

Macroalgae harvesting policy based on a fuzzy criticality index

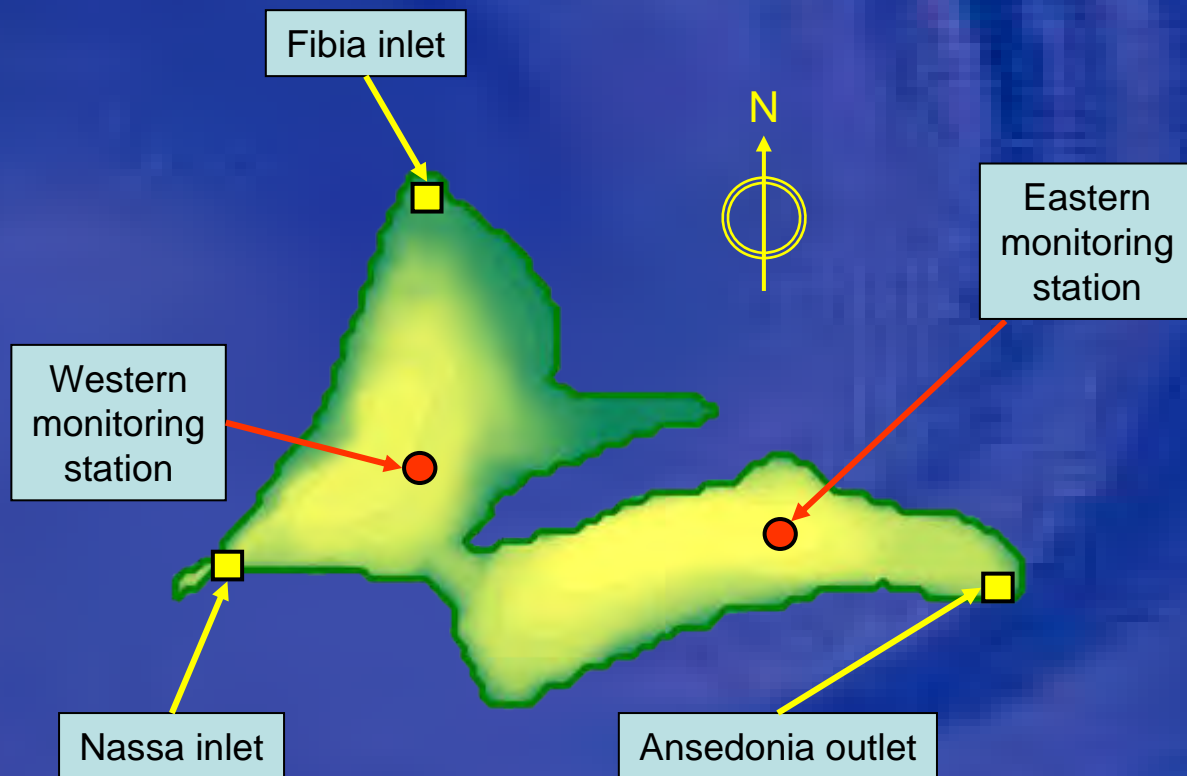
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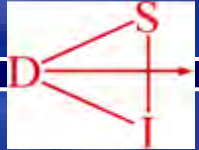
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The Orbetello Lagoon



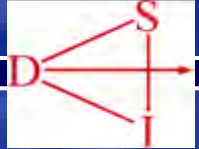
Summer eutrophication



During the warm months, intense solar radiation and high temperature produce eutrophication with oxygen depletion, vegetation decay and a generalized collapse of the entire ecosystem



Harvesting practice

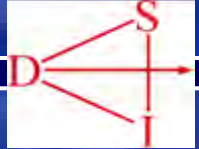


Macroalgae are collected with special boats equipped with an upward-moving conveyor belt.



Biomass is collected by ploughing through the vegetation canopy where the floating biomass (M and D) is retained by the rakes of the conveyor without affecting the rooted vegetation (R) which is beneficial for the lagoon welfare.

Harvest disposal



The disposal of the harvested biomass is a major economic and environmental problem.

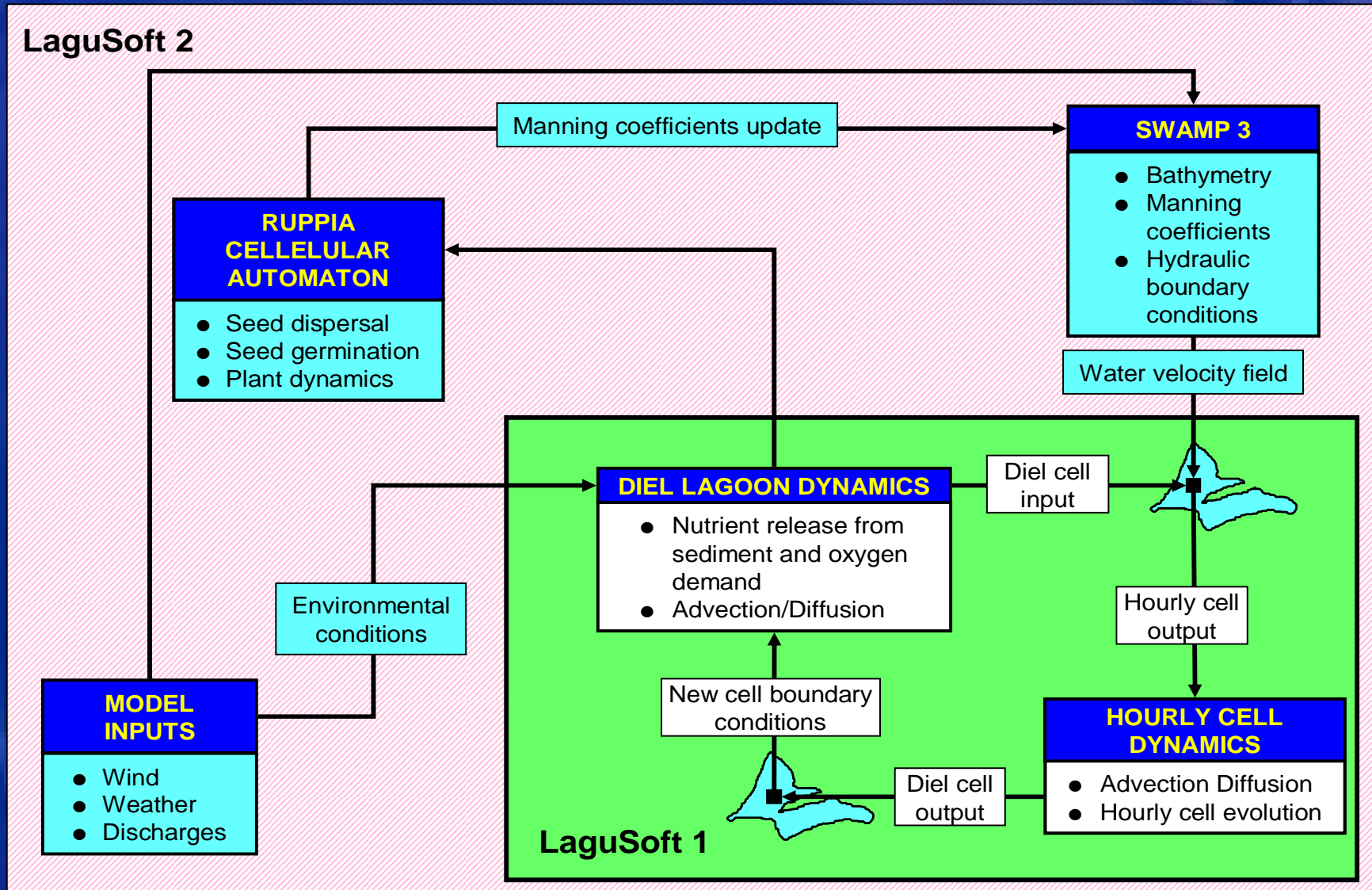


Integrating the model in the harvesting policy



- ❑ **LaguSoft 2** contributes to the lagoon management, providing lagoon simulation under several management options, e.g.
 - ❑ Reduction and/or redeployment of discharges
 - ❑ Variations in the water circulation patterns through inlet pumping
 - ❑ Separate macroalgae collection without macrophyte harvesting along their growth cycle
- ❑ The model takes into account the weather variations which influence the timing and extent of the vegetation development.

LaguSoft 2

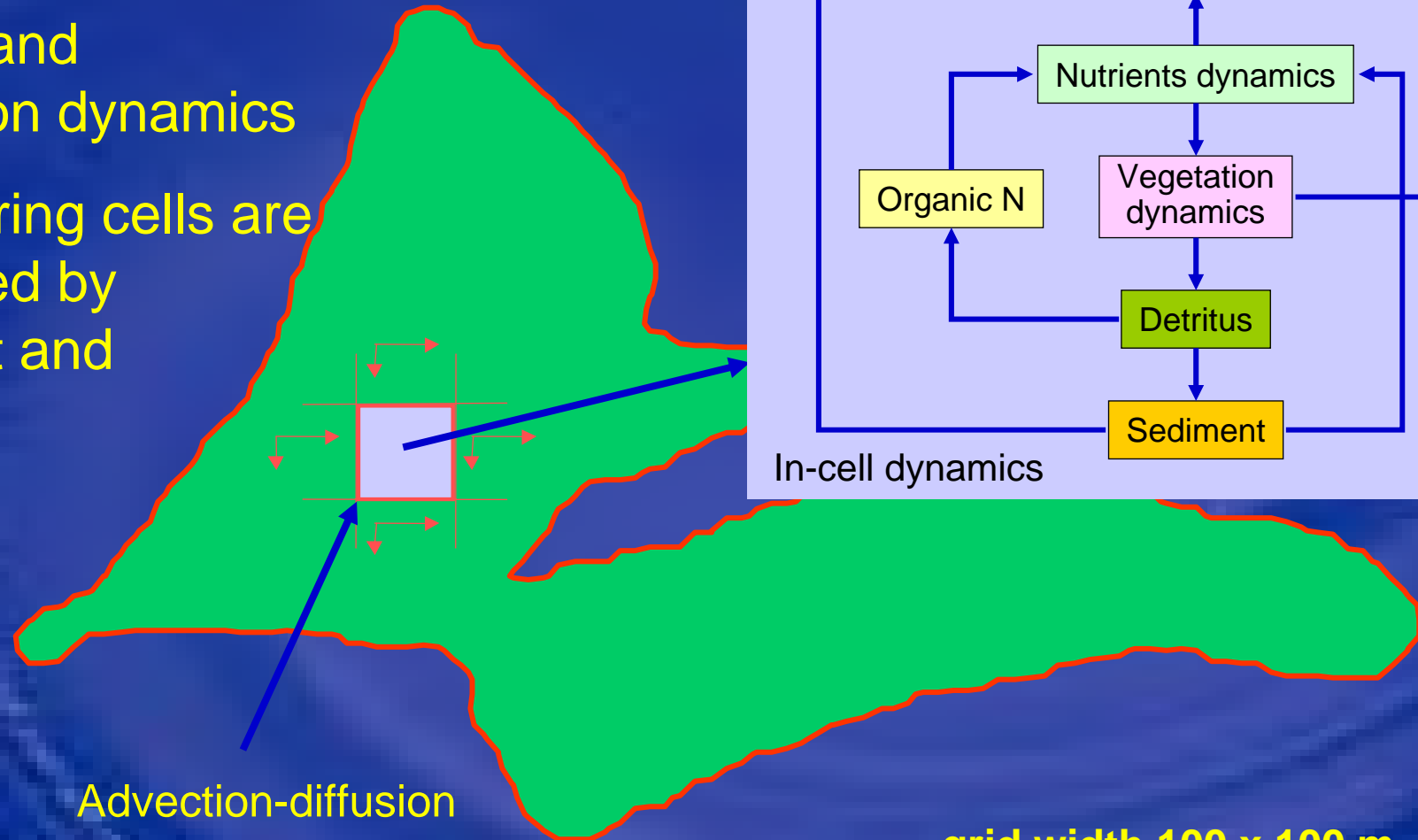


cell dynamics



Each cell models
nutrient and
vegetation dynamics

Neighboring cells are
connected by
transport and
diffusion



Advection-diffusion
from/to neighbouring cells

grid width 100 x 100 m

WIDGEON-GRASS ECOLOGY



Widgeon-grass

common and widespread
submersed macrophyte

The below-ground biomass
develops best
at well-oxygenated sites
in coarse-textured
bottom sediments



Reproduction by releasing
seeds (drupelets) at the
top of emerged stalks.

The root system is unable
to penetrate deeply into sediments.
The plants are sensitive
to water turbulence.

Cellular automata for widgeon-grass



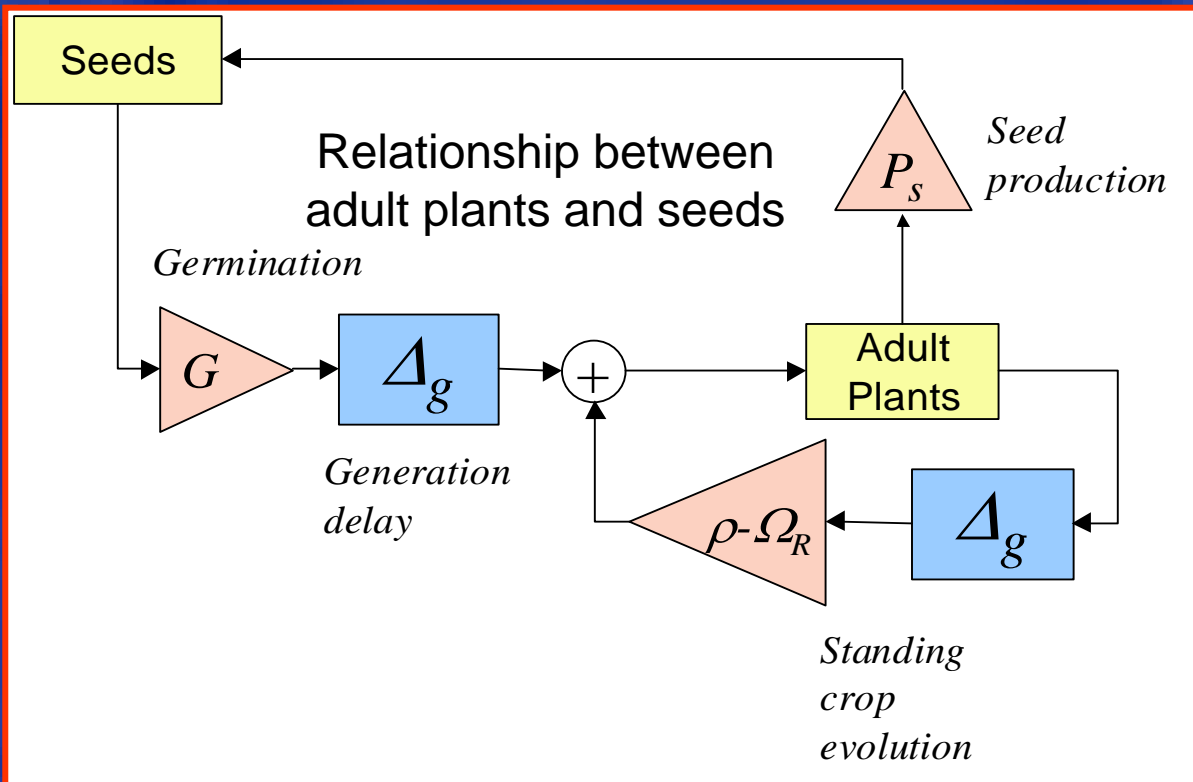
The basic growth and death mechanism underlying the vegetative cycle of widgeon-grass is modelled with a **cellular automata**, describing:

- seed production
- transport
- germination

The automata consists of a number of rules controlling the growth of *Ruppia* within the cell and seed dispersal in adjacent cells depending on their conditions.

These conditions are updated daily, subject to other model variables.

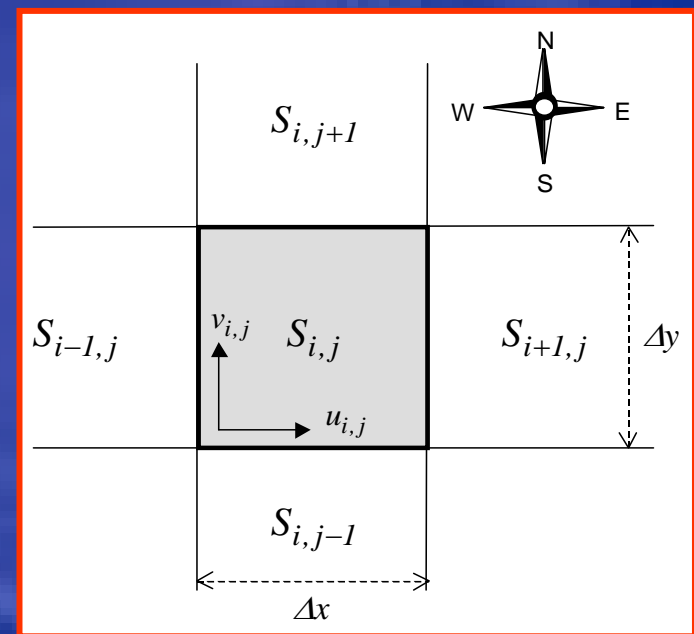
Cellular automata for seed dynamics



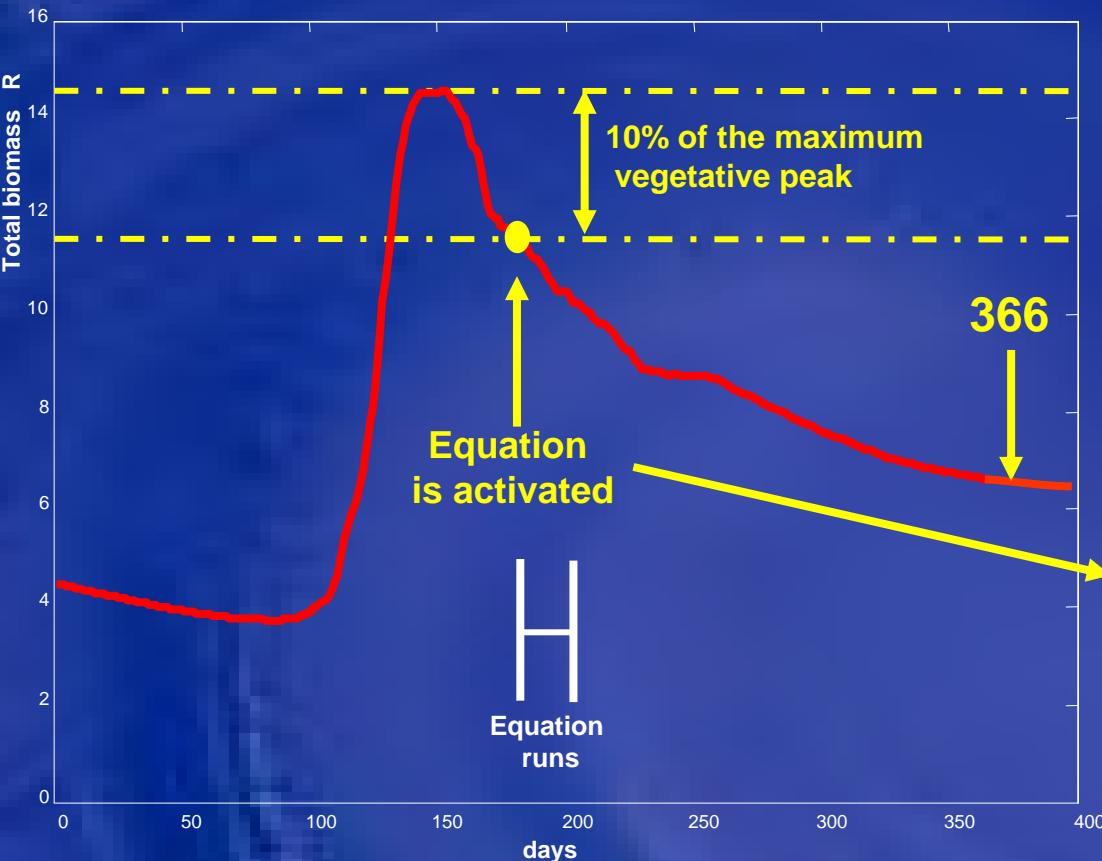
The adult plants generate seeds with rate P_s . The seeds lie dormant until the next season when a fraction G generates new plants.



To link seed production to adult biomass and take into account seed dispersal, the cellular automata introduces seed transport by water movements along the horizontal (W-E), and the vertical (N-S).



Cellular automata for seed dynamics



Seeds dynamics equation

1. discrete-time
2. cell evolution
3. daily time steps

$$\begin{aligned}
 V_{i,j} S_{i,j}^{t+1} = & V_{i,j} S_{i,j}^t + \Delta t P_s R_{i,j}^t \\
 & - \Delta t S_{i,j}^t A_x |u_{i,j}| \\
 & - \Delta t S_{i,j}^t A_y |v_{i,j}| \\
 & + \Delta t S_{i-1,j}^t A_x |u_{i-1,j}| \times (\Phi > u_{i-1,j} > 0) \\
 & + \Delta t S_{i+1,j}^t A_x |u_{i+1,j}| \times (-\Phi < u_{i+1,j} < 0) \\
 & + \Delta t S_{i,j-1}^t A_y |v_{i,j-1}| \times (0 > v_{i,j-1} > \Phi) \\
 & + \Delta t S_{i,j+1}^t A_y |v_{i,j+1}| \times (-\Phi < v_{i,j+1} < 0)
 \end{aligned}$$

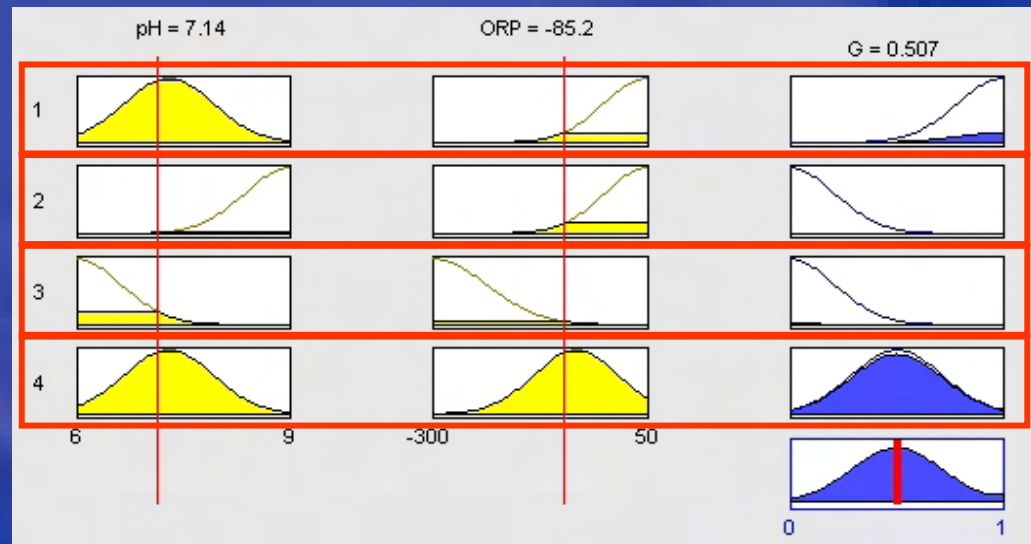
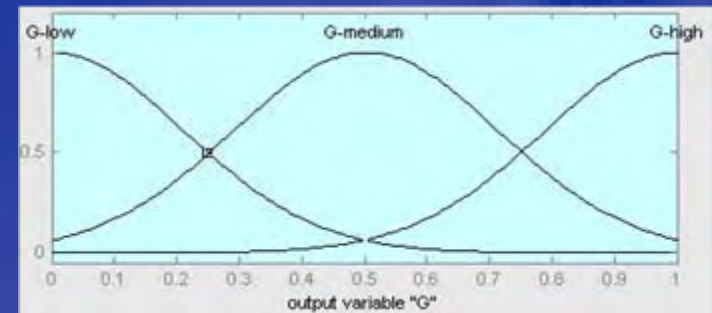
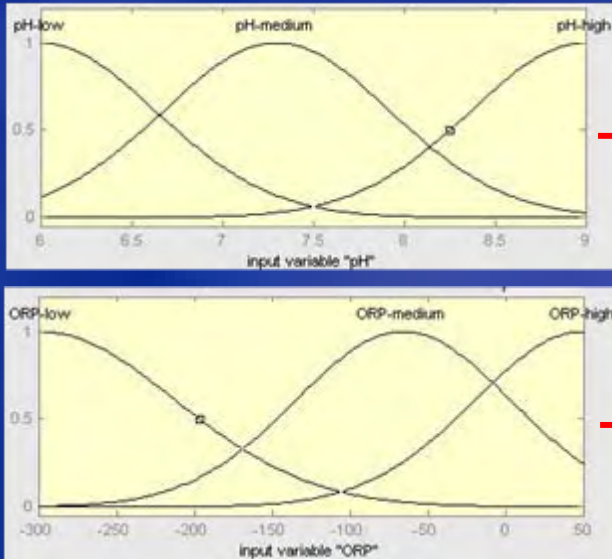
1. If $R = 10\%$ of $\max(R)$ then activate equation
2. Run equation for 3 days
3. At the end of the 3th days record the seed distribution into a matrix NS
4. At the start of the next year inherit last rule

seed deposition is possible only if the flow does not exceed a maximum shear velocity Φ



Fuzzy rules for seed germination

Fuzzy qualifiers (Low, Medium, High) for the two variables (*pH*, *ORP*)



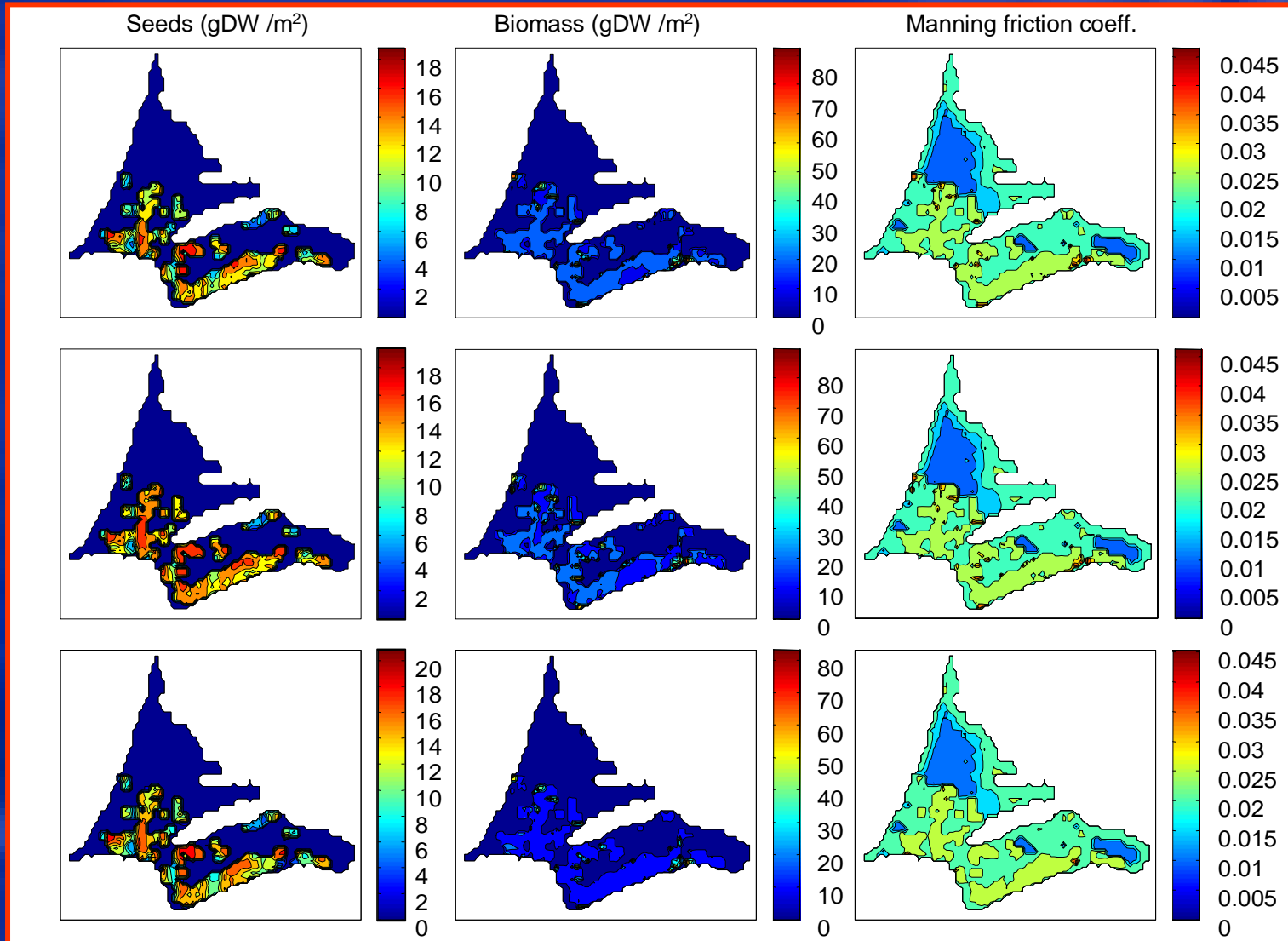
- R1: if pH is medium and ORP is high then G is high
- R2: if pH is high and ORP is high then G is low
- R3: if pH is low and ORP is low then G is low
- R4: if pH is medium and ORP is medium then G is medium

A simulation of three years

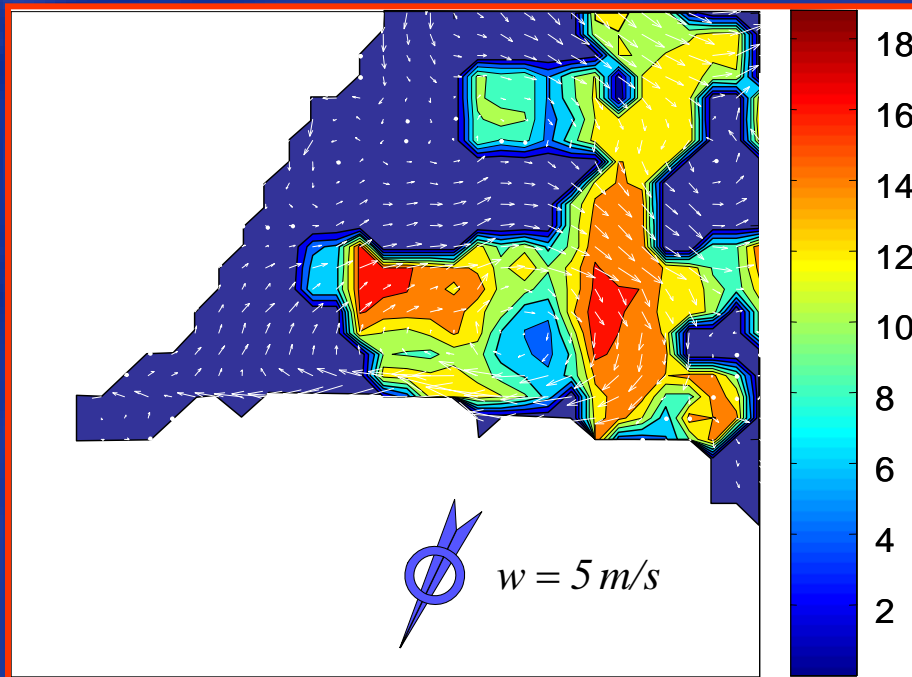


The meadow tends to spread in the direction of the prevailing winds from NW and germinate where currents are slower.

Model evolution over a 3 year horizon

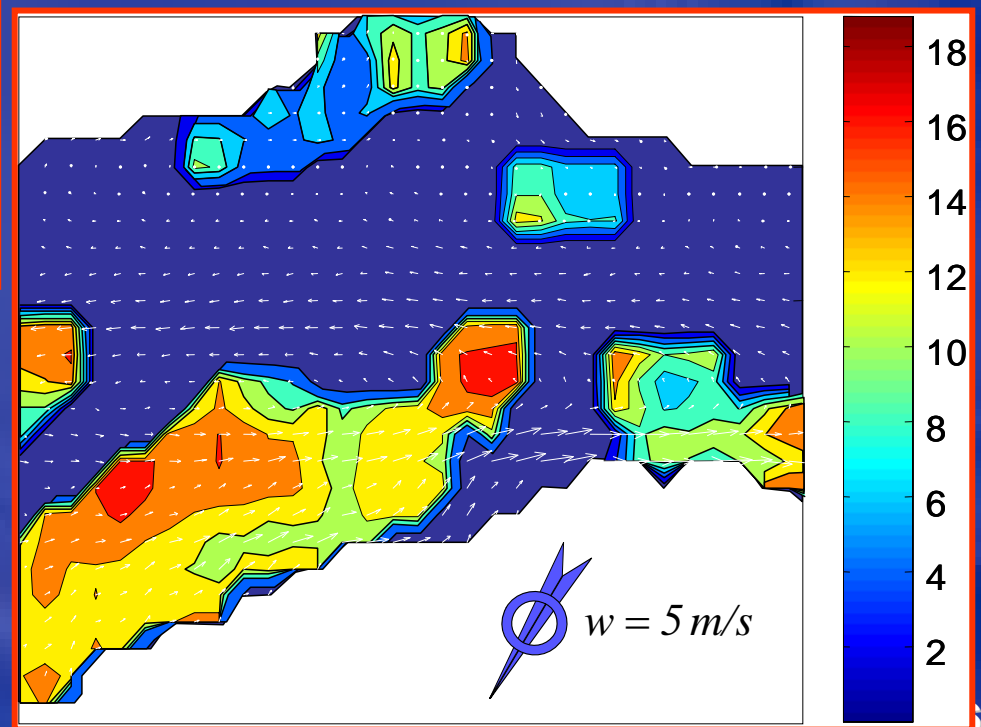


Spatial seed distribution



Western lagoon

Eastern lagoon

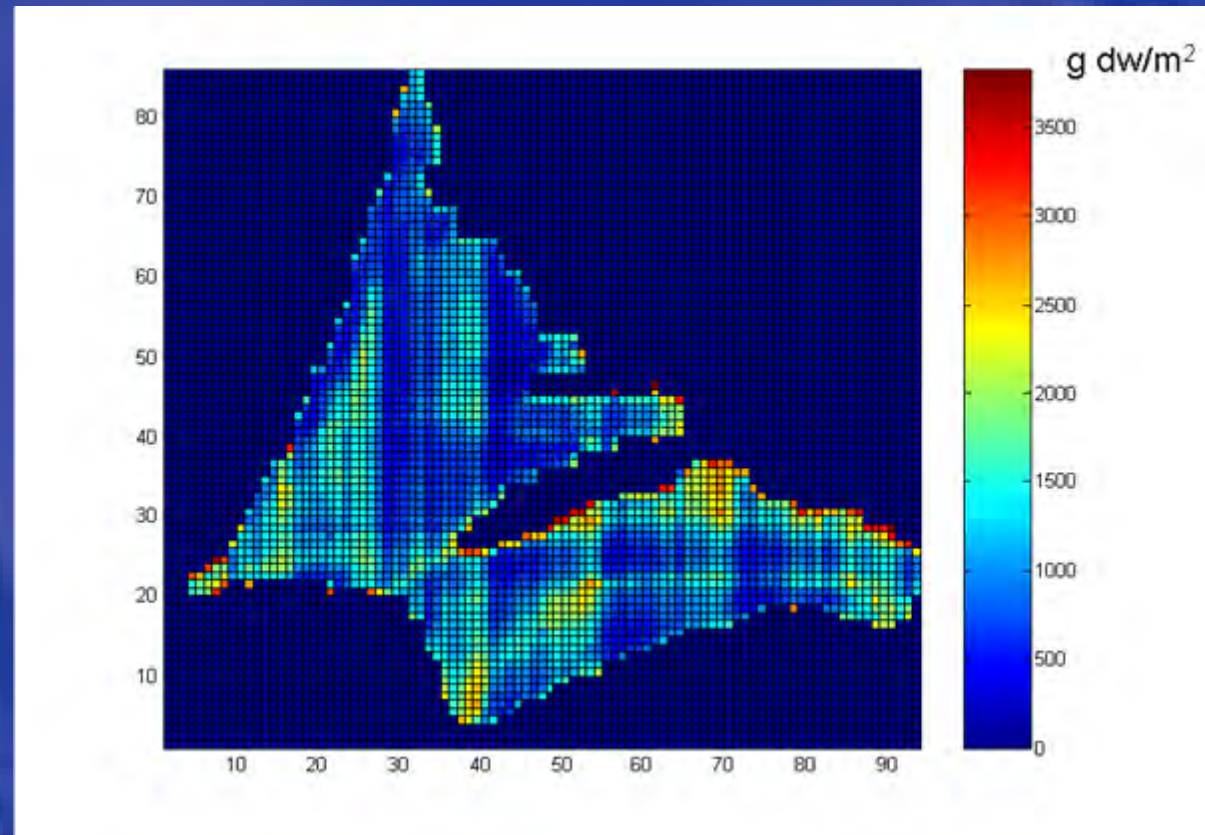


Dead biomass



One of the main problem is the disposal of dead biomass resulting from the shoring of floating non viable mass (*Ruppia* stems discarded after flowering and dead macroalgae).

This represents a considerable fraction of the total biomass and has been included in the model.



HARVESTING POLICY



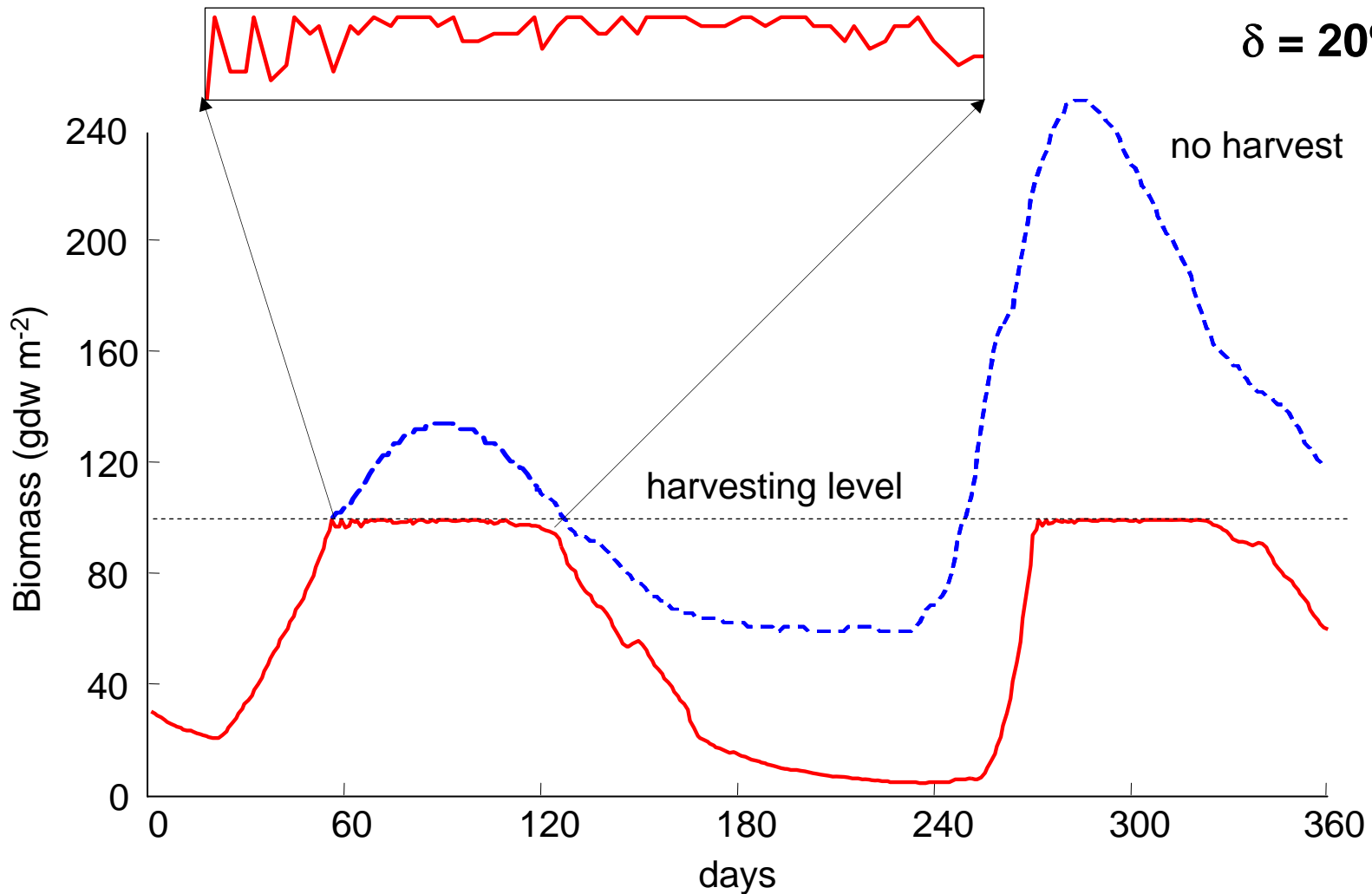
- The harvested vegetation is composed of:
Macroalgae (M) & Dead biomass (D)

- The harvesting policy is based on the daily model response to the environmental inputs (weather and loading data) and is active whenever the total floating biomass (M+D) exceeds a prescribed threshold in a minimum number of cells.
- When harvesting is activated, the macroalgae (M) and the dead biomass (D) in each harvested cell are reduced by a given percentage (δ) when computing the next-day values.

Effect of harvesting on a generic cell



$\delta = 20\%$



Constructing a Fuzzy Water Quality Index



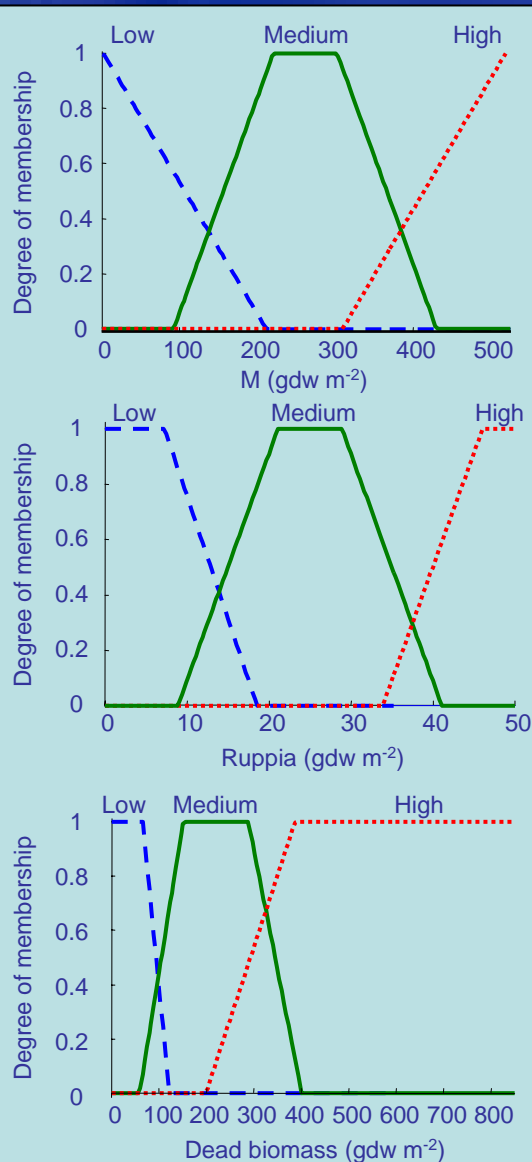
The following fuzzy rules defining water quality are used as a guideline for harvesting

$$f(M, R, D) \xrightarrow{\text{harvest}} Q$$

Only the coloured rules were implemented.

Macroalgae	Ruppia	Dead mass	Quality
low	low	low	1
low	low	med	3
low	low	high	4
low	med	low	
low	med	med	
low	med	high	
low	high	low	2
low	high	med	
low	high	high	
med	low	low	
med	low	med	4
med	low	high	5
med	med	low	
med	med	med	3
med	med	high	
med	high	low	
med	high	med	2
med	high	high	
high	low	low	
high	low	med	4
high	low	high	5
high	med	low	
high	med	med	
high	med	high	4
high	high	low	
high	high	med	
high	high	high	3

Membership functions



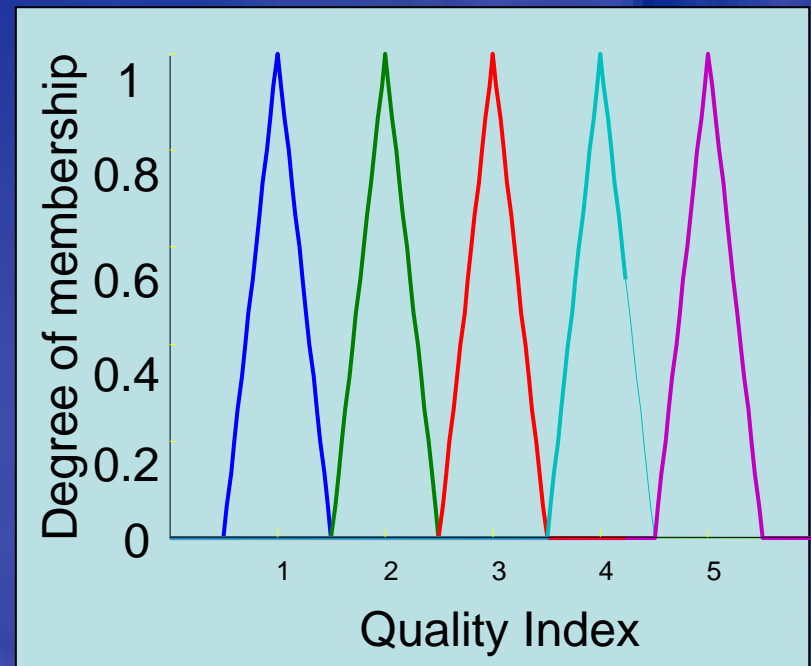
M

R

Q

D

The effect of harvesting is evaluated through simulation by the fuzzy algorithm described by the previous rules



The Fuzzy Quality Index



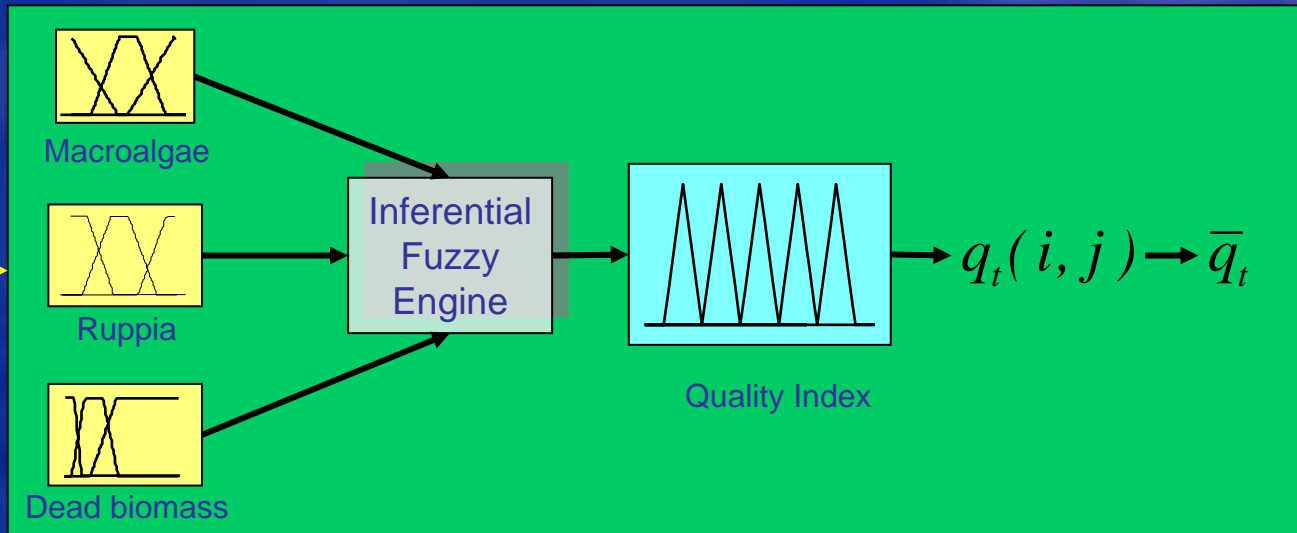
The quality index q is obtained by rounding to the nearest integer the membership weighted average in the Z set (1, 2, 3, 4, 5) of five quality classes, from best (1) to worst (5).

$$q_t(i, j) = \text{round} \left[\frac{\sum_{k \in \{1, \dots, 5\}} Q_k \mu_k}{\sum_{k \in \{1, \dots, 5\}} \mu_k} \right]$$

The Fuzzy Quality Index (FQI) is then computed over an yearly basis as the spatial average of the 15-day average quality index over the whole set of N_{cell}

$$\bar{q}_t = \frac{1}{N_{\text{cell}}} \sum_{i, j} q_t(i, j) \quad \longrightarrow \quad FQI = \frac{1}{24} \sum_{t=1}^{24} \bar{q}_t$$

Model evolution during harvesting



Compute new cell state after harvesting δ

$$M_{i,j}^{t+1} = M_{i,j}^t - \delta \frac{M_{i,j}^t}{M_{i,j}^t + D_{i,j}^t};$$

$$D_{i,j}^{t+1} = D_{i,j}^t - \delta \frac{D_{i,j}^t}{M_{i,j}^t + D_{i,j}^t};$$

Harvesting decision

Biomass and cells Threshold (M & D)

$t \rightarrow t+1$

Lagoon evolution with harvesting

LaguSoft 2

Fuzzy Quality index

FQI

Assessing the harvesting options



- ❖ Three factors have been considered in ranking the harvesting policies
 - ❖ improvement in the **Fuzzy Quality Index (FQI)**
 - ❖ total **Working days (W)**
 - ❖ total travelled **Mileage (K)** to implement the policy

$$G = FQI + \lambda_1 W + \lambda_2 K$$

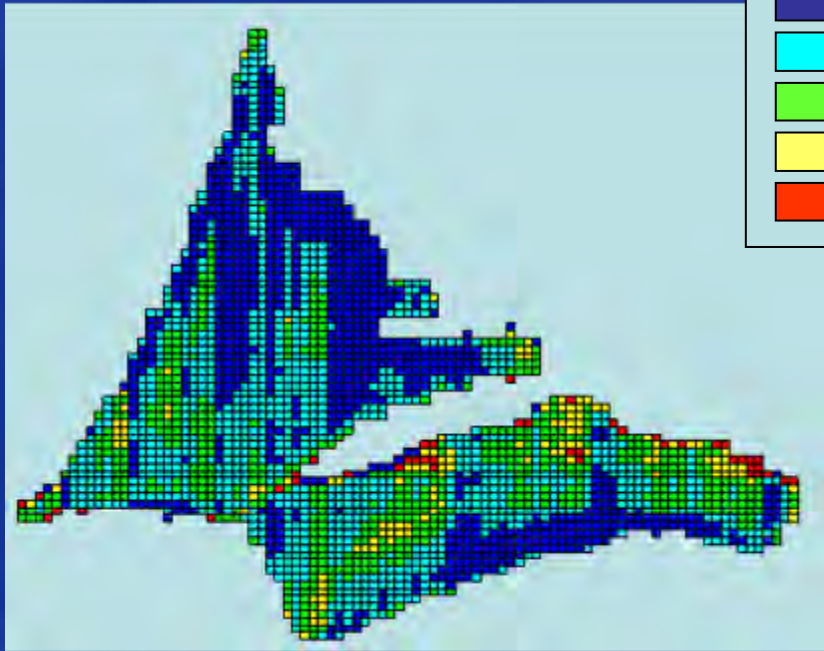
- ❖ Six simulations were run with differing thresholds, in addition to the base case of no harvesting, and the policy yielding the lowest G was selected

Harvesting Scenarios



Quality Index

-  1 Best
-  2
-  3
-  4
-  5 Worst



Reference scenario: no harvest
 $Q = 1.2695$; $W = 0$; $K = 0$



Harvest scenario S2
 $Q = 1.2210$; $W = 134$; $K = 109$

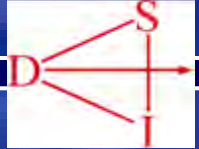
$$\lambda_1 = \lambda_2 = 0.005$$

Harvesting Scenarios



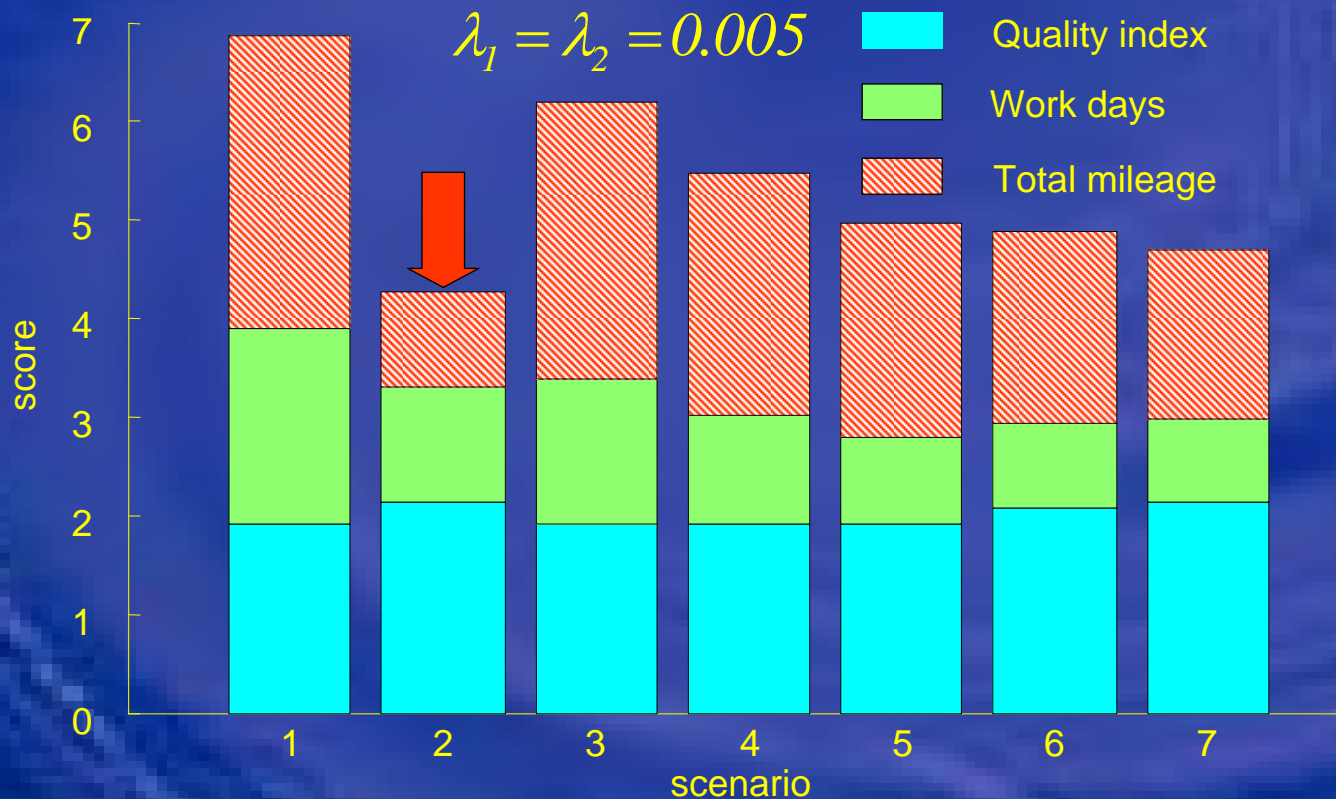
Scenario		FQI	Working days	Distance (km)
S0	No harvest	1.2695	0	0
S1	S=100 g dw/m ² harvest when 1 cell exceeds S	1.0983	226	340
S2	S=150 g dw/m ² harvest when 1 cell exceeds S	1.2210	134	109
S3	S=100 g dw/m ² harvest when 5 cell exceed S	1.0985	168	319
S4	S=100 g dw/m ² harvest when 10 cell exceed S	1.0986	125	282
S5	S=100 g dw/m ² harvest when 15 cell exceed S	1.0989	100	247
S6	S=150 g dw/m ² harvest when 10 cell exceed S	1.1913	98	221
S7	S=150 g dw/m ² harvest when 10 cell exceed S	1.2197	96	196

Comparison of scenarios



$$G = FQI + \lambda_1 W + \lambda_2 K$$

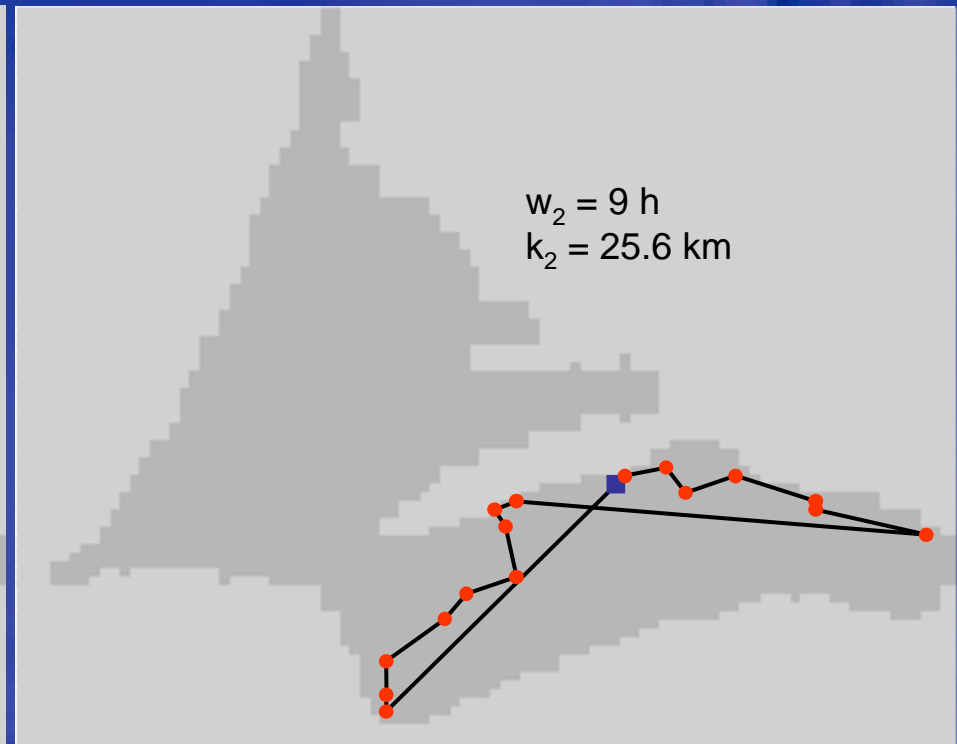
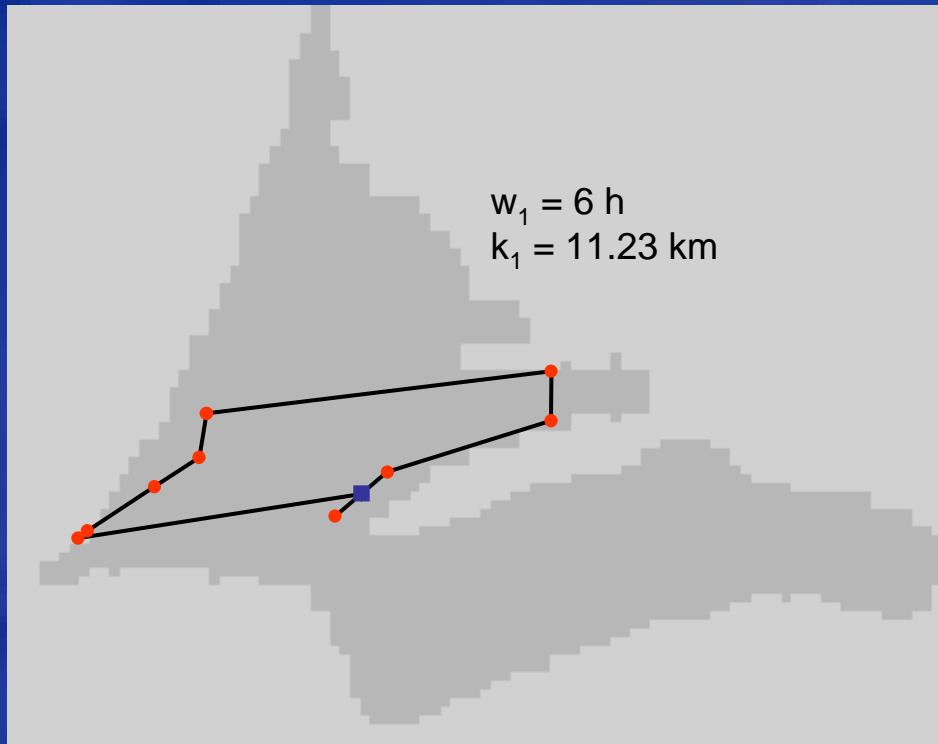
W = boat working days
K = total mileage daily rounds



Harvesting paths



Along the route the next harvesting point is selected on a nearest neighbor basis



■ The blue squares indicate the boat mooring.

Conclusion



- A harvesting policy to collect the floating biomass from the Orbetello lagoon has been proposed
- It was developed on the basis of a comprehensive lagoon model (LaguSoft 2) and a fuzzy water quality index
- The resulting policy optimizes a figure of merit composed of:
 - Water quality improvement obtained through harvesting
 - Total distance run by the boats
 - Total working hours