{CF} CF + \delta_{ZF} ZF$ 

 $-\beta_{\mathrm{DZ}}Z(1-Z/Z_{\mathrm{o}})H(D,D_{\mathrm{o}1})+\alpha_{\mathrm{D}}+\alpha_{\mathrm{D}}+\delta_{\mathrm{B}}B+\delta_{\mathrm{P}}P$ 

In the nutrient equation, a new parameter was introduced, 601  $\gamma_{\rm SSCN}$ , it denotes the leaching rate of nutrients from the partic-602 ulate phase (i.e. absorbed on the fine sediment) to the dis-603 604 solved phase.

In Eq. (2), because the model is run at a time step of 1 day, 605  $Q = Q_{\rm f}$ . There is thus no need to calculate the tidal dynamics; 606 these are parameterised by the term E. 607

608 When applying Eq. (2) to the zooplanktivorous fish equa-609 tion, Q is modified to incorporate the horizontal swimming by the fish as fish swim, by kinesis or taxis following environ-610 mental clues (Wolanski et al., 1997; Humston et al., 2000). 611 This velocity is assumed to be proportional to S. Thus the 612 fish in the model is able to swim, following taxis or kinesis, 613 614 along environmental gradients.

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### 616 3. Results and discussion

617 618 3.1. Application to the Guadiana Estuary

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620 In the Guadiana Estuary, field data of fine sediment concentration during low flow conditions ( $Q_{\rm f} < 50 \,{\rm m}^3\,{\rm s}^{-1}$ ) suggest 621 the presence of a weak turbidity maximum zone near the salin-622 623 ity intrusion limit, with a maximum SSC value of  $114 \text{ mg l}^{-1}$ at S = 12 while SSC is about 30 mg l<sup>-1</sup> in the freshwater rea-624 ches of the estuary (Portela, unpubl. data). Therefore, the 625 model assumes a suspended sediment concentration (SSC) 626 that is determined as follows: 627

628 SSC = 30 if S < 1

629 SSC = 30 + 7S if 1 < S < 12630

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SSC = 100 - 3.5(S - 15) if S > 12

The model needs the knowledge of all the ecological parameters. The parameter  $\alpha$  varies along-channel to correspond to the location of the salt marshes and riparian/terrestrial vegetation. The approximate values of the parameters are known from a number of studies and from comparison with other estuaries. The final values were selected as a result of a best-fit between observed and predicted values. The results of this calibration are shown in Fig. 5 for nutrients, zooplankton, bivalve, and fish, respectively. Table 1 lists the adopted values of the parameters.

While the calibration appears successful, it is important for the user to also judge whether the solution is realistic and stable (Hilborn and Mangel, 1997). This may be done by undertaking a sensitivity test to judge whether the model is unrealistically sensitive to a specific parameter, making it potentially unstable and unrealistic. A number of sensitivity runs were carried out, each one involving changing one parameter. Calculations were performed for  $Q_f = 2 \text{ m}^3 \text{ s}^{-1}$ , which is the environmental flow for the Guadiana River, i.e. the post-dam river discharge during the dry season. The list of sensitivity runs is summarised in Table 2.

The sensitivity tests show that phytoplankton (Chl a) is most sensitive in cases 2, 4 and 5, i.e. to  $\beta_{\rm NP}$ ,  $\beta_{\rm PB}$  and  $\delta_{\rm P}$ (Fig. 6a).

These results suggest that bivalves play a more important role in filtering phytoplankton than zooplankton. This can result from the fact that bivalves are benthic and sessile organisms, being able to resist currents as opposite to zooplankton populations, although some develop strategies to resist displacement forces (Simenstad et al., 1994).

The most important parameter for zooplankton is  $\delta_{Z}$  (the 662 death-excretion rate of zooplankton), and to a lesser degree 663  $\beta_{\rm NP}$  (uptake rate of nutrient by phytoplankton) and  $\beta_{\rm PZ}$  (uptake 664 rate of phytoplankton by zooplankton). The model zooplankton 665 (Z) is most sensitive in case 7 and to a lesser degree in cases 2 666 and 3 (Fig. 6). As detritus can also be included in zooplankton 667 diet, if  $\beta_{DZ} = 0.1 \text{ day}^{-1}$ . In fact, in a situation of low inflow – as 668 the one tested in the sensitivity runs (Fig. 6c) – the expected de-669 crease in detritus input caused by the reduction of inflow will 670 affect the zooplankton biomass in the estuary, which highlights 671 the importance of detritus as food source for estuarine zoo-672 plankton (Edwards, 2001; Kibirige et al., 2002). 673

The model also shows that zooplanktivorous fish (ZF) is 674 most sensitive to  $\beta_{ZZF}$ ,  $\beta_{DZF}$ , and  $\delta_{ZF}$  (i.e. respectively, the up-675 take rate of zooplankton by zooplanktivorous fish, the uptake 676 rate of detritus by zooplanktivorous fish, and the death rate of 677 the zooplanktivorous fish; cases 6, 11 and 12) (Fig. 6d). In 678 fact, salinity changes caused by modification of freshwater/ 679 seawater balance may affect zooplankton-prey distribution 680 and impact zooplanktivorous fish species distribution. More-681 over, it suggests that the export of detritus from the salt marsh 682 683 does not seem to be the most important source of food for these fish. 684

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Fin	I values of the parameters. Rates are expressed as day	
$\beta_{\rm NI}$	0.2	
$\beta_{\rm PZ}$	0.1	
$\beta_{\rm PE}$	0.1	
$\delta_{ m P}$	0.05	
$\beta_{ZZ}$	0.1	
$\delta_{\rm Z}$	0.1	
$\beta_{BC}$	0.1	
$\delta_{\rm B}$	0.1	
0 <sub>CF</sub>	0.1	
β <sub>D2</sub>	- 0.1 0.1	
OZF	0.1	
ρ <sub>SS</sub>	N 0.3	
PZC	0.03	
PD0 B	F 0.05	
PDI	0.1	
ρ <sub>D</sub>	0.05 = 0.05	vater reaches)
α <sub>B</sub>	0.15 (=0  in freshv)	vater reaches)
α <sub>D</sub>	0.05 (=0  in freshv)	vater reaches)
~ ~ ~	0.05 (=0 in near	· aler reactions)

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Table 2 Model sensitivity runs. All the runs were carried out for a steady, freshwater discharge  $Q_f = 2 \text{ m}^3 \text{ s}^{-1}$ . Rates are expressed as day<sup>-1</sup>

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8 21	I I I I I I I I I I I I I I I I I I I
Run 1:	Standard run
Run 2:	$\beta_{\rm NP}$ decreased from 0.1 to 0.05
Run 3:	$\beta_{\rm PZ}$ decreased from 0.1 to 0.05
Run 4:	$\beta_{\rm PB}$ decreased from 0.1 to 0.05
Run 5:	$\delta_{\rm P}$ decreased from 0.05 to 0.025
Run 6:	$\beta_{\rm ZZF}$ decreased from 0.1 to 0.05
Run 7:	$\delta_{\rm Z}$ decreased from 0.1 to 0.05
Run 8:	$\beta_{\rm BCF}$ decreased from 0.1 to 0.05
Run 9:	decreased from 0.1 to 0.05
Run 10:	$\delta_{\rm CF}$ decreased from 0.1 to 0.05
Run 11:	$\beta_{\rm DZF}$ decreased from 0.1 to 0.05
Run 12:	$\delta_{\rm ZF}$ decreased from 0.1 to 0.05
Run 13:	$\beta_{\rm SSCN}$ decreased from 0.3 to 0.15
Run 14:	$\beta_{\rm ZCF}$ decreased from 0.03 to 0.015
Run 15:	decreased from 0.03 to 0.015
Run 16:	$\beta_{DB}$ decreased from 0.1 to 0.05
Run 17:	$\alpha_{\rm Z}$ and $\alpha_{\rm B}$ decreased from 0.15 to 0.075
Run 18	$\alpha_{\rm D}$ in the freshwater zone increased from 0 to 0.05
Run 19:	$\beta_{\rm DZ}$ increased to 0.1 day <sup>-1</sup> (run 19) and 0.05 day <sup>-1</sup>
	(run 19a, open circles)
Run 20:	$\alpha_D$ increased to 0.15 in the saline region and 0.05 in
	the freshwater region
Run 21:	$\beta_{PCF}$ increased to 0.1; $\alpha_z$ and $\alpha_B$ increased to 0.15



Fig. 6. Along-channel distribution of predicted variables in the Guadiana Estuary for various sensitivity runs shown as numbers (see Table 2). (a) Phytoplankton biomass (Chl a), (b) zooplankton biomass, (c) zooplankton (cont), (d) zooplanktivorous fish biomass, (e) carnivorous/omnivorous fish biomass, and (f) detritus biomass. To convert biomass to concentration, see Fig. 5 and for Chl a  $3.5-7.8 \,\mu g l^{-1}$ . 

Distance (cell no.)

In the model carnivorous/omnivorous fish is measurably sensitive only to  $\delta_{CF}$  (the natural death rate of carnivorous/om-nivorous fish; case 10, Fig. 6e). The model suggests that no other parameter than the natural death rate significantly influ-ences the omnivorous fish. These fishes are mainly freshwater 855 Barbus spp. These species are located mostly in the upper

Distance (cell no.)

reaches of the estuary and the model suggests that this fish is highly vulnerable to a salinity increase, as a result of reduction in river inflow. The model also suggests that the lower estuary has more detritus than it can consume, thus the additional detritus from salt marshes is unimportant. In the upper areas, detritus mainly originates from the decomposition of

Distance (cell no.)

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- 913 riparian vegetation, this source of detritus seems more impor-914 tant in the middle and lower estuary (Fig. 6f).
- 915 The model sensitivity tests are useful because they show 916 that:
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  918 1. the model appears robust because large, but reasonable, changes in the parameters do not lead to instabilities
  920 such as the destruction of trophic layers;
- 921
  92. the biomass of organisms is directly affected by its consumption of prey or being consumed by predators the next level up in the food chain. Indirect effects across two trophic levels are generally small; for instance if we compare ZF from runs 1 and 5, i.e. there is no impact of the death rate of phytoplankton on carnivorous fish.
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### 929 3.2. Examples of management application of the model

931 The ecological sub-model is also simple, though still real-932 istic. It incorporates the dominant six state variables. The 933 model integrates physical, chemical and biological processes 934 in the estuary; it predicts the ecosystem health as determined 935 by the following variables: nutrients, suspended particulate 936 matter, phytoplankton, zooplankton, bivalves, zooplanktivo-937 rous fish and carnivorous/omnivorous fish. Thus the model is 938 simpler than a number of other models (e.g. Flindt and 939 Kamp-Nielsen, 1997 – this comprises 12 state variables) 940 that are often too complex and unwieldy for practical applica-941 tions, especially when data are unavailable or insufficient.

942 The model can readily be used to test management sce-943 narios when querying the impact of developments and 944 disturbances to land-use and water-resources in the river 945 catchment. For instance, the model predicts (Fig. 7) the impact 946 of doubling the nutrient concentration in the Guadiana River 947 as a result of irrigation farming downstream of the Algueva 948 dam. Such farming is indeed planned. The phytoplankton con-949 centration is predicted to increase, particularly in the phyto-950 plankton maximum zone located in the upper reaches of the 951 estuary. This suggests that the system is becoming eutrophi-952 cated and the risk of toxic algae blooms has increased.

The model can also predict the impact of the salt marshes
being destroyed by developments. The model predictions for
phytoplankton are shown in Fig. 7. Clearly the risk of eutrophication and of toxic algae blooms would be further
increased.

958 The model was used to assess the influence on the estuarine 959 ecosystem health of the Alqueva dam that in 2002-2003 sub-960 stantially decreased the river discharge  $Q_{\rm f}$  (Fig. 8a). The pre-961 dictions (Fig. 8b, c) show that without the dam the system was 962 highly variable during a freshwater pulse, while with the dam 963 the system was at steady state. The predicted influence of the 964 Alqueva dam is particularly dramatic for the carnivorous/om-965 nivorous fish (Fig. 8d, e) because without the dam the fish was 966 able to spread over much of the estuary for up to a month after 967 a freshet, while with the dam the fish is restricted to the upper-968 most region of the estuary. Zooplankton and zooplanktivorous 969 fish also are predicted to decrease in the presence of the



Fig. 7. Along-channel distribution of predicted phytoplankton (Chl *a*) biomass in the Guadiana Estuary for the standard run ('as is'), for a doubling of nutrient concentration in the river (' $N \times 2'$ ), and for the additional impact of removing the salt marshes ('No marsh,  $N \times 2'$ ) for a freshwater discharge equal to  $2 \text{ m}^3 \text{ s}^{-1}$ . To convert biomass to concentration for Chl *a* 3.5–7.8 µg l<sup>-1</sup>. 995

Alqueva dam because their renewal and distribution depend 996 on freshets. 997

998 Moreover, the model can also be used for finding solutions for practical existing environmental problems in the Guadiana 999 Estuary such as toxic algal blooms and eutrophication risk. After 1000 the dam construction the estuary reached a man-made quasi- 1001 steady state characterised by poor productivity and low biomass 1002 in all communities (Fig. 8). Indeed, the fluctuations in river dis- 1003 charge – as freshets – as occurred historically, increased diver- 1004 sity and variability in plankton and nektonic communities 1005 (Fig. 8b-e), and promoted ecosystem dynamics. This model 1006 prediction is supported by the observations of Roelke (2000) 1007 in the Nueces Delta, Texas. This ecosystem response to freshwa- 1008 ter discharge pulses can be used as a management solution for 1009 toxic algal blooms or eutrophication in the Guadiana. In the 1010 Guadiana, the model suggests that increasing  $Q_{\rm f}$  to 50 m<sup>3</sup> s<sup>-1</sup> 1011 for 5 days will flush the estuary and promote the development 1012 of a diverse phytoplankton and zooplankton communities. 1013

The model is restricted to the estuary. It cannot predict im- 1014 pacts on the coastal zone. Studies are needed to determine if 1015 longer-duration and possibly higher intensity freshets may 1016 be needed to maintain coastal marine ecosystem health, 1017 as suggested by Doornbos (1982), Quiñones and Montes 1018 (2001), Chícharo et al. (2002) and Simier et al. (2004). 1019

Thus the estuarine ecohydrology model is able to provide 1020 answers to a number of practical questions. These answers 1021 must always be taken carefully because the model, like any 1022 ecosystem model, over-simplifies reality, and the data set is in- 1023 adequate for a detailed calibration. In that sense, the model 1024 predictions are somewhere between quantitative and qualita- 1025 tive. Detailed field studies are needed to better understand, 1026



Fig. 8. (a) Time series plot of the Guadiana River discharge entering the estuary in the dry season of 2003 in the presence of the Alqueva dam, and the predicted river discharge if the dam had not been constructed (middle). Time series plot of the predicted distribution of phytoplankton biomass in the Guadiana Estuary in 2003 (b) without and (c) with the Alqueva dam. Time series plot of the predicted distribution of carnivorous/omnivorous fish biomass in the Guadiana Estuary in 2003 (d) without and (e) with the Alqueva dam. To convert biomass to concentration, see Figs. 5 and 6.

1074 and hence better parameterise in the model, the various pro-1075 cesses driving the ecosystem. The model should be seen as 1076 a living model - it has been written using subroutines that 1077 are readily edited, so that the new knowledge on individual 1078 processes can readily be incorporated in the model. For the 1079 model to remain a useful tool, it is suggested that its complex-1080 ity should be increased only as fast as additional physical, 1081 chemical and biological processes can be quantified through new field and laboratory studies. For example, the import 1082 1083 rate  $\alpha$  from salt marshes and riparian ecotones, which is

presently set as a constant, is probably varying seasonally and possibly stochastically – data on this are missing and are needed. Also, as the new data become available, the model should be improved by subdividing the phytoplankton compartment into the main classes (Domingues et al., 2005).

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For science, the model provides a tool to enable the 1136 exchange of information between oceanographers, biologists, 1137 ecologists, engineers, sociologists, economists and water-resources managers at regional and national government 1139 levels, and the community. 1140

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It is hoped that the model can also be useful for management. The model shows that it is possible to predict — within likely error bounds provided by the sensitivity tests — the consequences on the estuary ecosystem health of human activities throughout the river catchment. The model does show that, to maintain the ecosystem services provided by the estuary, integrated coastal management needs to take the whole river catchment as the fundamental planning unit. It is necessary

catchment as the fundamental planning unit. It is necessary
to bring together land-use managers, water-resources managers, and coastal and fisheries managers. The model offers
thus a tool for using ecohydrology as a holistic approach to
the management of rivers, estuaries and coastal zones within
entire river catchments.

### 4. Conclusions

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1157 The ecohydrology model is original in that it links physical, 1158 chemical and biological processes over the entire estuary for 1159 the entire food web as a function of catchment output and 1160 the oceanic open boundary condition. Despite the fact that 1161 a number of simplifications are made, the model is encourag-1162 ing in that it reproduces satisfactorily the observations in 1163 2001–2003. These data are still sparse and the model may 1164 need improvements as additional data become available. 1165

The model can readily be used to assess future impact on 1166 the Guadiana Estuary ecosystem health caused by urbanisation 1167 or other factors that reduce the salt marsh area, by an increase 1168 in nutrient loads as a result of changes in agriculture practices 1169 in the catchment area due to increase in water availability by 1170 the Alqueva dam, by extreme high freshwater discharges, e.g. 1171 due to release of high volume of water storage in the dam, and 1172 by the introduction of exotic species. 1173

The model can also be used to predict the efficiency of remedial measures, such as creating wetlands, creating freshets by releasing water from the Alqueva dam, managing bivalve species in the freshwater part of the estuary, and removing nutrients from the river.

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