APPENDIX

Glass eel behavioral model

(after Pardo 2002, PhD thesis, Pau-Adour University)

Description of the model

Let $C = C(t, x, z)$ be the glass eel density at time *t* and at a given point of the estuary of coordinates (x, z). We model the time variation of C by a two-dimensional equation:

$$\frac{\partial C}{\partial t} + div\big(V(t,x,z)\,C\big) - div\big(D(t,x,z)\,\nabla C\big) = -\mu(t,x,z,C)\,C\,.$$

The vector $V = \big(a(t,x), -b(t,x,z)\big)$ is responsible for horizontal and vertical transport of glass eels in the estuary, and $D = \begin{bmatrix} e(t,x) & 0 \\ 0 & d(t,x,z) \end{bmatrix}$ is the matrix controlling their horizontal and vertical diffusion. Glass eel mortality is given by $\mu(t,x,z,C) = \mu_n(t,x,z,C) + \mu_p(t,x,z,C)$, where $\mu_n(t,x,z,C)$ is the coefficient of natural mortality, and $\mu_p(t,x,z,C)$ the coefficient of mortality due to fishery.

The coefficients of V and D are

$$a(t,x) = u(t,x)\,H(u(t,x))\,\big[1 - H(E(t,x,z) - \hat{E}_1)\,d_{hide}\big],$$

$$b(t,x,z) = V_C\;f_Z(t,x,z)^{\alpha}\;f_0(t,x,z) - V_C\,\big[1 - f_Z(t,x,z)\big]^{\alpha}\,\big[1 - f_0(t,x,z)\big]\,f_1(t,x,z;\beta_1,\beta_2),$$

with $\alpha \geq 1$,

$$d(t,x,z) = H\big(u(t,x) - \hat{u}\big)\,H\big(\hat{E}_1 - E(t,x,z)\big)\,k_v(z)\;f_2(t,x,z;\gamma_1,\gamma_2),$$

$$e(t,x) = H\big(u(t,x) - \hat{u}\big)\,k_h(x)\,.$$

We also have the following conditions in the estuary:

$[VC - D\nabla C].\,\eta = 0$ on the bottom and the surface (η is the domain exterior normal),

$C(t, x_0, z)$ on the downstream side, x_0 is a known quantity,

$C(0, x, z = C) = C_0(x, z)$ as the initial condition is also known.

Other notations

u : current speed.

$\hat{u}$: maximum current speed allowing glass eel migration.

E : lighting function. It defines different lighting levels: strong (daylight) when $E > \hat{E}_1$, medium (full moon, weak nebulosity) when $\hat{E}_0 < E < \hat{E}_1$, and weak (strong turbidity, new moon, strong nebulosity) when $E < \hat{E}_0$.

d_{hide} : this parameter is equal to 1 if glass eels hide in the sediment during the day, and 0 otherwise (e.g. in the case of diurnal migration).

H : Heaviside function ($H(x) = 1$ if $x \geq 0$; otherwise, $H(x) = 0$).

V_C : own speed of glass eel.

k_h : horizontal diffusion coefficient (related to current).

k_v : vertical diffusion coefficient (related to glass eel behavior).

$f_Z(t,x,z) = \left(\dfrac{z - z_{bottom}(x)}{\zeta(t,x) - z_{bottom}(x)} \right)$: f_Z action infers that if glass eels are close to the bottom of the river $z_{bottom}(x)$, they will move towards the bottom less quickly than if they were close to the surface $\zeta(t,x)$.

$f_0(t,x,z) = H(\hat{u} - u(t,x)) + H(u(t,x) - \hat{u})\, H\big(E(t,x,z) - \hat{E}_1\big)$: f_0 will be activated (equal to 1) during the day or if the current speed does not allow glass eel migration, to make them dive towards the bottom. Otherwise, it will be zero and glass eels may move towards the surface.

$$\begin{aligned} f_1(t,x,z;\beta_1,\beta_2) = {} & H(\beta_1 - f_Z(t,x,z))\, H\big(E(t,x,z) - \hat{E}_0\big) \\ & + H(\beta_2 - f_Z(t,x,z))\, H\big(\hat{E}_0 - E(t,x,z)\big), \quad 0 \leq \beta_1 \leq \beta_2 \leq 1 \end{aligned}$$

this function is responsible for glass eel vertical transport directed to the surface. It decides the quantity of glass eels allowed to move towards the surface. If the lighting is at medium level ($\hat{E}_0 < E < \hat{E}_1$), only glass eels located beyond a β_1 fraction of the total height of water will be able to move towards the surface. If the lighting is weak ($E < \hat{E}_0$), it will be the case for glass eels beyond a β_2 fraction of the total height of water. As a result, with an average lighting and a small β_1 all glass eels will be located in the water column, whereas with a weak lighting associated to a strong β_2, glass eels come close to the surface.

$$\begin{aligned} f_2(t,x,z;\beta_1,\beta_2) = {} & H(\gamma_1 - f_Z(t,x,z))\, H\big(E(t,x,z) - \hat{E}_0\big) \\ & + H(\gamma_2 - f_Z(t,x,z))\, H\big(\hat{E}_0 - E(t,x,z)\big), \quad 0 \leq \gamma_1 \leq \gamma_2 \leq 1. \end{aligned}$$

This function is responsible for glass eel vertical diffusion. It decides the quantity of glass eels allowed to diffuse. If the lighting is at a medium (or weak) level, only glass eels located beyond a γ_1 (or γ_2) fraction of the total height of water will take part in vertical diffusion. Therefore, with an medium lighting and a small γ_1, a small part of glass eels will be involved in vertical dispersion, whereas with a weak lighting associated to a strong γ_2 a lot of glass eels will be involved in it.

This model was built to fit with *in situ* observations of glass eel migration in an estuary. Glass eels migrate in the longitudinal direction at the same speed of the current *u* if the latter is positive, i.e. directed from the downstream part to the upstream part of the estuary. Otherwise, they do not move in the longitudinal direction. The current *u* is a parameter of our glass eel behavioral model. It can be determined by any one-dimensional hydrodynamic model taking into account the tide coefficient and the river flow. We chose for the *u* calculation a hydrodynamic model based on Saint-Venant equations (Prouzet et al. 2002). This model also provides the evolution over time of the height of water $\zeta(t,x)$ (calculated from the zero water level of the marine charts). A lot of work has been done on Saint-Venant equations, and the mathematical and numerical validity of such models (e.g. Graf 1998) is acknowledged.

The vertical behavior of glass eels has been studied (De Casamajor 1998; De Casamajor et al. 1999; Prouzet et al. 2003). In our model, we use a simplified logical scheme of this behavior (Fig. A1). To summarize it:

- During the day or if $u<\hat{u}$, with $\hat{u}$ = - 0.3 m s^{-1}, glass eels are on the bottom of the river. It should be noted that since the $\hat{u}$ threshold is negative, this situation corresponds to a negative current *u*, i.e. directed towards the downstream part of the estuary. Thus, we can see that the longitudinal river current has an effect on the vertical behavior of glass eels. If $u>\hat{u}$, the current *u* is either negative and inferior in absolute value to $\hat{u}$ = - 0.3 m s^{-1} (*u* is still directed towards the mouth), or positive, i.e. directed towards the upstream part of the estuary. In such conditions, glass eels can move through the vertical water column depending on the lighting conditions (turbidity, lunar phases, nebulosity). The $\hat{u}$ threshold has been determined *in situ* by Prouzet et al. (2003).
- If the turbidity is higher than 40 NTU, glass eels are located close to the surface; otherwise, their position in the water column depends on the lunar phases and the nebulosity. The value of 40 NTU experimentally corresponds to the difference between a clear water and a muddy to very opaque water (De Casamajor et al. 1999).

Model validation

In the longitudinal direction, glass eels are transported by the river current. When the current is directed towards the mouth, glass eels cannot migrate to the upstream part of the estuary.

Regarding the vertical displacement of glass eels, simulations with the different possible hydroclimatic conditions were performed to ensure that the simulated results match with the logical scheme (Fig. A1).

We present two nocturnal situations on the Adour River (Table A1, Fig. A2-A3). In both cases, we “inject” a glass eel density of 0.5 g m^{-3} at the estuary mouth the day before the simulation.

Table A1. Adour estuary lighting conditions on 28 November and 22 December 1999.

Adour estuary	Date	Turbidity (NTU)	Moon phase	Nebulosity	Figure
Situation 1	28 Nov. 1999	20.2	Last quarter	Weak	A2 & A3
Situation 2	22 Dec. 1999	59.5	Full moon	Weak	A4

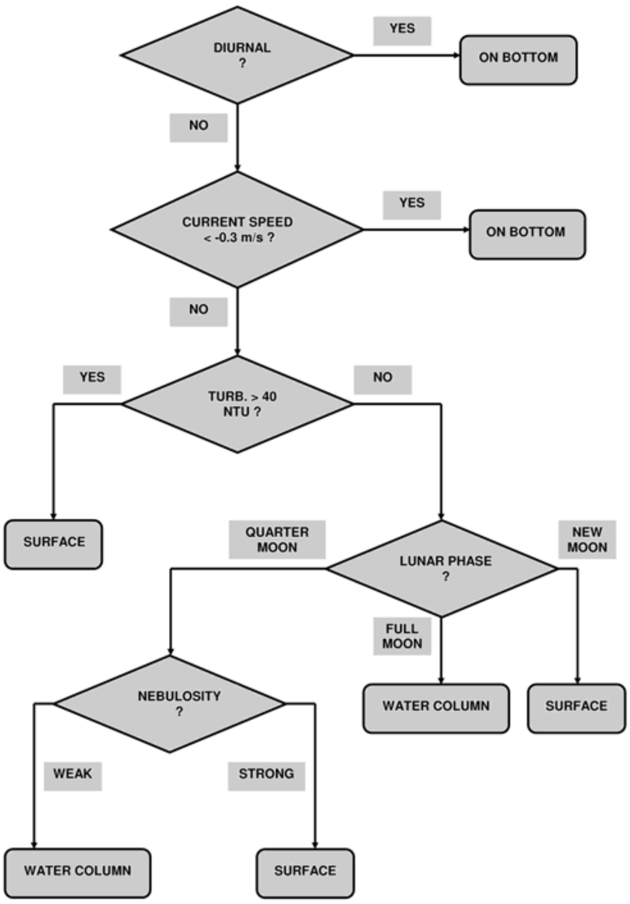

Fig. A1. Logical scheme of the glass eel behavior in the vertical water column.

At 02:00 and 04:00 a.m. on 28 November, the run is located between 13 and 19 km from the mouth:

- at 02:00 the water current is directed towards the downstream part of the estuary (Fig. A2b), so glass eels bury themselves as shown in Fig. A2a.
- at 04:00 glass eels move upstream (Fig. A3a), since the water current is directed towards the upstream part in the first twelve kilometers from the mouth (Fig. A3b). As the turbidity is inferior to 40 NTU, with a moon in the last quarter and a weak nebulosity (Table 1A), we find the glass eels moving through the water column.

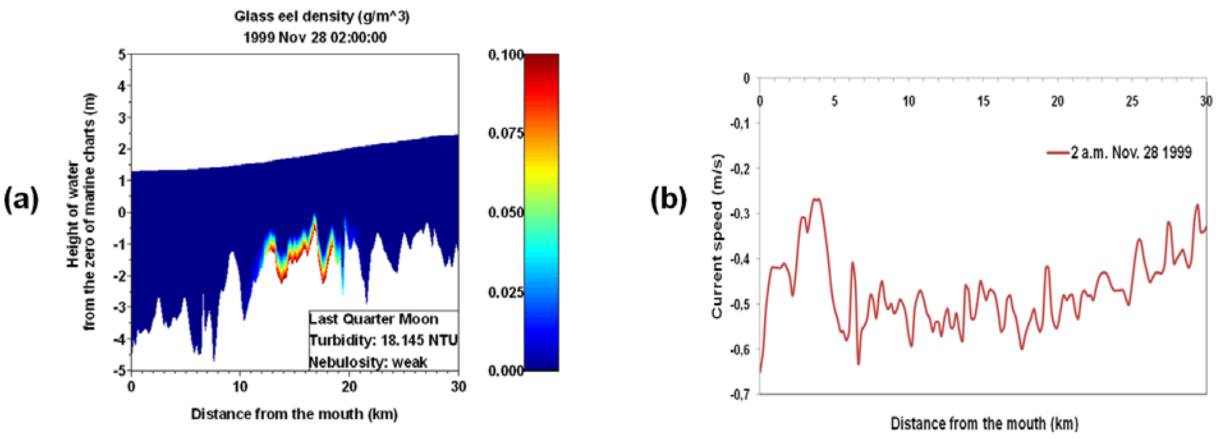

Fig. A2. Vertical behavior of a run in low turbidity, last quarter moon phase and low nebulosity on 28 November 1999 **at 02:00** a.m.The current is downstream.

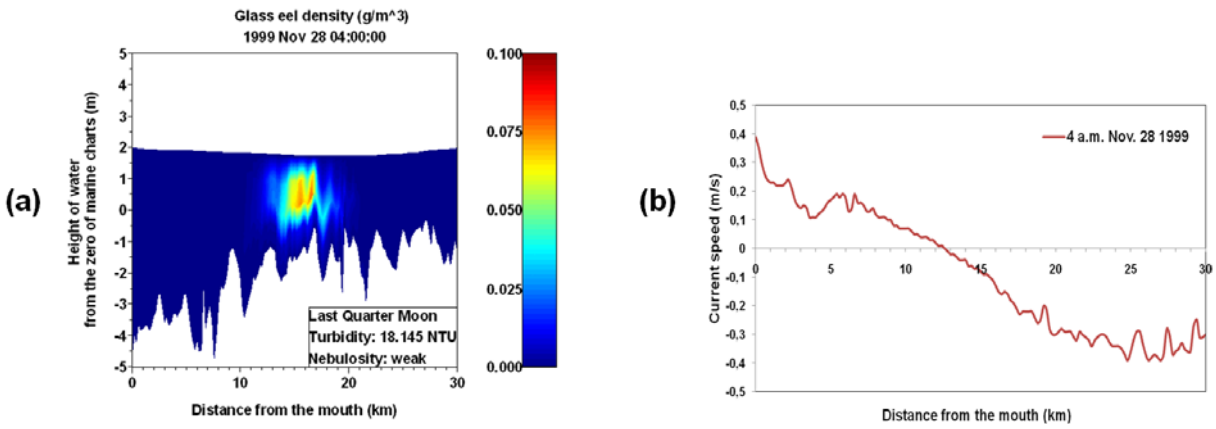

Fig. A3. Vertical behavior of a glass eel run in low turbidity, last quarter moon phase and weak nebulosity on 28 November 1999 **at 04:00** a.m. The current is upstream within the first 12 km from the mouth.

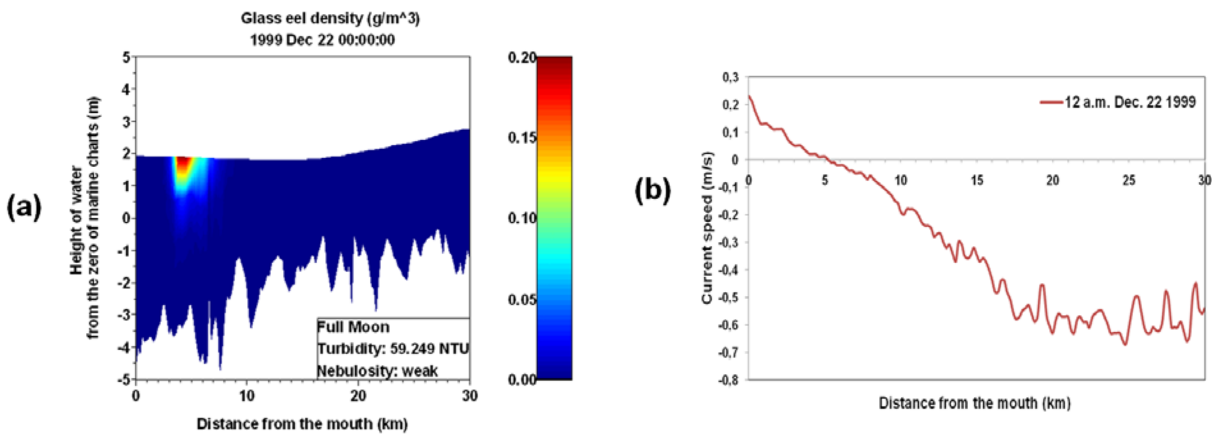

Fig. A4. Vertical behavior of a glass eel run in **high turbidity**, full moon, and weak nebulosity on 22 December 1999 at 12:00 a.m. The current is upstream within the first 5 km from the mouth.

The main difference with the previous situation is the turbidity level, superior to 40 NTU (Table A1). When the current is flowing towards the upstream part of the river, glass eels are close to the surface and very accessible to the fishing gears (Fig. A4).

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