UNIVERSIDADE TÉCNICA DE LISBOA
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INTEGRATED WATERSHED MODELING

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Dissertação para obtenção do grau de Mestre em
Ecologia, Gestão e Modelação dos Recursos Marinhos

Documento provisório
Janeiro de 2006

Resumo:

Dois modelos de bacias foram aplicados à bacia de hidrográfica da albufeira de Montargil de forma a avaliar a quantidade e qualidade associada ao escoamento nesta bacia. Foi utilizada a metodologia aconselhada pela OSPAR para avaliar as fontes de poluição difusa e pontual na bacia.

Esta informação foi posteriormente utilizada para forçar o modelo MOHID a simular a albufeira, recorrendo às rotinas de qualidade implementadas no modelo CE-QUAL-W2 permite inferir sobre o grau de Eutrofização da albufeira e avaliar os impactes das diferentes cargas estimadas.

Palavras chave:

SWAT; CE-QUAL-W2; MOHID; Eutofização ; Modelação; Bacias hidrográficas

Abstract:

Two watershed models were applied to the Montargil reservoir basin. This modeling effort along with the methodology proposed by the OSPAR guidelines for diffuse pollution was used to estimate riverine loads to the reservoir.

This information was used as a boundary condition for the MOHID model to simulate the reservoir, using the same water quality routines as CE-QUAL-W2. This allows the author to conclude over the degree of eutrophication in the reservoir and the impact of each load source.

Keywords:

SWAT; CE-QUAL-W2; MOHID; Eutrophication ; Modeling; Watersheds

Agradecimentos:

Este trabalho não teria sido possível sem o contributo de várias pessoas as quais não posso deixar de agradecer:

Aos Mestres Pedro Chambel e Frank Braunschweig pela companhia na luta de desbravar uma nova frente de investigação na Maretec.

Ao professor doutor Ramiro Neves pela orientação da minha tese e por conseguir suportar um grupo da dimensão da Maretec.

Aos elementos da Maretec pelo bom ambiente de trabalho.

A minha mãe, pai e irmão por me terem orientado para este percurso.

A minha melhor amiga e companheira, a pessoa mais corajosa que conheço.

A todos obrigado

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1 Introduction

Integrated watershed modeling is a somewhat tricky concept. The definition is wide enough to embrace several subjects that are study areas by themselves, but sheds no light over which methods are used and what sort of "integrated" modeling is performed.

The initial idea was the application of a numerical model that would model both processes that occur in the watershed and on reservoir. Watershed models and dedicated reservoir models would be coupled and applied over a study site with eutrophication problems that was monitored during 3 years.

Historically, watershed and reservoir/estuaries models have followed different development paths.

Watershed models must characterize processes (streams, overland flow, vadoze zone, saturated zone) that are very difficult to describe mathematically, due to the large heterogeneity of the subsoil and landscape. The fact that for overland flow, small water columns must be modeled, and in the subsoil two or three phase mediums should be described causes even more difficulties.

This created a situation where empirical or simplified methods are used to describe most of the physical processes that occur in a watershed. The use of hydrologic response units and distributed models is a common approach. As a consequence of these simplifications, most watershed models still haven't gained the confidence of part of the modeling and engineering community more accustomed to the physical approach of hydrodynamic models.

However, the integration of these modeling tools is a pressing issue. Pressure from water authorities for inland waters regarding trophic levels is focused on Reservoirs and lakes.

A reservoir by it self represents a large investment in construction and maintenance with the goal of providing water with sufficient quality. Water quality variations are easily converted to an economical gain or loss depending on how it will affect water usages.

On the other side rivers act as a transport mean. The larger velocities and seasonal variability makes the exploitation of these resources difficult. Thus the large number of reservoirs built in Portugal to explore these natural resources. It was recognized early on that problems associated with the trophic level in reservoirs, estuaries and lakes were connected with events that occur upstream.

To correctly model inland water bodies and provide useful information for water authorities and managers, nutrient inputs are a key concept.

The production of nutrients and they're transport by overland and subsurface flow to streams occurs naturally in all watersheds. Human activities may result in an increased load of these compounds, originating from point sources such as wastewater treatment plans or diffuse sources like farming. While point sources are relatively easy to estimate, diffuse sources are almost indistinguishable from the natural production and exportation of nutrients.

This makes the usage of modeling tools for watersheds a relevant issue. These tools allow users to evaluate management options according to the expected weight of each nutrient source. The impacts of the nutrient loads can be understood by the usage of a dedicated reservoir model. As so the integration or coupling of both sorts of models is a relevant subject.

Several tools were used in this study to achieve the proposed goal. For watershed modeling the SWAT model was used along with the recently developed MOHID LAND (whose development the author is a proud contributor). For the reservoir CEQUAL-W2 and MOHID WATER were used. MOHID Water includes the same water quality processes described by CEQUAL. This allows us to evaluate the need of using a complete three-dimensional model for reservoir modeling as opposed to a laterally averaged model.

A monitoring program included in the ICReW (improving costal and recreational waters) project was carried out to obtain field data. This along with data available from the INAG national database for water resources was used as calibration and comparison input.

2 Study Site Characterization

Portugal is characterized by plain areas in the South and a mountain landscape in the northern part of the country. The south, especially the Alentejo region where the study site is located, has a typical Ibero-Mediterrenean climate with dry springs and summers. The north has a more humid climate with almost the double of the annual precipitation of the southern part.

To manage this uneven water distribution, several reservoirs were constructed during the last century, most of them between 1950 and 1960.

The main purpose of most of the reservoirs in the south is irrigation while the reservoirs in the north are more directed on power production and drinking water supply. Agriculture on most of the Alentejo region depends heavily on the storage of winter precipitation for use during the growing season.

The Sôr river watershed was selected as a study site. The main reservoir for this watershed is the Montargil reservoir.

This watershed is located on the North part of Alentejo on the Sôr river basin, Figure 2-1 . This catchment is located close to the geographic center of Portugal and it is part of Tejo Hydrographic basin. Downstream from the reservoir the Sôr river joins with the Raia river becoming the Sorraia. This river discharges at the Tejo stream estuary. Montargil reservoir is one of the largest Portuguese reservoirs on a dry area.

The reservoir is Part of the Vale do Sorraia watering system, composed by three independent reservoirs, Magos, Montargil, and Maranhão. The system was created between 1951 and 1959 and benefits a total of 16 351 acres of agricultural land in six different councils. Montargil reservoir is the second largest reservoir in this group after Maranhão. The watering system is controlled by the "Associação de Regantes e Beneficiários do Vale do Sorraia", since 1970[1].

Over the years the use of the reservoir for recreational purposes has increased, benefiting from short distances to major urban habitation areas (about 100km to Lisbon) and warm water temperatures during the bathing season.

However, bathing water quality issues have been raised as some sites in the reservoir have failed do comply with the 76/160/CEE directive due to high bacterial concentrations. The reservoir also has a history of cyanobacteria blooms.

[1] http://www.idrha.min-agricultura.pt/a_hidroagricolas/exploracao/ahsorraia.htm#voltaq1

Reports of cyanobacteria blooms exist since 1995, with a highlight for 1996 as the worst year with several blooms of toxic species such as, *A.flos-aquae*, *A.gracile*, *Anabaena spiroides*, *M.aeruginosa* and *A.flos–aquae* (Pereira et al. 2000).

The association between agricultural activities, point sources and nutrient enrichment of the reservoir is an open subject for this area. As is the relationship between nutrient enrichment and cyanobacteria domination over certain periods of time.

These relationships are fundamental for both policies of reservoir management and bathing water usage, under the increasing bathing water demand placed upon this reservoir.

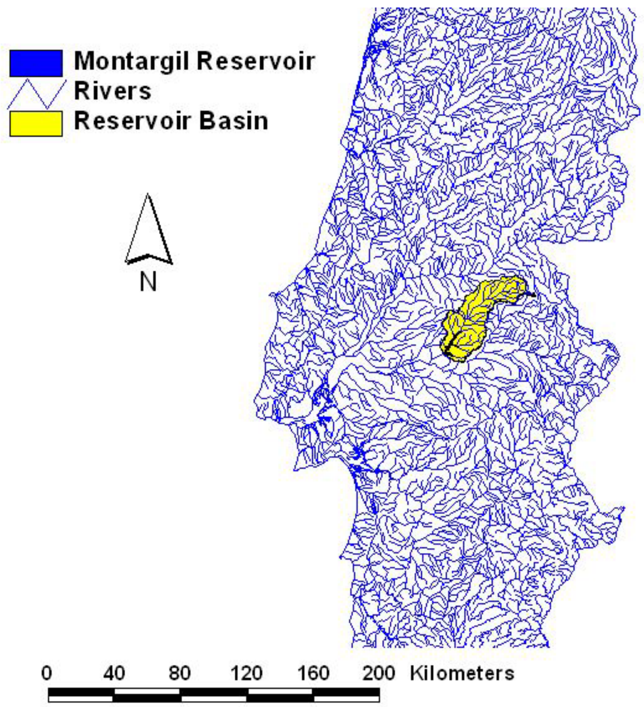

Figure 2-1 - Watershed and Reservoir Location

The delineation of the watershed for the reservoir is the final definition of our study area. MOHID basin delineator was used to accomplish this.

This tool can be used from the MOHID GIS system developed within Maretec (Braunschweig F. et al. 2005). The delineation is accomplished by an algorithm similar to TOPAZ (Srivastava 200). All algorithms of this sort require altimetric data, usually under the form of a digital terrain model (DEM), where data is available in a grid of values.

In this case this data was obtained from NASA "Shuttle Radar Topographic Mission"[2]. Since this data is encoded as binary in Big Indian format, a small toll was developed by the author to port it to MOHID's ASCII grid format.

The data set used was SRTM-3, which has 3 arc-seconds sample spacing for individual data points. This corresponds to a planar resolution of about 90 meters in the equator (around 70 [m] in the study area). Elevation intervals are of 1 meter.

A regular grid of 100X100[m] cells was produced using these topographic values. Based on that grid Montargil reservoir catchment was delineated (Figure 2-2Figure 2-2).

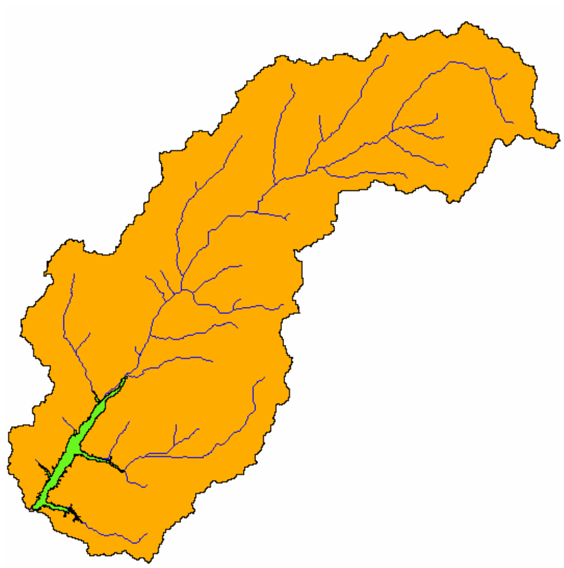

Figure 2-2- Montargil Reservoir Catchment delineation and derived drainage network

This approach generated a watershed with 1180[km2].

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[2] http://www2.jpl.nasa.gov/srtm/cbanddataproducts.html

2.1. Population

Population census is made based in Nomenclature of Territorial Units for Statistics (NUTS). Population data is only available at NUTS IV level (INE, 2001).

NUTS IV level name was more recently changed to Local Administrative Units (LAU), level 2 (LAU II). We will use this new nomenclature.

The geometrical description of all LAU were obtained from the digital edition of "Atlas do Ambiente[3]".

Figure 2-3 shows spatial LAU II distribution in the basin. Some of the administrative units shown are completely inside Montargil Reservoir Catchment while others are divided with other basins.

Figure 2-3- Spatial LAU II distribution in Montargil Reservoir Catchment

The total area and percentage of each LAU II within the defined watershed are described in Table 1. All the administrative units that had less than 1% of their total area inside the basin were disregarded.

3 http://www.iambiente.pt/atlas/est/index.jsp

Table 1 – Fraction of LAU II inside Montargil Reservoir Catchment

LAU II	Area [km^2]	Fraction of LAU II inside catchment
Ponte de Sôr	166	99%
Montargil	160	54%
Aldeia Velha	109	86%
Tramaga	97	99%
Comenda	91	100%
Galveias	80	100%
Vale de Acor	61	90%
Monte da Pedra	59	97%
Margem	58	100%
Longomel	47	100%
Gafete	46	100%
Valongo	35	21%
Amieira do Tejo	26	13%
Alpalhao	24	72%
Tolosa	24	100%
Avis	16	4%
Espirito Santo	15	8%
Arez	14	27%
Vale do Peso	14	10%
Maranhao	12	16%
Gaviao	7	4%
Foros de Arrao	6	7%
Sao Joao Baptista	1	2%

The last available population census dates back to 2001 (INE, 2001). Figure 2-4 shows population distribution of the main LAU II units in the Montargil Reservoir Catchment.

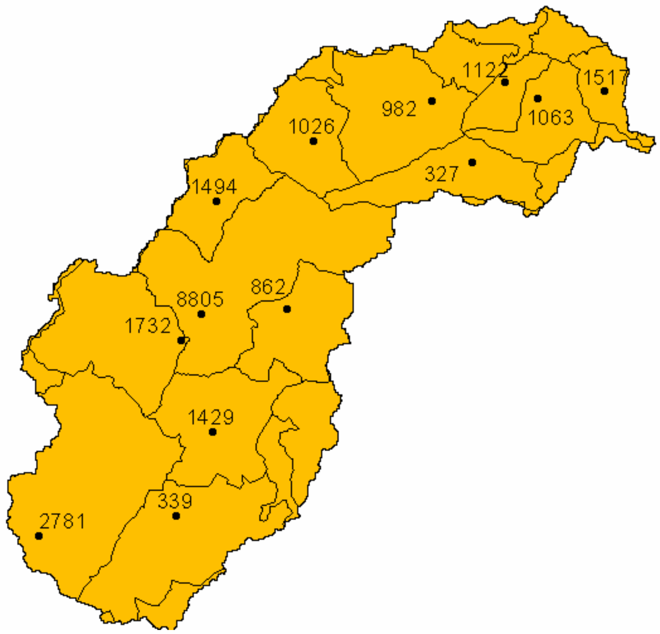

Figure 2-4- Population Distribution on Montargil Reservoir Catchment according with national census of 2001 (INE, 2001)

The population within the watershed was estimated multiplying the calculated area of each LAU II inside the watershed by the population of each LAU II (Table 2). This calculation considers that the population is uniformly distributed in each administrative unit. This approximation results in a total of 22190 inhabitants for the whole watershed.

Ponte de Sôr holds 39% of the catchment population in only 14% of the total area. This was expected, Ponte de Sôr is the larges urban agglomeration of the watershed.

Table 2 – Population per LAU II and population inside Montargil Reservoir Catchment

LAU II	Population for each LAU II	Fraction of LAU II	Population for each LAU II x Fraction of LAU II
Ponte de Sor	8805	99%	8717
Tramaga	1732	99%	1715
Montargil	2781	54%	1502
Longomel	1494	100%	1494
Galveias	1429	100%	1429
Tolosa	1122	100%	1122
Alpalhão	1517	72%	1092
Gáfete	1063	100%	1063
Margem	1026	100%	1026
Comenda	982	100%	982

Vale de Açor	862	90%	776
Monte da Pedra	327	97%	317
Aldeia Velha	339	86%	292
Espírito Santo	2057	8%	165
Arez	362	27%	98
Avis	1950	4%	78
Gavião	1814	4%	73
Foros de Arrão	1037	7%	73
Valongo	321	21%	67
Amieira do Tejo	309	13%	40
Vale do Peso	344	10%	34
São João Baptista	1034	2%	21
Maranhão	98	16%	16
Total			22190

Another source for population data was supplied by CCDR-Alentejo. When updating the point source inventory, this institute has collected data for the location of urban agglomerates. This data Reports back to 1991.

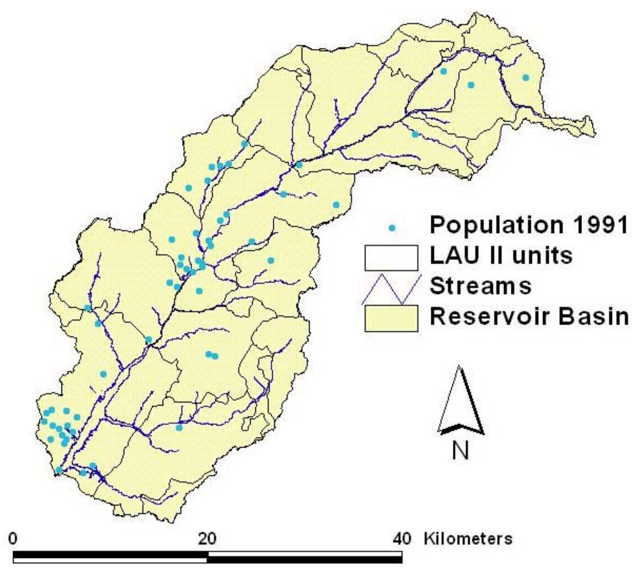

Figure 2-5 - Urban Agglomerates and LAU II units

This distribution points the exact location of the main urban agglomerates in the watershed with a total of 20391. No agglomerates are represented at seven LAUII units. Since this data is older and it isn't significantly different from what was calculated with the previous method, data from the 2001 census will be used.

2.2. Urban Point Sources

Has seen in the previous chapter census data from 2001 shows that a total of 22 190 people live inside the Watershed. According to the distribution on Figure 2-6. Of this 77% of population (15 801) is in the Sôr River area that drains to Montargil. The remaining population is distributed along the remaining smaller streams.

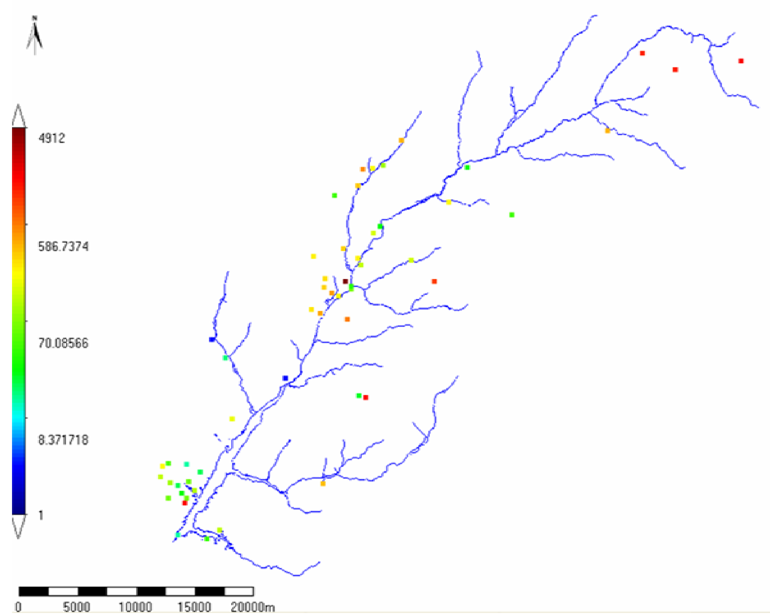

Figure 2-6- Population Distribution on Sôr Catchment (source: CCDR)

Urban point sources associated with wastewater treatment plants drain a total of 17 000 equivalent inhabitants. Point sources without any treatment are responsible for 3 600 equivalent inhabitants, making a total of 20 946 inhabitants for the identified point sources.

Only one point source of relevant size is associated with an Industrial area, but the associated equivalent population is unknown.

Looking at the distribution presented in Figure 2-6 three main groups seam to be present. The first group is located very close to the reservoir and is located around Montargil Figure 2-7 .

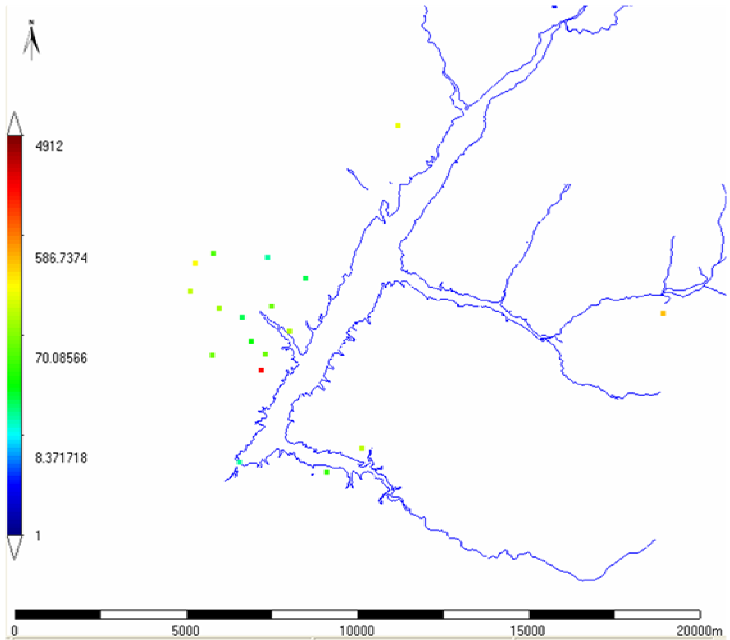

Figure 2-7 – Population Distribution near Montargil (source: CCDR)

The estimated total population is around 2370 inhabitants, with Montargil alone holding 1500 inhabitants. The wastewater treatment plant associated with this group is located nearby and is dimensioned for 1464 equivalent inhabitants.

The second group is located around Ponte Sôr with about 10 000 inhabitants. Ponte Sôr is the largest city in the watershed with 5 000 habitants Figure 2-8.

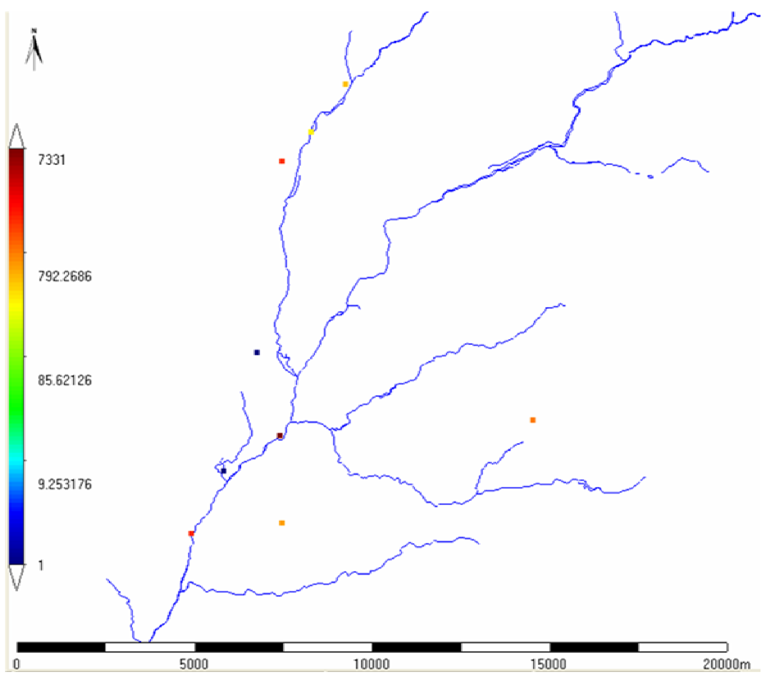

Figure 2-8- Ponte de Sôr wastewater treatment plants (source: CCDR)

Five wastewater treatment plants are located nearby with a total of 9 000 equivalent habitants. Only one discharge without treatment was identified for a population of 500 equivalent habitants. The largest wastewater treatment plant is Located at Ponte Sôr and holds up to 7 000 users. The associated wastewater treatment plant is currently under renewal. So the associated discharge is currently unknown.

Figure 2-9 - Ponte de Sôr wastewater treatment plant

Considering "Ponte de Sôr" the main discharge, the distance to the reservoir is about eight kilometers, fifteen to the first bathing area location.

The last group is located at the top of the basin and is characterized by less density than the remaining groups and a total population of about 4 000, divided by four wastewater treatment plants, three of them holding over 1000 habitants each (Figure 2-10).

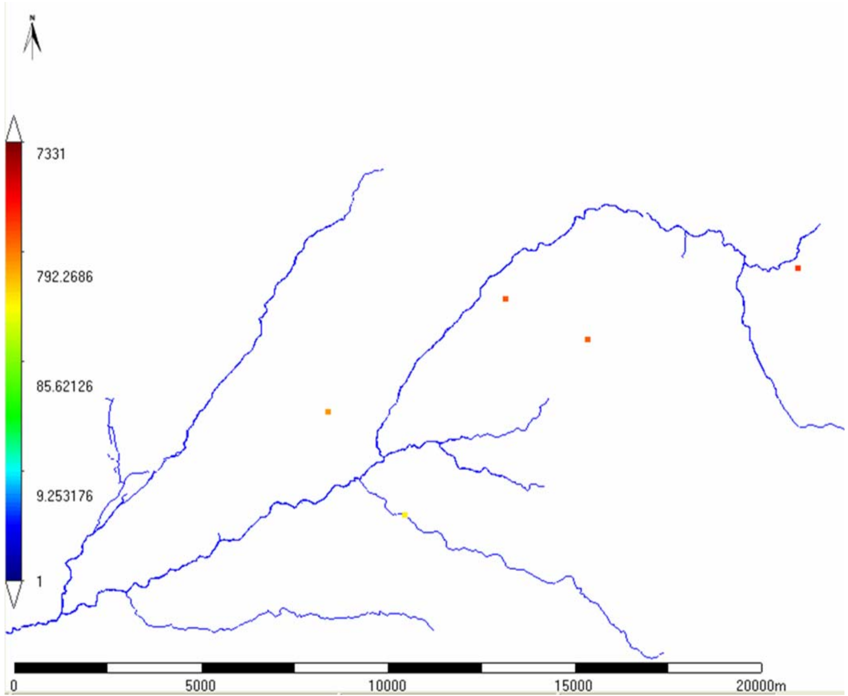

Figure 2-10- Wastewater treatment plants in top of basin (source: CCDR)

In conclusion most of the sewage from urban point sources is currently under primary treatment, some with secondary treatment.

2.3. Non Point Sources

Point sources originate pollutant loads discharged at a specific location from pipes, outfalls, and conveyance channels from either municipal wastewater treatment plants or industrial waste treatment facilities. Point sources can also include pollutant loads contributed by tributaries to the main receiving water stream or river

Pollution from multiple sources over a relatively large is considered to originate from Non point sources.

The relative importance of different nutrient sources varies spatially and temporally. Bibliography claims that for most U.S rivers, nonpoint sources are responsible for most N and P delivery. Allan et al (2002) cites a studied of 86 rivers by Newman (1995), over half of the rivers studied received > 90% of their N, and one-third of the rivers studied received > 90% of their P, from nonpoint sources. However, the same study by Newman (1995) states that point sources of N and P can contribute over half of the N and P load to urban river reaches.

Nonpoint sources can be divided into source activities related to either land or water use. This includes failing septic tanks, improper animal-keeping practices, forest practices, and urban and rural runoff (EPA, 1999).

Goolsby et al (1999) present a work to understand what are the loads (flux) of nutrients transported from the Mississippi-Atchafalaya River basin and what is the relative importance of specific human activities such as agriculture, point source discharges, and atmospheric deposition in contributing these loads to the Gulf of Mexico and where do they come from within the basin. For this, data on nitrogen and phosphorus inputs and outputs in agriculture and other were obtained from numerous sources (Table 3).

Table 3 – Source data collected for work on Mississippi-Atchafalaya River basin Goolsby et al (1999)

Group of data	Type of data	Source
Non point	crop production, livestock, and poultry	U.S. Department of Commerce (USDC) Census of Agriculture and the USDA National Agricultural Statistics Service (NASS)
	nitrogen and phosphorus inputs from fertilizer	NASS, the Tennessee Valley Authority, the

		Fertilizer Institute, and published reports
	Nitrogen inputs and outputs from soil mineralization and immobilization, denitrification, and volatilization	soil scientists in the USDA and the academic sector, and from the literature
	Nitrate and ammonium in rainfall	National Atmospheric Deposition Program (NADP).
	Nitrogen in dry deposition	Statistical models from CASTnet (CleanAir Status and Trends network), AIRMoN (Atmospheric Integrated Research Monitoring Network), and NADP programs.
Point	nitrogen and phosphorus from municipal and industrial point sources	U.S. Environmental Protection Agency (EPA)
	Historical data on point source discharges	published reports

Similarly to Goolsby et al (1999) we also pretend to use all data available to calculate inputs and outputs in to Montargil basin. The most widely available data is in the last National agricultural inventory, which dates back to 1999, and goes down to the LAU II level (INE, 1999). Data for fertilizers at the LAU I or II level doesn't seem to exist and the author was unable to find data on atmospheric deposition of N in Portugal.

All this data will be used under the orientation provided by OSPAR guidelines, see 3.3 (Ospar 2000), to obtain loads that will be used has boundary conditions for the reservoir water quality model.

The next chapters describe a quick review of farm animal populations in the watershed and associated nutrient loads.

2.4. Farm Animal population in the watershed

Animal manure can be a significant source of N, P, and other nutrients that are needed for crop growth. If properly utilized manure applications can also add organic matter, improve soil quality, increase water and nutrient holding capacity, and increase resistance to soil compaction.

The nutrients in most animal manure are "recycled", since they originate from feed produced in the basin and given to the animals.

Table 4 – Nº of animal heads in Montargil Reservoir Catchment (INE, 1999)

Animal Species	Number of heads	Percentage of total heads
Bovines	7,157	8%
Swines	10,984	13%
Sheeps	63,509	73%
Goats	4,391	5%
Horses	621	1%
Total	**86,662**	**100 %**
Rabbits	5,683	19%
Poultry	24,307	81%
Total	**29,990**	**100 %**

The nutrient content of manure is highly variable and dependent upon factors such as the type of feed, type and age of livestock, bedding material and storage and handling practices. "Ministério da Agricultura" (1997) presents indicative values of yearly load of N and P for each species. In some cases it also accounts for the animal development stage. These values were taken from Ryser et al (1994).

Table 5 - Per-animal estimates of N and P generation (Ministério da Agricultura, 1997)

Species	Animal description	kg N per animal per year	kg P per animal per year
Bovines	Dairy Cow	105.0	15.3
	Heifer	84.0	12.2
	Calf for fattening 1 year	26.0	3.9

	Calf for fattening 2 year	42.0	6.1
	Calf for fattening 3 year	63.0	9.2
	Calf place fattening	8.0	1.1
	Beef cattle place 125-500 kg	35.0	7.4
Pigs	fattening pig 25 - 100 kg place	15.0	3.1
	Nursing sow place with piglets until 25 kg	35.0	8.7
Poultry	Laying hens place	0.7	0.2
	Pullet place	0.3	0.1
	Broilers place	0.4	0.1
Ovines	Ram place	16.0	2.6
	Sheep place	21.0	3.9
Equine	Horse	22.0	5.2

In a study about source assessment in Albemarle-Pamlico Estuary (North Carolina and Virginia), livestock inputs were determined using county estimates of livestock data combined with per-animal estimates of nutrient generation to calculate total production (EPA, 1999). Using a similar approach, inputs for Montargil Reservoir Catchment were calculated (Table 6).

Table 6 – Calculation of yearly N and P animal production for Montargil Reservoir Catchment, based in Table 5 and Table 4. Per-Human estimates of nutrient generation obtained in Ospar (2000).

Species	N [ton/year	P [ton/year]	N [%]	P [%]
Bovines	406	69	20%	18%
Swine	188	40	9%	10%
Sheep	1,270	235	61%	61%
Goats	89	16	4%	4%
Horses	14	3	1%	1%
Rabbits	2	0	0%	0%
Poultry	13	3	1%	1%
Human	98	20	5%	5%

Total	2,079	388	100%	100%

Total N added to the basin, through animal and man, reaches about 2.000 tones per year. Total P added is about 400 tons per year. Considering the total area of the basin, the input per hectare is 17 kg of N per year and 3.4 kg of P per year. These loads are almost ten times greater than loads calculated from point sources and population equivalents. Even though part of values shown in Table 6 include point sources, the N and P from non point sources seams to be much higher (moreover this values do not include fertilization application which is also a non point source of nutrients in the basin).

Of all the added N and P, sheep account for 61%. Considering that sheep are typically maintained in pastures, this means that 61% of these nutrients are probably scattered around the basin.

Sheep can become even more important considering that Ponte de Sor, Galveias, Montargil, Aldeia Velha and Tramaga are responsible for about 67% of the Sheep in the basin (Table 7). These local administrative units are all around Montargil Reservoir and represent only 45% of basin area.

Table 7 – Distribution of Sheep by LAU II in Montargil Reservoir Catchment

LAU II	Number of Sheep	Percent of total number of Sheep
Ponte de Sor	15896	25%
Galveias	10024	16%
Montargil	8340	13%
Aldeia Velha	4935	8%
Alpalhão	4768	8%
Vale de Açor	4053	6%
Tramaga	3157	5%
Gáfete	2709	4%
Tolosa	1955	3%
Monte da Pedra	1707	3%
Comenda	1257	2%
Valongo	809	1%
Longomel	770	1%
Margem	688	1%
Arez	609	1%
Avis	455	1%
Espírito Santo	394	1%
Foros de Arrão	331	1%
Vale do Peso	280	0%
Amieira do Tejo	236	0%

Gavião	91	0%
São João Baptista	46	0%
Maranhão		0%
Total	63509	100%

Figure 2-11 shows animal distribution close to the main streams that discharge in Montargil reservoir. These values were obtained from National statistics at the level of the smallest administrative region (in Portuguese "Freguesia" and in Eurostat Local Administrative Unit II formerly NUTS level 5).

It was considered that animals and humans are uniformly distributed in each administrative unit. It's possible to associate to each stream contributing to the reservoir, a number of animal heads and population. These numbers give an idea of the loads in each stream area. A part of this load is point source pollution and other is diffuse.

These values must be compared with point sources since some of the animals and individuals could be concentrated in small areas. For example, as shown in Figure 2-7, most of the population of Montargil is concentrated around Coutos. In this case the assumption that humans are uniformly distributed in each administrative unit won't produce good results. In fact considering values from 1991 the population inside area that drains for point designated as Coutos is 612 when estimated value with INE data was 147 (Figure 2-11).

For Sôr River, results are better than for Coutos because of its larger basin. In fact considering INE data about 84% (18 598) of population was concentrated in that stream while for data from 1991obtain by CCDR 77% (15 801) of population was in that area. However these results still show that assuming that population is uniformly distributed in each administrative unit will not produce accurate results. This approximation is more adequate to animal distribution since they are spread over the basin area.

According with numbers in Figure 2-11 about 70% of sheep and bovines are concentrated in Sôr River basin. However, it was estimated that 8% of sheep in the basin are in the area around the reservoir. For the same area it was estimated a value of 6% bovines.

Due to the proximity to reservoir, these animals could have an important negative impact in the reservoir. Because of that this area should be confirmed and included in nutrient and bacteria load calculations.

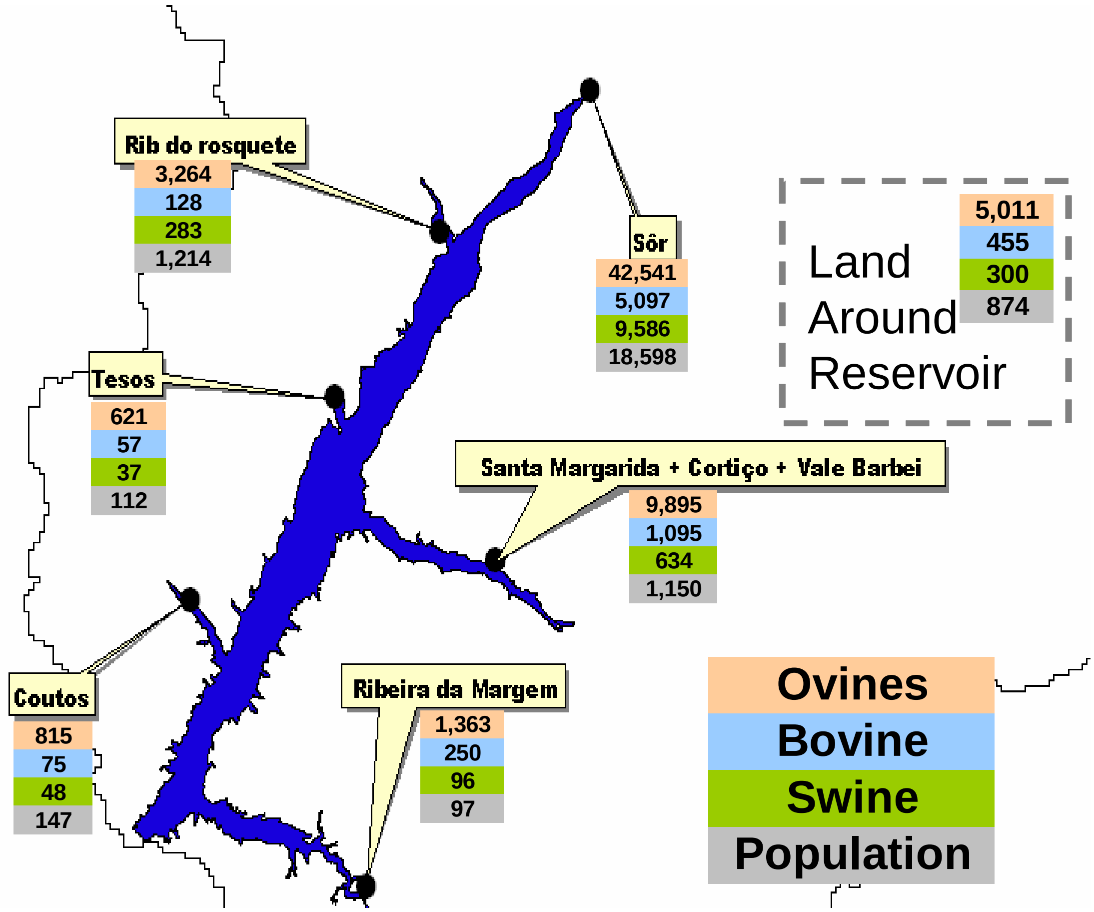

Figure 2-11- Animal and human distribution in area of main streams arriving in Montargil reservoir, assuming that animals and humans are uniformly distributed in each administrative unit (INE, 1999)

3 Watershed modeling

3.1. Introduction

As described previously watershed modeling has to cope with several processes that are difficult to describe mathematically.

In this chapter an initial data analysis is performed on available data for both flow and water quality. Hopefully this will help in the creation of a conceptual model that can act as a guideline for the implementation of numerical models.

For nutrient loads the OSPAR guidelines for diffuse pollution were used as an evaluation tool. These guidelines are the result of a European project named Euroharp <http://euroharp.org>.

This project targeted the implementation of the Water Framework Directive calls for harmonized methodologies/ tools to quantify nutrient losses from diffuse sources. The created methodologies/ tolls were tested in a network of 17 catchments throughout Europe. Unfortunately there were no Portuguese partners in this project.

One of the outputs already available from the project is a list of nine guidelines that were adopted by OSPAR as a way of estimating nutrient loads from watersheds.

The amount of data that is necessary for this sort of modeling was the first difficulty encountered. The available information is scarce and scattered throughout several institutions. A tool was developed by the author that allows the search of the INAG hydraulic resources database using geographic locations. This toll was created using .net C# and the open source database postgreSQL with geographic capabilities enabled through postgis. The fact that a geographic enabled database is used makes the use of spatial SQL possible. This makes the retrieval of spatial data from the database trivial.

3.2. Data Analysis

The first questions that must be answered are related to water flow in Sôr river. We must estimate not only the amount of water that passes through the river must, but how much of it is supplied form surface and subsurface flow.

Water flow in any river is obviously related to rainfall, so besides analyzing river flow some analysis is also performed on relevant atmospheric parameters.

Once the hydrologic analysis is complete, available water quality data is evaluated

3.2.1. Hydrologic / Atmospheric data

Water supplied by precipitation has three available destinations:

- Infiltration
- Evaporation
- Surface flow

Simplistically we will assume that water that evaporated is eliminated from our system. This is a simplification, since in an integrated watershed/ atmospheric model the amount of water that evaporates will affect several atmospheric parameters including rainfall.

Water that infiltrates can either be eliminated from the system by percolation to deep aquifers (it could be retrieved later by irrigation), or it can contribute to the river "base flow".

The most direct pathway for precipitation to contribute to river flow is trough surface runoff.

Both the applied watershed models MOHID LAND and SWAT, rely on the quality of the supplied weather data to produce surface runoff and stream flow.

There are several weather stations close to the watershed.

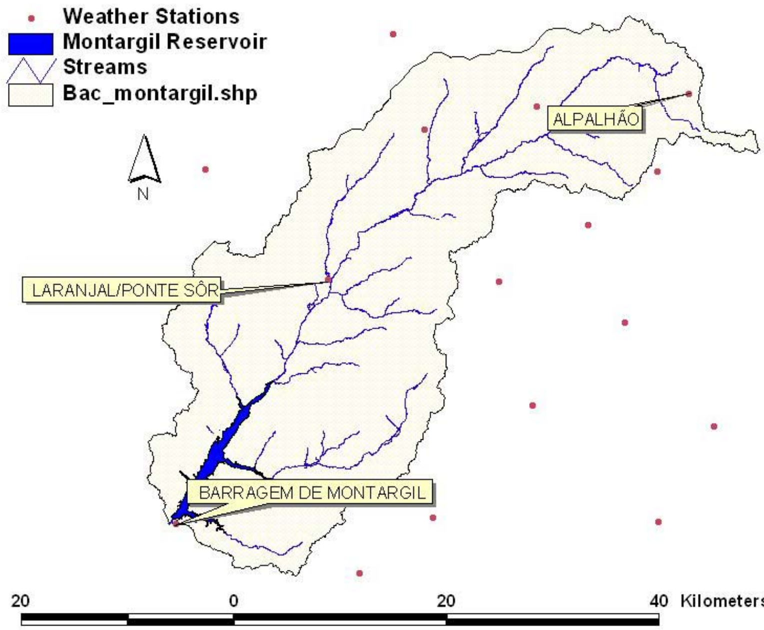

Figure 3-1 Weather stations close to the watershed

Three stations were selected to supply weather data for both models.

- Laranjal
- Alpalhão
- Albufeira de Montargil

The selection criteria included the periods of available data and the availability of daily precipitation data. Hourly precipitations are a requirement of MOHID Land, SWAT method's used to create flow can use daily precipitation.

A calibration period was selected using five hydrologic years from 1985 to 1990, during this period only daily precipitation is available for all three weather stations. A second period was selected with the 2000-2005 period.

For both periods of analysis the average monthly values recorded for all three stations show a high level of conformity Figure 3-2 and Figure 3-3

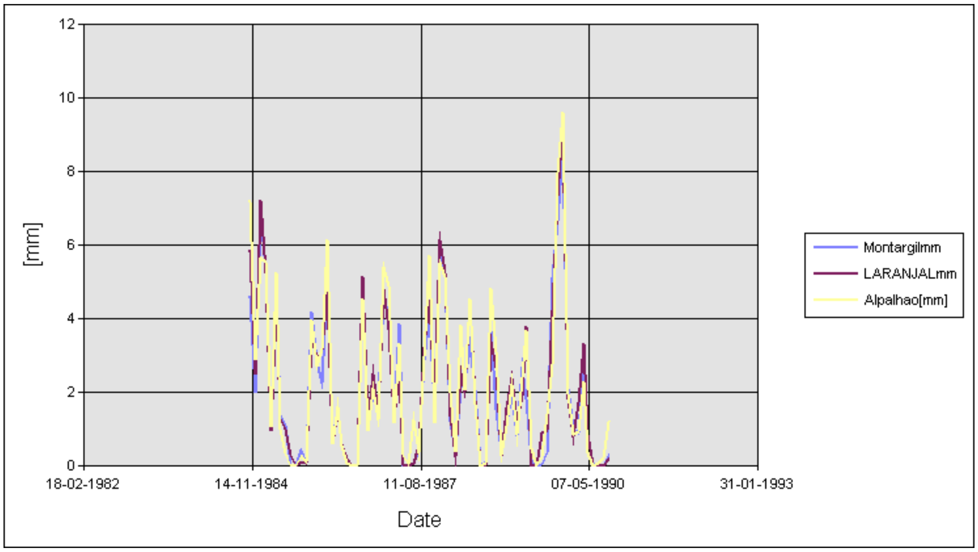

Figure 3-2 - Average monthly precipitation on selected stations

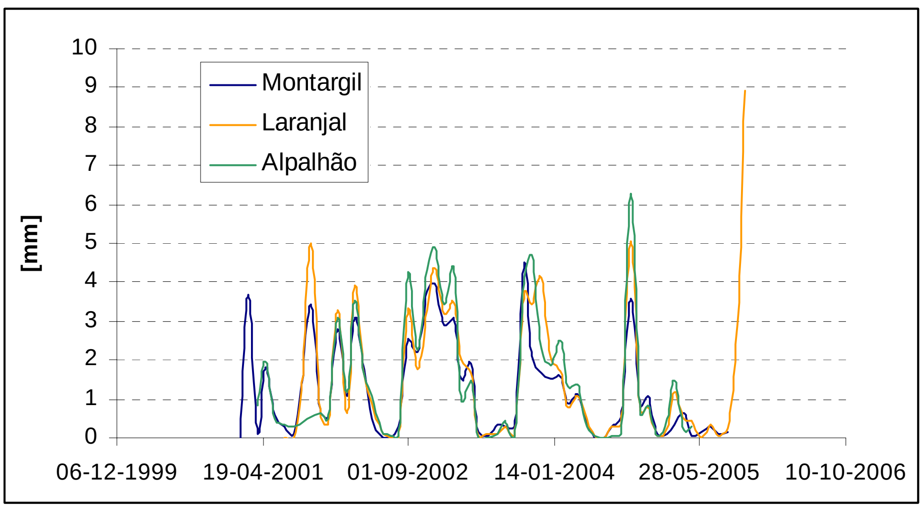

Figure 3-3 - Average monthly precipitation values on selected stations for the second period of analysis

Albufeira de Montargil weather station also has some data for daily temperature. This data was disregarded. All the remaining atmospheric parameters where obtained from climatological time series available for two weather stations operated by IM[4] close to the basin.

Once the models convert precipitation to stream flow, there is only one gage station on the Sôr river that can be used for calibration and comparison. This station is

[4] Instituto de Meteorologia

located at Moinho Novo and started recording the stream level in the hydrologic year of 1982-1983.

Traditional monitoring that consisted of manually recording the river level every day at 9:00 am, was abandoned in September 1990. The station was reactivated in March 2001. with automated sensors that record the stream level at hourly intervals.

The discharge curve isn't available for neither of the periods. However discharge and stream level values are available from 1982 to 1990. A discharge curve can be estimated from this data using a common discharge curve equation (Quintela 1996):

$$Q = a\left(h - h_0\right)^b \tag{1.1}$$

Where $Q\left[m^3/s\right]$ is the discharge a and b are calibration parameters, $h\left[m\right]$ is the stream level and $h_0\left[m\right]$ is the minimum cutoff stream depth. Linearizing the equation using a logarithmic function:

$$\log\left(Q\right) = \log\left(a\right) + b\log\left(h - h_0\right) \tag{1.2}$$

Plotting all recorded values of level and flow for a period from 1985 to 1990 Figure 3-4 is obtained.

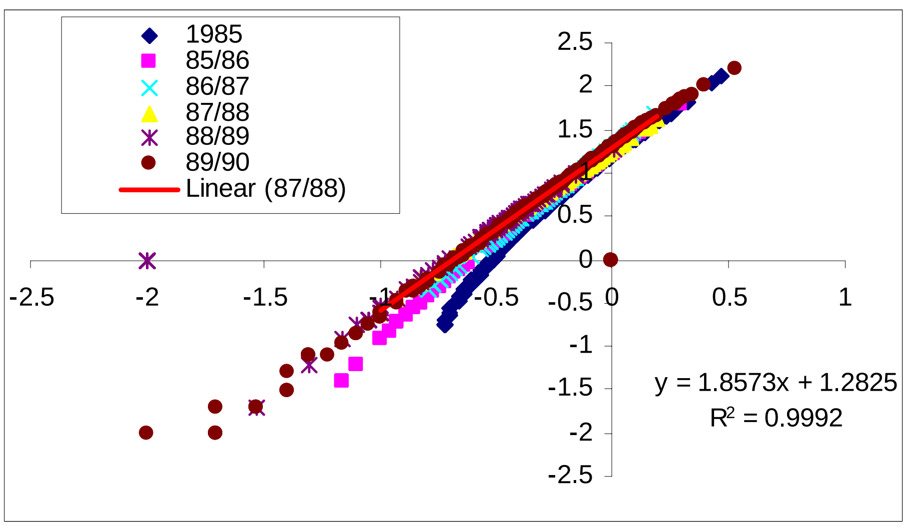

Figure 3-4 Linearized INAG data for Moinho novo station

It is clear from this plot that several discharge curves were used between 1985 and 1990. It is during the low flow conditions that are recorded during the summer season that the bigger differences are registered.

Figure 3-5 Precipitation / Flow relation shows yearly recorded flow against precipitation

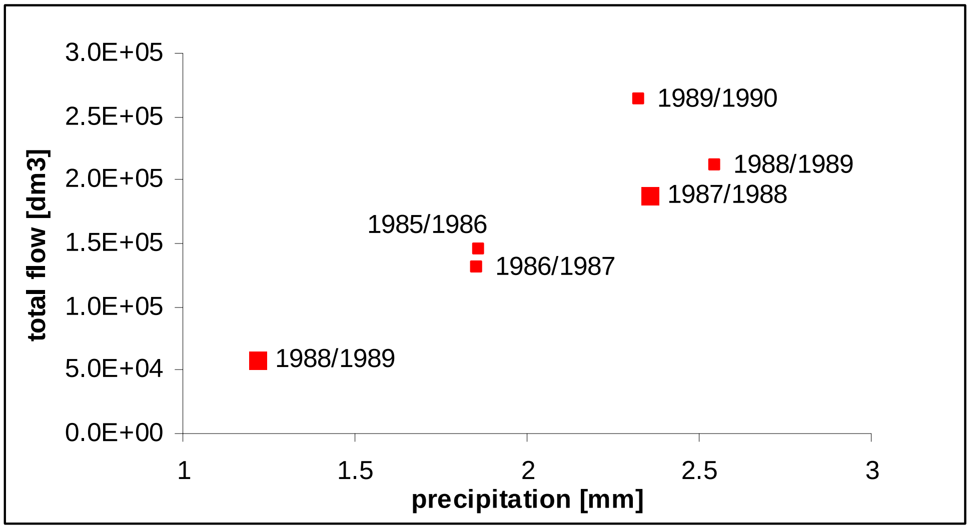

Figure 3-5 Precipitation / Flow relation

The hydrologic year of 1989/ 1990 has higher flow values than 1984/ 1985, even thought precipitation values here higher for the second period. This higher flow value is also inconsistent with the recorded average annual level that was lower in 1984, Table 8.

The explanation for this inconsistency should be related to a change of discharge relation. Figure 3-4 confirms that this hydrologic year has the highest scatter of data in the relation between flow and water level.

Table 8 - Recorded stream level and flows

Year	Average yearly discharge [m3/s]	Average level [m]	Total volume [hm3]
1984/1985	6.69534799	0.672508449	211144.4942
1985/1986	4.602628381	0.57655857	145148.4886
1986/1987	4.153477855	0.541339158	130984.0776
1987/1988	5.953250185	0.606800519	187741.6978
1988/1989	1.855337494	0.378847094	58509.9232
1989/1990	8.347223851	0.592260508	263238.0514

For the second period of analysis there is no discharge relation available. Some attempts to build a discharge relations were carried out during the monitoring campaigns carried under the ICReW project. Unfortunately these attempts were unable to supply enough data to build a reliable relation, due to the large drought period that affected Portugal during 2005.

The installed system that currently monitors the stream level has a cutoff value of $0.23[m]$. This causes the station to record a constant level during periods with lower flows, Figure 3-6.

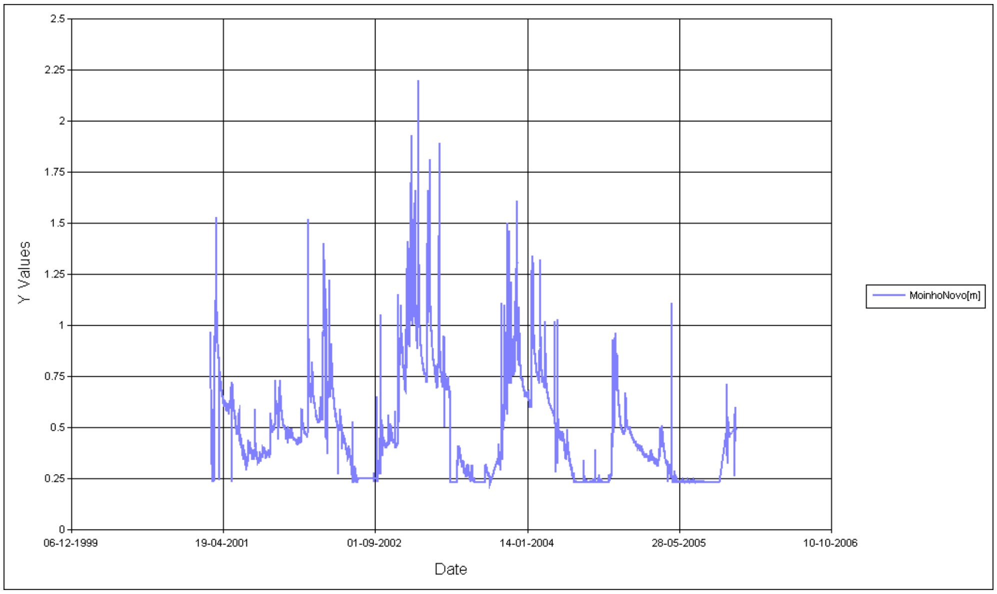

Figure 3-6 - Data from Moinho novo hydrometric station

The yearly average level relates well to available precipitation data.

Table 9 - Moinho novo levels and total precipitation

Year	Montargil[mm]	Laranjal[mm]	Alpalhão[mm]	Average Year Level at Moinho Novo
2001/2002	507.4123752	600.6429466	535.1627842	0.484553
2002/2003	620.8498114	623.4337915	678.9801299	0.590631
2003/2004	447.4558954	553.7606229	572.0905837	0.524734
2004/2005	225.3712981	292.7885619	incomplete	0.344386

3.2.2. Water quality data

INAG's national hydraulic resources database has results of an ongoing water quality monitoring program for the Sôr River. This monitoring program started in November 1999 with monthly sampling at Moinho Novo for the parameters in Table 10 since.

Table 10 – INAG database data

Physical/Chemical Parameters		Biological Parameters
	Orthophosphate	Fecal streptococcus
Total Phosphorous		
pH	Nitrate	Total Coliforms
Suspended Solids	Nitrite	Fecal Coliforms
	Oxidability	Chlorophyll-a
Ammonium		
Dissolved Oxygen	Temperature	
QOD		

There is also an automatic water quality station located at Moinho Novo. This station is also managed by INAG and is active since March 2001. It monitors the parameters described in Table 11

Table 11 - Moinho Novo automatic station data

Parameters	
pH	Dissolved Oxygen
Conductivity	Turbidity

At the beginning of the ICReW project 6 sampling locations, located along the watershed were selected, Figure 3-7.

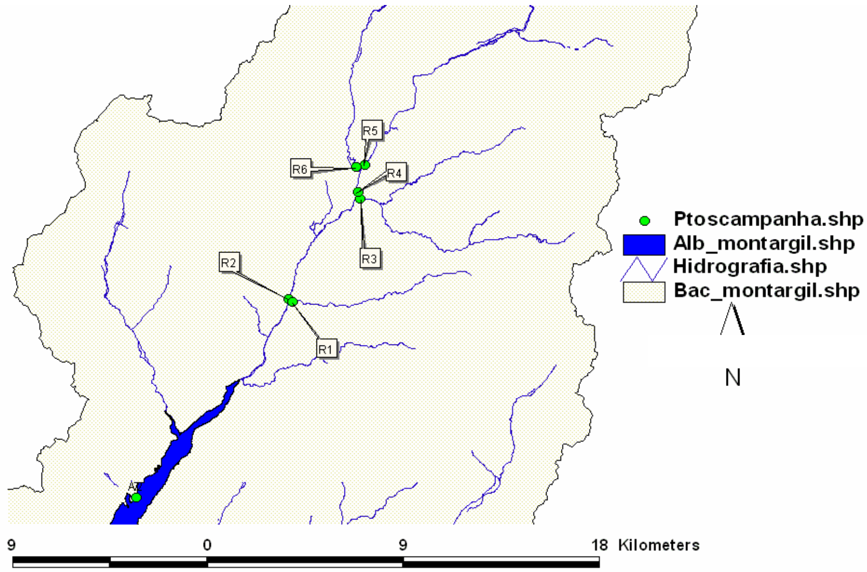

Figure 3-7 - Watershed sampling locations

Point R1 is just a few hundred meters from Moinho Novo. Analysis on point R1 were dropped due to the difficult access to this point.

On the remaining points and with the joint effort of three laboratories (IST, IA and INSA), the parameters in Table 12 were monitored bimonthly from July 2003 to December 2005.

Table 12 – ICReW collected data

Chemical/Physical Parameters		Biological Parameters
Total Nitrogen	Dissolved Oxygen	Chlorophyll-a
Ammonium	Oxidability	Pheopigments
Nitrates	CBO_5	Microcystins
Phosphates	CQO	Coliform Bacteria
Total phosphorous	pH	E. Coli
Total suspended solids	Temperature	
Turbidity		

3.2.2.1. Phosphorous

Data available at the INAG water quality database for "Moinho Novo" has an average concentration of total phosphorous around $0.6\left[mgP/l\right]$, with a maximum value of $3.8\left[mgP/l\right]$.

This doubles what was registered during ICReW campaigns, an average value of about $0.3[mgP/l]$ and $0.7[mgP/l]$ maximum.

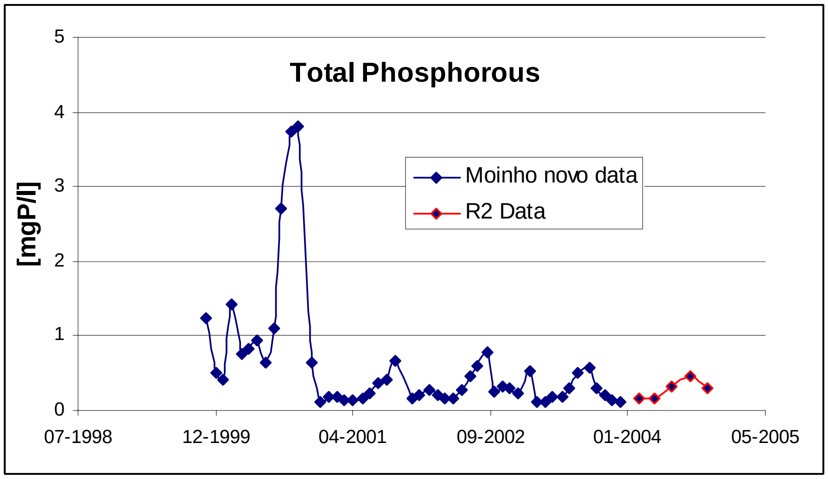

Figure 3-8 - Total phosphorous variations in Moinho Novo station and R2 sampling points

$0.54[mgP/l]$ is the national average for streams, calculated from all values present in INAG database.

Data collected by INAG after 2000 is significantly similar to values recorded during the ICReW monitoring program, Figure 3-8.

The values that caused INAG average to rise were all registered before 2000. If only data collected after this year is considered, the average value drops to the same recorded in ICREW sampling.

The higher concentration values are recorded around August, when precipitation values reach their minimum. Apparently total phosphorous concentrations increase during months with a low flow regime Figure 3-9. This figure was obtained with a moving average with a monthly period for available phosphorous data (200-2004), and historical flow values (1980-1990). This event is also noticed for most streams registered in the INAG database.

One explanation for this event could be the release of phosphorous trapped in the river bed under organic forms. This supply of phosphorous is often referred to as internal pool, and under certain conditions can release mineralized nutrients such as phosphorous to the water column. This combined with a low flow regime would increase the total phosphorous values in the water column due to the increase of orthophosphate (dissolved phosphorous).

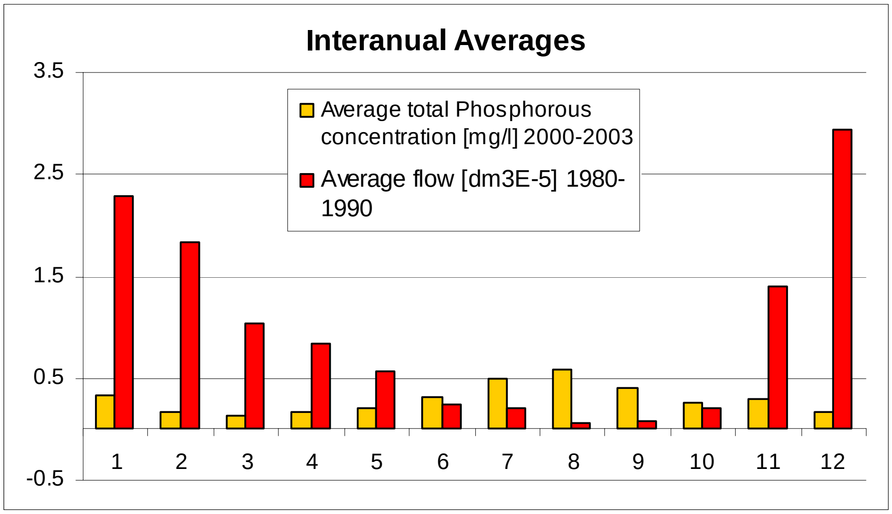

Figure 3-9 - Average Monthly flow at Moinho Novo (data from 1980-1990) and Monthly average phosphorous concentration (2000-2004)

Discharges from point sources are another possible explanation. During summer months phosphorous discharges from point sources remain the same as during winter months. On the other hand loadings from diffuse sources tend to diminish, since no surface runoff is produced due to low precipitations. If less water exists in the river the same discharge from point sources will produce a higher concentration.

This would highlight the importance of point sources has an input of phosphorous to the reservoir during summer months. Most of the phosphorous that could reach the reservoir under these conditions would have a point source.

Bibliography (Turner, R. E. And Rabalais, N. N. (2003)) describes the major source for phosphorus in a river the discharges produced from precipitation. After reaching the soil, par of rainfall is be converted to overland flow, dragging phosphorous or sediments that contain phosphorous in the soil to the nearest stream.

Apparently the described increase of phosphorous concentrations during summer months seams incompatible with what is described in the bibliography. However if total phosphorous mass that passes trough "Moinho Novo" is calculated, using mobile averages with a monthly period of both flow and concentration, Figure 3-10, we can verify that the increase of concentration during summer moths isn't enough to compensate the low flow regime that occurs.

The monthly average loading of total phosphorous that pass trough "Moinho Novo" increase with the flow regime Figure 3-10, pointing out the importance of diffuse pollution in this system.

More phosphorous will reach the reservoir during the winter months. According to this data an average of about $23[t]$ of total phosphorous will reach the reservoir every year.

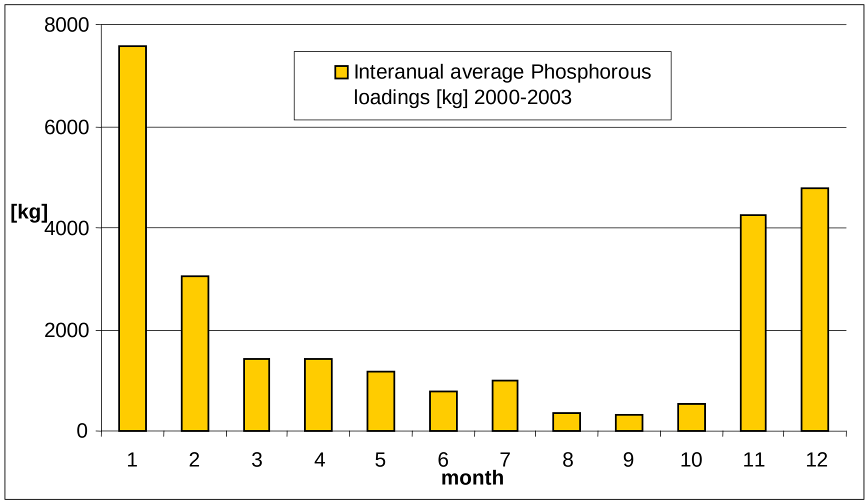

Figure 3-10 – Monthly moving averages for phosphorous mass at Moinho Novo (2000-2004)

Dissolved phosphorous variations at "Moinho Novo" and R2 follow the same tendency as total phosphorous Figure 3-11 and Figure 3-9. Months with low precipitations and consequently low flow experience the higher concentrations Figure 3-11.

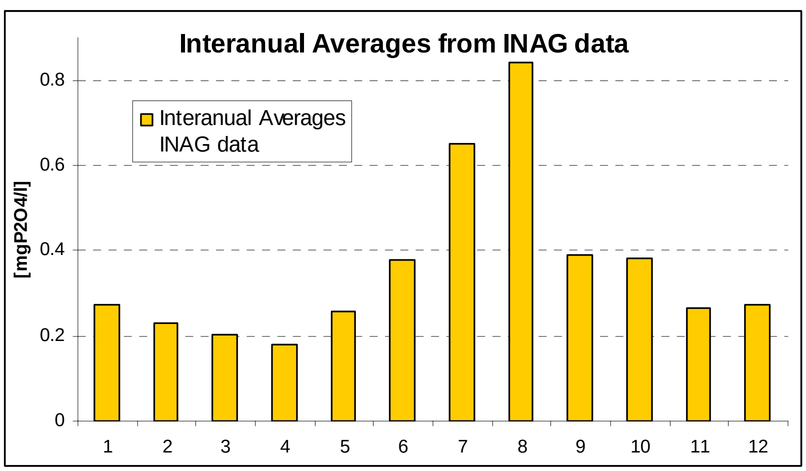

Figure 3-11 – Monthly moving averages for orthophosphate variations at Moinho Novo (2000-2004)

In average, orthophosphate levels account for 38% of total Phosphorous levels. However no clear patter for this percentage is recognized.

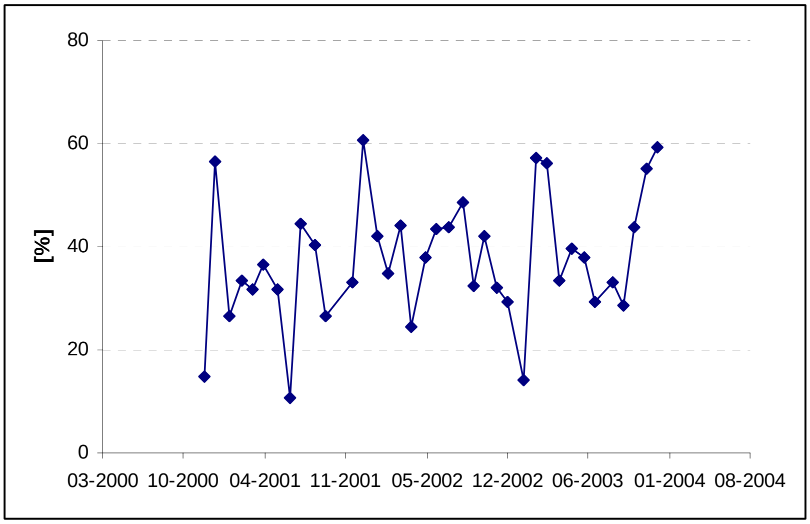

Figure 3-12 - Percentage of Orthophosphate in Total phosphorous

3.2.2.2. Nitrogen

Data from the INAG water quality database doesn't contain any values for total Nitrogen or Kjeldhal Nitrogen at "Moinho Novo" station. Only Nitrate and Ammonia were monitored.

An average concentration of $4.1[mgN0_3/l]$ is recorded in INAG data from 1999 to 2003 about the same as the average value recorded during ICReW campaigns at R2, $5.1[mgNO_3/l]$. Unlike phosphorous there is no clear patter for concentration variations for Nitrate with the flow regimes. Nitrate concentrations seam to show some inertia, characterized by small variations year long. This is usually related to the constant contribution of groundwater as the main source for nitrogen in a river. Concentration in groundwater has small variations over time and could condition the concentration of this nutrient in river flow.

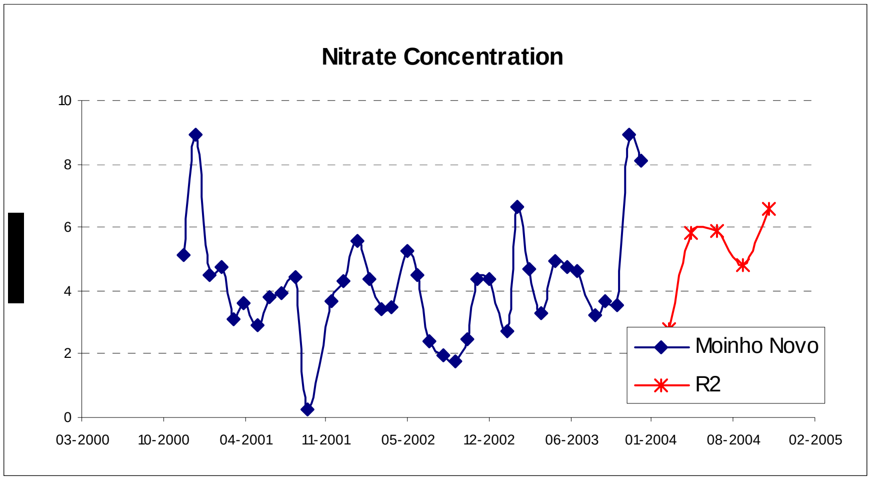

Figure 3-13 - Nitrate variations at Moinho Novo and R2

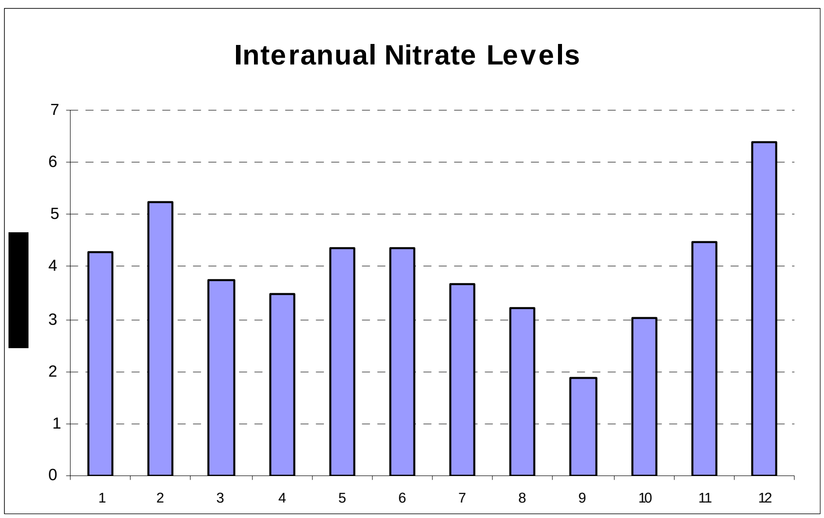

Figure 3-14 - Monthly moving averages for Nitrate at “Moinho Novo” (2000-2004)

For Ammonium variations at “Moinho Novo“ and R2, a clear relation with the flow regime can be seen from both monthly moving averages, and time series variations Figure 3-15 and Figure 3-16.

Once again these variations could re related to the mineralization of organic forms of Nitrogen trapped in the river’s internal pool. This associated with a low flow regime will increase ammonia concentration during (spring - summer) months.

Ammonium is the first inorganic form of Nitrogen to be used by most primary producers, decreasing its life span in natural waters. This makes ammonium a good indicator of point sources contamination.

Wastewater treatment plants discharge most nitrogen under the form of ammonium, so a high concentration of ammonium is an indicator that a point source may be near by.

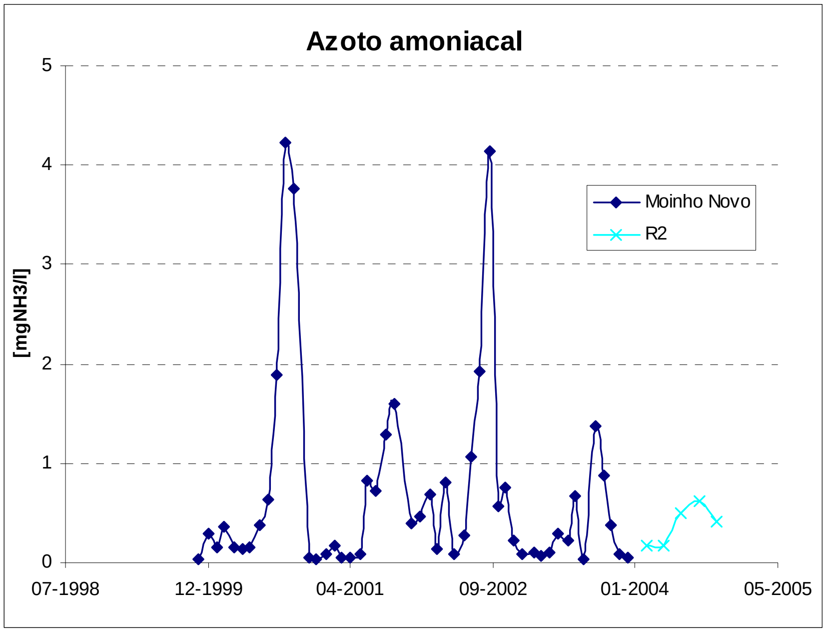

Figure 3-15 - Ammonium Variation at Moinho Novo and R2

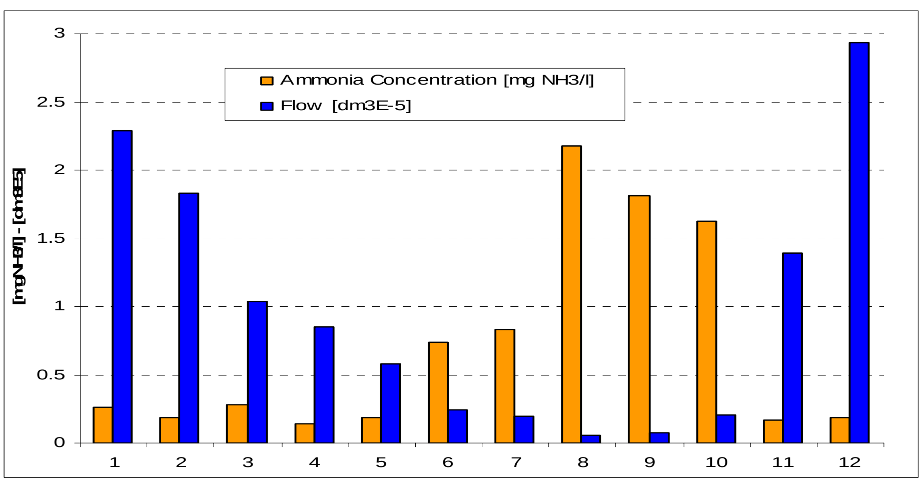

Figure 3-16 - Monthly moving averages for Ammonium (2000-2004) and Flow (1980-1990)

The proximity to "Ponte Sôr" wastewater treatment plant, the largest in the watershed with 7000 equivalent inhabitants, could be another explanation for these variations.

Ammonium discharged from this treatment plant should remain constant year round. The same discharge will produce a higher concentration during low flow regimes due to less dilution.

3.2.2.3. Chlorophyll-a

Even in a river system, characterized by short residence time, an increase in chlorophyll-a concentration during summer months is expected.

This event is present in both data from "Moinho Novo" and R2 monitoring point Figure 3-17. Unfortunately there is no sampling at October for this parameter in INAG's database data.

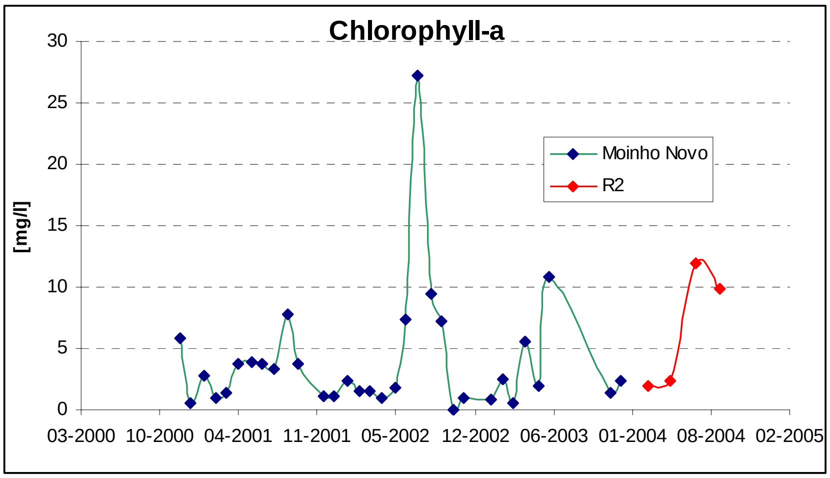

Figure 3-17 - Chlorophyll-a variation at Moinho Novo and R2

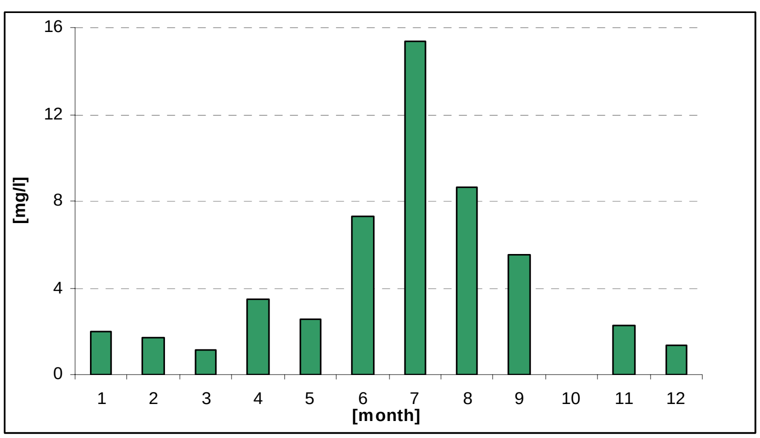

Figure 3-18 – Monthly moving averages for Chlorophyll-a at Moinho Novo (2000-2004)

Looking at moving averages Figure 3-18, the higher concentrations occur in July. A single "bloom" event that occurred in 2002 with a concentration of $27[mg/l]$ is responsible for this. Discarding this value the monthly average for July drops to $3.4[mg/l]$, less than August.

3.2.3. Conclusions

Most of the nutrient loads (Phosphorous and Nitrogen) reach the reservoir during month with higher flows and associated precipitations. However the effect of point sources is notices at the monitoring point due to an increase of ammonia and phosphorus concentrations during low flow conditions (when no surface runoff occurs). Nitrate has a much stabler pattern registering only small variations.

There is a clear increase of chlorophyll-a levels during the summer months. This increase is related to the higher residence of water and environmental conditions such as higher temperatures and improved luminosity conditions.

Using averaged monthly flows for historical data, a total load of $23[t]$ of phosphorous and of mineral Nitrogen should reach the reservoir. These values are only an approximation. It was registered during this analysis that flow and nutrient concentrations are tightly related and as so using average flow values recorded at different periods from the water quality analysis could generate some errors.

3.3. OSPAR Guidelines application

Watersheds have emerged as environmental units for assessing, controlling and reducing non-point-source pollution within the framework of the international conventions, such as OSPARCOM, HELCOM, and in the implementation of the EU Water Framework Directive.

It is important to define strategies in controlling eutrophication by reducing nitrogen and phosphorus losses from both point and nonpoint sources and help assess the performance of pollution reduction strategies. OSPAR Guidelines were developed to quantify and report on the individual sources of nitrogen and phosphorus discharges/losses to surface waters (Source Orientated Approach). These results can be compared to nitrogen and phosphorus loads measured at downstream monitoring points (Load Orientated Approach).

Nitrogen and phosphorus retention in river systems represents the connecting link between the "Source Orientated Approach" and the "Load Orientated Approach". This retention includes losses to air and deposition in sediments of rivers and water bodies. Figure 3-19 shows, for Montargil Reservoir Catchment, the delineation of monitored area and the non monitored area. This delineation was made using "Moinho Novo" monitoring station see 3.2.2.

Figure 3-19- Montargil Reservoir Catchment divided between Monitored area and non-monitored area

This guideline delineates a framework and approach of the Harmonised Quantification and Reporting Procedures for Nitrogen and Phosphorus.

Summary of calculation in guidelines related with the source oriented approach for the monitored area is shown in Table 13. These results show a predominance of Industry and animal production sources with a fraction of global N load of 50% and of Global P load of 54%. Approximately half of this load is originated in animal production. The other half is from olive oil plants (defined in table Table 13 as Industry).

Table 13 – Total Summary of sources calculated with Source Orientated Approach using OSPAR Guidelines for monitored area

Discharges and losses of nitrogen and phosphorous	Guideline	Nitrogen [Ton N/year]	Global N load fraction	Phosphorous [Ton P/year]	Global P load fraction
Aquaculture	2	0	0%	0	0%
Industry and animal production	3	158	50%	33	63%
Sewage treatment works and sewerage	4	61	19%	13	24%
Households not connected to sewerage	5	12	4%	2	3%
Diffuse anthropogenic nitrogen losses	6	85	27%	5	9%
Natural nitrogen background losses	6	2	0.8%	0	0.3%
Sum of all nitrogen and phosphorous losses/discharges	1	318	100%	52	100%

The result of the load reconciliation from the Source Orientated Approach and the Load Orientated Approach is presented in Table 14. Notice that for the period on witch water quality samples exist for Moinho Novo, there are no flow measures due to lack of an appropriate discharge curve see 3.2.1. To overcome this difficulty flow values estimated using a numerical model (see 3.4.1)

Table 14 – Load reconciliation by comparing loads from Source Orientated Approach (Table 13) and Load Orientated Approach for monitored area

Calculation Number	Discharges and losses of nitrogen and phosphorous	Nitrogen [Ton N/year]	Phosphorous [Ton P/year]
1	Sum of all nitrogen and phosphorous losses/discharges	318	52

2	Quantified nitrogen and phosphorus retention in surface waters	69	19
3	Total estimated transport of nitrogen and phosphorus at the monitoring point (derived from the Source Orientated Approach) (3=1-2)	248	32
4	Total (from Load Orientated Approach)	208	41
5	Difference between estimations obtained with the Source Orientated Approach and the Load Orientated Approach (5=3-4)	40	19

For the non monitored area it is only possible to apply the source oriented approach (Table 15). Based on this estimation, agriculture is the major contributor to riverine loads with a fraction of global N load up to 71% and of 68% for global P.

Table 15 –Source Orientated Approach for non-monitored area

Discharges and losses of nitrogen and phosphorous	Guideline	Nitrogen [Ton N/year]	Global N load fraction	Phosphorous [Ton P/year]	Global P load fraction
Aquaculture	2	0	0%	0	0%
Industry and animal production	3	2	1%	1	5%
Sewage treatment works and sewerage	4	6	3%	1	8%
Households not connected to sewerage	5	20	12%	3	19%
Diffuse anthropogenic nitrogen losses	6	118	71%	10	67%
Natural nitrogen background losses	6	22	13%	0	1%
Sum of all	1	166	100%	15	100%

nitrogen and phosphorous losses/discharges

The sum of all sources for the basin is presented in Table 13. According to these results olive oil processing and animal production (“Industry and animal production”) and agriculture (“Diffuse anthropogenic nitrogen losses”) are responsible for 75% of global Nitrogen. On the other hand 77% Phosphorous is originated from olive oil processing, animal production and Sewage treatment works and sewerage.

Table 16 – Total Summary of sources calculated with Source Orientated Approach using OSPAR Guidelines for monitored area

Discharges and losses of nitrogen and phosphorous	Guideline	Nitrogen [Ton N/year]	Global N load fraction	Phosphorous [Ton P/year]	Global P load fraction
Aquaculture	2	0	0%	0	0%
Industry and animal production	3	174	40%	36	59%
Sewage treatment works and sewerage	4	84	19%	17	28%
Households not connected to sewerage	5	17	4%	2	4%
Diffuse anthropogenic nitrogen losses	6	152	35%	5	8%
Natural nitrogen background losses	6	5	1%	0	1%
Sum of all nitrogen and phosphorous losses/discharges	1	432	100%	62	100%

3.4. Watershed Model Results

Watershed modeling is a relatively new study area for the Maretec research group. The selected approach to this new theme consisted on the usage of an established model while a team of four people, of which the author is part of, develops MOHID Land.

The SWAT model was selected as the first model to be used. This model is based on the water balance equation. A distributed SCS curve number is generated for the computation of overland flow runoff volume, given by the standard SCS runoff equation (USDA, 1986).

A soil database must be used to obtain information on soil type, texture, depth, and hydrologic classification. In SWAT, soil profiles can be divided into ten layers. Infiltration is defined in SWAT as precipitation minus runoff. Infiltration moves into the soil profile where it is routed through the soil layers.

A storage routing flow coefficient is used to predict flow through each soil layer, with flow occurring when a layer exceeds field capacity. When water percolates past the bottom layer, it enters the shallow aquifer zone (Arnold and others, 1993).

Channel transmission loss and pond/reservoir seepage replenishes the shallow aquifer while the shallow aquifer interacts directly with the stream. Flow to the deep aquifer system is effectively lost and cannot return to the stream (Arnold and others, 1993).

The irrigation algorithm developed for SWAT allows irrigation water to be transferred from any reach or reservoir to any other in the watershed. Based on surface runoff calculated using the SCS runoff equation, excess surface runoff not lost to other functions makes its way to the channels where it is routed downstream.

Sediment yield used for instream transport is determined from the Modified Universal Soil Loss Equation (MUSLE) (Arnold, 1992). For sediment routing in SWAT, deposition calculation is based on fall velocities of various sediment sizes. Rates of channel degradation are determined from Bagnold's (1977) stream power equation. Sediment size is estimated from the primary particle size distribution (Foster and others, 1980) for soils the SWAT model obtains from the STATSGO (USDA 1992) database. Stream power also is accounted for in the sediment routing routine, and is used for calculation of re-entrainment of loose and deposited material in the system until all of the material has been removed.

SWAT can also model reservoirs was zero dimensional ponds with no hydrodynamic movement.

Adding to this the qual2E water quality model is used for instream water quality processes and WASP water quality module is used for reservoir water quality calculations.

This Setup makes SWAT a very complete model. However many of the processes modeled rely on empirical or simplified formulas to model physical processes such as infiltration or surface flow.

To overcome these obstacles MOHID Land has been developed. In this model the equations that describe the physical processes associated to water flow in a watershed are solved. As so the model simulates a two dimensional overland flow, one dimensional flow in rivers using the cinematic wave approach or the complete St. Venant equation. The vadoze zone is modeled by solving the tree-dimensional Richards equation along with a two dimensional aquifer (vertically integrated).

A transport model and bacterial decay model are already coupled to MOHID Land, along with two water quality modules, MOHID water quality and CEQUALW2.

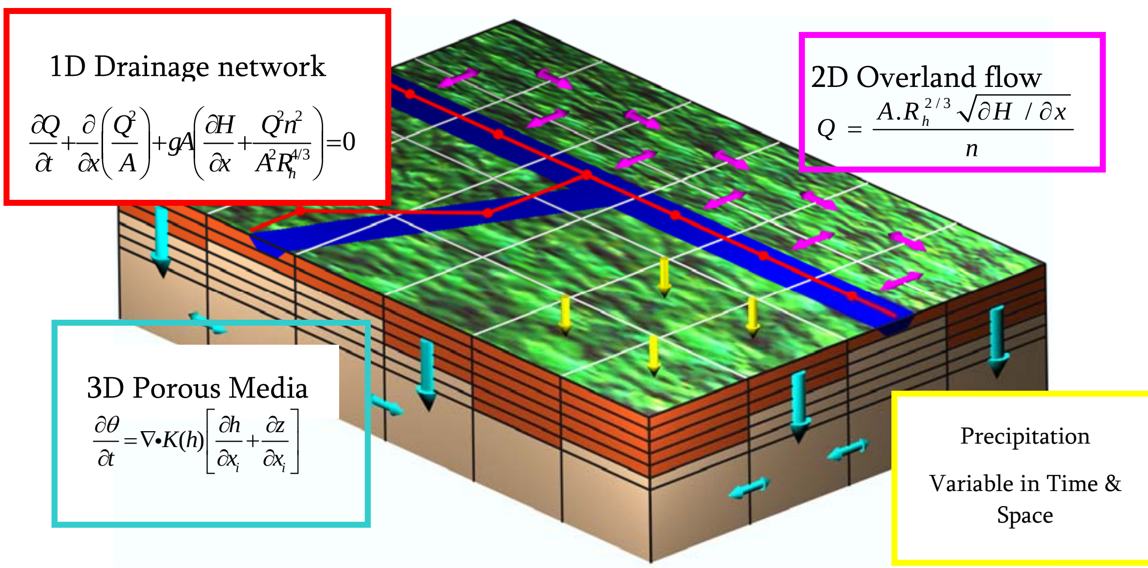

Figure 3-20 - MOHID Land simulated processes

The problems currently associated with MOHID Land are related to the computational time required, especially for the vadoze zone modeling. The model also requires hourly or sub hourly precipitation values that are much harder to obtain.

The development of inland water quality routines and plant growth is still under development.

3.4.1. SWAT model results

The three basic inputs needed for swat to produce results are:

- Digital terrain model

- Soil type map
- Land Use maps

The solution for the first item was described in Chapter 2

Unfortunately the Portuguese soil classification used in soil maps of the national territory has no direct relation with hydraulic parameters needed to model infiltration either using daily CN curve number, Green-Ampt approximation or the complete Richards equation.

To overcome this difficulty textural soil maps were obtained for the study site from a map developed by "The Commission of the European Communities, Directorate General for Agriculture, Coordination of Agricultural Research", (1985). The distribution of soil types in the basin is is shown in Table 17

Table 17 – Soil Textural classes in Montargil reservoir basin according to The Commission of the European Communities, Directorate General for Agriculture, Coordination of Agricultural Research

Textural class	Area (Km^2)	Area (%)
Medium	230	19%
Coarse	904	76%
MediumFine	50	4%

A pedotransfer function developed by Saxton et al. (1986) was used to obtain physical properties based in soil textures.

Table 18 - Soil characteristics

Textural class	Clay [%]	Sand [%]	SCS Hydrologic group	Density [kg/dm3]	Available Water Content [mm/mm]	Saturated Hidraulic Condutivity [mm/hr]
Fine	47.5	52.5	D	1.30	0.09	1.0
Medium	17.5	82.5	A	1.51	0.20	9.2
MediumFine	35.0	65.0	C	1.37	0.20	1.6
Coarse	9.0	91.0	A	1.73	0.07	38.0

For soil cover data two maps were considered: "Corine land cover" and "Carta de ocupação de solo". Both this maps are available at www.igeo.pt.

The first has a scale of 1:100 000 and refers to the years 85-87, while the second one has a scale of 1:25 000 and is based on data from 90-91. However "Carta de ocupação de solo" does not cover some parts of the national territory. Corine Land cover was used to fill the gaps of the more detailed Portuguese map. Table 19 shows the areas of the most important soil cover types.

Table 19 – Total area of each soil cover type in the basin according with Corine and Cos

Soil cover type	Area of each cover type - Montargil [ha]	Fraction of the area of each cover type - Montargil [%]
Oak	49253	41.8%
Cold season annual	15775	13.4%
Eucaliptus	14772	12.5%
Pine	9508	8.1%
Olive	8874	7.5%
Annual species + Forest species	5429	4.6%
Bush	3287	2.8%
Irrigation	2631	2.2%
Mix Forest species	2074	1.8%
Water	1742	1.5%
Orchard	1576	1.3%
Other surfaces	1474	1.3%
Rangeland	1109	0.9%
Rice	283	0.2%
Vines	102	0.1%
Total	117889	100.0 %

Based in this two maps one can say that the basin is mainly occupied with forest. Agriculture is clearly dominant in valleys, and also in plain parts in the top of the basin and in valley strip that goes from Ponte de Sor to the reservoir and along it.

Once these basic inputs are known the SWAT interface divides the watershed into subbasins and the subbasins into HRU (hydrologic response units). These units are to swat what a grid cell is to MOHID Water or any similar model. Inside an HRU all properties are considered uniform, from sediment and nutrients to soil type and landuse and management.

The user can specify the percentage under witch a given landuse or soil type is disregarder under each subbasin when each URU is created. In this case only combinations of these parameters under 10% were disregarded so that the Agricultural area is maintained.

The three weather stations described in Chapter 3.2.1 were used to supply daily precipitation values for both the calibration period and simulation period. Unfortunately no other data is available on INAG database for atmospheric parameters.

SWAT can use a weather generator to supply atmospheric parameters for every simulation see Neitsch et al. 2000 for more details. For this weather generator stations are necessary. These stations must have monthly averages obtained with more than ten years of data for each atmospheric parameter. Two stations were created close to the watershed using historic data from two IM stations, namely Alvega e Portalegre. The first has data for temperature, wind intensity, sunshine hours, humidity and precipitation from 1949 to 1985 and the second station from 1951 to 1988.

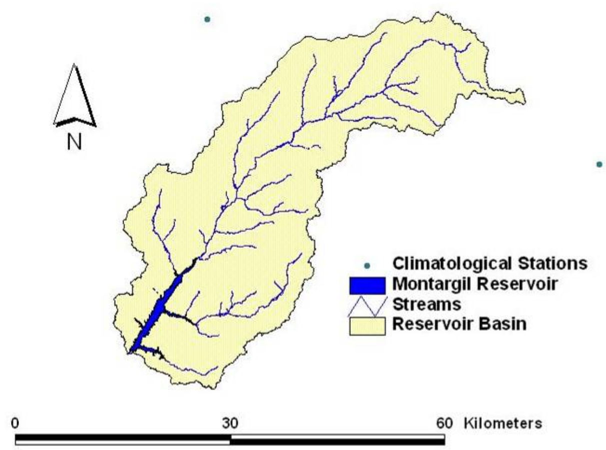

Figure 3-21 - Climatological weather station location

The main calibration that must be obtained with swat for water flow is related to the amount of water that flows out of the basin and how much of it comes from underground flow.

To adjust excess of surface flow there are three parameters that can be adjusted

- CN for each subbasin - Different curve number will affect the amount of water that produces flow.
- The available water content for each type of soil – This will affect mainly evaporation
- The depth of evaporation parameter, this will cause water to evaporate from deeper soil profiles increasing evaporation.

For subsurface or return flow, there are three main parameters that must be calibrated.

There is no groundwater movement in either of the aquifer types modeled by swat. All water that infiltrates in a given HRU will either reach the deep aquifer or contribute to river flow on the outlet of that HRU. The aquifer recharge is calculated with an exponential decay function proposed by Venetis (1969) and used by Sangrey et al. (1984) in a precipitation/groundwater response model (Neitsch et al. 2000). This equation depends on a user supplied parameter that supplies how much time in days water will need to reach the shallow aquifer after infiltration occurs.

The base flow to the stream is calculated using a similar function that depends on the base flow reception constant. This parameter depends on the saturated hydraulic conductivity, the aquifer specific yield and the distance from the ridge or subbasin divide for the groundwater system to the main channel.

Finally the amount of water that is lost to the deep aquifer is simply a percentage of the total volume that reaches the shallow aquifer on a given day. This is calibrated with another user supplied parameter.

These are the three main parameters than can be adjusted to improve the contribution of groundwater to stream flow.

For the calibration period that included the 1985-1990 hydrologic year the simulated and measured data can be seen in

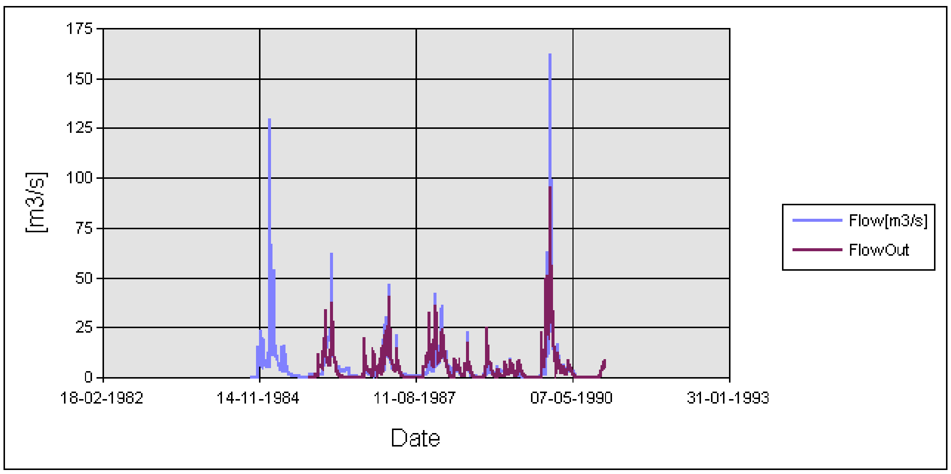

Figure 3-22 - Model results for Calibration period

The model has difficulty for both very high flows and very low flows. These are however the situations where the discharge curves used are ore prone to errors (see chapter 3.2.1).

Looking closer to the results, the base flow on the model is overestimated. In Figure 3-23 after a high flow event the modeled flow decreases slower than in real data.

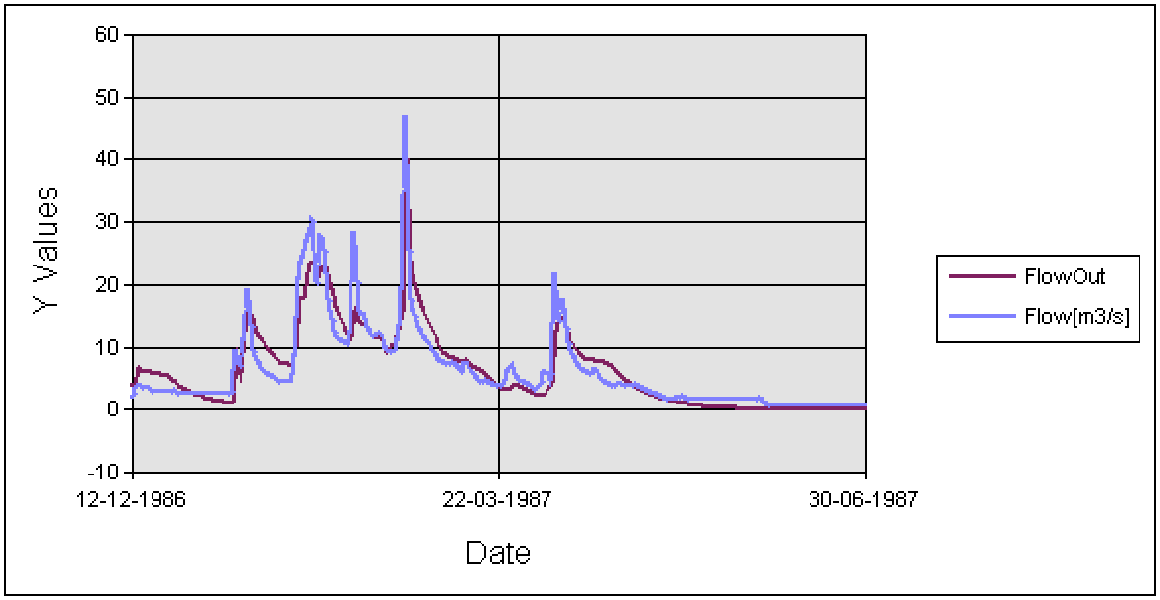

Figure 3-23 - Model Results and base flow

However as the flow decreases the observed data eventually overtakes the model results. Field observation has proved that the Sõr River never stops flowing. Even during 2005 when an extreme drought was registered in Portugal the river still had a small flow close to the reservoir. This probably happens due to aquifer recharge. As long as the aquifer level is high enough flow water will pass from the aquifer to the stream. This effect is very difficult to obtain with SWAT since we must establish in days the time that aquifer will contribute to stream flow.

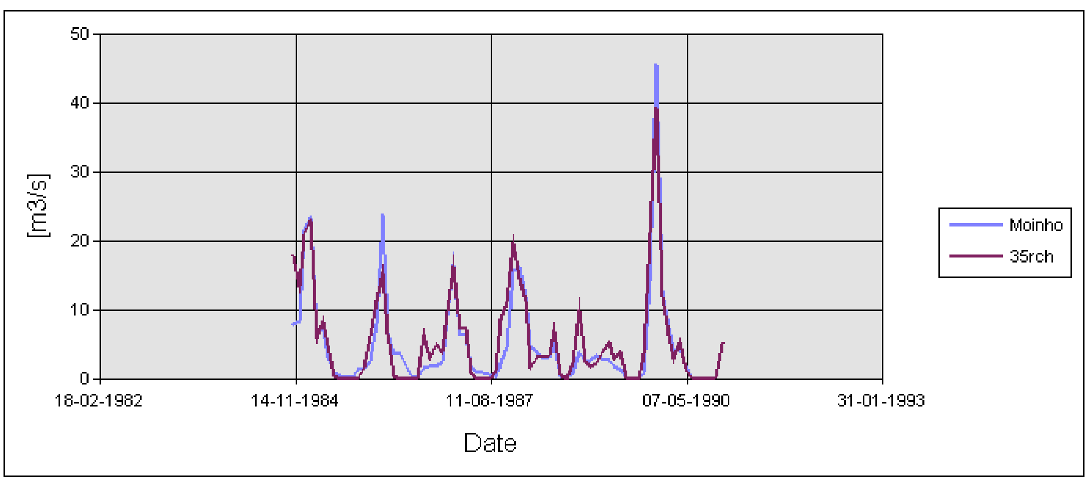

Figure 3-24 - Average monthly flows

Looking at yearly values, the model has a tendency to overestimate flow. The hydrologic year of 1989-1990 has the worst results, but that could be associated with faulty measures see chapter 3.2.1.

Oliveira 2004 has used a filter program to evaluate the surface and groundwater contributions to the flow recorded at Moinho novo.

Table 20 - Yearly results

Year	Precipitation [mm]	Precipitation Model [mm]	Total flow [mm]	Total flow model [mm]	Surface Flow [mm]	Surface Flow model [mm]	Base flow [mm]	Base flow model [mm]
1984-1985	942	958	322	323	154	145	167	197
1985-1986	703	683	179	161	74	63	105	106
1986-1987	669	671	199	206	69	75	130	141
1987-1988	959	931	291	282	99	122	192	177
1988-1989	597	572	90	138	23	46	67	98
1989-1990	912	892	375	293	165	155	211	158

Overall the model shows a good relation with the values presented by Oliveira 2004. The principal differences on precipitation are related to different interpolation methos used to evaluate rainfall.

The model efficiency for water flow was analyzed according to the criteria proposed by Fitz et. all as in Evans et al., including model bias, root mean square error (RMSE), Pearson product-moment correlation coefficient (R2), and the Nash-Sutcliffe coefficient. Brief overviews of these statistical measures are provided below.

Bias is calculated as follows:

$$\frac{\sum(y-x)}{n} \tag{1.3}$$

Where x is the observed value, y is the model-simulated value, and n is the number of observations. As can be seen from this equation, bias is calculated as the mean differences between paired observed and simulated values. Bias values closer to zero indicate better overall model performance.

RMSE is calculated as:

$$\sqrt{\frac{\sum(y-x)^2}{n-1}} \tag{1.4}$$

Where x is the observed value and y is the predicted value. As shown, RMSE is the square root of the average values of the prediction errors squared. This statistic is used to measure the discrepancy between modeled and observed values on an individual basis, and indicates the overall predictive accuracy of a model. Due to the quadratic term, greater weight is given to larger discrepancies. With this measure, smaller values indicate better model performance.

Pearson Product-Moment Correlation Coefficient (R2) is calculated as:

$$R^2 = \left(\frac{\sum (y - y_m)(x - x_m)}{\sqrt{\sum (y - y_m)^2 (x - x_m)^2}} \right)^2 \tag{1.5}$$

where xm is the mean of the observed (x) values, and y is the model-simulated value. The R2 value is a measure of the degree of linear association between two variables, and represents the amount of variability that is explained by another variable (in this case, the model-simulated values).

Depending on the strength of the linear relationship, the R2 can vary from 0 to 1, with 1 indicating a perfect fit between observed and predicted values.

The Nash-Sutcliffe coefficient is calculated as:

$$1 - \frac{\sum (y - x)^2}{\sum (x - x_m)^2} \tag{1.6}$$

where xm is the mean of the observed data, and y is the model-simulated value. Like the R2 measure described above, it is another indicator of "goodness of fit", and is one that has been recommended by the American Society of Civil Engineers (ASCE, 1993) for use in hydrological studies (Evans et al.). With this coefficient, values equal to 1 indicate a perfect fit between observed and predicted data, and values equal to 0 indicate that the model is predicting no better than using the average of the observed data. Therefore, any positive value above 0 suggests that the model as some utility, with higher values indicating better model performance.

For daily flow the model reaches reasonable results on all parameters Table 21 and the results improve even further for monthly averaged results, Table 22.

Table 21 - Model evaluation for daily results

Modeled average	5.1[m3/s]	**Observed average**	4.74[m3/s]
Bias	0.36	**RMSE**	4.22
R2	0.784	**Model efficiency**	0.782

Table 22 - Model evaluation for monthly results

Modeled average	5.26[m3/s]	**Observed average**	5.01[m3/s]
Bias	0.25	**RMSE**	2.75
R2	0.861	**Model efficiency**	0.86

The fact that the model has a tendency to over estimate flow is associated with the longer return flow discussed previously.

After this initial calibration the model was applied to the 2001-2005 period. No flow values are available for this period as described in chapter 3.2.1.

The only available values for comparison are monthly averaged flows that were obtained with a volume balance of the reservoir volumes and discharges. Unfortunately discharge data is only available up to the end of 2003. This turns the watershed model the only source for stream flow for the 2004-2005 period for reservoir modeling.

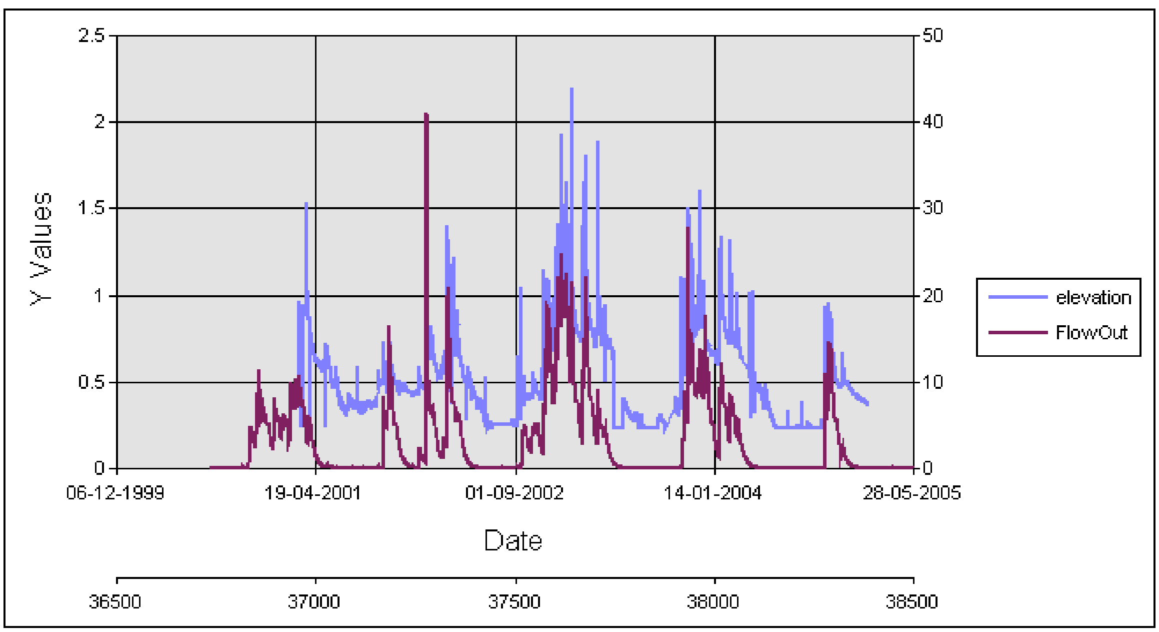

Figure 3-25 - Flow results and Moinho novo levels

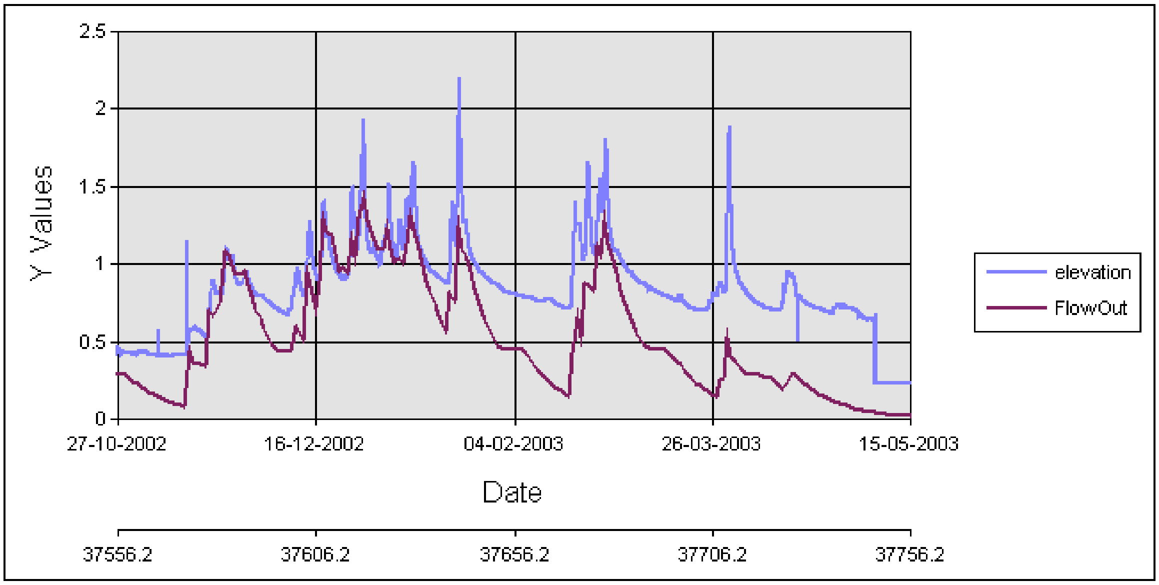

Figure 3-26 - Detail of modeled flow and registered level

A visual analysis shows a good relation for modeled flows and registered levels, Figure 3-25 and Figure 3-26.

The monthly flow values calculated from the reservoir volume balance and the monthly averaged flows can be seen in Figure 3-27

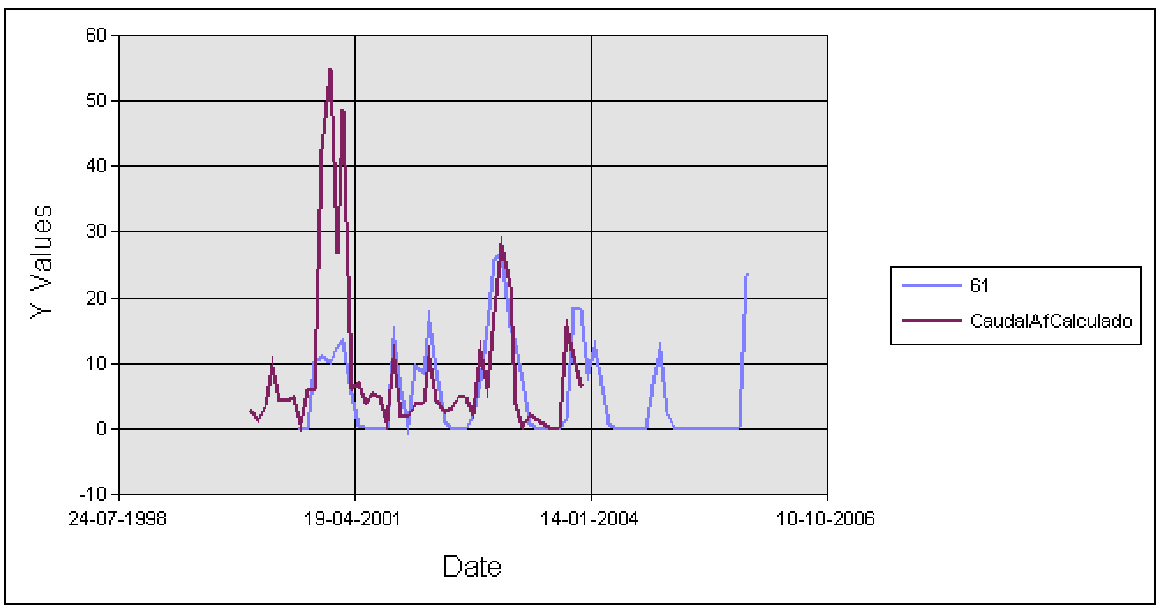

Figure 3-27 - Monthly average modeled flows and reservoir mass balance calculated flows

There are two big differences in both methods. The flow values that were calculated for 2000 with the mass balance method are impossible to obtain. This must be due to some error either on the reservoir discharges or on the reservoir volume it self. The second difference is related to an increase in flow for the mass balance method during

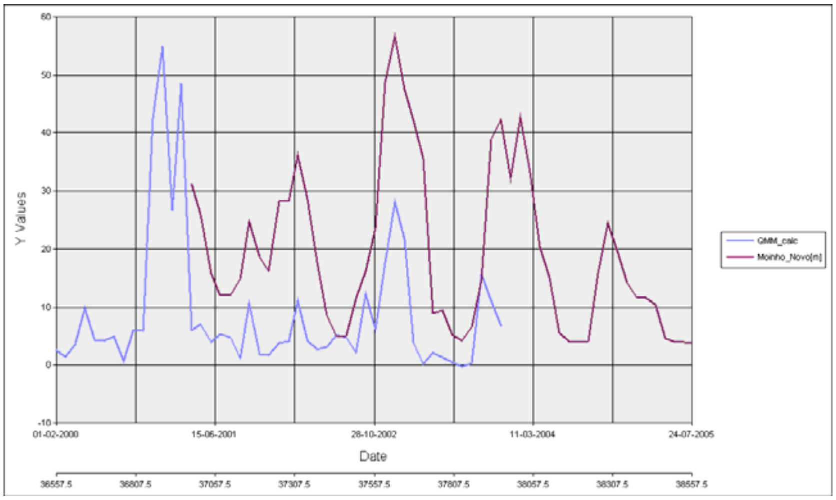

Figure 3-28 - Moinho novo average monthly levels and average monthly flow

the summer periods. Again this is probably related to some error on either the reservoir volume or discharges since no such increase is noticed on the registered levels at Moinho Novo Figure 3-28.

3.4.2. MOHID Results

Unfortunately MOHID Land hasn't reached a point of maturity that allows results to be compared to stream flow gages.

Soil Characterization is an even greater difficulty for MOHID Land than for SWAT. The Curve number protocol used by SWAT to generate "effective" precipitation only needs soil to be classified form A to D. This along with land cover will generate the CN number for normal conditions (two other numbers are estimated for dry and wet conditions).

MOHID needs soil to be characterized with all the parameters necessary for Van Gnuchten equation that will relate head to water content allowing us to solve Richards equation (Galvão 2002). After infiltration occurs a diffuse waver type equation will transport water to the streams. This equation is calibrated thought a Manning like parameter (Haan, et al. 1981). This parameter is offcource dependent on soil cover. The longer water takes to reach the channel the longer water is exposed to the infiltration phenomena.

Other than this a vertical characterization of the soil profile is necessary since MOHID models the hydrodynamic of the shallow aquifer.

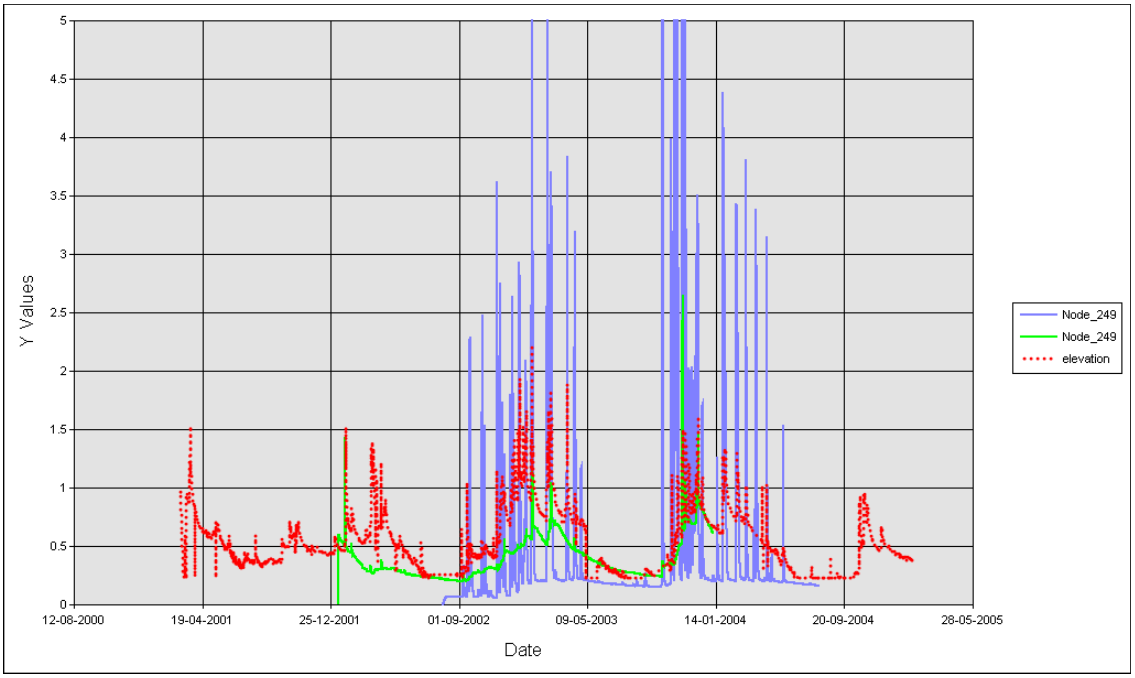

Figure 3-29 - MOHID Land Results

Even with all these difficulties the initial results that where obtained with MOHID land are promising:

The difference between the results in green and blue is simply the soil characterization. While the blue soil is more impermeable it will generate higher surface flows and lower subsurface return flow. The soil in green has higher infiltration capabilities and will generate more return flow and less surface contribution.

Notice that return flow is obtained from head differences between the aquifer and water level in streams. This creates a situation where the vertical structure of the soul has to be described correctly; otherwise it will modify the aquifer hydrodynamics and associated return flow to streams.

4 Reservoir modeling

4.1. Introduction

In freshwater systems phosphorous and Nitrogen are the most important nutrients for phytoplankton production. Phosphorous usually assumes the limiting factor role for phytoplankton growth.

The increase of these nutrients in freshwater systems is usually defined as the main cause for the eutrophication process characterized by primary production exceeding consumption and decomposition. Currently the most accepted definition for eutrophication highlights not only this excessive growth of organisms due to nutrient enrichment but also the undesirable impacts that this process will cause.

As so eutrophication is defined as the process of enrichment with excess nutrients of natural waters associated with the increase of primary producers such as macrophyte, algae or cyanobacteria. This process leads to the decrease of water quality and other symptomatic changes that are undesirable and will affect water usage (OECD,1982; Thomann & Mueller, 1987; Rast & Thornton, 1996; Walmsley, 2000; OSPAR, 2001a).

The usage of reservoir water for bathing or recreational purposes is one of the usages that can be affected by the eutrophication process. The particular reservoir under study has a long history of cyanobacteria blooms.

In Portugal an eutrophication criteria was created by agreement of several entities, public organisms and Universities, based on the OECD (1982) criteria (Pereira & Rodrigues, 2005;). In this criteria three trophic states are defined (Oligotrophic, Mesotrophic and Eutrophic) according to three analytical parameters, Total phosphorous, Chlorophyll-a and dissolved oxygen. This standard is summarized in Table 23.

Table 23 - National Criteria for trophic state of reservoirs

	Oligotrophic	Mesotrophic	Eutrophic
Total Phosphorous [mgP/m3]	<10	10-35	35
Chlorophyll-a [mg/m3]	<2.5	2.5-10	>10
Dissolved oxygen % saturation	-	-	<40

The trophic state will be that of the least favorable parameter.

The fact that phosphorous and not nitrate is used as a parameter to define the trophic state is related to the Redfield ratio (106:16:1 C:N:P). This is accepted as the basic ratio of carbon/nitrogen/phosphorous that phytoplankton needs to grow in natural surface waters and will imply that in natural waters phosphorous is the limiting nutrient (Redfield, 1958, Mateus S. 2005). As so if primary production is to be restrained phosphorous should be the nutrient to monitor.

For instance urban point sources have a NP ratio of 4:1 (usually due to phosphate in detergents) which will change the limiting factor from phosphorous to Nitrate favoring species than can overcome this limitation (like the Nitrogen fixing cyanobacteria). However this will be expressed as an unusual increase of phosphorous concentration and will affect the eutrophication criteria.

Having this in mind an initial analysis on historical data supplied by INAG database is performed, followed by the analysis of data collected during the ICReW project.

4.2. Data Analysis

Montargil reservoir exploration started in 1958. The reservoir was created at the Sôr river with a watershed of about 1 180 km2. The main purpose of the reservoir is to store water for irrigation, but it is also used for electric power generation, fishing and water sports. The tourist potentialities of the location (close to Lisbon) are currently recognized in the reservoir ordinance plan (approved by the Portuguese minister council resolution nº 94/2002).

There are three bathing locations in the reservoir:

- Pintado (close to a camping location) is classified as a bathing location according to the 76/160/CEE directive.
- Tesos and Foros do Mocho, are present in CCDRA monitoring campaigns as potential bathing sites (under study according to Decreto-Lei n. º 236/98 de 1 de Agosto).

In Portugal reservoir and generally public waters are classified by "Decreto-Regulamentar Nº 2/88" accordingly to the reservoir characteristics and the primary usages of the reservoir by the time the decree was accorded. This decree classifies reservoir into 4 classes:

- Protected reservoirs (reservoirs with water with potential for human consumption or in Natura 2000 protected areas)
- Conditioned Reservoirs (secondary usages are prohibited)
- Restricted usage Reservoirs (reservoir with touristy potentialities)
- Free usage reservoir

Montargil reservoir was declared a "Restricted usage Reservoir" and as so some secondary usages are prohibited (speed boating) but bathing, fishing and sailing are allowed.

Morphometric data for the reservoir at full storage is described in Table 24.

Table 24 - Morphometric data for Montargil reservoir

Drainage Area	1185 [km2]
Reservoir Area	16.46 [km2]
Mean depth	10 [m]
Max depth	30 [m]

Total Volume	164 [hm3]
Usable capacity	143 [hm3]
Mean energy production	7.5
Mean annual residence time	0.3-0.7 [yr]
Mean Annual water load	116 [hm3] (average 1980-1990)

Sôr River supplies most of the water to the reservoir (60-70%). Several ephemeral streams make minor contributions during winter runoff (Cabeçadas 1998). The water level is regulated by irrigation water demand and depends on climatic conditions. Usually the reservoir is filled during winter and drawn down gradually due to irrigation during the rest of the year.

The outflow from the reservoir is controlled by several structures. Water for irrigation and for the turbines is located 15m above the reservoir bottom. The emergency spillway is located at 27m from the bottom. There is also a bottom discharger located only 5m from the bottom.

Due to the annual variation of waterlevel on the reservoirs, the zone between the highest and the lowest waterlines –the drawdown zone- shows no terrestrial vegetation and sandy / arid conditions. During the driers years a deeper zone is exposed showing a darker soil with higher contents of organic mater and nutrients Figure 4-1.

Figure 4-1 - Montargir Reservoir during drought conditions

Like in the previous section an initial analysis is performed on available hydrometric data, followed by water quality parameters analysis.

4.2.1. Hydrometric Data

The reservoir water level has an average annual variation around 4 [m] Figure 4-2. These variations are influenced by irrigation needs and power production. These are the main usages for the reservoir water. The annual average of water usage for power production is of the same magnitude as for irrigation, 7684[dm3] for irrigation and 9278[dm3] for power production.

Usually irrigation takes place from April to October. Power production appears to follow no clear pattern with large interannual variations of both volume and distribution, Figure 4-2.

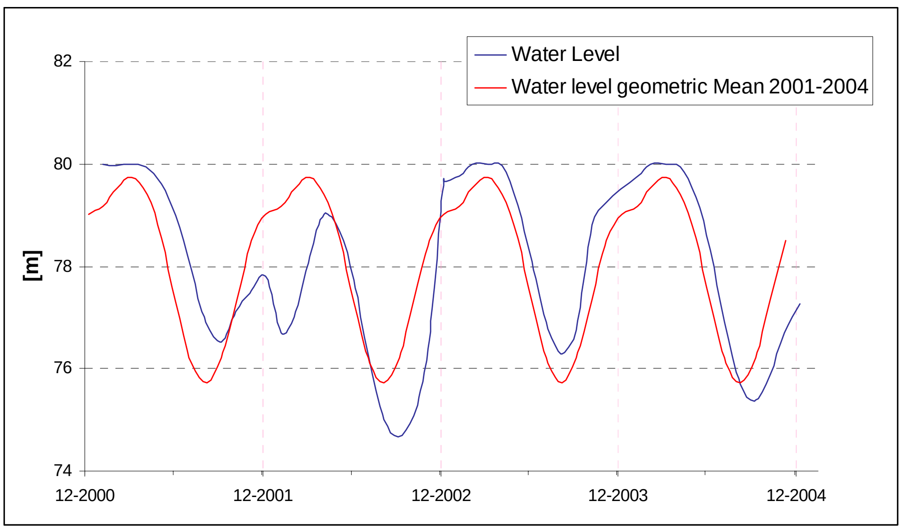

Figure 4-2 - Reservoir water level variations

This consumption pattern along with the pluviometer regime leads to an annual reservoir minimum during September. There is a clear reduction of irrigation consumption during this month, probably due to the reservoir low level Figure 4-3.

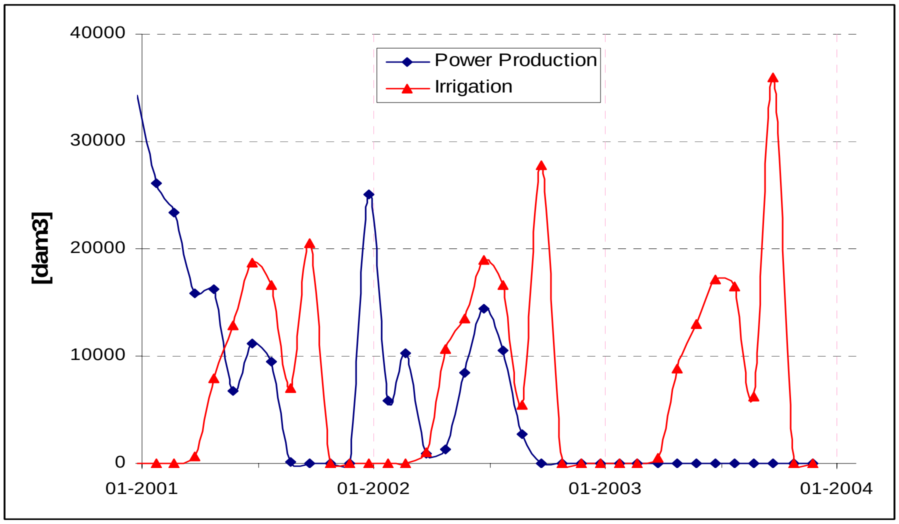

Figure 4-3 - Water consumption for irrigation and power production

During 2003 there was no consumption for power production. This along with the fact that in 2001 the reservoir recorded very low values (Figure 4-2) explains why 2003 has an average higher volume than 2002 even thought there were higher precipitation values in 2002.

Sôr River, the main effluent to the reservoir outputs an annual average of 116 [hm3] (average for 1980-1990) almost the volume of full storage for the reservoir. The annual Irrigation needs would be less than 7% of the annual flow, 8% for power production.

Since 2000 the gauge station located at Rio Sôr (operated by project partner INAG) was automated. Unfortunately the discharge curve for this new station isn't available. IST is measuring a new discharge curve using ICReW funded equipment stream-pro. However since 2005 was a dry year this discharge curve still isn't complete.

In this version of the report only an analysis of the recorded level was done.

2004 was the year with less contribution from river Sôr (consistent with the fact that it was the year with less precipitation).

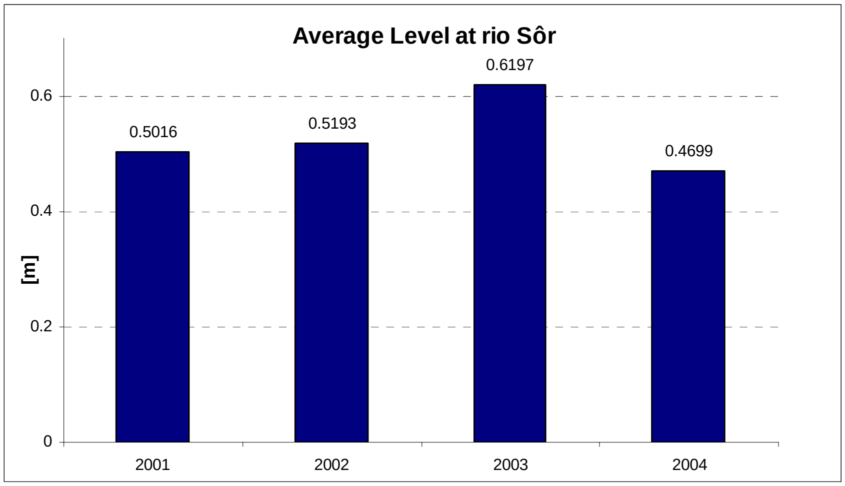

Figure 4-4 - Annual averages for recorded level

Even though 2002 had an overall higher precipitation than 2003, the average level of the gage station was higher. This could be related either to the annual distribution of precipitation (more concentrated in the wet season) or to the distribution of rain fall over the entire basin (these precipitation values are from the weather station located closer to the reservoir while the whole basin occupies an area of 1180 km2).

The lower values recorded for the reservoir level in 2001 are related to an over exploitation of the reservoir for power production, as this year had a higher contribution from Sôr river than 2004.

4.2.2. Water quality data

INAG's national hydraulic resources database has results of the ongoing water quality monitoring program for the Montargil Reservoir. Currently this monitoring program samples 70 parameters, some started in November 1994 while other only have recorded values since January 2002. The sampling point is located close to the reservoir wall Figure 4-5. The most relevant parameters are listed in Table 25.

Table 25 – INAG database data

Physical/Chemical Parameters		Biological Parameters
Total Phosphorous	Orthophosphate	Fecal streptococcus
pH	Nitrate	Total Coliforms
Suspended Solids	Nitrite	Fecal Coliforms
	Oxidability	Chlorophyll-a

Ammonium	
Dissolved Oxygen	Temperature
QOD	

The ICReW sampling program for the reservoir was coordinated between IST, IA, CCDRA and SRSP.

In Montargil seven points in the reservoir were monitored, Figure 4-5, some with monthly sampling, (all three bathing sites) others with bimonthly sampling (A1 and A2).

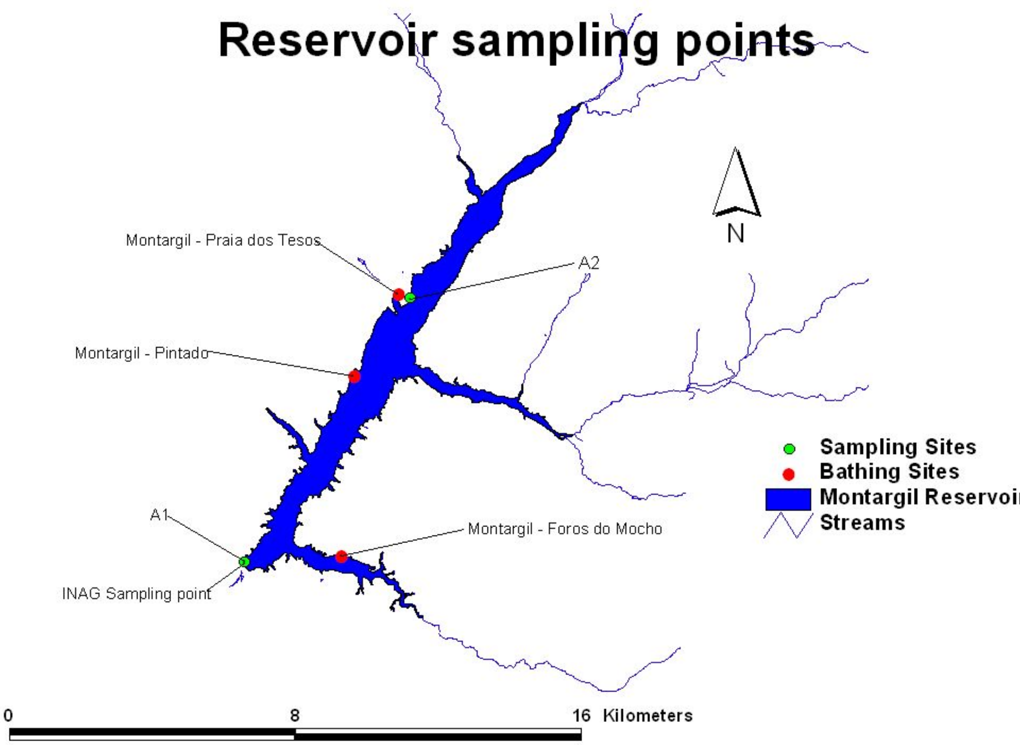

Figure 4-5 - Reservoir Monitoring Points

This way a temporal and spatial characterization of the reservoir was obtained according to Table 26

Table 26 – ICReW collected data

Chemical/Physical Parameters		Biological Parameters
Total Nitrogen	Dissolved Oxygen	Chlorophyll-a

Ammonium	Oxidability	Pheopigments
Nitrates	CBO_5	Microcystins
Phosphates	CQO	Coliform Bacteria
Total phosphorous	pH	E. Coli
Total suspended solids	Temperature	
Turbidity		

Point A1 was used to obtain surface and depth measurement without the use of a boat. This point is located over a water tower built to capture water for human use. This water tower was never used since water from this reservoir was never used for human consumption. The water level monitoring system managed by "Associação de Regantes e Beneficiários do Vale do Sorraia" is also located in this tower .

Figure 4-6 - Water tower in drought conditions

Figure 4-7 - Water tower in normal conditions

Some logistic problems stopped the usage of this point and to replace it three extra points were added by summer of 2005, A3S, A3M and A3F. These points correspond to a vertical profile with a surface point, a point at the limit of the euphotic zone (measured with Secchi disk) and a point close to the bottom of the reservoir.

When ICReW funded equipment was purchased a mapping system using a YSI-6600 water quality monitoring equipment was used along the centerline of the reservoir.

Because of the reservoir's size (14 km length), the use of continuous single point monitoring will face the problem of spatial variability. Taking discrete samples at several key points helps to diminish this problem but for a reservoir this large it would take too many points to obtain a complete description of the spatial variability.

4.2.2.1. Phosphorous

INAG water quality database has analysis for total phosphorous in the reservoir from April 2001 to December 2004, with an average of $0.0403[mgP/l]$ Figure 4-8. Almost half of the national average for all reservoirs present at the same database, $0.07[mgP/l]$.

This will classify the reservoir as Eutrophic but very close to the top limit of the Mesotrophic category.

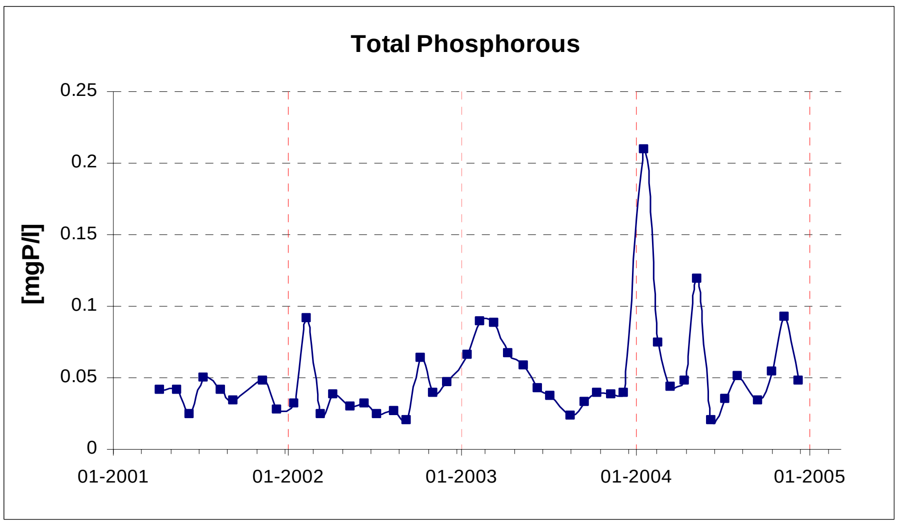

Figure 4-8 - Total Phosphorous variations from INAG database

The total phosphorous seam to follow a steady increase since the monitoring has begun with a geometric average concentration increasing since 2001, Figure 4-9.

This becomes clear by looking at the geometric average of each year

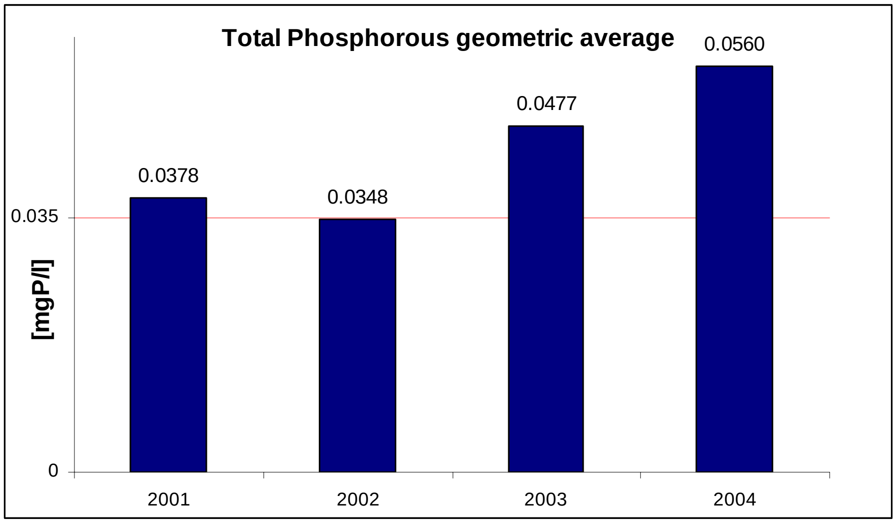

Figure 4-9 - Geometric average Variation

In 2002 total phosphorous values were within the Mesotrophic category. During the next years (ICReW started in April 2003) phosphorous measures were over this limit.

During 2004 the highest values to date were recorded with two values over the $0.1[mgP/l]$ boundary, one of them (in January 2004) was even over the $0.2[mgP/l]$ limit, affecting the yearly average for 2004.

Overall if a moving geometric average is used to create the average concentration for each month throughout these 4 years, February seems to be the month with the highest total phosphorus concentration. From June to the end of the year the overall concentration seams lower than during the first months of the year.

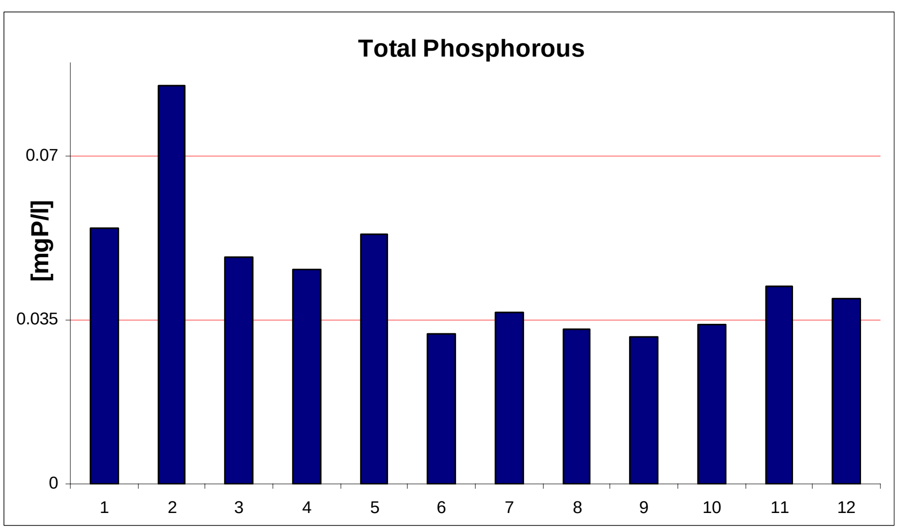

Figure 4-10 Monthly moving average

Orthophosphate concentrations represent the dissolved fraction of the total phosphorous.

Like total phosphorous, orthophosphate concentrations seem to reach their maximum values during winter months when primary production is at its lowest point and water inputs form Sôr river and remaining effluents are at maximum value Figure 4-11 and Figure 4-12

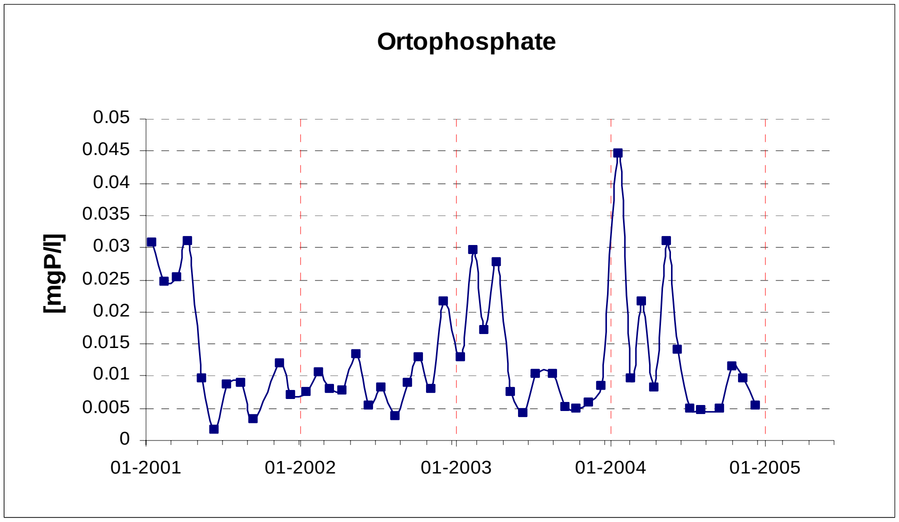

Figure 4-11 - Orthophosphate variations for INAG data

During the wetter months some of the dissolved phosphorous values are even higher that the total phosphorous limit for Mesotrophic systems.

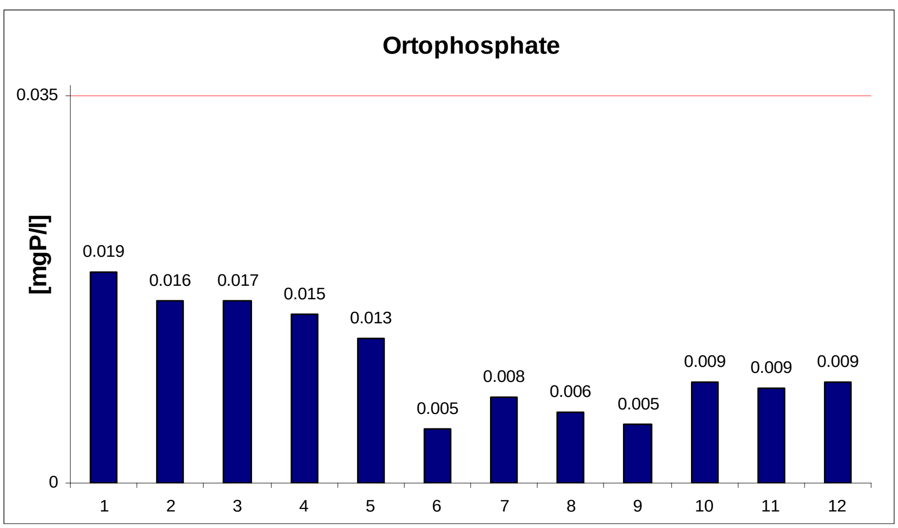

Figure 4-12 - Monthly Averages of Orthophosphate

This is the opposite of what was calculated with river monitor data at "Moinho Novo" (PA2 report), where dissolved and total phosphorous concentrations increased during the summer months.

Unlike the total phosphorous annual averages there is no significant increase of dissolved phosphorous concentration on the reservoir since 2001, there is even a slight decrease for 2004, Figure 4-13.

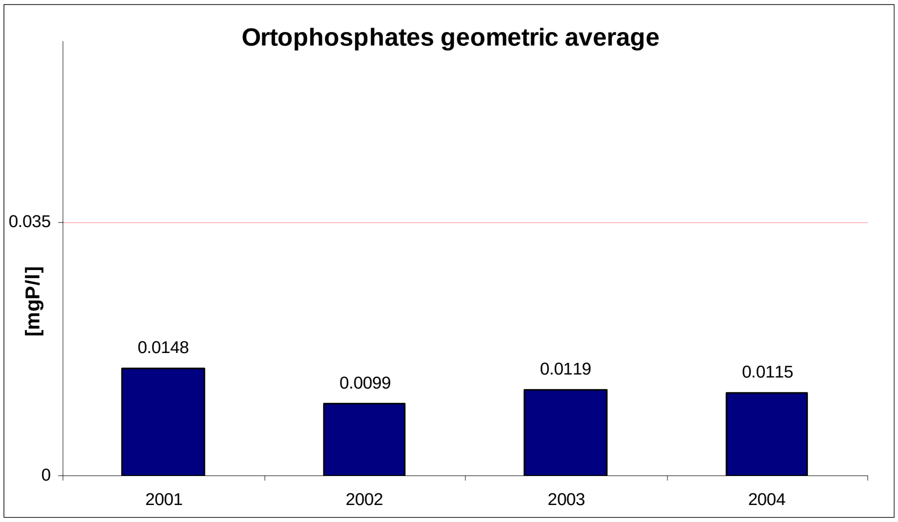

Figure 4-13 - Annual geometric averages for Orthophosphate [mgP/l]

The dissolved fraction of total phosphorous increases when the total concentration diminishes, varying between 21 and 34%.

From this we can conclude that during 2004 the percentage of total phosphorous in the dissolved form was less than in previous year. The mineralization capacities of this system were lower than in previous years.

4.2.2.2. Nitrogen

There are no records for total Nitrogen of Kjeldhal Nitrogen at the INAG database, making it difficult to estimate the total concentration of this nutrient. However Nitrate, Ammonium and Nitrite samples exist on a monthly basis since January 2001.

To try and correct this during ICReW sampling Total Nitrogen was sampled from the beginning of the project at three different locations see Figure 4-5.

The main form of Nitrogen in natural waters, Nitrate follows the same tendency as the total Nitrogen and Phosphorous concentrations, increasing until April and decreasing during the summer months Figure 4-15. A geometric average concentration of $0.76\left[mgNO_3/l\right]$ is calculated from INAG dataset.

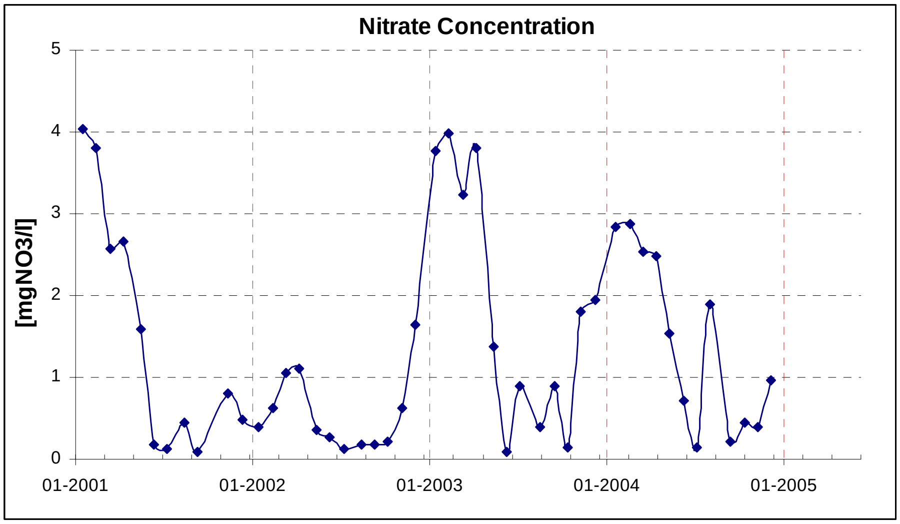

Figure 4-14 - Nitrate concentration variations

During the winter months the contribution of the several tributaries to the reservoir will increase the input of nutrients (phosphorous and Nitrate). Associated with the low consumption of these nutrients by the primary producers due to the lack of solar radiation and low water temperatures typical of winter months, explains the higher

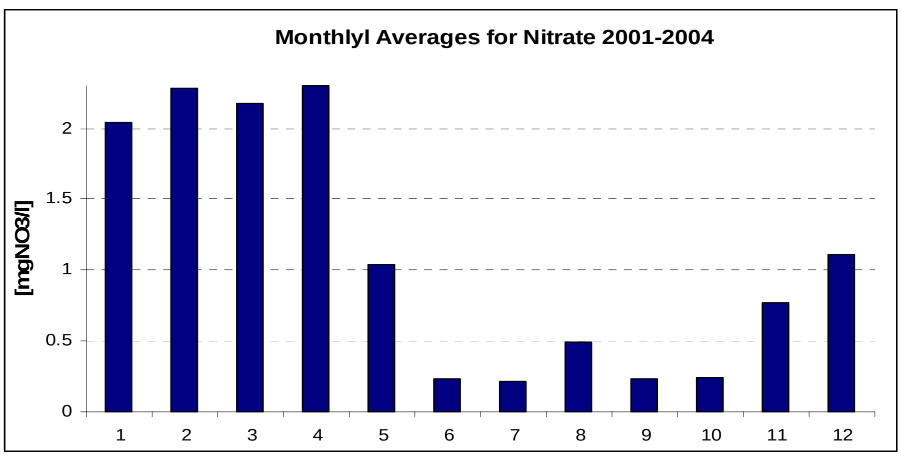

Figure 4-15 - Monthly Averages for Nitrate

concentrations during the winter period when compared to the summer months.

Like in total phosphorous there is a noticeable increase of Nitrate concentrations during these four years, even thought the concentration has diminished during the last year.

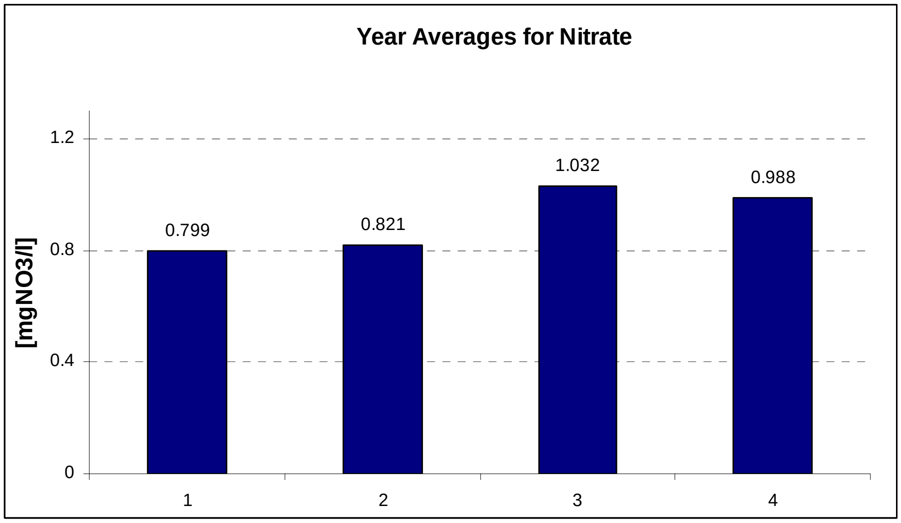

Figure 4-16 - Average annual Nitrate concentration 2001-2003

Ammonium concentrations are usually bellow detection limits in INAG data ($0.04[mg\ NH4/l]$). During the winter of 2002 the higher values of ammonia were registered, but during 2004 a higher annual average of $0.086[mgNH4/l]$ was registered. There were several high values registered during this year alternated with values below detection limit Figure 4-17 - Ammonia Variations.

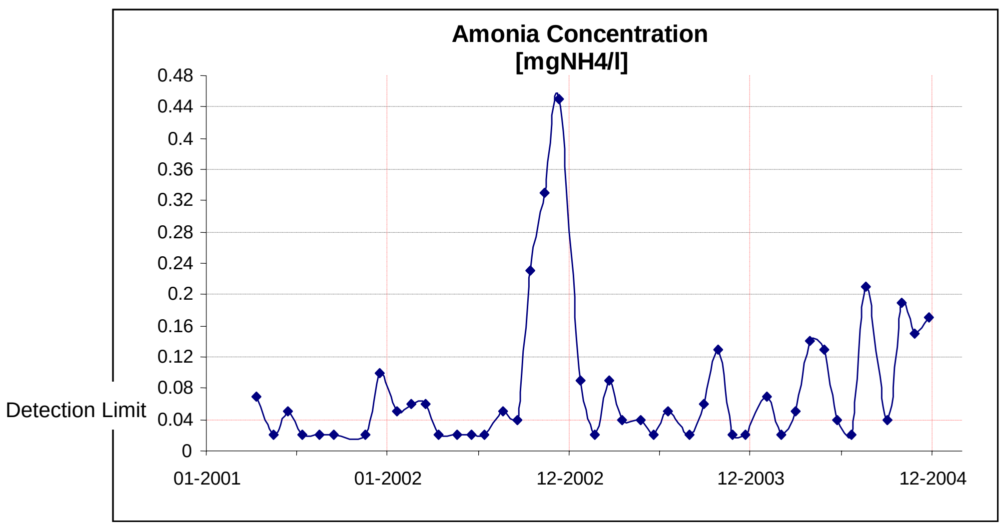

Figure 4-17 - Ammonia Variations

If INAG historical data for inorganic forms of Nitrogen are added and averaged, a concentration of $0.3[mgN/l]$ can be calculated.

Repeating the same procedure for ICReW data, an average value of $0.28[mgN/l]$ is found, about half of the total Nitrogen concentration in the reservoir.

Using the rough approximation that inorganic Nitrogen forms are one half of the total concentration we would expect that an average concentration of total Nitrogen in the reservoir around $0.6[mgN/l]$.

4.2.2.3. Chlorophyll-a

Chlorophyll variations for the reservoir are dependent not only on physical parameters (radiation, water temperature, etc) but also on nutrient availability. All organisms need a delicate balance of several nutrients and photosynthetic algae are not an exception. In this case the two main nutrients considered to limit growth are phosphorous and nitrogen.

The average concentration of chlorophyll-a in the reservoir during the four years is around $8.4[\mu g/l]$, classifying the reservoir as Mesotrophic for this parameter. However according to the national eutrophication criteria the overall classification is overruled by the Eutrophic classification for total phosphorous.

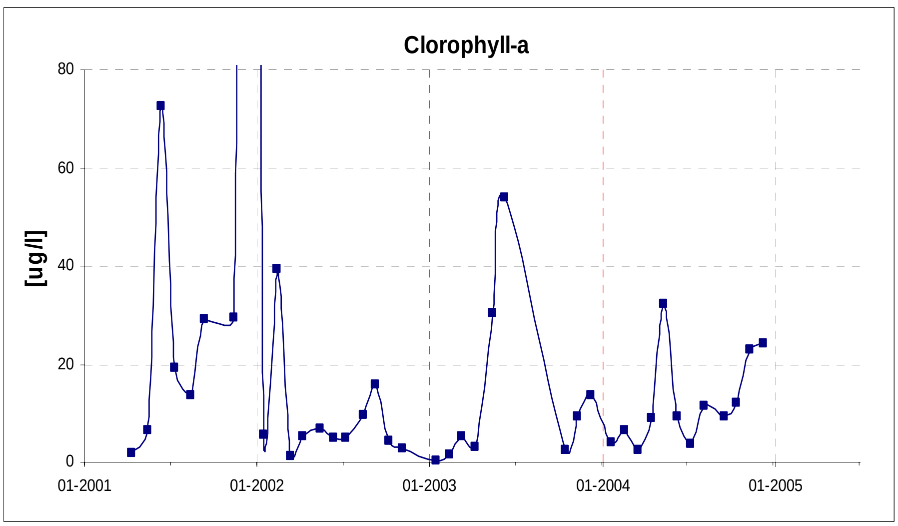

Figure 4-18 - Chlorophyll-a variations

This classification is probably affected by the incomplete dataset used. Only 2004 has one sample for every month. In 2001 there is no data for October, in 2002 no data for December and in 2003 no data for July August and September.

There is a discrepancy on the time of year when concentrations are higher. There seams to be a tendency for three yearly maximums of chlorophyll-a. The first year maximum happens around May followed by a smaller bloom in September and a final maximum at the end of the year in December, Figure 4-19.

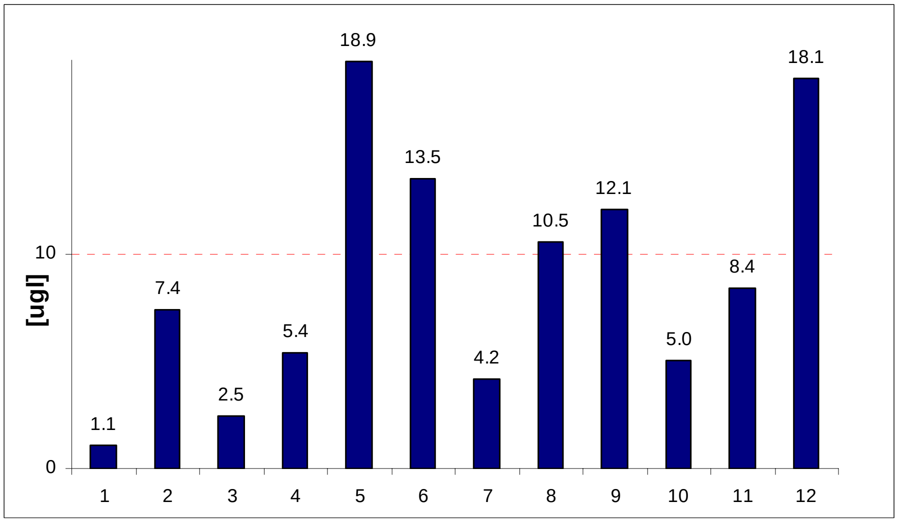

Figure 4-19 - Interannual averages for chlorophyll-a variations

Bibliography (Mateus 2005) describes similar situations. The first bloom would correspond to "normal" Chlorophyceae algae, the second would be related to Cyanophyceae, and the third would relate to Diatoms algae.

This distribution along with the lower nutrient concentration during the summer points to a situation where primary production could be limited during most of the summer due to lack of nutrients.

The bloom that occurs in May would drain the system of most of the dissolved nutrients accumulated during the winter months, following a period of nutrient limited production. This situation is eventually overcome due to mineralization of the biomass of the initial bloom causing the second bloom around September. Stratification phenomena may also play an important role during both the depression period and the second bloom due to the anaerobic release of nutrients from the sediments.

The December bloom is the hardest to explain since December is clearly the month with less radiation and lower water temperatures. Diatoms algae would have the advantage under these circumstances.

The fact that this bloom shows in the interannual averages could be the effect of lack of data in December since both 2002 and 2003 lack sampling in this month. Because there was a reasonable bloom in December 2004 the overall averages are affected.

4.2.2.4. Phosphorus in ICReW data

For total phosphorous the average concentration registered on 2003 and 2004 were lower than in INAG database data. Foros do Mocho registered the highest overall average for total phosphorous with $0.044[mgP/l]$ less than estimated from INAG database for the main segment of the reservoir $0.056[mgP/l]$. Pintado and Praia dos Tesos registered values close to the upper limit of the Mesotrophic division with $0.038[mgP/l]$ and $0.033[mgP/l]$.

For 2004 (the only complete dataset; project started in 2003 and 2005 sampling is still in progress at the time of writing) the average values are a bit higher with $0.045[mgP/l]$ for Foros do Mocho $0.042[mgP/l]$ for Pintado and $0.039[mgP/l]$ for Tesos all values in the Eutrophic category.

Both Pintado and Praia dos Tesos register the same pattern of variation and don't register some of the higher values registered at Foros do Mocho at the end of 2003 and early 2004.

These results are consistent with the location of both the first beaches at the same segment of the reservoir, and Foros do Mocho at one of two main arms.

Even thought the annual average values registered at any of these stations are inferior to data from INAG database, the values measured during May are higher than any registered for INAG data.

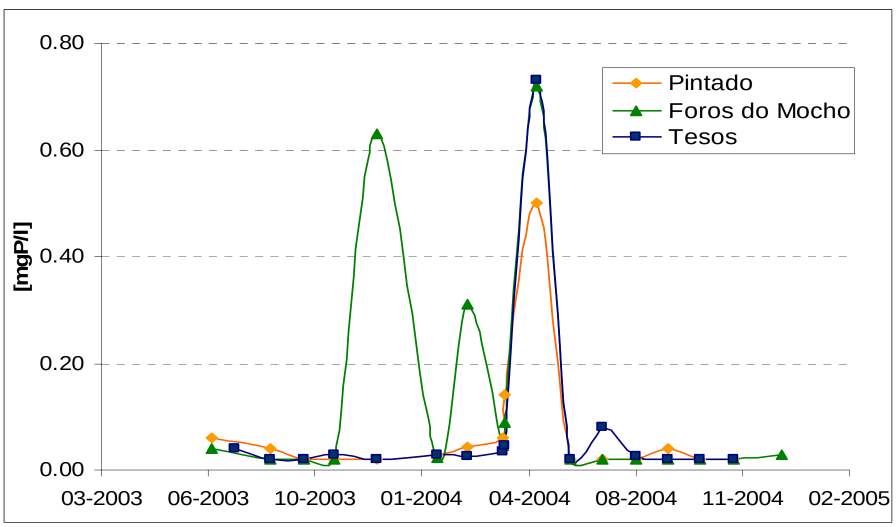

Figure 4-20- Total phosphorous variations over the three reservoir beaches

Orthophosphate analysis confirms the existence of a concentration increase during May, and Phosphorous increases during February for Foros do Mocho.

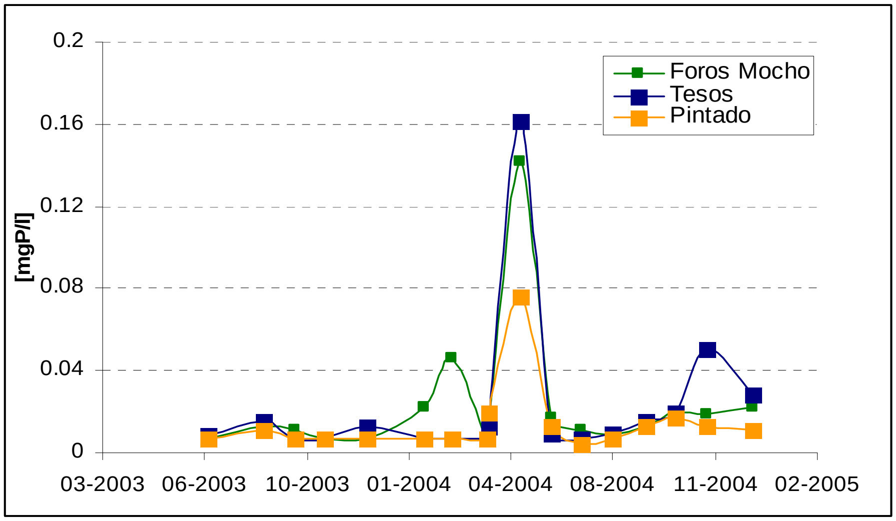

Figure 4-21 - Orthophosphate variations

Point A1 was only sampled bimonthly and there are no values for May, all remaining values ff orthophosphate are consistent with INAG database data and point A2 with Praia dos Tesos.

This suggests that there can be some events associated with this phosphorous increase that did not affect the reservoir close to point A1 or CCDR-A sampling point.

Overall the percentage of dissolved phosphorous is about the same as for INAG data, 30% for Foros Mocho, 34% for Tesos and 25% for Pintado.

4.2.2.5. Nitrogen

Total Nitrogen in ICReW sampling shows an average concentration around $0.5[mgN/l]$ for all sampling points. Overall there is a steady increase from the beginning of the year until April. During the summer months low values are registered followed by a second increase after September Figure 4-22.

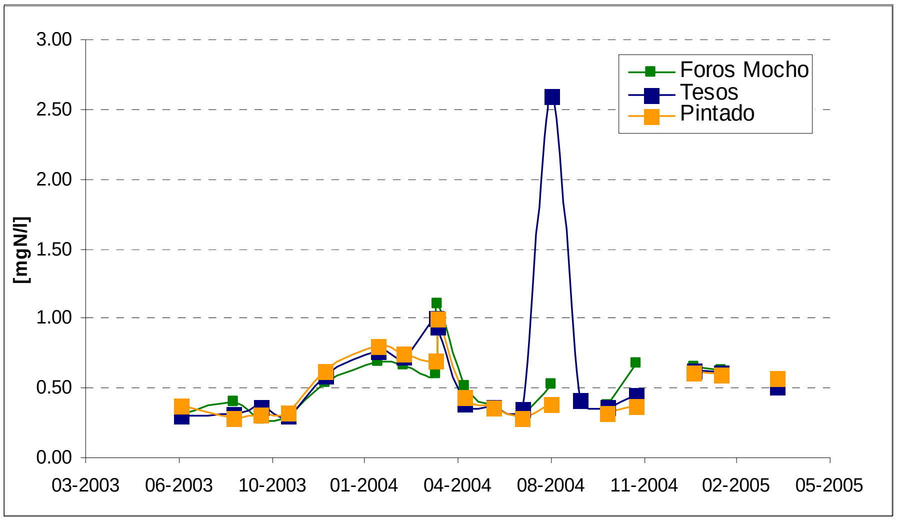

Figure 4-22 - Total Nitrate Variations

There is an exception for Praia dos Tesos were high values for total Nitrogen were recorded in August.

Nitrate concentrations are uniform throughout the reservoir with and increase from the beginning of the year to March – April followed by low values during the summer and an increase after September Figure 4-23.

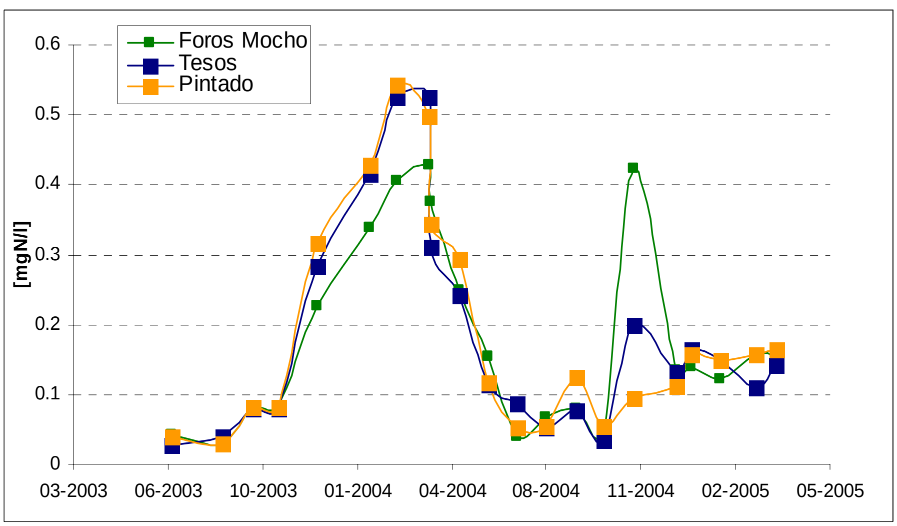

Figure 4-23 - Nitrate Variations

For ammonia Tesos has shown the lowest values throughout the year with yearly average 3 times lower than the remaining points $0.035[mgN/l]$.

The sudden increase close to April could be related to the sudden drop in Nitrate concentrations close to this month.

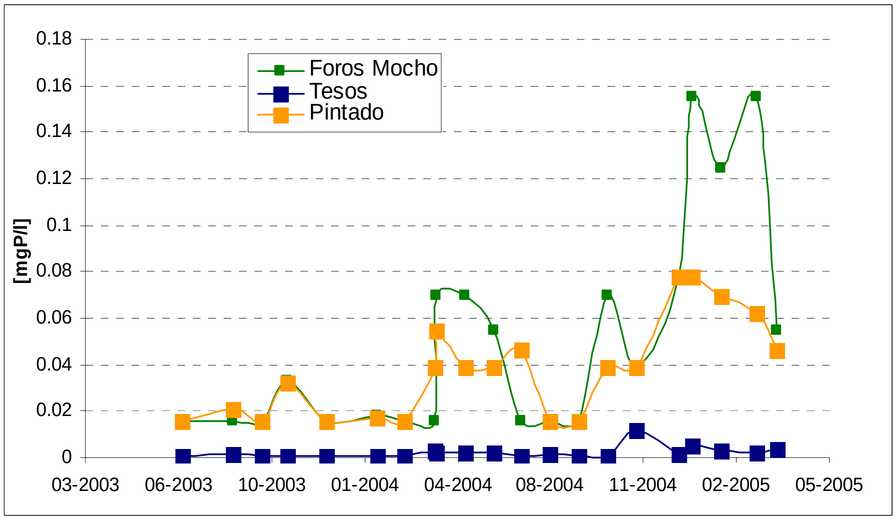

Figure 4-24 - Ammonia Variations

The percentage of organic nitrogen is consistent with the previous descriptions, Figure 4-25. The percentage decreases from the beginning of the year to April. This happens because Nitrate concentration is increasing (discharges from tributary streams).

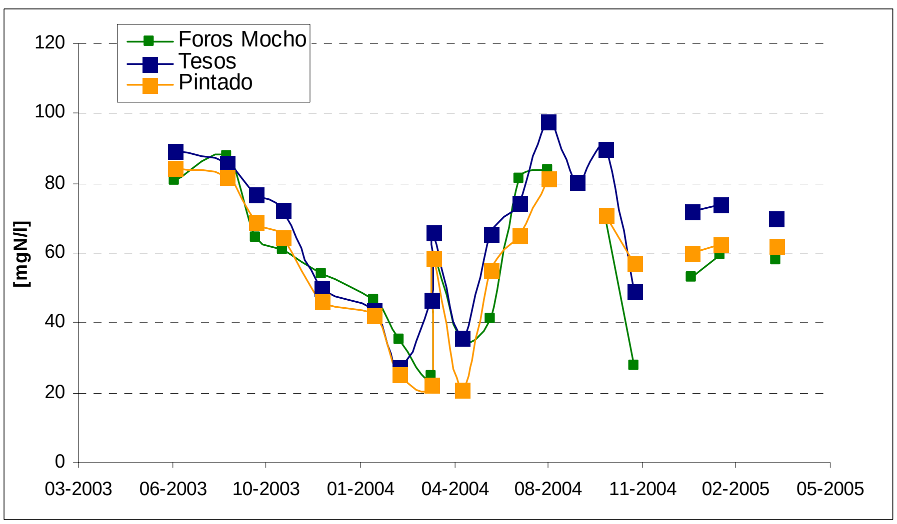

Figure 4-25 - Percentage of organic Nitrogen

Around April the organic Nitrogen percentage of total Nitrogen increases (up to almost 100% during August). Nitrate and other mineral forms of Nitrogen are immobilized in the phytoplankton biomass making up organic nitrogen. This also suggests that during the summer months the growth of primary producers is nutrient limited.

Due to autumn rainfall colder water temperatures and lower radiation values the percentage of organic Nitrogen decreases once again.

4.2.2.6. Chlorophyll-a

The Values Recorded for chlorophyll-a in ICReW sampling are much higher than values available at INAG database. Averages of $20[ug/l]$ were recorded for Foros do Mocho, and $17[ug/l]$ for both Pintado and Tesos. All values in the Eutrophic category.

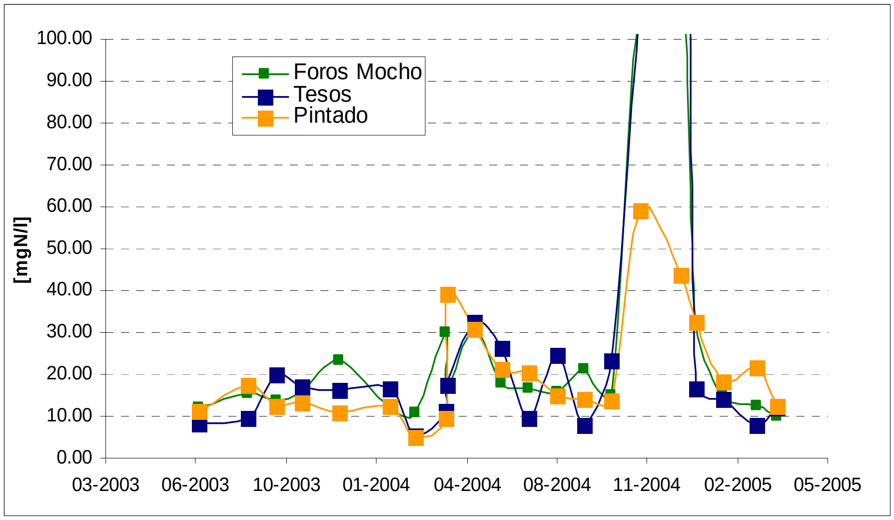

Figure 4-26 - Chlorophyll-a variations

However the variation pattern is consistent with the data from INAG database and historical chlorophyll-a variation patters. Two blooms are registered one close to April and one close to the end of the year.

Both blooms are corresponded by an increase of organic Nitrogen and decrease in Nitrate see Figure 4-22 - Total Nitrate Variations and Figure 4-23 - Nitrate Variations.

The point where both datasets diverge is the November – December rise of chlorophyll-a. The higher values recorded for ICReW data causes the average concentration in 2004 to raise.

4.2.2.7. N/P ration

In 1977 Schindler attempted to explain the dominance of cyanobacteria with the usage of NP ratio. He established that high concentrations of phosphorous and a low NP ratio are favorable conditions for the occurrence of cyanobacteria blooms.

Smith (1983) evaluated data from lakes in temperate zones and concluded that a ratio of total Nitrogen to total phosphorous lower than 29 (TN:TP<29:1) would be favorable for cyanobacteria dominance.

The mechanism proposed by this author for cyanobacteria dominance in low TN:TP ratios concerns the competitive advantages that most species of cyanobacteria have when compared to other phytoplankton species in low Nitrogen environments.

Smith et al. (1983) established a lower limit for cyanobacteria dominance of 22:1, while, Havens et al. (2003) defined this value as 10:1 when only the dissolved forms of Nitrogen and phosphorous are considered.

The average N/P ratio recorded in the reservoir is summarized in Table 27.

Table 27 - Yearly averaged NP ratios

	Foros do Mocho	Pintado	Tesos
Total N/P ration	14	21	22
Mineral N/P ration	25	40	29

All values for total NP ratio are close to the limit proposed by Smith et al. (1983) for cyanobacteria domination. However the dissolved NP ratio is distant from the 10:1 ratio proposed by Havens et al. (2003).

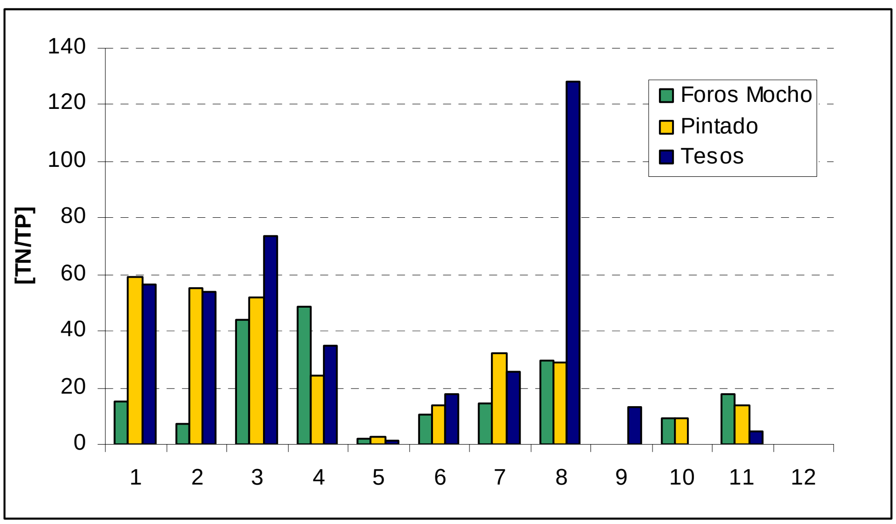

Figure 4-27 - Total N / Total P ratio variation

The total Nitrogen /phosphorous ratio variation (Figure 4-27) is characterized by a strong decrease in April-May, when the first chlorophyll-a bloom occurs. After this initial bloom the ratio rises probably due to mineralization of the biomass of the first bloom.

After this event the ratio decreases again from September to the end of the year.

A similar behavior exists for the mineral Nitrogen/phosphorous ratio (Figure 4-28). Except in this case values are always above the cyanobacteria dominance ratio of 10:1. Only during May the recorded value were close to this limit.

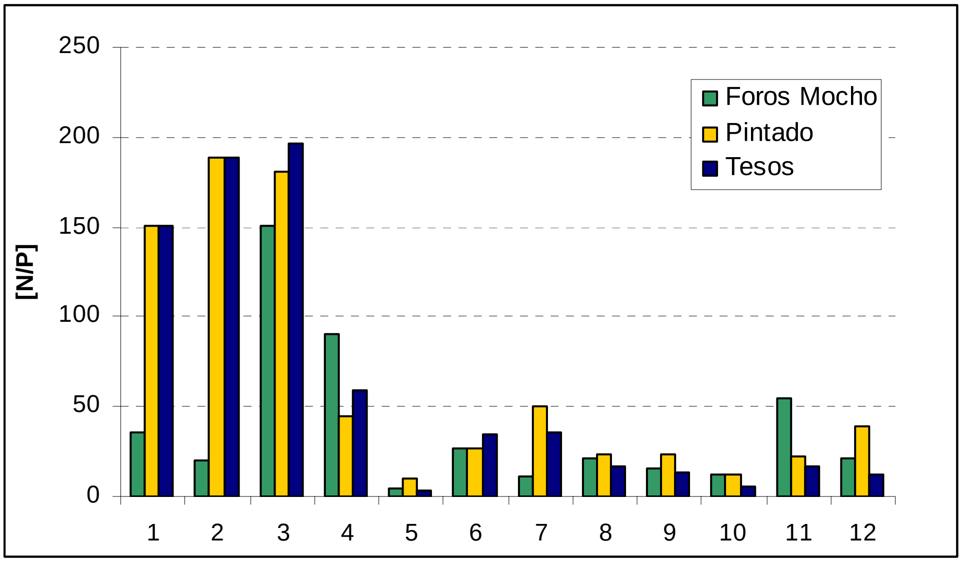

Figure 4-28 - Mineral NP ratio variation

4.2.2.8. Cyanobacteria reports in the reservoir

Cyanobacteria blooms in Montargil have been monitored with various degrees of success since 1995. The most common species present in these blooms belong to the genera:

- *Aphanizomenon (A. flos aquae. A.issatschenkoi)*;
- *Anabaena*
- *Microcystis (M.aeruginosa, M.wesenbergii)*;

The two first have the capacity to use atmospheric nitrogen (N_2) as a source of Nitrogen, obtaining an advantage during N depression periods. The third genera (*Microcystis*) isn't considered a N_2 fixing bacteria (Reynolds, 1984). However it can control its floatability, optimizing light and nutrient supplies.

Historically there was some allusion to blooms in 1995. In 1996 there were several blooms, from May to July, *A.flos-aquae*, *A.gracile*, *Anabaena spiroides* were registered. From July to August, the presence of *M.aeruginosa* and *A.flos–aquae* was noticed (Pereira et al. 2000).

No data exists for 1997, but in May July and August 1998 there were blooms of M.aeruginosa. In September 1999 high values for *M.aeruginosa* and *A.flos–aquae*.

July 2000 there was an intensive bloom of *M. Aeruginosa* in *Pintado*.

2001 registered high values of *A.flos–aquae* and lower values of *Anabaena* e *M.aeruginosa* in May. During August of the same year the roles were reversed and high values of *M.aeruginosa* and lower values de *A.flos-aquae* were registered.

In 2003 there were blooms from April to May of *A.flos -aquae*, *M.aeruginosa* and lower values of *Anabaena*. In September a new bloom of *M.aeruginosa* and *M.wesembergii* was noticed and in December a new bloom of *M.aeruginosa* occurred, continuing thought January 2004.

During the rest of 2004 only one bloom in April with *Woronichinia naegeliana* $27.9\text{E}6[\text{cells/ml}]$, *Aphanizomenon flos-aquae* $17\text{E}3[\text{cells/ml}]$ and *Microcystis aeruginosa* $1.0\text{E}3[\text{cells/ml}]$. This only generated a slight increase of Microcystin to $0.91[\mu g/l]$, since *oronichinia naegeliana* is not referenced as a toxin producing specie.

Unfortunately no data for total Nitrogen is available for most of this period, so total N/P ratios are difficult to estimate, Table 28 resumes all data available for each bloom.

Table 28 - Cyanobacteria event dates and calculated N/P ratios

Date	Species	N/P ratio	Estimated total N/P ratio
5-1996	*A.flos-aquae* *A.gracile* *Anabaena spiroides*	?	?
6-1996	*A.flos-aquae* *A.gracile* *Anabaena spiroides*	?	?
7-1996	*A.flos-aquae* *A.gracile* *Anabaena spiroides*	?	?
8-1996	*M.aeruginosa* *A.flos –aquae*	?	?
10-1996	*M.aeruginosa* *A.flos –aquae.*	?	?
6-2000	*M. Aeruginosa*	?	?
5- 2001	*A.flos–aquae* *Lower* *Anabaena* *M.aeruginosa.*	29.2	?
8-2001	*M.aeruginosa* *Lower* *M.aeruginosa.*	2.6	?
4-2003	*A.flos-aquae* *M.aeruginosa* *Lower* *Anabaena*	58	?
5-2003	*A.flos-aquae* *M.aeruginosa* *Lower* *Anabaena*	19.7	?
9-2003	*M.aeruginosa* *M.wesembergii*	10	?
12-2003	*M.aeruginosa*	29	?
1-2004	*M.aeruginosa*		?

4-2004	*Woronichinia naegeliana* *Aphanizomenon flos-aquae* *Microcystis aeruginosa*	?

4.3. Modelling Results

In order to simulate water quality in the Montargil Reservoir in a way that management options can be considered, two different systems have to be modeled, Rio Sôr Basin and the reservoir it self.

Rio Sôr basin is studied in chapter 3 . The outcome of this study is essential to correctly evaluate the nutrients loads that the watershed discharges in the reservoir. These loads are the key to evaluate the basin management options impacts in the reservoir water quality.

However as seen from the previous data analysis water quality processes in the reservoir are quite complex.

The modeling of these processes requires a model that is capable of:

- Simulate vertical stratification
- Take into account the horizontal heterogeneity
- Simulate hydrodynamic processes so that residence times are correctly taken into account
- Simulate Nitrogen and phosphorous cycle
- Simulate primary producers

These needs eliminate bi-dimensional models with vertical integration (or else the vertical stratification phenomena would be lost). The parameterization of vertical mixing will also require an adequate turbulence model. One-dimensional vertical models wouldn’t allow the simulation of horizontal heterogeneity.

Finally this hydrodynamic model must be associated with an adequate water quality model that simulates the main nutrients, primary producers, organic mater and dissolved oxygen.

Having this in mind the CE QUAL W2 model could be selected, since it satisfies all of the necessary requirements.

CE QUAL W2 is an hydrodynamic and water quality model supported by US Army Corp’s of Engineer’s, in the Waterways Experiments Station (WES). It simulated the relevant chemical and physical processes that occur in water systems such as the relation between temperature, nutrients, algae and oxygen.

The model is in continuous development since the 70´s. Originally the model was known as LARM (Laterally Averaged Reservoir Model), a model developed by Edinger and Buchak (1975).

Initially it was written in FORTRAN 77. Later the model was actualized to an object oriented version and with other changes that allowed the use of several reservoir segments and border conditions for estuaries. This resulted in a code known as GLVHT (Generalized Longitudinal-Vertical Hydrodynamics and Transport Model). Water quality algorithms added by WES originated CE-QUAL-W2 version 1.0 (created by Environmental and Hydraulic Laboratories in 1986).

The water quality routines present in CE-QUAL-W2 allow the simulation of Nitrogen and phosphorous cycle along with carbon cycle and oxygen. Any number or primary producer may also be specified.

MOHID water is a numerical model initially developed for application on estuaries and costal areas. The development of this model started in 1985 with a vertically integrated bidimensional model (Neves, 1985). Lagrangian and Eulerian transport routines were coupled to this model.

Later in 1995 MOHID went 3D with a phd thesys (Santos 1995), with a double sigma vertical coordinate (Braunschweig 2001). The limitations imposed by this type of vertical coordinate led to the development of a general vertical coordinate model that would allow the vertical coordinate to be selected according to the type of application. This finite volume model is described in (Martins 1999). A Turbulence model was implemented by Celho 1996 and three dimensional Lagrangian transport by Chambel 1996.

The first water quality model was coupled by (Miranda 1999) and the generalization of this model for reservoirs was accomplished in 2001 by Braunschweig 2001. This this adaptation a vertical harmonic coordinate was implemented allowing better description of the vertical stratification process (Braunschweig 2001).

In 1998 MOHID suffered a general restructuration driven by an object oriented philosophy (Miranda et. al. 2000). This created a very modular model where new calculation routines can easily be included.

Taking advantage of the modular object oriented structure of MOHID the CE-QUAL-W2 routines were included in a new MOHID module (Afonso 2003). During this thesis these routines were upgraded to be compatible with the new inter fortran compliler.

The next section describes the application of the MOHID model to the Montargil reservoir using the CE-UAL-2 water quality routines.

During this thesis an adaptation of an orthogonal grid generator was added to MOHID GIS. The original source code is available online by CSIRO marine at http://www.marine.csiro.au/~sakov/. This orthogonal grid generator for the interior of polygonal regions is based on the CRDT algorithm (Tobin A. Driscollu and Stephen A. Vavasisz, 1998), which, in turn, uses Schwarz-Christoffel transform. Later the source code for this generator was ported to a windows c++ library by a former Maretec researcher, Hernani Teias during 2003.

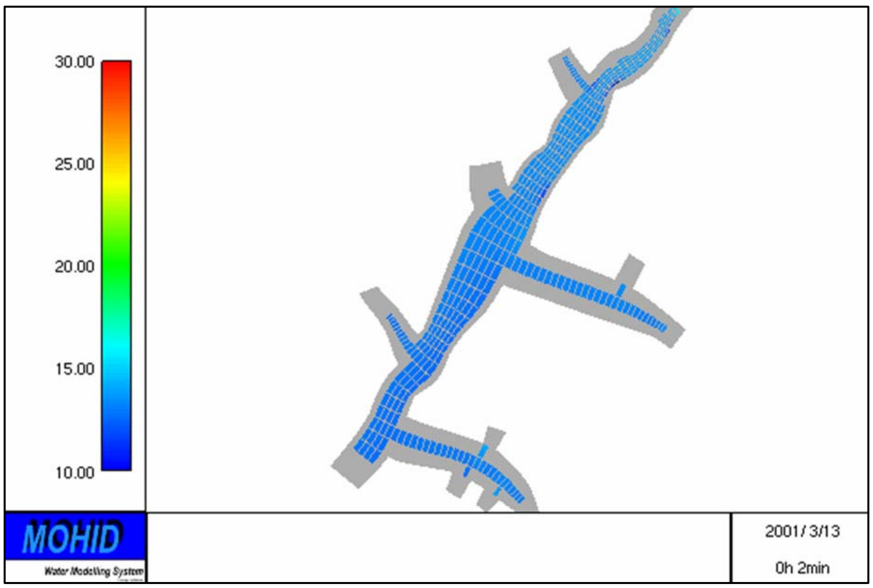

Figure 4-29 - Curvilinear grid used to simulate the Montargil Reservoir

The inclusion of the ability to simulate hydrodynamic in curvilinear grids was implemented by another Maretec researcher Paulo Chambel during 2004. Even thought the author didn't participate directly in the implementation of these calculus routines a small explanation of how this was accomplished follows.

The dietortion caused by the grid is added to the momentum equation under the form of an inertial force. This methodology is used in POM (Mellor, 2003) and other similar models. In this case the force in the X and Y directions are described by:

$$F_{x\,centrifugal} = f_x \cdot v \cdot V \wedge f_x = v\frac{(\Delta y3 - \Delta y1)}{\Delta x2 \cdot \Delta y2} - u\frac{(\Delta x3 - \Delta x1)}{\Delta x2 \cdot \Delta y2}$$

$$F_{y\,centrifugal} = f_y \cdot u \cdot V \wedge f_y = u\frac{(\Delta x3 - \Delta x1)}{\Delta x2 \cdot \Delta y2} - v\frac{(\Delta y3 - \Delta y1)}{\Delta x2 \cdot \Delta y2} \qquad (1)$$

Where $\Delta x1, \Delta x2, \Delta x3, \Delta y1, \Delta y2, \Delta y3$ are described in Figure 4-30 and u and v are the velocities along the x and y axis.

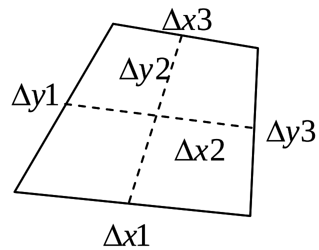

Figure 4-30 – Control volume geometry.

4.5. Results

A calibration period between 2001 and the end of 2003 was selected to adjust the reservoir model.

Simulation includes no epiphyte and three algae, with parameterizations suggested by Sullivan and Stewart A. Rounds 2000 when using the original CE-QUAL-W2 model to simulate Chlorophyceae, Cyanophyceae, and Diatoms.

Whether data from only Montargil weather station was used for wind intensity, direction and air temperature and humidity and solar radiation.

Temperature calibration can be seen in Figure 4-31. Unfortunately there was no available data on vertical temperature distribution, the INAG data explorer application points Albufeira do Monte Novo as the only reservoir with a monitoring program that includes temperature measures at three depths.

Figure 4-32 shows the simulated vertical temperature profile. There is a clear stratification pattern at the beginning of summer that is later broken when cold water form the initial winter months floods the reservoir.

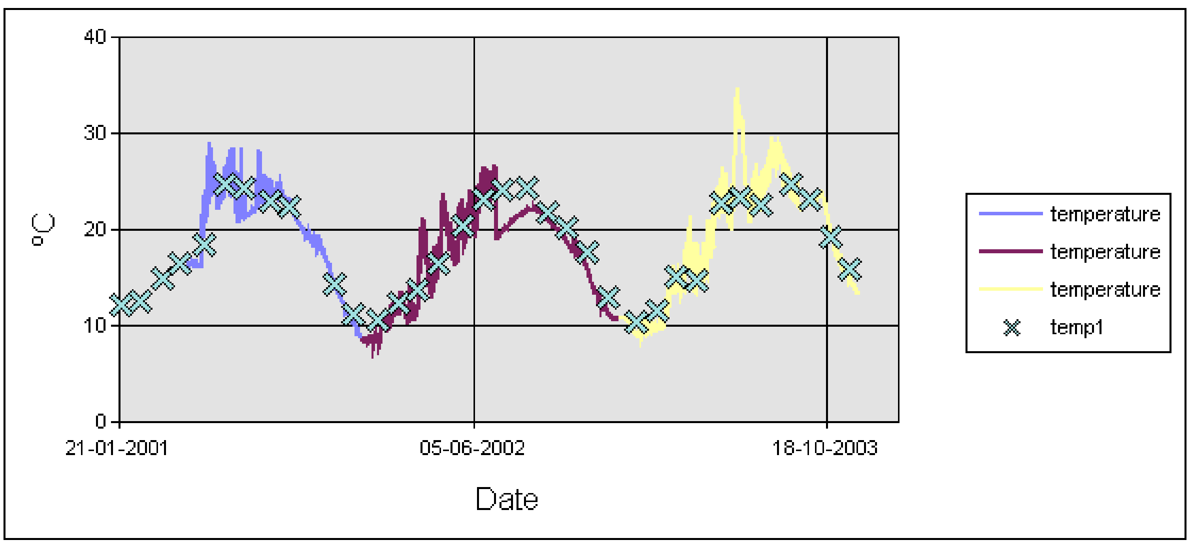

Figure 4-31 - Simulated and recorded surface temperature

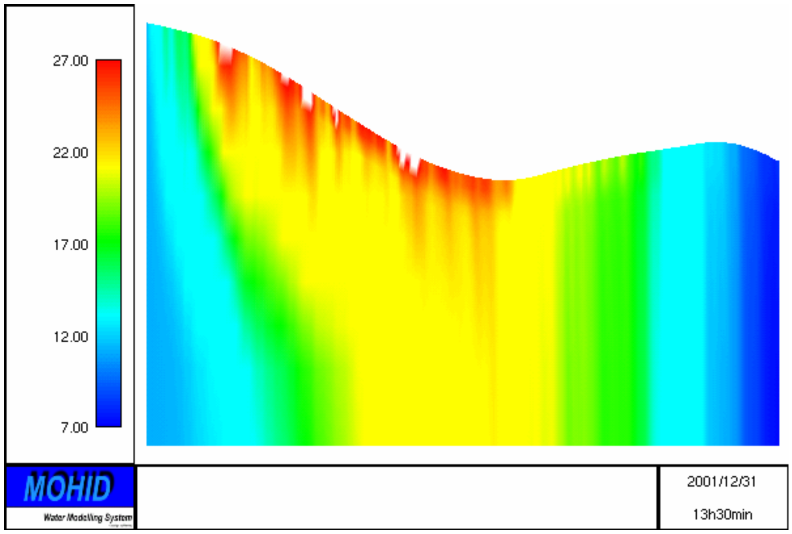

Figure 4-32 - TZ simulated temperature distribution

The modeled NP rations are far from conditions that will enable cyanobacteria dominations due to atmospheric N fixations.

Figure 4-33 shows the measured chlorophyll-a data in $[\mu g/l]$ and total Chlorophyceae biomass. Both datasets relate well except for the high values registered in December 2001. These values where accompanied by a decrease in Nitrate and orthophosphate in the reservoir. A parameterization for different algae in needed to correctly simulate this measure.

The simulated nitrate levels have a good relation with registered levels in the reservoir, except for the decrease during start of 2002 (accompanied by the registered chlorophyll-a increase).

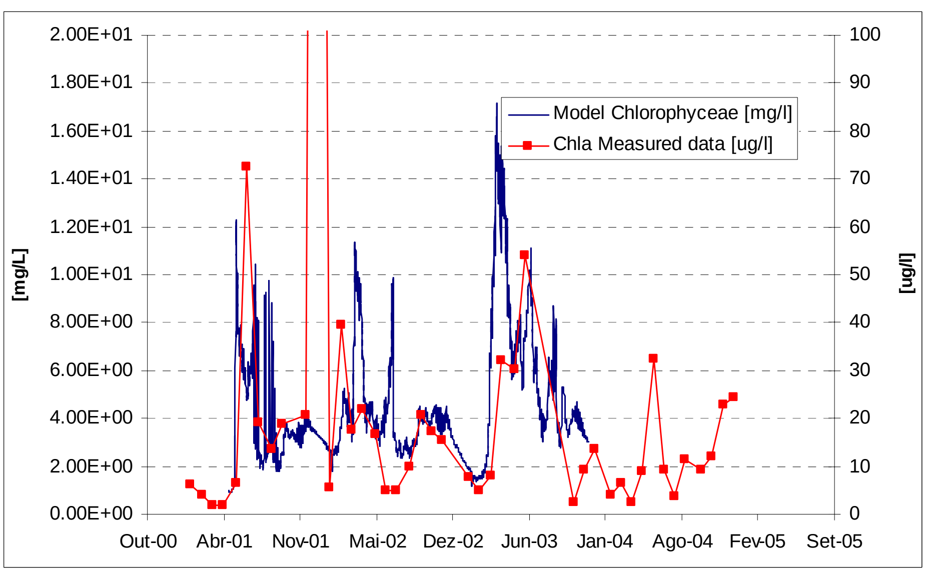

Figure 4-33- Nitrate

However results for orthophosphate show depression period during the summer months that isn't registered in the observed data.

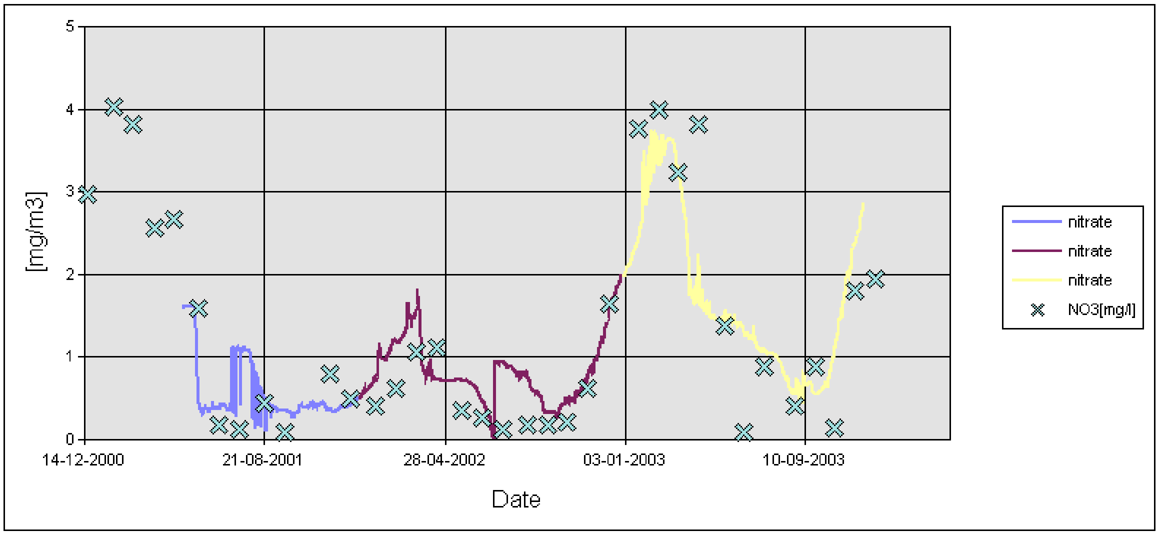

Figure 4-34 - Modeled and observed Nitrate levels

This creates a phosphorous limited situation at the surface giving advantage to algae that can control it's floatability like the *M.aeruginosa* cyanobacteria.

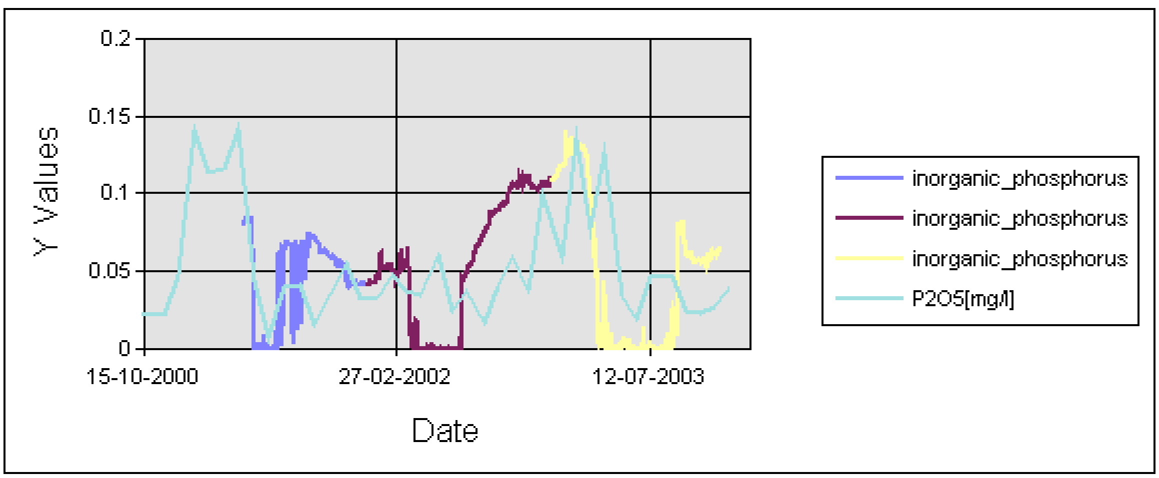

Figure 4-35 - Ortophosphate variations

5 Conclusions

The Montargil reservoir is currently not a nitrogen limited reservoir observed and modeled NP ratios are high enough to avoid nitrogen fixing bacteria problems.

However due to high turbidity in the reservoir species such has *M.aeruginosa* might gain a competitive advantage by optimizing light form upper layers and nutrient availability from deeper levels. To correctly simulate this situation new parameterization for algae parameters in CE-QUAL-W2 must be experimented.

Nutrients loads to the reservoir have a high influence from Olive oil production plants see 3.3. This causes an unstable situations since most of the production plants on Montargil have productions that are very variable in time. Some years the olive oil production may even be zero.

Human pressure on the reservoir from urban point sources has much lower values than agriculture. However the impact of point sources is noticed during the summer period close to Moinho novo. This influence causes ammonia and orthophosphate concentrations to increase during this period.

5.1. Future Directions

MOHID Land has proven to produce some interesting results; however simpler methods should be implemented to generate runoff. This would allow users to make a fast calibration of other processes than infiltration and surface runoff.

SWAT can be used to estimate hydraulic parameters for the Portuguese soil classification using stream flow stations with daily flow values. This would be a great contribution for the implementation of a homogeneous basin model for the national territory.

MOHID has increased its speed by 40% during the execution of this theses, part because of a new compiler (almost 20% faster), new processors with higher cache values and code changes that allow the usage of smaller grids to describe the domain and variable time steps. However at the time of writing MOHID still needs two days to simulate three years with the grid used to simulate the Montargil reservoir. The original CE-QUAL-W2 application can do this in three hours. Once again this makes the calibration of MOHID more difficult than the original applications.

Even thought the fully three dimensional hydrodynamics used in MOHID has opposed to the simpler laterally averaged hydrodynamic used by CE-QUAL-W2 accounts for most of this speed decrease, the transport routines used in MOHID seem to suffer with the high number of species needed in this sort of simulations.

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