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How do we define coastal lagoons?

✓ Coastal semi-enclosed basins where intense mixing of fresh and saline water takes place;
✓ Areas of high biodiversity favored by the presence of increased salinity gradient;
✓ Areas of high fishery productivity due to the cultivation of euryhaline species;
✓ Buffer zones for the storage, transformation and transport of constituents from the terrestrial zone (drainage basin) to the adjacent coastal sea;
✓ Basins with intense dependence from the prevailing hydrologic, meteorological and oceanographic conditions of the broader area.
Mediterranean coastal lagoons are:

- Mostly small and shallow in size,
- Main basin with parallel to coast orientation,
- Sand bars developed by sediment supply of adjacent river mouth,
- Forced by low tidal oscillations (Micro-tidal environment);
- Important water circulation induced by:
  - Wind stress,
  - Fresh water inflow,
  - Density gradients, and
  - Non-linear interactions between tidal flow and lagoon topography.

Typical Lagoon Example
Emergent Properties of Lagoon Ecosystems

✓ Physicochemical processes play a very strong role in organizing and regulating lagoon ecosystems,
✓ The structure of lagoon ecosystems is both the consequence of and a factor in the action of ecosystem processes,
✓ Viewing lagoon–nearshore ecosystems in a hierarchical context is important to understanding ecological interactions and processes across different scales in time and space.

Fundamental Hypotheses

- Natural processes create structure;
- Structure produces habitat function;
- Functioning habitat supports specific biological organisms and communities;
- These relationships can be confirmed through a conceptual model.
Restoration Strategy for Lagoon Ecosystems

- Restoration projects should be based on carefully designed goals and objectives,
- Programs should take advantage of best interdisciplinary science and technical knowledge,
- Programs should focus on restoration of natural processes that create and maintain lagoon and nearshore ecosystem structure and function,
- Program efforts should promote protection of lagoon habitats and the processes that sustain them,
- Program efforts should include social, cultural and economic values at multiple scales in space and time.
Restoration Project Guidelines

Problem Statement

Define Mission and Goals

Pre-Restoration Description

Restoration Planning and Implementation

Post-Restoration Monitoring

Adaptive Management

Restoration Tips

- Study and examine the topography and bathymetry of the lagoon, as this determines internal circulation and mixing.
- Ensure the inflow of adequate freshwater into the system, as this determines the residence time of water and substances in the system.
- Study the timing that freshwater enters the system, as higher amounts are preferable during tidal flood and summer period.
- Test the water quality of the inflowing freshwater, and take measures to minimize pollution.
- Study carefully the lagoon mouth dynamics and propose geometric modifications (length, width, depth) or the construction of a second mouth.
Problem Statement

Drana Lagoon re-flooding was achieved by re-opening a communication channel with the open sea.

Define Mission and Goals

a) the restoration of the lagoon’s habitats structure and functions, b) the conservation of protected avifauna species, and c) the upgrade of management effectiveness applied in the lagoon’s broader area.

Pre-Restoration Description

Systematic data collection on broader area (climate, geology, soil properties, habitats, rare and endangered species, birds, terrestrial flora and fauna, fish and benthic flora and fauna, lagoon physicochemical parameters).
The control gates at the entrance of Drana Lagoon

View of the drained Drana Lagoon

<table>
<thead>
<tr>
<th>θ/ο</th>
<th>Έδαφος</th>
<th>Ελληνική συμπλήρωση</th>
<th>Κάθενα Βάθος*</th>
<th>Παρατηρητική σταθμισμένα*</th>
<th>Παραμέτροι 78/409 (ΕΟΚ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Danae striata</td>
<td>κυματοποιήση</td>
<td></td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Danae antarctica</td>
<td>κυματοποιήση</td>
<td></td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Pedocera gracilis</td>
<td>Κακοκυματοποιητικό</td>
<td>I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Pedocera aurita</td>
<td>ισορροπητικό</td>
<td></td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Pedocera nigroca</td>
<td>ισορροπητικό</td>
<td></td>
<td>K</td>
<td></td>
</tr>
</tbody>
</table>

**Πίνακας 2.3.1. Τα σημαντικότερα είδη της επιτροπής του Δέλτα Εβραίου**

**Anser erythropus**

**Phalacrocorax pygmeus**
Table 2. Summary characteristics of water flow during each tidal cycle sampled at Drana Lagoon.

<table>
<thead>
<tr>
<th>Tidal parameter</th>
<th>30-10-02</th>
<th>31-10-02</th>
<th>6-11-02</th>
<th>7-11-02</th>
<th>20-11-02</th>
<th>21-11-02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal Range (m)</td>
<td>0.202</td>
<td>0.181</td>
<td>0.206</td>
<td>0.290</td>
<td>0.219</td>
<td>0.294</td>
</tr>
<tr>
<td>Ebb Duration (min)</td>
<td>345</td>
<td>321</td>
<td>477</td>
<td>384</td>
<td>228</td>
<td>120</td>
</tr>
<tr>
<td>Time to Max. Ebb (min)</td>
<td>105</td>
<td>129</td>
<td>408</td>
<td>111</td>
<td>45</td>
<td>114</td>
</tr>
<tr>
<td>Max. Ebb (m s(^{-1}))</td>
<td>0.175</td>
<td>0.170</td>
<td>1.100</td>
<td>0.264</td>
<td>0.158</td>
<td>0.117</td>
</tr>
<tr>
<td>Mean Ebb (m s(^{-1}))</td>
<td>0.074</td>
<td>0.084</td>
<td>0.090</td>
<td>0.058</td>
<td>0.067</td>
<td>0.040</td>
</tr>
<tr>
<td>Flood Duration (min)</td>
<td>405</td>
<td>429</td>
<td>273</td>
<td>366</td>
<td>525</td>
<td>630</td>
</tr>
<tr>
<td>Time to max. flood (min)</td>
<td>39</td>
<td>168</td>
<td>93</td>
<td>171</td>
<td>96</td>
<td>111</td>
</tr>
<tr>
<td>Max. flood (m s(^{-1}))</td>
<td>0.078</td>
<td>0.133</td>
<td>0.194</td>
<td>0.185</td>
<td>0.062</td>
<td>0.030</td>
</tr>
<tr>
<td>Mean Flood (m s(^{-1}))</td>
<td>0.008</td>
<td>0.019</td>
<td>0.049</td>
<td>0.074</td>
<td>0.031</td>
<td>0.017</td>
</tr>
<tr>
<td>Tidal Range (m s(^{-1}))</td>
<td>0.253</td>
<td>0.303</td>
<td>1.294</td>
<td>0.449</td>
<td>0.220</td>
<td>0.147</td>
</tr>
<tr>
<td>Tidal Mean (m s(^{-1}))</td>
<td>-0.003</td>
<td>-0.025</td>
<td>-0.042</td>
<td>-0.010</td>
<td>-0.020</td>
<td>-0.006</td>
</tr>
</tbody>
</table>

Data Analysis to Understand Physical Processes

2-D NUMERICAL MODEL FOR OPEN SEA

Basic Equations:
• Depth-averaged continuity eq.
• Depth-averaged momentum eq.

\( \Delta X, \Delta Y = 500 \text{ m} \)
\( \Delta T = 30 \text{ sec} \)

Tide, Wind and Evros River Boundary Forcings
2-D NUMERICAL MODEL RESULTS

1-D MODEL FOR LAKI LAGOON & DRANA CANAL

Continuity Eq.
\[ \frac{\partial \eta}{\partial t} + \frac{1}{B} \frac{\partial Q}{\partial x} = 0 \]

Momentum Eq.
\[ \frac{\partial Q}{\partial t} + \frac{1}{A} \frac{\partial Q}{\partial x} = -g A \frac{\partial \eta}{\partial x} - g A S_f \]

Spring Tides Boundary Condition

Neap Tides Boundary Condition
1-D NUMERICAL MODEL RESULTS

Sea Level Tidal Elevation (m)

Time (hrs)

Tidal Inlet Dynamics

Existing Inlet

Entrance Channel

Lagoon Discretization
Lagoon Flushing Scenarios

Lagoon Flushing Scenarios under Different Flow Conditions

<table>
<thead>
<tr>
<th>Entrance Channel Width (m)</th>
<th>Residence Time (days)</th>
<th>Neap Tide</th>
<th>Spring Tide</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
<td>8.5</td>
<td>5.5</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>6.3</td>
<td>4.3</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>6.1</td>
<td>4.1</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>6.1</td>
<td>4.1</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>6.1</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Lagoon Tidal Prism Variability under Different Flow Conditions

<table>
<thead>
<tr>
<th>Entrance Channel Width (m)</th>
<th>Tidal Prism Volume (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neap Tide</td>
<td>Spring Tide</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>23</td>
<td>23</td>
</tr>
</tbody>
</table>

Scenarios to determine exchange volumes, residence time, mouth velocity, tidal range inside the reflooded lagoon.
Bathymetric and Topographic Adjustments

Estimate Lagoon Internal Circulation
Predict Physical Parameters' Distribution

Restoration Planning and Implementation

• Widening and deepening existing entrance channel
• Perimetric levee strengthening
• Bathymetry configuration for wintering canals inside the lagoon
• Topographic configuration and embankment for four small islands inside the lagoon
• Development of perimetric wet meadows
Post-Restoration Monitoring Network
Post-Restoration Monitoring

Table 1

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Alburnidae</td>
<td>Alburnus lentus (Risso, 1810)</td>
<td>Big-scale sand eel</td>
<td>E</td>
<td>12.6</td>
<td>3.4</td>
<td>1.9</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>Cyprinidae</td>
<td>Carassius auratus (L., 1758)</td>
<td>Goldfish</td>
<td>E</td>
<td>38.4</td>
<td>9.7</td>
<td>6.1</td>
<td>4.3</td>
</tr>
<tr>
<td>3</td>
<td>Cyprinidae</td>
<td>Micropogonias cephalus (Linnaeus, 1758)</td>
<td>Longnose sucker</td>
<td>E</td>
<td>75.2</td>
<td>23.7</td>
<td>8.5</td>
<td>4.1</td>
</tr>
<tr>
<td>4</td>
<td>Cyprinidae</td>
<td>Alburnus albula (Linnaeus, 1758)</td>
<td>Silver chub</td>
<td>E</td>
<td>377.2</td>
<td>23.7</td>
<td>9.8</td>
<td>4.7</td>
</tr>
<tr>
<td>5</td>
<td>Cyprinidae</td>
<td>Thymallus ardens (Linnaeus, 1758)</td>
<td>rainbow trout</td>
<td>M</td>
<td>98.8</td>
<td>86.4</td>
<td>65.5</td>
<td>49.8</td>
</tr>
<tr>
<td>6</td>
<td>Cyprinidae</td>
<td>Labeo rohita (Linnaeus, 1758)</td>
<td>Silver carp</td>
<td>M</td>
<td>110.3</td>
<td>87.8</td>
<td>65.5</td>
<td>49.8</td>
</tr>
<tr>
<td>7</td>
<td>Kuhliae</td>
<td>Poropontichthys kuhliae (Risso, 1810)</td>
<td>Kuhlia</td>
<td>E</td>
<td>0.8</td>
<td>0.6</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>8</td>
<td>Phoxinidae</td>
<td>Phoxinus phoxinus (L., 1758)</td>
<td>Greenling</td>
<td>E</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>9</td>
<td>Salmonidae</td>
<td>Oncorhyncus tshawytscha (Harrington, 1828)</td>
<td>Chinook salmon</td>
<td>M</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>10</td>
<td>Salmonidae</td>
<td>Oncorhyncus keta (Müller, 1776)</td>
<td>Coho salmon</td>
<td>M</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>11</td>
<td>Salmonidae</td>
<td>Oncorhyncus mykiss (Rafinesque, 1810)</td>
<td>Steelhead trout</td>
<td>M</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>12</td>
<td>Salmonidae</td>
<td>Oncorhyncus nerka (Rafinesque, 1810)</td>
<td>Pink salmon</td>
<td>M</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Note: E = endemic, M = migrant, T = transplanted

Richter et al. (2004).
Adaptive Management

The small number of fish species inhabiting the lagoon might be the result of the recent restoration and/or the above adverse conditions. Another reason for the small number of species caught could be related to the increased water flow observed at the lagoon mouth during the flood and ebb tidal phases, and also in the presence of a smooth bank in the concrete waterspout that connects the entrance channel with the lagoon.
Fish fauna recovery in a newly re-flooded Mediterranean coastal lagoon

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ABSTRACT
Diako Lagoon, located at the NW side of Euboea River Delta, was drained in 1967 and re-flooded in 2004. This study presents the results of a monitoring program of the lagoon in ichthyological, water quality and fish fauna characteristics, during the pre- and post-migration period. Results depict the presence of high salinity water type in April due to seasonal irrigation, strong evaporation in the summer and inadequate freshwater inflow. Overall, recruit...
Free-water surface constructed Wetland Development in three cells to process an inflow of 550 m$^3$/d