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A Budget Model of Water, Salt and non-Conservative Nutrients in Strymonikos and Ierissos Gulfs

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Abstract: Simple box models and steady-state budgeting methods were proposed to be used as an alternative to direct measurements of process rates, in an effort to assess the net rates of non-conservative nutrient processes in shallow coastal seas. In this contribution the application of the budgeting approach (according to LOICZ guidelines) was considered for Strymonikos and Ierissos Gulfs, two semi-enclosed coastal water bodies located at the northeast part of Chalkidiki Peninsula. Strymonikos Gulf is directly affected by the fresh water discharge of rivers Strymon and Richios, while Ierissos Gulf only by local torrents. The residence time of Strymonikos and Ierissos Gulfs was found 107 and 185 days, respectively. The phosphorus budget showed that Strymonikos Gulf is a net consumer of organic matter (2.68 mmol C m^{-2} d^{-1}) through net organic production, while Ierissos Gulf is a net producer of organic matter (5.11 mmol C m^{-2} d^{-1}) through respiration. Strymonikos Gulf is producing more nitrogen through nitrification (0.64 mmol N m^{-2} d^{-1}), while Ierissos Gulf is denitrifying (0.65 mmol N m^{-2} d^{-1}).

Key words: biogeochemical budget, water budget, residence time, nutrient cycling, Strymonikos Gulf, Ierissos Gulf.

1. INTRODUCTION

It has been well documented that self semi-enclosed seas and estuaries play an important role in nutrient recycling and organic matter decomposition, serving as buffer zones between terrestrial and marine systems. Furthermore, the shallow seas are areas in which the anthropogenic effects, such as increased nutrient discharges, have their most direct influence and where there is a great danger of adverse impacts. The Land-Ocean Interaction in the Coastal Zone (LOICZ, 1994) study of the International Geosphere-Biosphere Programme (IGBP) presented a series of guidelines in order to quantify the fluxes of the biogeochemically active components across the land-ocean boundary and to determine the capacity of a coastal water body to transform and store particulate and dissolved matter of nitrogen and phosphorus (Gordon *et al.*, 1996). Complete water, salt and nutrient budgets for a number of shelf seas and semi-enclosed coastal areas exist (Smith *et al.*, 1991; Simpson and Rippeth, 1998; Simpson *et al.*, 2001).

The present work comprises a first attempt to understand the functioning of Strymonikos and Ierissos Gulfs, in northern Greece, and to establish the water, salt and non-conservative nutrient fluxes using a simple steady-state box model approach. Therefore, this work can be compared with similar models of different coastal areas produced using the same methodology, and so can contribute to the knowledge on the role of the coastal zone in nitrogen and phosphorus cycling.

2. MATERIALS AND METHODS

2.1 Water and Salt Budgets

The water and salt budgets provide information on the exchange of water between the Strymonikos and Ierissos Gulfs and the open North Aegean Sea (Figure 1) by the processes of advection and mixing. The concept behind these budgets is the establishment of a compensating residual flow (V_R) to balance the fresh water volumes entering the system, such as surface runoff (V_Q), precipitation (V_P), groundwater (V_G), other inflows (V_O), and the evaporative losses (V_E). Salt must also be conserved in the system, thus, salt fluxes produced by the water budget terms, must be balanced by a mixing term.

The water balance for each period considered is calculated using the following equations:

$$dV/dt = VQ + VP + VG + VO + VE + VR \quad (1)$$

V_P is always considered a positive term, V_E is always negative, while V_R has a sign dependent on the water volume surplus or deficit, produced by the other terms. Assuming steady state (i.e., dV/dt = 0), then the residual flow (V_R) is:

$$VR = -VQ - VP - VG - VO - VE \quad (2)$$

The salt balance is described from equation (3), where a balance occurs between salt input via mixing and salt output from residual outflow. It is assumed that the salinity of outflowing water (S_R) is the average of salinity between the budgeted water body and oceanic salinity.

$$d(VS)/dt = VQSQ + VPSP + VGSG + VOSO + VESE + VRSR + VX(Socean - Sgulf) \quad (3)$$

where, V_X represents the mixing volume exchanged between the ocean and the gulf.

2.2 Budgets of Non-conservative Constituents

The non-conservative flux (ΔY) of any constituent Y can be estimated by:

$$d(VY)/dt = VQYQ + VPYP + VGYG + VOYO + VEYE + VRYR + VX\,(Yocean - Ygulf) + \Delta Y \quad (4)$$

ΔY is the change (addition or reduction) in the concentration of Y due to physical, abiotic chemical or biotic chemical processes that take place within the system. Using stoichiometric linkages between the fluxes, the phosphorus and nitrogen budgets can be used for calculations of primary production minus respiration (p-r) and nitrogen fixation minus denitrification [nfix-denitr], respectively, according to the procedures outlined by Gordon et al. (1996).

For the phosphorus budget, if it occurs that the difference in the concentration of dissolved inorganic phosphorus (ΔDIP) is positive, then DIP is moving from the sediment to the system and the system is a net producer of dissolved inorganic carbon (DIC) through respiration, [(p-r)<0]. If, on the contrary, ΔDIP is negative, then DIP is moving to the sediment and the system is a net consumer of DIC through net organic production, [(p-r)>0]. The value in the difference between primary production and respiration is given by:

$$[p-r] = -\Delta DIP \times (C:P)part \quad (5)$$

where (C:P)part is given by the Redfield ratio (C:P = 106:1) for plankton.

The nitrogen budget appears more complicated, since, during the measurement of dissolved inorganic nitrogen concentration (DIN) in the system, denitrification converts nitrate to nitrogen gas and nitrification converts nitrogen gas to dissolved inorganic nitrogen. The net effect of this transfer [*nfix-denitr*] is the difference between the measured dissolved nitrogen flux ($\Delta N = \Delta NO_3 + \Delta NH_4 + \Delta DON$) and that expected from the production and decomposition of organic matter:

$$[nfix - denitr] = \Delta Nobs - \Delta Nexp = \Delta Nobs - \Delta DIP \times (N:P)part \quad (6)$$

where (N:P)part is given by the Redfield ratio (N:P = 16:1) for plankton.

2.3 Site Description and Data

The study area consists of two semi-enclosed water bodies, Strymonikos and Ierissos Gulfs, located at the northeastern part of Chalkidiki Peninsula. Strymonikos Gulf receives most of the surface freshwater runoff from River Strymon (drainage area: 18.329 km^2), which outflows at the northern part of the gulf, supplying fresh water and domestic, agricultural and industrial effluents (Figure 1).

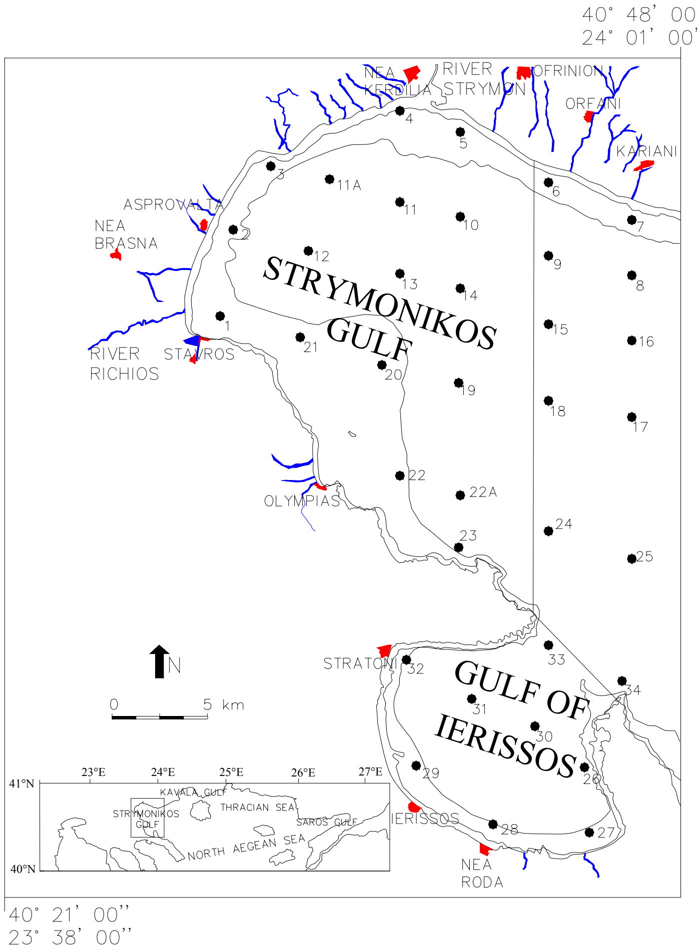

Figure 1. Map of Strymonikos and Ierissos Gulfs and sampling stations

River Strymon has a mean annual discharge of 45.2 $m^3\ s^{-1}$, directly related to the water level of Lake Kerkini, a man-made reservoir located 77 km upstream its mouth (Hatzigiannakis, 1999). River Richios, with a mean annual discharge 0.90 $m^3\ s^{-1}$, relatively constant throughout the year, transports fresh water from Volvi Lake to the western part of Strymonikos Gulf (Tryfon *et al.*, 1996).

Collected data on water salinity, density and nutrient distributions exist for Strymonikos and Ierissos Gulfs (Sylaios, 1999; Sylaios and Koutrakis, 2001), as obtained during four seasonal surveys (June, September and November 1997 and February 1998). Dissolved nutrient determination (nitrates, nitrites, ammonium and phosphates) was made at water samples collected with a 10 m vertical resolution grid, according to Strickland and Parsons (1972). Figure 1 presents the sampling grid (average station spacing 4.6 km) and the surface hydrographic network of this coastal zone.

Local mean monthly meteorological data are based on observations made at Kariani weather station during the period 1997-2001. Mean annual precipitation in the area was 486.0 mm, while mean annual evaporation was measured as 989.7 mm. These precipitation and evaporation rates are converted to volume fluxes by multiplying with the area of the system. Annual water, salt and nutrient budgets were developed for Strymonikos and Ierissos Gulfs, using as input data the values presented in Table 1. To gain further information, the system has been divided into two boxes: Strymonikos Gulf box and Ierissos Gulf box. For purposes of the budgetary analysis, both basins are treated as well-mixed systems, an assumption also valid for Strymonikos Gulf, since the freshwater layer occupies only a small portion (3-5 m) of the overall (55 m depth) water column.

Table 1. Input data for the annual budgets of Strymonikos and Ierissos Gulfs.

	Strymonikos Gulf	Ierissos Gulf
System Area (m^2)	4.52×10^8	1.20×10^8
System Volume (m^3)	1.70×10^{10}	8.4×10^9
River Discharge (m^3 sec^{-1})	47.0	0.48
Precipitation (mm d^{-1})	1.33	1.33
Evaporation (mm d^{-1})	2.71	2.71
System Salinity (psu)	35.6	36.3
Ocean Salinity (psu)	36.4	36.4
System DIP (mmol/m^3)	0.27	0.45
Ocean DIP (mmol/m^3)	0.32	0.32
River DIP (mmol/m^3)	1.16	0.60
System DIN (mmol/m^3)	2.65	1.61
Ocean DIN (mmol/m^3)	1.30	1.30
River DIN (mmol/m^3)	26.84	2.00

3. RESULTS AND DISCUSSION

3.1 Strymonikos Gulf Budgets

Figure 2 presents the steady state water and salt annual budget for Strymonikos Gulf. A water residual outflow (VR) of 3,438 × 10^3 m^3 d^{-1}, occurs as a result of freshwater river runoff (VQ), precipitation influx (VP) and evaporation outflux (VE).The mixing exchange term (VX), between the gulf and the open sea, is directed inward and has a value of 154,704 × 10^3 m^3 d^{-1}. The residence time of water in each gulf was estimated by dividing the total box volume with the sum of the mixing exchange flux (VX) and the residual flux (VR). Therefore, the water exchange time of Strymonikos Gulf was calculated to 107 days.

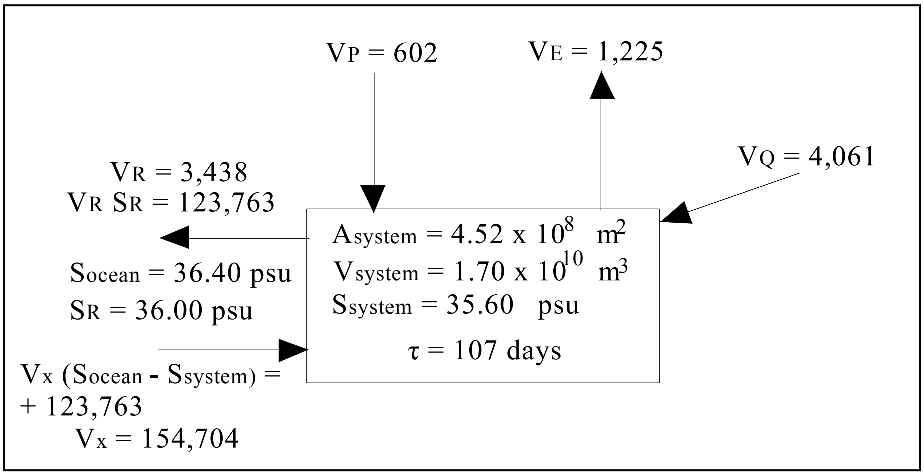

Figure 2. Annual water and salt budget for Strymonikos Gulf. Water fluxes in 10^3 m^3 d^{-1} and salt fluxes in 10^3 psu m^3 d^{-1}

According to the phosphorus budget of Strymonikos Gulf (Figure 3), stream inflow delivers 4,711 mol DIP d^{-1}, residual outflow removes 1,014 mol DIP d^{-1}, while mixing pushes inwards about 7,735 mol DIP d^{-1}. Thus, in order to support this net import, there must be a negative value for

ΔDIP, meaning that Strymonikos Gulf is in a process of internal uptake (change of phase from dissolved inorganic phosphate to particulate phosphate and sedimentation) at a rate 11,432 mol DIP d^{-1} (0.025 mmol DIP m^{-2} d^{-1}). Following equation (5), it occurs that the gulf is a net consumer of organic matter, since [p-r] >0, consuming 2.68 mmol C $m^{-2}d^{-1}$ through net organic production.

Figure 4 presents the annual nitrogen budget, showing that according to the stoichiometric calculations [nfix – denitr] is positive, meaning that the system is producing more nitrogen through nitrification, than is lost to denitrification, at a rate of 289.55×10^3 mol N d^{-1} (0.64 mmol N $m^{-2}d^{-1}$).

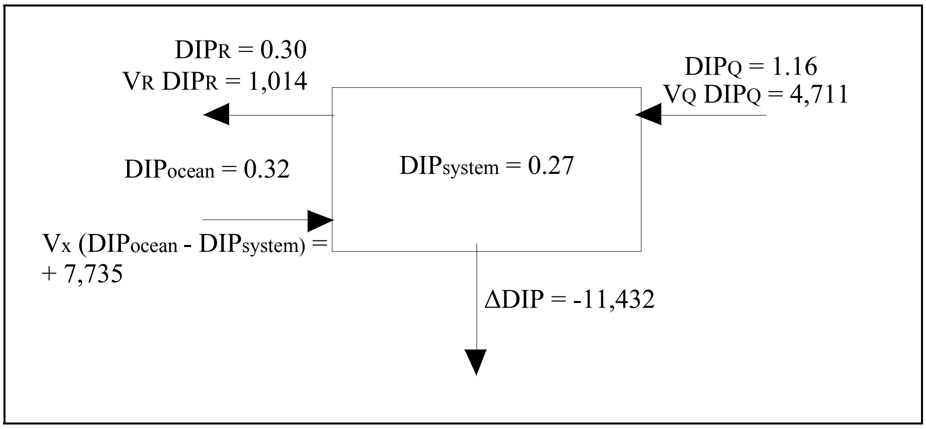

Figure 3. Annual phosphorus budget for Strymonikos Gulf. DIP concentrations in mmol m^{-3} and DIP fluxes in mol d^{-1}

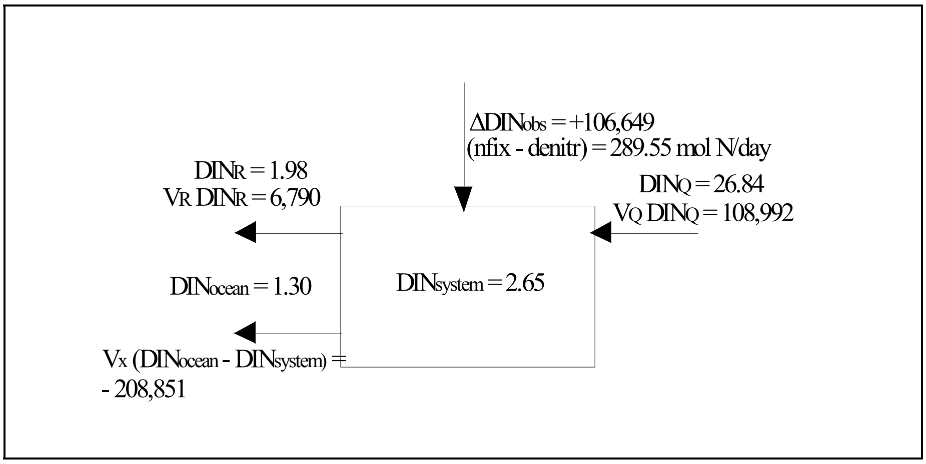

Figure 4. Annual nitrogen budget for Strymonikos Gulf. DIN concentrations in mmol m^{-3} and DIN fluxes in mol d^{-1}

3.2 Ierissos Gulf Budgets

Ierissos Gulf shows a water deficit of 124×10^3 m^3 d^{-1}, since evaporation exceeds river discharge and precipitation volumes. Thus, V_R has an inward direction, while V_X transports salt out of the gulf with a value of $45,135 \times 10^3$ psu m^3 d^{-1}. The residence time of Ierissos Gulf was estimated to 185 days. The residence time of both gulfs, considered as a single box system, was calculated to be 204 days, approximately.

An influx of 25 and 48 mol DIP d^{-1} results from surface freshwater runoff and residual inflow, respectively. The mixing term exports from Ierissos Gulf 5,868 mol DIP d^{-1}, due to the fact that system concentration is higher than the ocean. Thus, a positive value for ΔDIP of the order of 5,795 mol d^{-1} (0.05 mmol m^{-2} d^{-1}) was estimated, meaning that particulate phosphorus is released from bottom sediments to the water column of Ierissos Gulf. This value leads to a net ecosystem metabolism [p-r] = -106 × ΔDIP = -5.11 mmol C d^{-1}, therefore, the system is a net producer of organic matter through respiration.

The annual nitrogen budget shows an influx of 83 and 181 mol DIN d^{-1} due to freshwater runoff and water residual flow, at Ierissos Gulf. Water mixing between the gulf and the adjacent open sea removes 13,992 mol DIN d^{-1}, and hence, a ΔDIN value of 13,728 mol d^{-1} (0.11 mmol m^{-2} d^{-1}) was introduced. Using the ΔDIN and ΔDIP values to estimate nitrogen fixation minus denitrification, we have that [*nfix – denitr*] = ΔDIN – 16 × ΔDIP = - 79 × 10^3 mol N d^{-1} (- 0.65 mmol N m^{-2} d^{-1}). This suggests that Ierissos Gulf is denitrifying in excess of nitrogen fixation.

A summary of the results obtained from the annual phosphorus and nitrogen fluxes and the stoichiometric calculations in Strymonikos and Ierissos Gulfs is given at Table 2.

Table 2. Summary of annual phosphorus and nitrogen stoichiometric calculations for net ecosystem metabolism.

	Strymonikos Gulf	Ierissos Gulf
Residence Time (d)	107	185
ΔDIP (mol d^{-1})	-11,432	+5.795
ΔDIP (mmol m^{-2} d^{-1})	-0.025	+0.05
ΔDIN (mol d^{-1})	+106,649	+13,728
ΔDIN (mmol m^{-2} d^{-1})	+0.24	+0.11
[$p – r$] (mmol C m^{-2} d^{-1})	+2.68	-5.11
[*nfix – denitr*] (mmol N m^{-2} d^{-1})	+0.64	-0.65

4. CONCLUSIONS

The residence time of Strymonikos and Ierissos Gulfs was found 107 and 185 days, respectively. The phosphorus budget showed that Strymonikos Gulf is a net consumer of organic matter (2.68 mmol C $m^{-2}d^{-1}$) through net organic production, while Ierissos Gulf is a net producer of organic matter (5.11 mmol C $m^{-2}d^{-1}$) through respiration. Strymonikos Gulf is producing more nitrogen through nitrification (0.64 mmol N $m^{-2}d^{-1}$), while Ierissos Gulf is denitrifying (0.65 mmol N $m^{-2}d^{-1}$).

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