Nutrient sources for green macroalgae in the Ria Formosa lagoon – assessing the role of groundwater

Chapter · June 2013

DOI: 10.1201/b15003-14

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Chapter 13

Nutrient sources for green macroalgae in the Ria Formosa lagoon – assessing the role of groundwater

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ABSTRACT

The role of nitrate-contaminated groundwater discharge in the appearance of algal blooms in the Ria Formosa lagoon, south Portugal, is assessed by setting up a regional water balance for its drainage basin and determining annual N loads on groundwater. Of the estimated 80.8 million m^3 (hm^3) of natural recharge, 34% is consumed for irrigation, mainly in the western sector near Faro, largely reducing coastal groundwater discharge (CGD) in that area. In the east, since 2001 irrigation is performed with surface water, which has lead to an average annual increase in CGD by 24 hm^3, 3.5 hm^3 of which is artificial recharge. It is not known what part of CGD enters the lagoon, but estimates point towards 40–50%. Geophysical surveys are carried out to study groundwater seepage along geological faults. Total N load on the drainage basin of the lagoon is calculated in the order of 570 ton/yr, but due to restricted outflow near Faro and deep circulation, 300 ton/yr is estimated to enter the lagoon. Groundwater discharge may be important for triggering winter algae blooms on the mudflats, with little access to ocean water, as well as for the summer algae, which seemingly depend on the Ria Formosa as a nutrient source.

13.1 INTRODUCTION

Human activities, particularly those related to agricultural practices, have highly increased the nutrient load on groundwater and caused its contamination in many areas of the Algarve, in the south of Portugal. Currently, the highest nitrate concentrations are observed in the drainage basin of the Ria Formosa (Fig. 13.1), a mesotidal lagoon that is recognised both on a national and an international level as an extremely valuable and sensitive ecosystem. Every winter, blooms of green ulvoid algae develop in the intertidal zone, while in summer ulvoid blooms develop as well on the sandy beaches of the adjacent coastal zone. Winter species in the Ria Formosa are mainly *U. prolifera* forming thick mats on the mud flats, whereas summer species are mainly free-floating *U. rigida* and *U. rotundata*. A further increase of the nutrient load on the lagoon may cause denser populations of algal blooms and the development of new

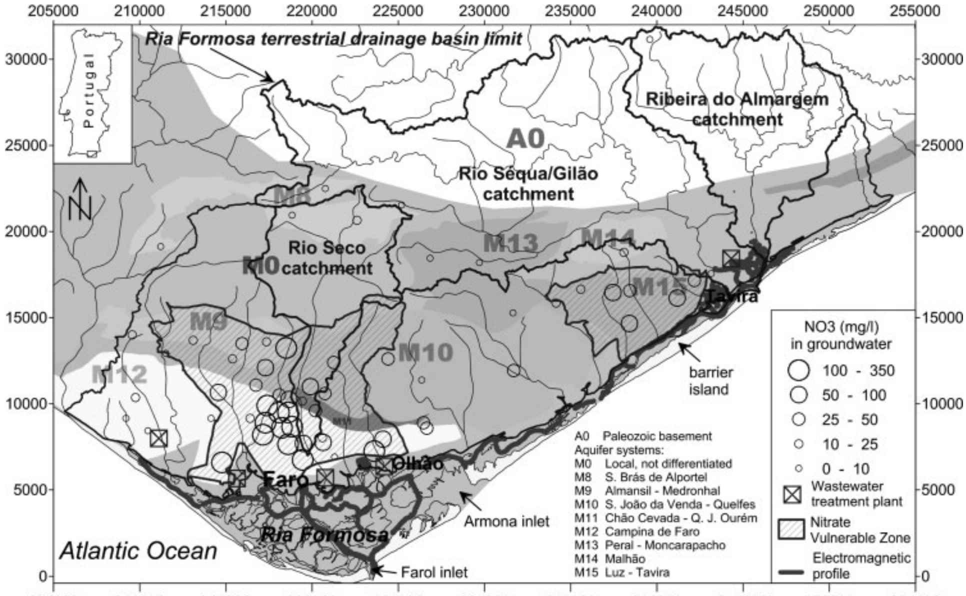


Figure 13.1 Location of the Ria Formosa lagoon, its drainage basin and the three major stream catchments, defined aquifer systems, nitrate concentrations in groundwater, the designated Nitrate Vulnerable Zones, waste water treatment plants and electromagnetic profiles.

bloom sites, with potentially serious impacts on biodiversity, seagrass meadows, shellfish and fish populations and tourism development. Groundwater flow may form an important contribution to the nutrient load of the lagoon, as monitoring in the area provides evidence that well-defined nitrate contaminant plumes are moving towards the lagoon (Stigter *et al.*, 2007; Stigter, *in press*).

In 2004 a scientific research project was initiated that seeks to identify the species-specific nitrogen (N) metabolism of the blooms both within and outside the lagoon and to relate them with the N mass balance between the lagoon and the adjacent terrestrial and coastal zones. A fundamental task in this project was the determination and quantification of the main sources of nutrients in the Ria Formosa, particularly N, as this element is considered to limit primary production in most shallow ecosystems and thus to be one of the driving forces in ulvoid growth rates (Howarth and Marino, 2006). Figure 13.2 shows all the known sources and sinks of N for the lagoon. The input of N (I1+I2) from coastal groundwater discharge (CGD) is difficult to assess, as several discharge mechanisms are known to exist: (G1) ‘diffuse’ outflow along the fresh/saltwater interface near the coast; (G2) ‘preferential’ outflow along geological faults that form water conduits and (G3) deep groundwater circulation that may extend beyond the limits of the Ria Formosa, leading to submarine groundwater discharge (SGD). In a study for the northern end of the Wadden Sea in Denmark, Andersen *et al.* (2007) concluded that the most significant freshwater discharge occurs in distinct zones near the high tide line.

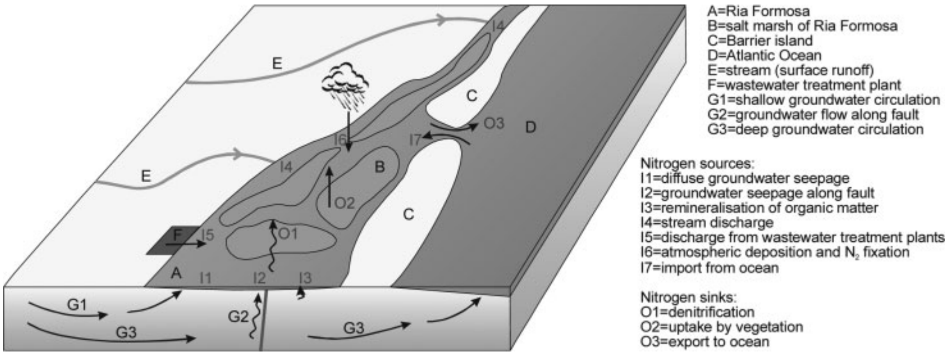


Figure 13.2 Schematic diagram (unscaled) of sinks and sources for nitrogen in the Ria Formosa.

13.2 STUDY AREA

The drainage basin of the Ria Formosa lagoon, located in the south of Portugal, is characterised by a Mediterranean climate with hot dry summers and mild rainy winters. Mean annual air temperature recorded in Faro is 17.3°C (Silva, 1988), whereas mean yearly precipitation in the basin is 664 mm (Nicolau, 2002). The total terrestrial drainage basin area is 741 km^2, with the two most important sub-basins of the rivers Rio Séqua/Gilão and Ribeira do Almargem (Fig. 13.1) which together cover 43% of the area and account for approximately 80% of total runoff. These two rivers have an intermittent behaviour, whereas all other streams are ephemeral. The hydrogeology is characterised by a Palaeozoic age basement of schists and graywackes that crop out in the north, with extremely low permeability (Fig. 13.1). The main aquifers are formed of karstified limestones and dolomites (with high secondary porosity) and fine- to course-grade sands.

Land use is characterised by intensive irrigated citrus and horticulture in two areas of the basin that have been designated Nitrate Vulnerable Zones (Fig. 13.1), in compliance with the Nitrates Directive (91/676/EEC). Nitrate concentrations in groundwater of these areas are well above the guideline value for drinking water (50 mg-NO_3/l) and locally can exceed 300 mg/l, mainly as a result of leaching of mineral fertilisers, irrigation and, to a lesser extent, losses from leaky septic tanks.

The Ria Formosa is a mesotidal lagoon, extending for approximately 55 km along the south coast of Portugal. Five sand barrier islands and two peninsulas separate the lagoon from the Atlantic Ocean and six inlets provide the water exchange with the ocean. The average water depth is less than 2 m; tidal height varies between 3.7 m (maximum spring tides) and 0.4 m (minimum neap tides). This results in the flushing of a large part of the water volume, thereby imposing an intense exchange of dissolved nutrients and particulate matter between the lagoon and the adjacent coastal waters. The Ria Formosa receives secondarily treated sewage inputs from three major cities bordering the lagoon, Faro, Olhão and Tavira, representing an important source of dissolved inorganic nutrients and organic matter.

13.3 METHODOLOGY

13.3.1 Radio frequency– electromagnetic surveys

Surveys employing the Radio Frequency – Electromagnetic Method (RF-EM) were carried out on the Ria Formosa lagoon, as well as on land, in several areas bordering the lagoon. The aim was to detect groundwater outflow through discontinuities and to discriminate different electrical resistivities, so that faults, lithological contacts and water-bearing structures could be identified. The RF-EM method, illustrated in Figure 13.3, uses radio frequencies ranging from 12 up to 300 kHz. The receiver antenna captures the horizontal primary field and the vertical components of the secondary magnetic fields, which are in-phase or out-of-phase with the primary field.

The relationship between the secondary (Hs) and primary (Hp) magnetic fields is studied as a percentage-expressed Hs/Hp ratio. The investigation depth (P) is a function of the resistivity (Rho) of the strata and the radio frequency (F, in Hertz) used:

$$P = 503\sqrt{\frac{Rho_{ap}}{F}} \tag{13.1}$$

The equipment has been designed for fast and extensive mapping of geological contacts by combining a Data logger, which registers every two seconds and a Global Positioning System. The field data are georeferenced, transformed into 3D data profiles and coupled with all the available information, by means of GIS format software. The direction of the profiles should be as much as possible perpendicular to the structure strike (Fig. 13.3). This is often difficult to achieve (Carvalho Dill *et al.*, 2009), due to the fact that geological contacts, faults, dykes and veins, are often deformed, folded or faulted, hindering the quantitative analysis of field data.

This method was used for the first time on a coastal lagoon. Previous work onshore on the peninsula of Tróia (south of Setúbal) had already shown, despite the attenuation effect of the salt water, that valuable information could be obtained with electromagnetic methods (Carvalho Dill *et al.*, 2009). Structures like fractures and faults are

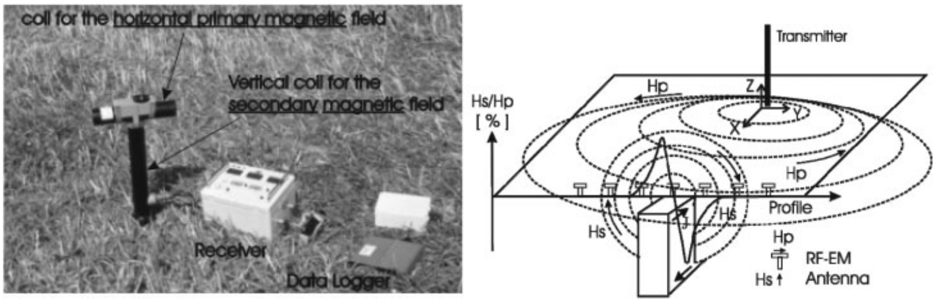


Figure 13.3 (*left*) Equipment used for the Radio Frequency-Electromagnetic survey; (*right*) principle of the RF-EM method, adapted from Turberg and Müller (1992).

revealed by the presence of freshwater, which circulates along them, creating significant contrasts with salt water. 104 km of profiles were performed on land (28 km) with a motorised vehicle and within the lagoon (76 km) using the manual antenna mounted on a boat. The direction of the profiles was conditioned by the navigability of the channels, which was tide-dependent. The antenna was put as far as possible from the outboard engine, in order to minimise interference, as the equipment could not be isolated. Electrical interference from the motor was detected occasionally, particularly whenever the velocity increased. Nevertheless it was possible to attained quite good measuring conditions.

13.3.2 Quantification of coastal groundwater and nitrogen discharge

In order to assess the nitrogen (N) transport towards the lagoon, the annual groundwater discharge from land needed to be quantified. A water balance approach was used, and for this purpose the groundwater catchment was assumed to have the same boundaries as the surface water drainage basin. In reality this is often not the case (e.g. Krause and Bronstert, 2005), due to geological heterogeneities and deep groundwater circulation. However, since the aim is to estimate total groundwater outflow from land, only a small error is involved, because the most significant recharge areas are located within the surface water drainage basin (see Fig. 13.1). Assuming there are no changes in storage, the average annual water balance of the Ria Formosa drainage basin can be considered to be:

$$G_o = P - ET - S_o - I_{ground,eff} + IRF_{surf} \tag{13.2}$$

where G_o is the groundwater outflow, P is precipitation, ET is evapotranspiration, S_o surface water outflow, $I_{ground,eff}$ effective groundwater irrigation, i.e. irrigation minus return flow and IRF_{surf} return flow from surface water irrigation in the eastern part of the basin, where it constitutes an additional recharge component since 2001 (Stigter *et al.*, 2006b). Average annual precipitation was obtained from Nicolau (2002), who used a kriging interpolator with external drift, using elevation as auxiliary variable, to map the spatial distribution of rainfall with a resolution of 1 km^2. Recharge ($P - ET - S_o$) was determined based on estimated infiltration rates for each outcropping lithology. These values are based on a review of recharge estimations performed in the Ria Formosa basin using: (i) the Kessler method in areas of carbonate rock outcrops; (ii) the semi-empirical formulae of Thornthwaite, Coutagne and Turc that calculate real evapotranspiration in areas of sedimentary deposits (Silva, 1984; Silva, 1988) and (iii) the chloride mass balance approach (Stigter *et al.*, 1998; De Bruin, 1999).

Average annual irrigation water requirements correspond to 800 mm/yr in areas of citriculture and horticulture (two crop cycles per year), based on data provided by the Instituto de Desenvolvimento Rural e Hidráulica (IDRHa) for the region. Irrigation return flow is estimated to be 15% for drip irrigation systems such as those used in the area (Beltrão, 1985; Keller and Bliesner, 2000). Keller and Bliesner (2000) refer that ‘the unavoidable excess depth of applied water is at least 10% on all parts of an area that is sufficiently irrigated to meet evapotranspiration demands’. In addition, it is a common and recommended practice to irrigate in excess of crop water requirements, especially in arid and semi-arid environments, in order to control soil water salinity and avoid salt accumulation. The excess irrigation constitutes additional recharge in surface-water irrigated areas (Stigter *et al.*, 2006b).

The N load on groundwater mainly originates from fertilisation and domestic effluents (septic tanks). Rainfall has revealed to constitute a relevant additional source, through dry and wet deposition of ammonia and nitrate, the presence of which in the atmosphere is mainly caused by the referred anthropogenic factors. The mean annual N budget (N_g) for groundwater of the Ria Formosa drainage basin can be written as:

$$N_g = R_n \times N_{Rn} + R_{IRF} \times N_{IRF} + R_{effl} \times N_{effl} - G_o \times N_{Go} - N_{sink} \tag{13.3}$$

where, on a mean annual basis, Rn, R_{IRF} and R_{effl} are natural recharge, recharge from irrigation return flow (IRF) and effluents, respectively, whereas N_{Rn}, N_{IRF} and N_{effl} are leached N contents from natural recharge, IRF and effluents, respectively. G_o is groundwater outflow, part of which enters the lagoon and N_{Go} is the N concentration in groundwater outflow. N_{sink} refers to all existing N sinks in groundwater, mainly reduction to N_2 (denitrification).

N_{Rn}, N_{IRF} and N_{effl} are difficult to quantify separately, in part because natural recharge from rainfall leaches out all existing N sources, from rainwater, soil, fertilisers and domestic effluents. Some simplifications are required in order to successfully determine the groundwater N budget. Soil N is considered not to change on a mean annual basis, whereas denitrification is considered not to occur, as has been discussed by Stigter *et al.* (2006c). Losses from fertilisation mainly occur in the two designated nitrate vulnerable zones (Fig. 13.1), where action programmes have been implemented to attempt to reduce these losses (Stigter *et al.*, 2007; Stigter *in press*). Annual N requirements are 200–300 kg/ha for the vegetable crops and citrus trees grown in the area and for this study average N losses to the groundwater are estimated to be in the order of 15–20%, based on literature findings. Alva *et al.* (2006) indicate a 10–15% leaching of applied fertiliser-N for nitrogen best management practices in citrus orchards, using fertigation. Similar practices are gaining importance in the studied region, but losses are currently expected to be higher and will have been considerably higher in the past. Other studies indicate much higher leaching rates for citrus culture (e.g. Dasberg *et al.*, 1984; Paz and Ramos, 2004; Boman and Battikhi, 2006) and horticulture (e.g. He *et al.*, 2006), as high as 50%.

Leaching of domestic effluents from septic tanks is an important point-source of N in areas not connected to the sewerage network, where roughly 20% of the population lives (CCDR-Alg, 2007). This is clearly revealed by the microbiological contamination observed in many groundwater wells, which is mostly of domestic origin, as livestock farming is practically non-existent. The total N load from septic tanks was estimated on the basis of average population density in each of the municipalities located within the limits of the Ria Formosa basin, water use per capita, average N concentrations in wastewater ($\approx$70 mg/l) and N removal efficiency of the "septic tank + soil" system ($\approx$25%, Costa *et al.*, 2002).

Mean annual outflow volumes of groundwater and dissolved N were compared to those of stream discharge, wastewater treatment plants (WWTPs) and direct rainfall on the lagoon (respectively I4, I5 and I6 in Fig. 13.2), for the hydrological year 2005/2006, when rainfall was equal to the yearly average. The quantification of discharges from streams and WWTPs is presented by Stigter *et al.* (2006a). For atmospheric deposition rain water was also sampled on a few occasions, but since nutrient concentrations in rainwater depend highly on the intensity, duration and frequency of rain events, an estimate of average nutrient content, based on collected samples, past rainwater samples and minimum observed nutrient increases in surface water was used. Total annual nutrient input from precipitation was then simply calculated as the product of rain volume and concentration.

To estimate the exchange of nutrients between the Ria Formosa and the ocean (I7 and O3 in Fig. 13.2), sampling campaigns were set up during spring tide and neap tide once every two months during one year (March 2006 to March 2007). Samples were taken every 2 h over a 24 h tidal cycle from the Farol inlet (see location in Fig. 13.1), responsible for 45–50% of the total water exchange (Pacheco *et al.*, 2010). During the other months, samples were taken at daily high and low tide during spring tide and neap tide from the Farol as well as the Armona inlet, together representing more than 90% of the total water exchange, to detect possible spatial differences. Water temperature, pH and salinity were recorded. Samples were filtered over glass fibre filters to determine particulate organic matter, particulate nutrients (C, N and P) and Chlorophyll-*a* (phytoplankton). Filtered water was analysed for DOC and inorganic nutrients.

13.4 RESULTS AND DISCUSSION

13.4.1 Geophysical study of the lagoon

Good measuring conditions were achieved and in some areas it was even possible to perform parallel profiles on the land in the adjacent shallow waters of the Ria Formosa. This fact not only confirmed that the anomalies detected on land are also detectable in shallow salt waters, which validates the use of this method in these environments, but also gave important information about the existence of geological structures, their orientation and their role in the genesis of such coastal environments.

Figure 13.4 illustrates a typical fault system anomaly followed by a change in lithology towards the sea: a geological formation with higher resistivity and which is covered by more recent sediments and water. The higher resistivity is reflected by a lowering of the Hp/Hs ratio (blue line) – ‘lower step’ – in this prototype device. The black line drawn on top indicates the running average of the Hs/Hp. The upper EC graphic (red line) shows that this anomaly is accompanied by a decrease in water salinity, possibly due to groundwater outflow associated with the fault system. The anomaly was detected along the River Gilão (Tavira) but was also identified towards the southwest (hatched area), parallel to the channel (NE/SW), suggesting the structural control of this lagoon.

Another example is shown in Figure 13.5 corresponding to a lateral changing in lithology (step-fault?) that was detected south east of Faro (Fig. 13.1). Its direction seems roughly parallel to one of the directions of the meandered channel, possibly causing its form. This can lead to the hypothesis that tectonic features have much more to do with the morphology of the Ria Formosa than previously considered.

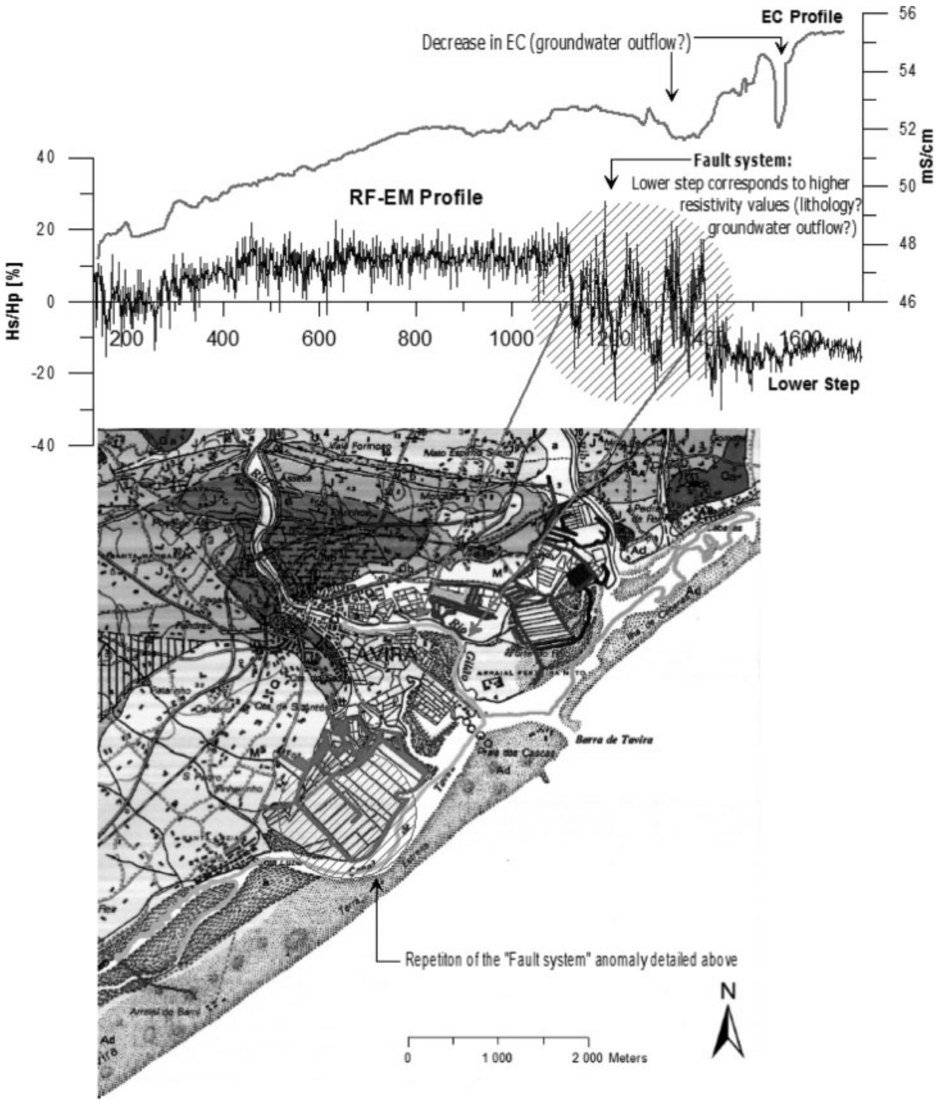


Figure 13.4 RF and EC profiles showing a major anomaly corresponding to a Fault system detected along the river Gilão (Tavira) and also southwestwards (hatched area). The RF profiles are plotted on the Geological Map 53-B, 1:50 000 (copyright LNEG). Lithology: J^2c, J^3 and J^4: Jurassic marly limestone and marl; M^5 Miocene sandy limestone; Qa Quaternary fine silt and sand; Qb Quaternary sand and gravel; Ad Holocene dune sand.

13.4.2 Groundwater and nitrogen discharge into the lagoon

Table 13.1 characterises the hydrogeological units of the Ria Formosa drainage basin (see Fig. 13.1 for location) and quantifies some of the water balance components on

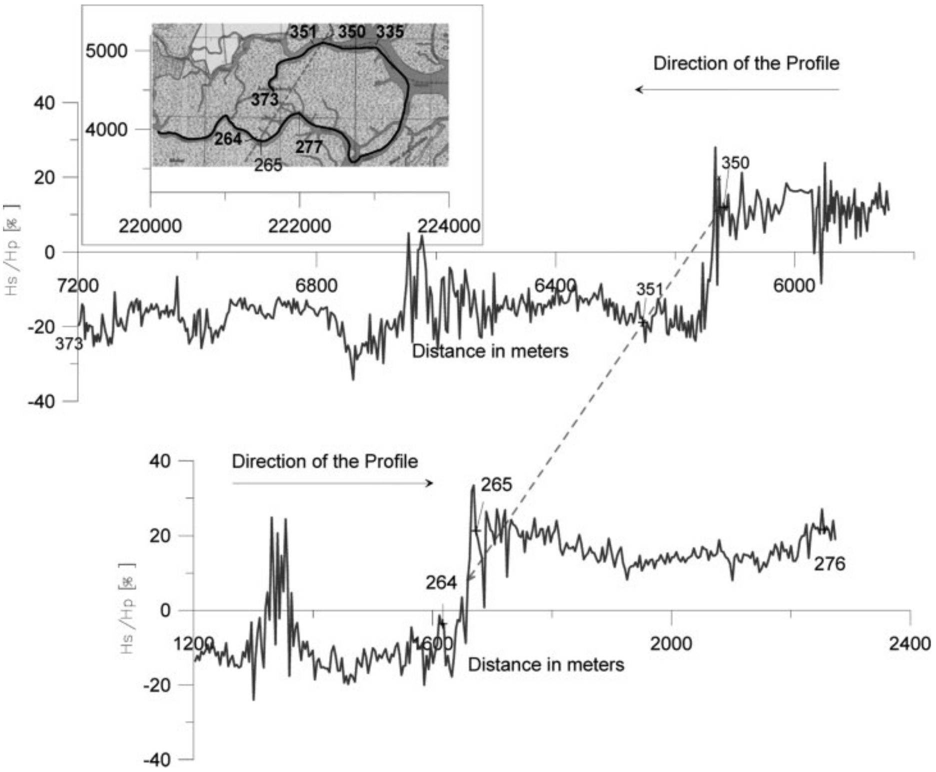


Figure 13.5 Parallel profiles showing the lateral changing of lithology due to a step-fault system, with increasing resistivity towards the east; note the vertical scale (Hs/Hp [%]) ranging from −40 to +40%; also shown is the location of the profile in the lagoon on topographic map (© IGeoE, Portuguese National Grid coordenate system).

an average yearly basis, namely natural recharge ($R_n = P - ET - S_o$) and groundwater outflow (G_o) before and after the implementation of the surface water irrigation district in the eastern part of the basin. The spatial distribution of these two parameters (R_n and G_o) is shown in Figure 13.6. Though P is higher in the north, recharge is very low, due to the low infiltration capacity in the Paleozoic basement. Average S_o is 30% of rainfall, whereas only 5% is considered to infiltrate. The remaining 65% is lost via ET. In the aquifer systems, the infiltration capacities are higher, reaching 50% in the highly karstified limestones (Stigter *et al.*, 2009). Systems M8, M9, M11 and M13 receive the highest recharge per m^2, but due to their large area, besides M13, M0 and M10 receive the highest volumes. Total calculated natural recharge is 80.8 hm^3($\times 10^6$ m^3). For the aquifer systems the values are comparable to those reported by Almeida *et al.* (2000), though the total is 15% higher.

On an average annual basis, 34% of natural recharge is consumed for irrigation, mainly in the aquifer systems M10 and M12, creating a large deficit in the latter. This deficit is compensated by groundwater flowing in from the north, preventing a

Table 13.1 Characterisation of hydrogeological units of the Ria Formosa basin and their water balance.

					Recharge		*Go (present)*		*Go (past)*	
Aquifer system		*Main lithology*	*Area (km^2)*	*P (mm)*	*mm*	*hm^3*	*mm*	*hm^3*	*mm*	*hm^3*
M8	S. Brás de Alportel	limestone, dolomite	21.15	829.6	255.6	5.4	255.6	5.4	255.6	5.4
M9	Almansil – Medronhal	limestone, dolomite	20.53	621.6	236.0	4.8	150.4	3.1	150.4	3.1
M10	S. João da Venda – Quelfes	sand, limestone, marl	108.56	633.2	119.3	12.9	54.4	5.9	−8.6	−0.9
M11	Chão Cevada – Qta. João Ourém	limestone, dolomite	5.34	619.7	259.7	1.4	42.3	0.2	42.3	0.2
M12	Campina de Faro	limestone, sand	79.37	569.9	94.6	7.5	−96.1	−7.6	−96.1	−7.6
M13	Peral – Moncarapacho	limestone	44.06	708.2	330.5	14.6	331.0	14.6	327.2	14.4
M14	Malhão	limestone, dolomite	11.83	638.0	168.2	2.0	169.1	2.0	162.9	1.9
M15	Luz – Tavira	limestone, sand	27.72	605.0	172.9	4.8	229.1	6.4	−146.0	−4.0
M16	S. Bartolomeu	limestone, dolomite	3.28	585.5	114.7	0.4	127.6	0.4	41.6	0.1
A0	Paloezoic basement	Shales, greywackes	226.31	716.1	35.8	8.1	35.8	8.1	35.8	8.1
M0	Local, not differentiated	clay, marl, sand	191.55	673.5	98.7	18.9	95.7	18.3	64.2	12.3
Total			743.51			75.49		51.46		27.65

G_o (past) = groundwater outflow before the existence of surface water irrigation

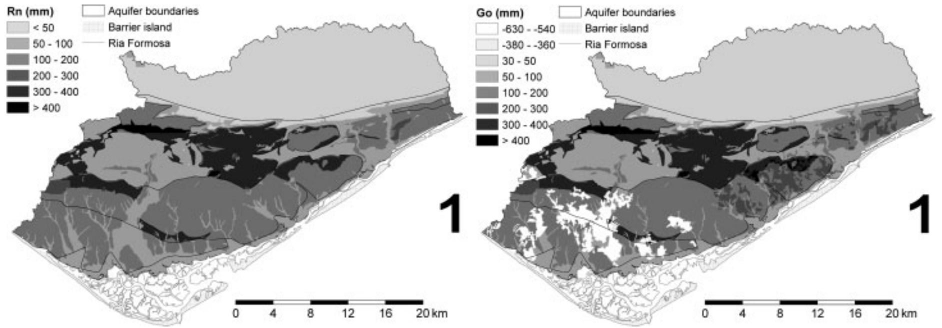


Figure 13.6 Mean annual groundwater recharge (*Rn*, *left*) and outflow (G_o, *right*), based on spatial distribution of rainfall, determined infiltration/precipitation ratios, as well as irrigation and return flow volumes.

decrease of water levels. Indeed, hydraulic heads of the M12 aquifer only show decreasing trends in consecutive years of below-average rainfall. Groundwater discharge along the coastline of this area is limited and the long residence times promote groundwater salinisation and nitrate contamination (Stigter *et al.*, 2006c). Before the integration of the eastern area in the surface water irrigation district in 2001, 60% of groundwater recharge was consumed by agriculture. The shift to surface water irrigation provides 3.5 hm^3 of artificial recharge per year, and together with the ceased groundwater extractions in this area leads to an overall increase of groundwater outflow from the Ria Formosa basin of 24 hm^3.

Table 13.2 Quantification of water and nitrogen discharge from land for each outflow component.

Discharge	*Mechanisms*	*Water (hm^3/yr)*	*Ntot (ton/yr)*	*Period*	*Method*
G1/I1+ G2/I2+ G3	Groundwater	37	570[a]	Throughout the year	Estimated from average N losses from fertilisation, septic tanks and precipitation, considering that input = output from land
I4	Streams	40	27	Only in winter	Calculated (see Stigter *et al.*, 2006a)
I5	WWTPs	10	417	Throughout the year	Calculated (see Stigter *et al.*, 2006a)
I6	Direct rainfall on the lagoon	50	12	Only in winter	Calculated, based on N analyses and spatial distribution of rainfall (Nicolau, 2002)

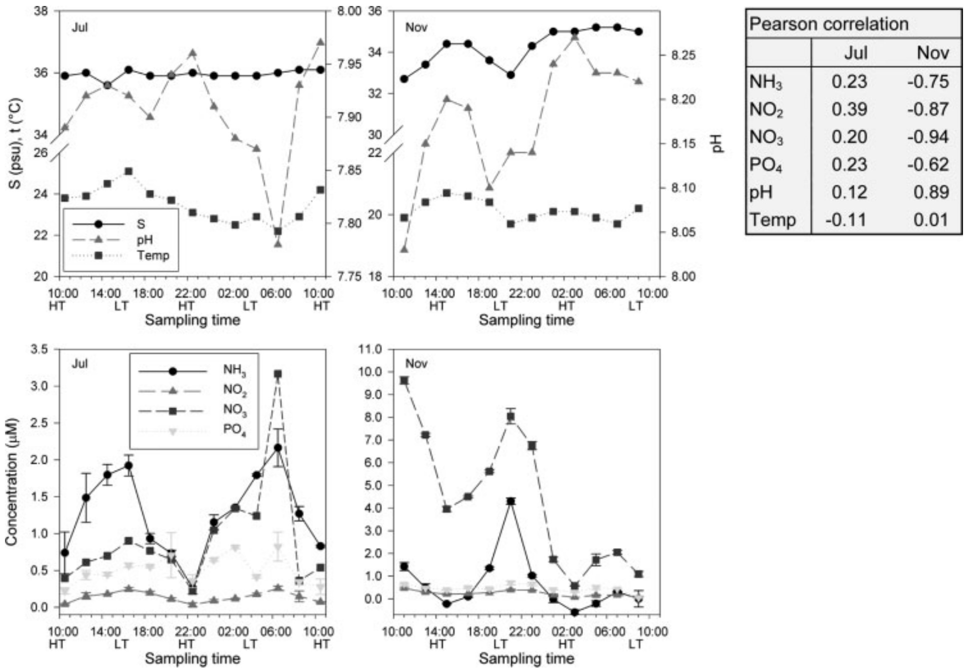
[a] 300 ton/yr is estimated to enter the lagoon, due to restricted outflow near Faro and deep circulation

It is not known precisely how the present groundwater outflow (*Go*) of 51.5 hm^3 is distributed among each of the referred outflow components of Figure 13.2. Deep circulation below the lagoon (*G3*) is particularly important in the east and in a GIS environment was estimated to be 50–60% of *Go*, by considering the contribution of recharge north of aquifer systems M10 and M15 and east of M8.

A value of 570 ton-N/yr was obtained on the basin. Once again, it is not known in detail what fraction enters the lagoon (I1 + I2), but considering the restricted outflow in the area of Faro and combining the location of the N sources with that of the areas where recharge contributes to groundwater discharge into the lagoon (G1), it is estimated that 300 ton-N/yr enters the lagoon. Table 13.2 compares this value with other N sources and shows the importance of groundwater. Based on local seepage measurements, Leote *et al.* (2008) also identify coastal groundwater discharge in the Ria Formosa as a major source of N to the lagoon's internal nutrient mass balance. However, the authors do not consider the large variations between the eastern and western sectors.

The WWTPs provide an important point source, but may have a limited range, as was indicated in earlier studies (Cabaço *et al.*, 2008), in the order 500/1000 m from the discharge point. Most likely, nutrients here are rapidly assimilated in biological processes, such as uptake by vegetation and bacterial denitrification. Curiously, direct rainfall accounts for the largest freshwater input, but N concentrations are much lower. Stream discharge is calculated for the hydrogeological year of 2005/2006. Rainfall in this year was very near the average annual values, so that stream discharge can be compared to the other components, except for the catchment of Rio Seco. Here runoff was low, because the preceding period of long-lasting drought had drastically increased the infiltration capacity of the soil.

The effect of freshwater discharge can be determined by analysing salinity. A very clear signal of stream discharge could be observed during the spring tide 24 h campaign of 7 and 8 November 2006. The days preceding this campaign were characterised by heavy rainfall, causing significant stream discharge. Rain stopped shortly after the first samples were taken, so the effect of direct atmospheric deposition on the Ria is



Pearson correlation	Jul	Nov
NH_3	0.23	-0.75
NO_2	0.39	-0.87
NO_3	0.20	-0.94
PO_4	0.23	-0.62
pH	0.12	0.89
Temp	-0.11	0.01

Figure 13.7 Exchange of the Ria Formosa lagoon with the Atlantic Ocean, results of samples taken every 2 h during a 24 h tidal cycle in the main exchange channel (Barra do Farol) in July and November 2006 (note different scales).

assumed to be low. The clear tidal dynamics of nutrient concentrations (see Fig. 13.7) show a strong negative correlation with salinity, which is most noticeable for nitrate, indicating a dominating terrestrial input and river outflow (in rainfall ammonium is the dominant N compound). Another interesting aspect is that with incoming tide, nutrient concentrations are still high, whereas salinity is still lower than the typical ocean salinity. This means that mixing of outgoing water with ocean water is not complete and that some of the outgoing water returns with the next incoming tide, so that the nutrients will again be available for plant uptake in the Ria Formosa. Finally, the last period to low tide (outgoing water) shows the short-living effect of river outflow both in nitrate and in salinity, corroborating the discharge observations of the most important streams in this region of the Ria Formosa.

A complete presentation of the exchange data with the ocean is provided by Malta *et al.* (*in prep*). In general, the results based on inorganic nutrients seem to confirm earlier studies (Newton and Mudge, 2005) in that, on an annual basis, there is a net export of nutrients to the ocean. It is clear however that there is large heterogeneity in time. Most export takes place in winter, whereas in summer export is limited. Occasionally, import from the ocean may occur (see July night sample in Fig. 13.7) probably due to upwelling of nutrient rich water from the deep sea.

13.5 FINAL CONSIDERATIONS

The role of groundwater as a nutrient source for the algal blooms continues to be a matter of investigation. It is known that winter blooms reach their peak biomass in December–January after which they decline. The algae probably survive the summer heat and high light as tiny life stages (germlings) in the sediment of tidal mud flats (Malta and Santos, 2008). The role of sediment fluxes, i.e. groundwater and remineralisation, can be particularly important for the winter algae, present on the mudflats and with little access to nutrients in ocean water. Algae sampled earlier in the year generally have higher nutrient contents than algal samples in late spring and summer, even when growth rates are high as is the case for the winter blooms, which could also be related to a higher N input. Groundwater discharge in the summer will be much lower, especially in the western part of the drainage basin, where irrigation consumes a large fraction of annual recharge. In the east this is not the case now that irrigation is performed with surface water, causing a water and N flux towards the lagoon and the ocean throughout the entire year, with potential consequences for the appearance of algal blooms. Interestingly, major summer blooms spots were located in the eastern part of the lagoon and along the eastern beaches (Malta *et al.*, 2007). As these blooms start to develop in early spring, the contribution of rainfall and stream outflow to the nutrient budget is already minimal and oceanic concentrations are low, hence it is likely the groundwater outflow and/or remineralisation are the major nutrient sources for the algae in this period.

The lower nutrient content in the algae in the summer is also due to the improved conditions (light, temperature) that stimulate production and cause dilution of internal cell nutrient quota by high growth rates. Apart from the seasonal trend, there are indications that algae growing in the Ria Formosa have higher nutrient contents than algae grown in the sea, independent of the season. From the aerial and underwater surveys carried out in 2006, it became clear that the main algal concentrations in summer can be found in and around the tidal inlets connecting the lagoon with the ocean, suggesting that the Ria Formosa is the main source for these blooms. Moreover, results from trawls carried out by boat in March 2008 showed the presence of high amounts of summer bloom algae on the bottom of the channels, especially around the Armona outlet and the central – eastern sector of the lagoon, supporting this hypothesis. There may be some production in the ocean as well, but considering the low production rates at oceanic nutrient concentrations found in the experiments, this might be just enough to maintain the biomass (Malta *et al.*, 2007).

Algal biomass is also highly variable between years; in the summers of 2005 and 2006 blooms were hardly observed, whereas 2004, 2007 and 2008 showed large accumulations on the beaches of the eastern Algarve. This could be related to climate factors, such as water temperature and rainfall, and surface and groundwater discharge (Malta *et al.*, 2007). Rainfall in 2005 was extremely low, but in 2006 reached average values, so that groundwater storage could be replenished. The winters of 2004 and 2007 also had below-average rainfall (65%), so apparently no direct link can be established, although both years were preceded by relatively wet years. Also in this case further study is required.

ACKNOWLEDGEMENTS

The present study is performed in the scope of the research projects POCI/MAR/58427/2004 and PPCDT/MAR/58427/2004 and the authors gratefully acknowledge the *Fundação para a Ciência e a Tecnologia* for funding the projects.

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