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Modeling nitrate-contaminated groundwater discharge to the Ria Formosa coastal lagoon (Algarve, Portugal)

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Abstract

A numerical flow and transport model is developed to assess groundwater discharge and nutrient transport to the Ria Formosa coastal lagoon in southern Portugal. A total N load of 350 ton/year is estimated for the considered area, of which agriculture accounts for 73% of total N load, and domestic effluent and atmospheric deposition for the remaining 9% and 18% respectively. Model results suggest that nutrient recycling has led to the high concentrations observed in the *Campina de Faro* (M12) aquifer, but is still insufficient to account for observed values at the coastline. Furthermore results suggest that even for the best case mitigation scenario, good quality status will not be achieved by 2027, as mandated by the EU Water Framework Directive.

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Keywords: groundwater discharge, numerical model, coastal aquifer, algal blooms, nitrate transport, regional scale

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1. Introduction

In the past, the joint pressures of overexploitation and inadequate agricultural practices in southern Portugal caused nitrate contamination and seawater intrusion problems in several groundwater systems in the region. Changes in water resources use have led to improvements in most of the region, however the group of aquifers that drain in to the Ria Formosa coastal lagoon still suffer from high concentrations of nitrate (Fig.1). In fact, the only two nitrate vulnerable zones (NVZ) designated according to the EU's Nitrate Directive in the Algarve are within this area and continuous monitoring provides clear evidence of the continued elevated levels of nitrate and movement of the contamination plume towards the lagoon[1].

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The Ria Formosa is a coastal lagoon located in the south of Portugal, recognized as an important wetland at both European and International level by its acceptance as a Natura 2000 and a Ramsar site. Coastal lagoons are particularly vulnerable to eutrophication as they are regions of restricted exchange with the adjacent ocean and may accumulate nutrients supplied by the surrounding watershed[2]. The role of groundwater discharge as a vector for nutrient transport to the lagoon has been well established[3-5]. Initial estimates of the contribution of groundwater borne nitrogen (N), based on regional water balance and N loads for the entire catchment of the lagoon is in the order of 700 ton/year[1]. However, a recent study in the area has shown that the N loading does not explain the high concentrations of NO_3 observed in the field[6], and that salinization processes caused by irrigation return flow may be the cause. The following paper describes the development and application of a numerical flow and transport model of the aquifer systems that discharge directly to the Ria Formosa, to evaluate the potential effect of return flow on concentration levels and assess the relative effect of potential mitigation measures.

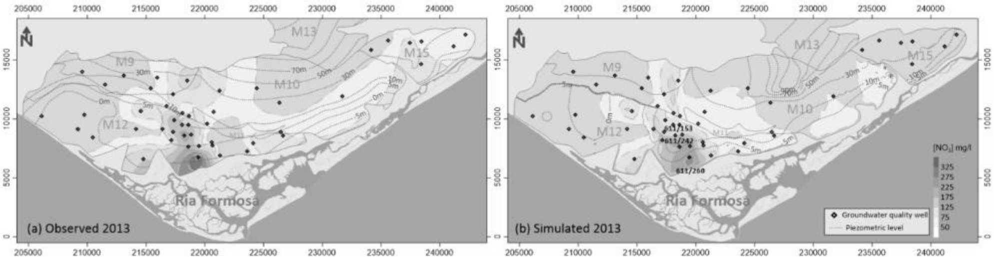

Fig. 1. (a) Location of the study area, main aquifer systems and (a) observed and (b) simulated hydraulic head and concentration of NO_3 in 2013.

2. Methods

2.1. Water budget and N load

The spatial distribution of rainfall[7] and recharge ratios according to outcropping lithology[8] were cross-referenced to estimate total available groundwater recharge. Current groundwater use in the area is mostly for agricultural purposes. Irrigation water demand was estimated based on land use maps for 2007 provided by the regional environmental agency (APA-ARH Algarve) and average crop water demands.

Annual N requirements for the crops grown in the area are in the order of 200-300 kg/ha. An average N loss of 20% to the groundwater[1] is applied to land use map to determine the total N load to groundwater. Leaching of domestic effluents from septic tanks is an important point source of nitrogen in areas not connected to the sewerage network (c.a. 20% of the population), which is clearly revealed by the microbiological contamination observed in many groundwater wells. The total N load from septic tanks was estimated assuming the following values[1]: average population density in the Ria Formosa basin of 165 hab/km^2, water use per capita of 150 l/day, 70 mg/l N concentrations in wastewater and N removal efficiency of the treatment system of 25%. The contribution from atmospheric deposition was calculated based on the spatial distribution of rainfall[7] and average concentration of N in rainwater (20 μmol/l) measured in the area[1].

2.2. Numerical flow and transport model

A two-dimensional flow and transport model of the aquifer systems that discharge directly into the Ria Formosa was developed using finite element code FEFLOW[9]. The geometry of the groundwater management units, geological outcrops, main hydrogeological features were used to generate a triangular finite element mesh with 193,709 elements and 98,208 nodes. Constant head boundary conditions were imposed along the coastline and channels of the coastal lagoon. Well boundary conditions were assigned to nodes within irrigated areas. Abstraction rates were spatially distributed according to calculated water demand for each specific plot of land. Recharge and atmospheric deposition was assigned according to the spatial distribution of rainfall[7] and recharge ratios according to outcropping lithology[8]. Additionally, irrigation return flow was assigned to agricultural areas. A source of mass was assigned to elements corresponding to irrigated areas. Leaching from domestic effluent was distributed uniformly over non-agricultural areas. Constant mass boundary conditions were assigned at nodes along the coast, the lagoon and the streams.

Spatial distribution of transmissivity (*T*) was estimated by inverse modeling under steady-state conditions, using the Gauss-Marquardt-Levenberg method as implemented in the nonlinear parameter estimation software PEST[10]. Uniform hydraulic property zones were considered for all aquifers except the *Campina de Faro (*M12) and *São João da Venda-Quelfes* (M10). In the latter, the pilot-point method[11] was used to describe the spatial distribution of *T* as these systems are relatively heterogeneous, yet there is little geological evidence on which to base the geometry of a further sub-division of property zones. Transport parameters, effective porosity (*ne*) and aquifer thickness (*b*), were manually adjusted by trial and error for a 17 year simulation between 1995/96 and 2012/13, considering initial distribution of NO_3 interpolated from average observed values from 1995/96. Longitudinal and transverse dispersivity were assumed as 20m and 2m respectively as a compromise between numerical stability and realistic parameter values according to the literature[12].

3. Results and Discussion

Average annual input from domestic effluents was estimated at 31.1 ton/year for the model area and atmospheric deposition at 63.8 ton/year. A total N load of 350 ton/year is estimated for the considered area, of which agriculture accounts for 73% of total N load, and domestic effluent and atmospheric deposition for the remaining 9% and 18% respectively.

A steady-state simulation of average conditions shows that the model does not explain high values of NO_3 observed in the field with calculated values of N loading. Sensitivity analysis shows that even at the extreme ranges of physically acceptable parameter values (dispersivity and transmissivity) simulated concentrations are generally an order of magnitude below observed values. Previous studies have suggested that irrigation with contaminated groundwater is a likely cause of the elevated concentrations[13]. In fact, abstracted mass accounts for 70% of average annual N load to the system, with only the remaining 30% occurring as discharge to the lagoon.

To test this hypothesis, a 30 year simulation was carried out in which mass removed via abstraction is re-applied with return-flow in 5 year periods. Model results corroborate the idea that return flow accounts for recycling of N and the increasing concentrations and observed spatial distribution. However, 80-100 years (depending on parameters) of recycling are necessary for concentrations to reach observed levels in the late 1990s'. This is assuming an average loss of 20% of crop N requirements. In practice, higher loads are likely to have occurred in the past[1], which would account for the higher concentrations observed in the field. To test the effect of mitigation measures, a simulation is run starting from observed distribution of NO_3 in 1995/96 until 2027. Agricultural areas in the *Campina de Faro* (M12) suffer the greatest increase in loading, as wells in this system are re-circulating contamination that flows from aquifers upstream (Fig. 2(a)). The model is able to represent the overall change in NO_3 concentrations, and shows a good fit with average values measured in 2013 (Fig.2(b and c)). The effect of several mitigation measures are compared in Fig.2(d). If *business as usual* (BAU) is maintained, nitrate levels in most of the systems would stabilize at current values or decrease slightly as the excess NO_3 is slowly flushed to aquifers downstream. The exception being in M12 near the coast, where concentrations would be expected to continue to increase in the mid to short term as NO_3 continues to be recycled. Simulated values for observation wells 611/242 and 611/153 follow the observed decrease, with a slight increase predicted for the BAU scenario. This may be an artifact of the model, as re-circulated mass from the entire system is distributed uniformly over agricultural areas within the aquifer, thus abstracted mass is being artificially migrated back upstream.

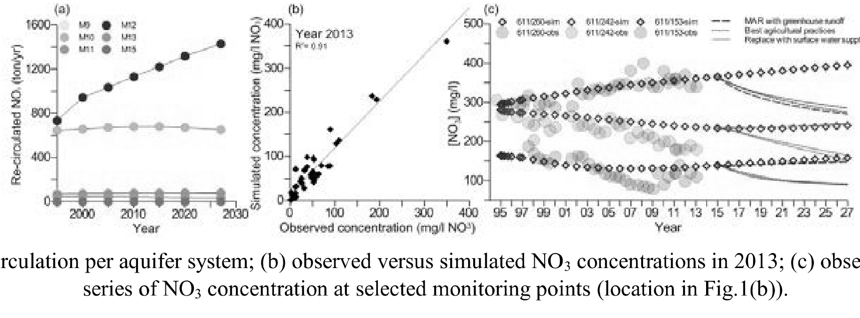

Fig. 2. (a) Rate of re-circulation per aquifer system; (b) observed versus simulated NO_3 concentrations in 2013; (c) observed and simulated time series of NO_3 concentration at selected monitoring points (location in Fig.1(b)).

Replacing irrigation supply with surface water and improving agricultural fertilization practices contribute the most to reducing NO_3 concentrations. Managed aquifer recharge schemes (increasing stream infiltration and injecting rainwater harvested from greenhouses) have a localized effect, as seen for well 611/260 in Fig.2(c). However, even in the best case scenario, the physical characteristics of the system will not allow the existing contamination plume to dissipate within a short time period and that to reach good quality status by 2027 further measures may be necessary.

4. Conclusions

Simulations show that even the recirculation of nutrients via irrigation return flow does not account for high concentrations of NO_3 observed in the aquifer systems in the Ria Formosa basin, reinforcing the idea that higher loads were applied in the past. Nutrient recirculation via return flow provides an explanation for the elevated levels in the *Campina de Faro* (M12), where contamination from upstream is being captured by abstraction and re-applied in this area. Several mitigation measures were assessed, and even the most optimistic mitigation measure does not lead to acceptable contamination levels in the near future, meaning that it is unlikely that good quality status will be attained within the deadlines imposed by the EU.

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