EUTROPHICATION VULNERABILITY ANALYSIS: A CASE STUDY

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ABSTRACT

River Cavado water quality variability was studied for eutrophication vulnerability assessment at a new surface water supply intake. Since the river flow regime is artificially controlled by upstream multipurpose reservoirs, mathematical modelling was applied in evaluating alternative management scenarios. Due to the fact that surface water quality at intake location is mainly affected by a 5 km upstream wastewater treatment plant effluent discharge, algae and nutrients concentration simulations have been worked out in order to identify critical situations. Different algal concentration profiles along the river were obtained for local conditions of light energy, water temperature and estimated nutrient loads, showing high probability of eutrophication occurrence for some of the simulated scenarios. The discussion of results of this study appears to be very useful for river basin wide water management policies evaluation.

KEYWORDS

Algal growth; eutrophication modelling; limitative factors; sensitivity analysis; water quality assessment.

INTRODUCTION

Problems related to water supply uses can range from shortage of water to water quality degradation mainly due to intensive urbanisation and industrial policies as well as uncontrolled agricultural practices. The presence of macroscopic plants causing blockage of intake screens, and microscopic planktonic algae producing taste and odour, must be investigated and controlled in order to protect the quality of river water intake for water supply purposes.

The river Cavado basin (Fig. 1), located in the north-western region of Portugal, is used intensively for water supply, agricultural irrigation and hydropower generation. A new water supply project serving the Oporto metropolitan area, with a population of 0.9 million people and a design flow of 2.7 m^3/s, will introduce new challenges in the river water quality management.

Eutrophication vulnerability analysis of river water, in particular at the intake location of the planned water treatment plant (Areias de Vilar WTP), was carried out in order to predict algae content in raw water. A comprehensive water quality data collection programme was followed for characterisation of present situation in the river basin. Data analysis were carried out and different scenario alternatives for the river basin management were simulated using mathematical modelling (Vieira and Lijklema, 1989). Critical detention times and hydrometeorological conditions for eutrophication occurrence at the intake location were worked out in order to define operation conditions for upstream dams.

STUDY AREA

With a drainage area of 1589 km^2 and a mean width of 16 km, river Cavado basin has a mean elevation of 564 m with several peaks above 1500 m, and an average population density of 200 inhabitants/km^2 (minimum of 22 at Montalegre and maximum of 1770 at Braga). The annual mean rainfall is 2200 mm, 42 % of which is concentrated in the months of December, January and February. The water is intensively used for hydropower generation, domestic and industrial water supply and agricultural irrigation. Main tributaries are river Rabagão (left side, with a drainage area of 257 km^2) and river Homem (right side, with a drainage area of 246 km^2). Due to the river basin characteristics, six large hydropower plants (apart from several other small units) are in operation with an installed power of 377.6 MW and a mean annual energy production of 1535 Gwh. A total reservoir volume of 1170 hm^3 is possible with these dams, which represents a high regulatory capacity for river flows. For this reason, this water use constitutes a very important factor to be considered in any water management policy adopted for the basin.

The study area occupies the lower level part of the basin, where the main residential and industrial areas are located, and distributed over five municipalities: Amares, Vila Verde, Braga, Barcelos and Esposende. All of these municipalities are served by WTP and wastewater treatment plants (WWTP). For modelling purposes, the river reach considered in this study begins downstream Caniçada dam (Ponte do Porto) and ends near the river mouth, in a distance of approximately 48 km; the flows of River Homem are considered as a point discharge downstream Braga WTP; wastewater inputs from the urban areas include Amares and Braga WWTP effluents and untreated domestic and industrial discharges from the municipality of Barcelos.

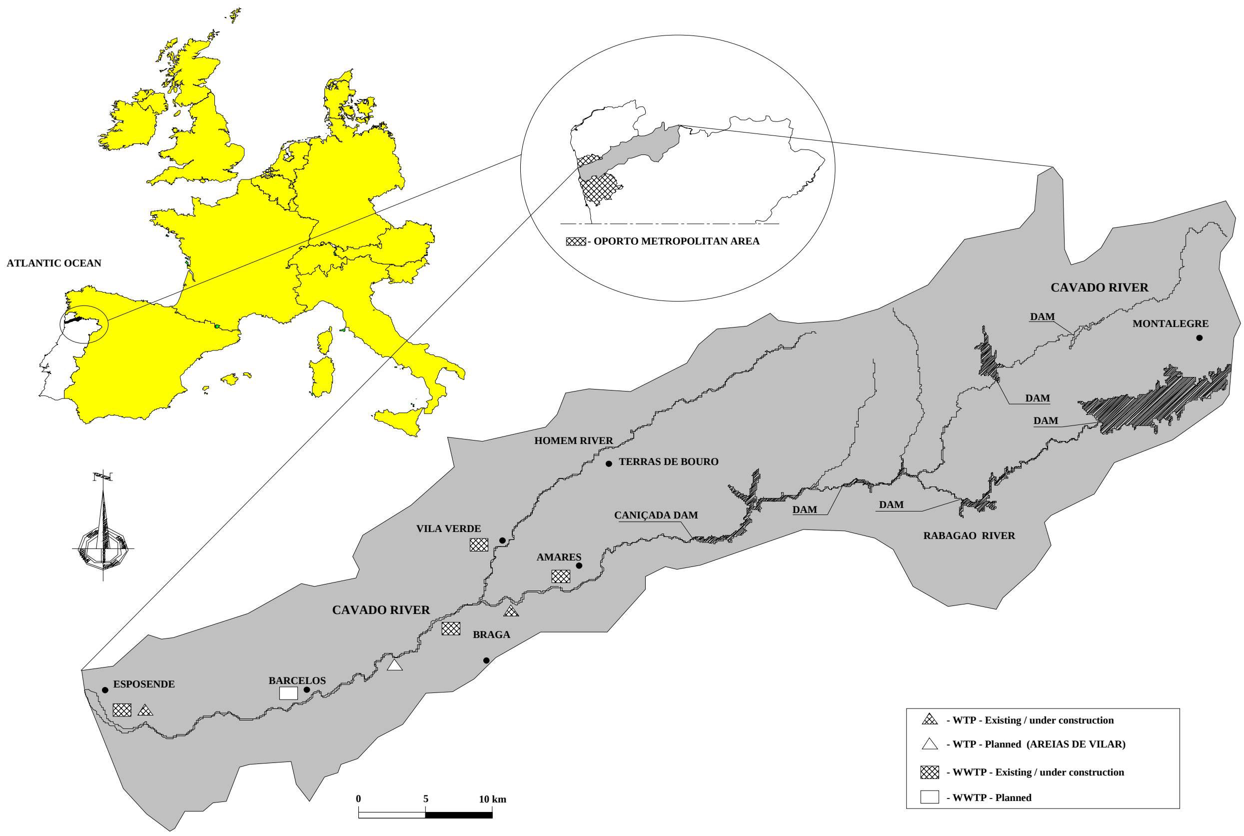


Figure 1. General layout of the river Cavado Basin.

MODEL DESCRIPTION

The DUFLOW model (ICIM, 1992) was designed to cover a large range of applications, such as propagation of tidal waves in estuaries, flood waves in rivers, operation of irrigation and drainage systems and water quality problems. The package is based on the one-dimensional partial differential equation that describes non-stationary flow in open channels (Abbott, 1979). As the relationship between quality and flow gets special attention nowadays and this package is suitable for modelling both, it becomes a useful tool in water quality management. In the water quality part the process descriptions can be supplied by the user. The basic transport equations used in DUFLOW, which are the mathematical translation of the laws of conservation of mass and of momentum, are discretized in space and time using *the four point implicit Preissmann scheme*. This scheme is unconditionally stable, shows little numerical dispersion and allows non-equidistant grids. It computes discharges and elevations at the same point.

The quality part of the DUFLOW package is based upon the one dimensional transport equation. This partial differential equation describes the concentration of a constituent in a one dimensional system as function of time and place. The production term of the equation includes all physical, chemical and biological processes to which a specific constituent is subject to. The eutrophication model (EUTROF1) includes nitrogen, phosphorus and oxygen (Fig. 2) and is based on EUTRO4 (USEPA, 1992). The growth of one phytoplankton species is also simulated. The interaction between the sediment and the overlaying water column is not included in a dynamic way. However, sediment exchange fluxes of oxygen, ammonia and phosphorus may be specific location and time dependence (reflecting temporal and seasonal variations), that can be specified by the user.

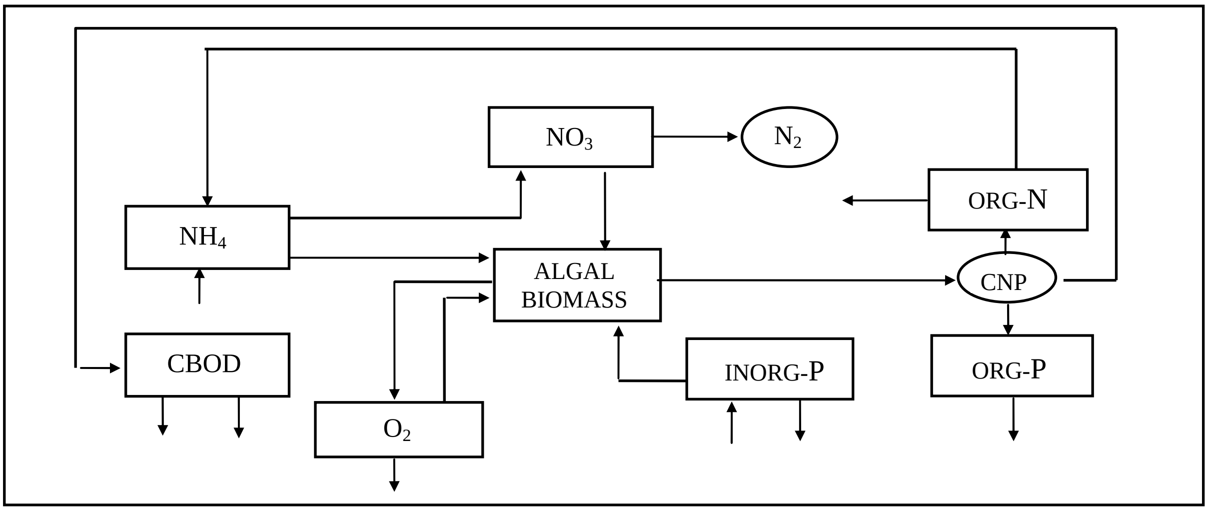


Figure 2. EUTROF1 state variable interactions (ICIM, 1992).

The model is suitable to study the short term behaviour of systems, like to examine the impacts of a discharge on the oxygen dynamics or to explore the effects of flushing on the Chl-a concentration. Algal growth is considered to be limited by nutrients, light and temperature. It is assumed that algae can use ammonia and nitrate for their growth. The uptake of both nitrogen constituents is controlled by the ammonia preference factor. Assumptions and processes can be found in the model user's manual (ICIM, 1992).

METHODS

Data Analysis

River flows were obtained from continuous water discharges measurements in Caniçada dam (DPH/PHGP,1996). The flow rates are significantly influenced by upstream hydropower plants operation, which have an impounding effect of 40 % of the basin mean annual runoff. The reservoirs regulatory capacity effect allows monthly low-flow augmentation in dry-weather conditions. For short operational periods, weekly and daily fluctuations must be considered in the river flow regime.

Water quality data used for simulation purposes were obtained from intensive field sampling programmes (PGHIRN, 1992, and University of Minho, 1995). Model segmentation assumes thirty different river reaches each of them including or a tributary input, or a wastewater discharge, or an abstraction water point. Since weirs have been noticed to play an important role in the river flow regime, nine main weirs were considered as shown in Fig. 3.

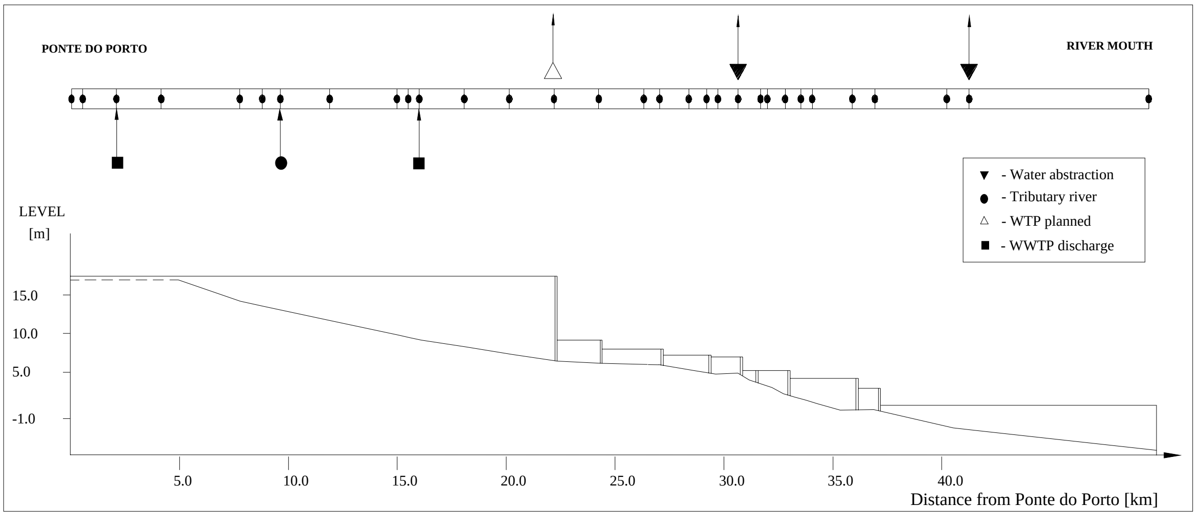


Figure 3. Model schematization and longitudinal profile.

Nutrients and chlorophyll-a concentrations at Ponte do Porto were adopted as water quality boundary conditions and as initial conditions for all river sections. The nutrient point sources are Braga and Amares WWTP discharges and river Homem (includes Vila Verde WWTP), that were considered without treatment. Non-point source loads from agricultural and forest areas were estimated using literature values (Thomann, 1987). The results obtained for the most severe values (Table 1) show that others sources are negligible when compared with Braga WWTP discharge.

Table 1. Waste loads and average concentration of nutrients and chlorophyll-a

Location	Phosphorus		Ammonia		Nitrate		Chlorophyll-a
	(mg P/L)	(g P/s)	(mg N/L)	(g N/s)	(mg N/L)	(g N/s)	(µg/L)
Ponte do Porto	0.07	---	0.06	---	0.86	---	3.8
Amares WWTP	---	0.15	---	1.30	---	0.11	---
Braga WWTP	---	4.45	---	14.32	---	1.22	---
River Homem	0.10	---	0.05	---	1.18	---	---
Distributed sources	---	0.11	---	1.52	---	0.30	---

Model Calibration

Calibration procedure consisted of comparing actual measured values with simulated model output results. The river hydrodynamic behaviour was approximated with weir water levels error of ±2 cm. Dissolved oxygen analysis was performed calibrating the model for the most relevant parameters (Vieira et al., 1996). Eutrophication model was calibrated for chlorophyll-a using data obtained from field survey in six sampling points (Fig. 4). Adopted model parameters (Table 2) fall in common default ranges stated in similar studies (ICIM,1992) and a chlorophyll-a to carbon ratio of 30 µg Chl-a/mg C was considered.

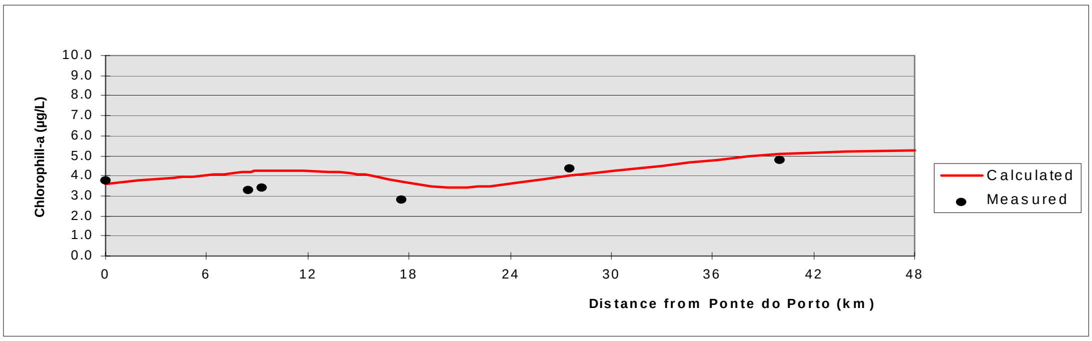


Figure 4. Model calibration for chlorophyll-a.

Table 2. Adopted model parameters

Parameters	Value	Dimension
Background extinction	1.0	m^{-1}
Optimal light energy	100	$W.m^{-2}$
Monod constant nitrogen	0.01	mg N/L
Monod constant phosphorus	0.005	mg P/L
Respiration rate constant	0.1	d^{-1}
Die rate constant	0.2	d^{-1}
Maximum specific growth rate algae	1.5	d^{-1}

Assuming that calibration procedure wasn't based on a sufficient wide range of measured values a sensitivity analysis was carried out to evaluate the influence of model parameters with large range of variability: optimal light energy; maximum specific growth rate algae; background extinction; die rate constant; respiration rate constant; Monod constant for nitrogen and phosphorus. Results for two different WTP abstraction points (Areias de Vilar and Esposende) are depicted in Fig. 5, where the relative increase of Chl-a concentration is shown for the most influent parameters under simulated frequent conditions (scenario S9 in Table 3). As can be seen the influence of model parameters variability is higher in the estuarine zone. Since the maximum specific growth rate algae seems to be the most influent factor in uncertainty of Chl-a concentration, further comprehensive study of algae population is recommended.

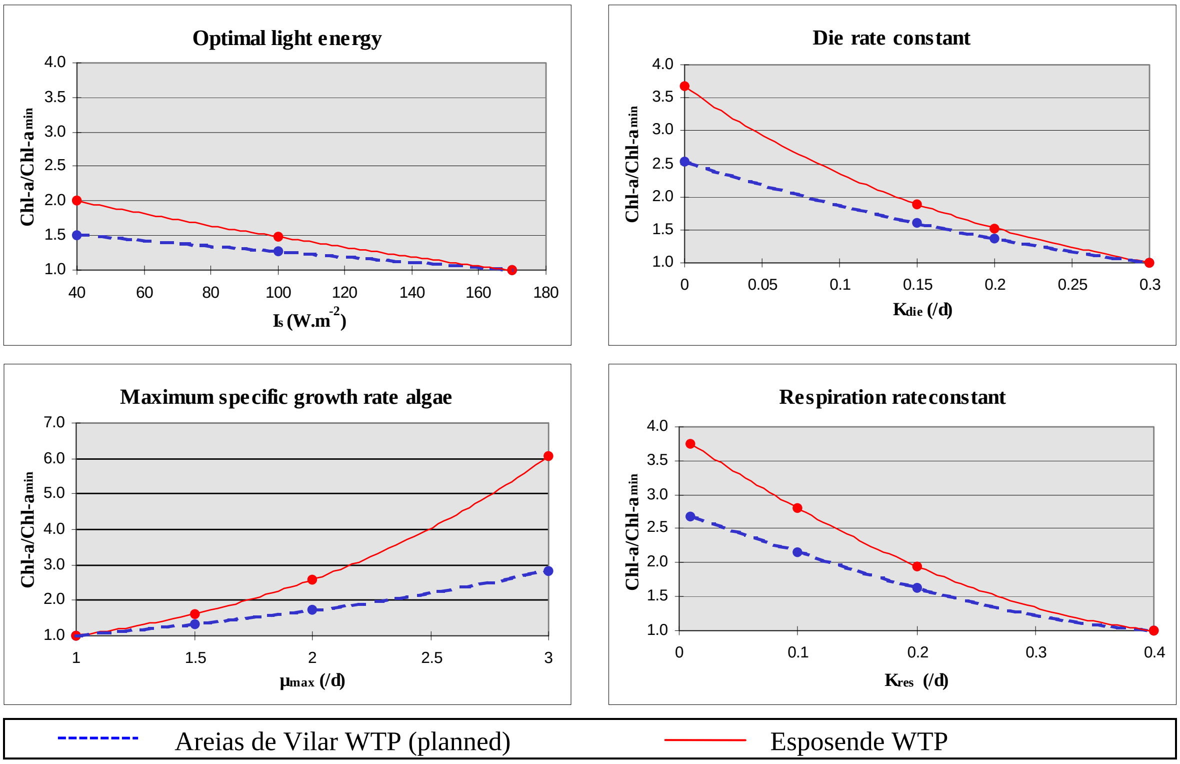


Figure 5. Model parameters sensitivity analysis.

RESULTS AND DISCUSSION

Simulated Scenarios

After model calibration, various receiving waters alternative conditions were considered. The scenarios worked out are summarised in Table 3, where variation of flow discharged at Ponte do Porto and algae growth limitation factors (light energy, water temperature) are considered. Adopted mean daily light energy values – 150 and 300 $W.m^{-2}$ – represent typical frequent and exceptional summer situations, respectively. For water temperature, two values were considered: 15 ºC and 20 ºC, corresponding to mean and maximum mean of observed values, respectively.

Table 3. Simulated scenarios

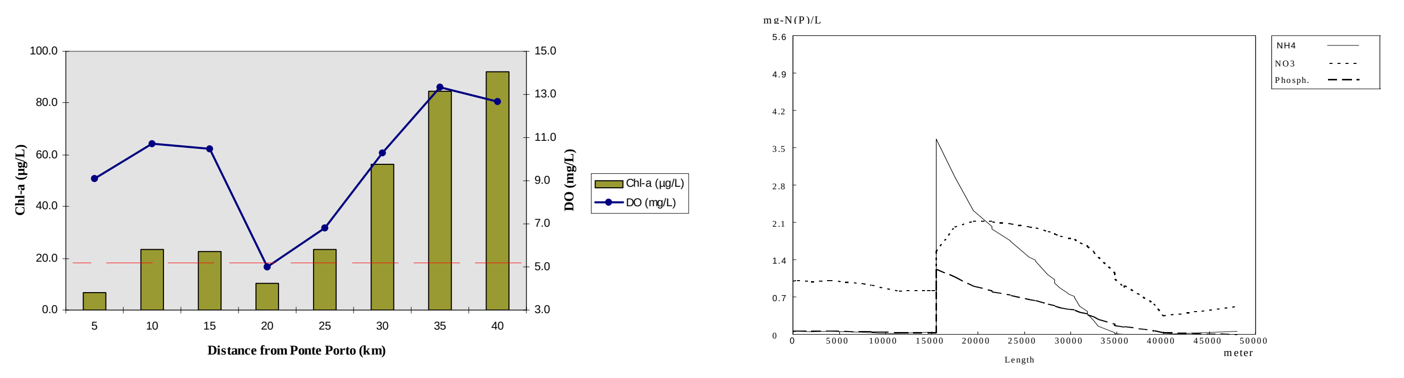
Light Energy	Water Temperature	Ponte do Porto discharges [m^3/s]		
($W.m^{-2}$)	(ºC)	8	16	45
150	15	S1	S5	S9
	20	S2	S6	S10
300	15	S3	S7	S11
	20	S4	S8	S12

These scenarios represent the most relevant situations for evaluation of the river water trophic conditions, considering algal and nutrients concentration trends and DO profiles in the river reaches. The impact of Caniçada dam discharge flow can be evaluated in frequent (S1, S5, S9) and exceptional (S4, S8, S12) light energy and water temperature conditions. Comparison of scenarios S1-S3, S5-S7, S9-S11, allows the evaluation of the light energy effect in the river system for typical values of discharged flows and water temperature. The water temperature effect under extreme light energy conditions for different flows can be analysed by means of scenarios S3-S4, S7-S8, S11-S12. For this short term analysis, different maintenance time periods (MTP) – 5, 10, 15, 20 days – were considered in order to evaluate the algal growth dynamics.

Chlorophyll-a concentration

Model results for chlorophyll-a give frequent concentration values above 10 µg Chl-a/L, which is the reference value for lake eutrophication condition (USEPA,1983), meaning high probability of eutrophication vulnerability since DO concentration is significantly affected by the water trophic state. At Areias de Vilar WTP, lower concentration values are predicted (due to nitrification of organic matter discharged by Braga WWTP). This occurrence can have negative impacts on water quality of storage reservoirs to be built at the inlet of the planned WTP. Results for exceptional events with ten days time period, and for frequent dry-weather situations with twenty days maintenance time period are presented in Fig. 6.

Results - Scenario S4



Results - Scenario S6

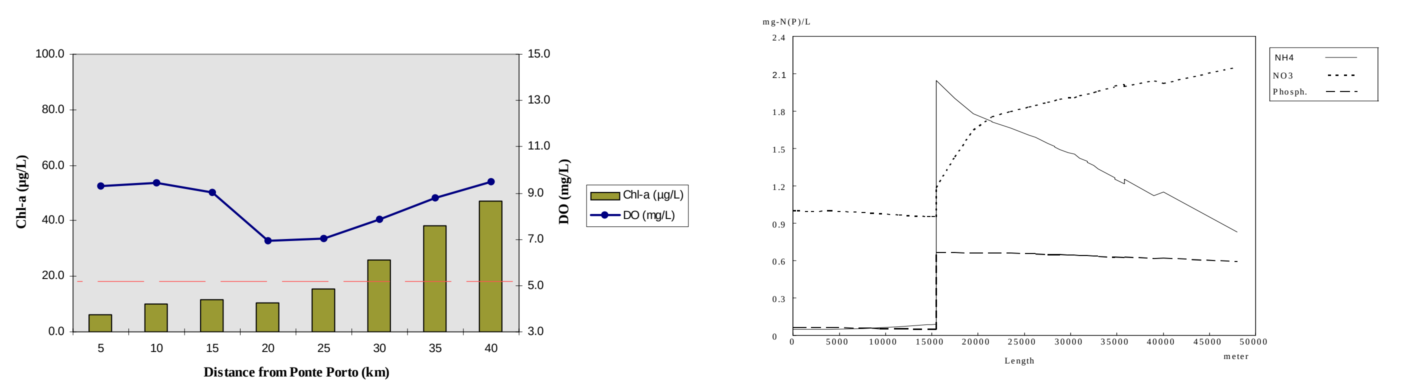


Figure 6. Chlorophyll-a and nutrients concentrations for exceptional and frequent dry-weather conditions.

For river flows higher than 16 $m^3.s^{-1}$, the nutrients availability remains downstream Braga WWTP. Maximal Chl-a concentration occurs upstream Areias de Vilar WTP when Braga WWTP nutrients discharge are negligible.

Detailed results analysis at Areias de Vilar WTP has been done. Fig. 7 shows Chl-a and DO concentration values for all of the scenarios simulated. Chl-a concentration minimum values occur at planned WTP location, except for river flows higher than 45 $m^3.s^{-1}$. River flow variation has a significant influence on the water trophic state only for extreme light energy and temperature conditions. Temperature elevation is a major factor on algal growth for river flows lower than 16 $m^3.s^{-1}$, and the influence of light energy variation appears to be independent of river flow. Eutrophication critical situations, illustrated by low DO concentration, can be anticipated in case of Braga WWTP failure associated with flows below 8 $m^3.s^{-1}$ (e.g. weekend operational regime or work break for maintenance purposes at Caniçada dam).

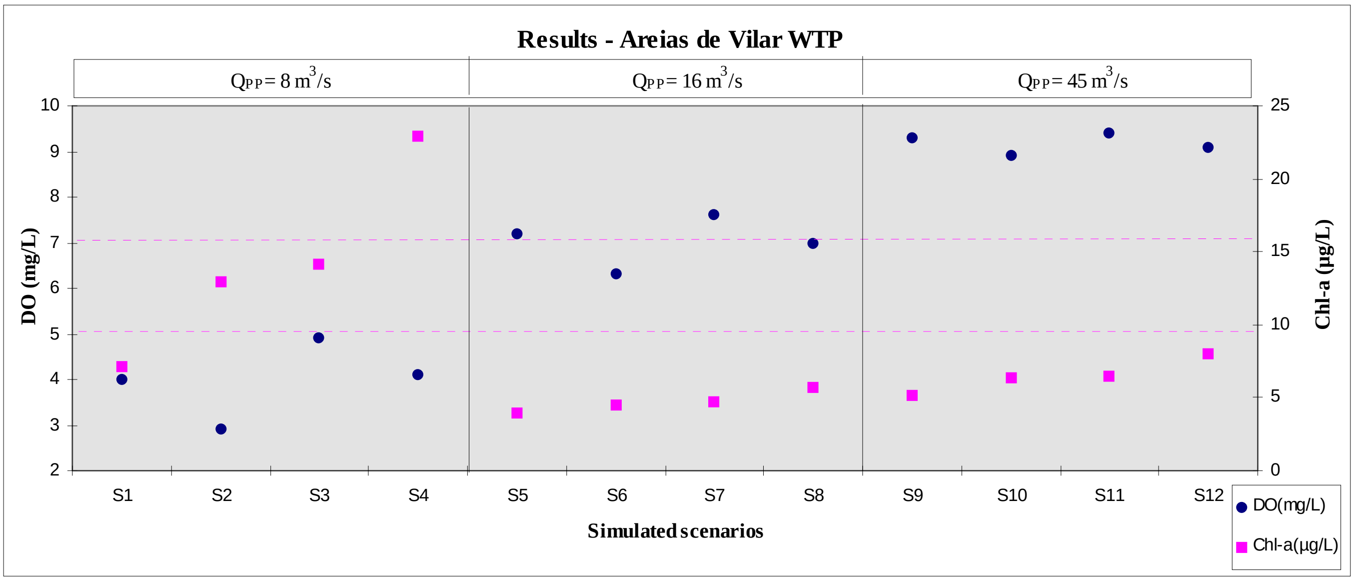


Figure 7. Global results for Areias de Vilar WTP location.

Algal Growth Dynamics

Short term analysis results for algae dynamics was worked out. Fig 8 shows chlorophyll-a spatial distribution for three different MTP (5, 10, 20 days) under frequent dry-weather conditions (scenario S6).

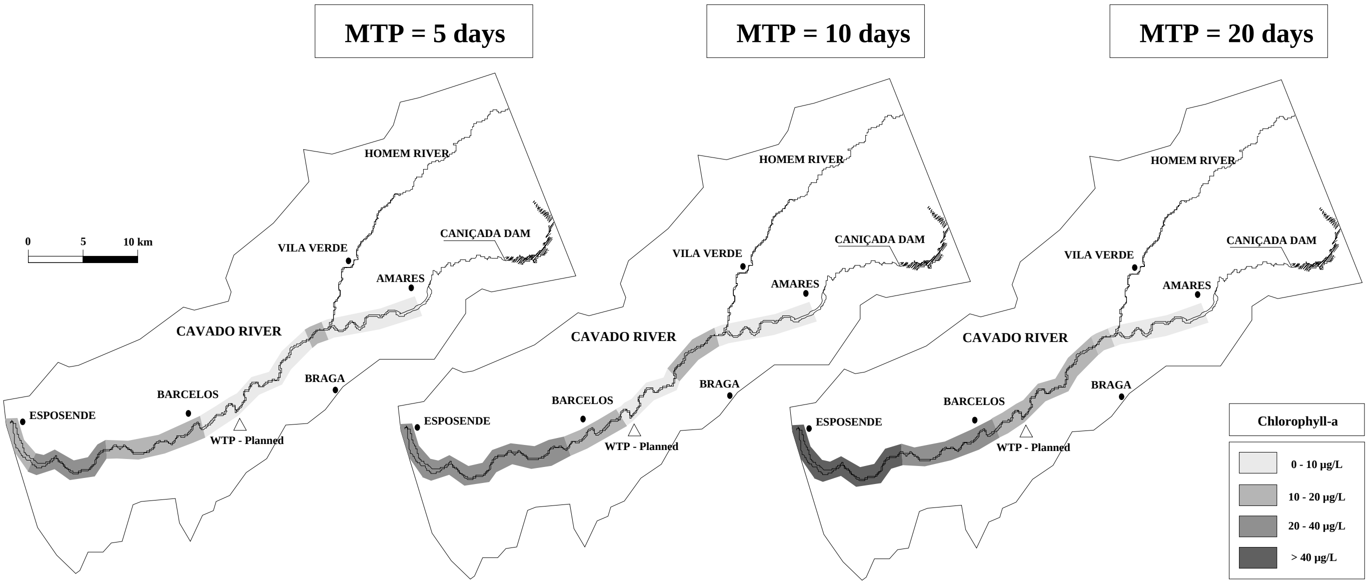


Figure 8. Algal growth dynamics for different time periods.

MTP have determinant influence on Chl-a concentration profile. For MTP longer than 20 days (in case of work breaks for maintenance purposes) eutrophication critical situations can happen in river reaches downstream River Homem confluence.

CONCLUSIONS

From eutrophication vulnerability analysis in river water, algal growth conditions at planned water abstraction point (Areias de Vilar) can be anticipated. Actual concentrations strongly depends on water temperature, light energy and nutrients (N, P). Braga WWTP failure seems to be the major factor for river water eutrophication, even when other nutrient sources are considered.

This evidence suggests a cost-benefit analysis for alternative WTP abstraction point in a location upstream Braga WWTP effluent discharge. In fact, public health reasons (avoidance of pre-chlorination, and toxic compounds control difficulties) as well as technical-economical reasons (treatment process scheme simplification, and lower costs for alarm system, investment and operation costs) must be taken into account in order to define an integrated water management policy in the river basin.

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