Assessing the impact of historical urbanization evolution patterns on surface water quality - the case of the Cértima catchment in central Portugal

Henrique Alves[a], Peter Roebeling[b], João Rocha[c] Pedro Almeida[d]

(a) Dept. Environment and Planning - CESAM - University of Aveiro, Portugal
henriqueteloalves@ua.pt

(b) Dept. Environment and Planning - CESAM - University of Aveiro, Portugal
peter.roebeling@ua.pt

(c) Dept. Environment and Planning - CESAM - University of Aveiro, Portugal
joaocrocha@ua.pt

(d) Dept. Environment and Planning - CESAM - University of Aveiro, Portugal
pedrof.almeida@ua.pt

ABSTRACT

As the urbanization around the world continues to grow, concerns over the degradation of water quality and increasing pollution have arisen in the majority of experts discourse in the areas of planning, ecology, economics and biology leading to the study of land use processes beneficial to improvement and maintenance of water quality. In Portugal the urbanization process started later than in most parts of western Europe, mostly since the mid 70's and took the heaviest toll in the coastal areas which are, in some cases, severely threatened by a boost in pollution levels affecting the water quality, ecosystems processes, economic development and the quality of citizens life. Located in the Vouga river basin, in central Portugal, the Cértima catchment is the most polluted in Portugal and amongst the top-ten of most polluted in Europe. The river Cértima flows into the Pateira de Fermentelos, a shallow and natural freshwater lagoon hosting an important wetland area and corresponding vulnerable ecosystem showing serious eutrophisation problems. Using a spatial stream flow model we assess the extent to which historical urbanization patterns impacted the surface water quality in the Pateira de Fermentelos.

Results show that while urban land use increased from only 5% to 8% over the concerned period of 1975 to 2006, nitrogen water pollution from urban areas increased 25%. By 2006, more than half of N and P loads originated from urban areas – largely explaining eutrophisation issues in the lagoon. We show the potential benefits of crossing the data outputs of a calibrated SWAT model with multitemporal land use cartography aiming at studying and understanding the impacts of urbanization evolution patterns on water quality.

KEY WORDS: *urbanization, watershed modelling, water quality, eutrophisation, SWAT .*

INTRODUCTION

While water resources have been considered vital to the possibility and quality of human life, it has only been in recent years that the relevance of a holistic management of water resources has become apparent. Based on social, environmental and economic sciences, water resources management frameworks have been developed within the research community to cope with the complexity of water resources management issues as to improve its outcomes (Medema *et al.*, 2008). Integrated Water Resources Management (IWRM) is a water resources management framework with a multi-decade history of development and application (Medema *et al.*, 2008), generally described as a continuous "process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP-TAC, 2000). The key objective of IWRM is to achieve more holistic sustainable water resources management through stakeholder coordination and integration (Braga, 2001) – i.e. resources management knowledge being produced by those stakeholders that most adequately reflect the complex relationships between water, land and related processes as well as their governance systems (Medema *et al.*, 2008).

The EU Water Framework Directive (WFD) is a European legislation that establishes an integrated approach on management and protection of Europe's aquatic environment. The main objective of the WFD is to achieve good chemical and ecological status for receiving waters by 2015, and mandates Member States to develop river basin management schemes. This planning mechanism is intended to ensure integrated management of the river environment, providing a decision-making framework for setting environmental objectives (WFD, 2000). It mainly focus on agricultural and urban areas (WFD, 2000) as urban wastewater and agriculture activities are the main sources of urban water pollution and of eutrophying nutrients in many water ecosystems (Elnabousi, 2011).

As the world population increasingly concentrates in urban areas the landscapes have suffered a series of human induced transformations which have caused various effects on stream ecosystems namely increase in impervious surface cover within urban catchments, increase in municipal and industrial discharges resulting in increased loading of nutrients and sediments among other stream contaminants which have led, in turn, to the decline of the richness of algal, invertebrate and fish communities, impairment of use of water for drinking, industry, agriculture, recreation and other purposes (Paul, 2001; Carpenter 1998). Also as the bare ground, scrub and forest cover within and around urban areas are transformed to impervious surfaces like roads, parking, roof tops and other impermeable surfaces and thus increasing the total imperviousness of an area, the increase in runoff and additional avenue for the transportation of nonpoint source pollutants contributes to degrade the water quality (Wilson, 2010).

Despite all the threats urbanization poses to catchments water quality, there has not been a synthesis of the ecological effects of urbanization on streams (Paul, 2001). However, urban land cover and its associated population and domestic water use have been positively associated with increases in water pollution and included as an important explanatory variable for variations in all water quality parameters across different scientific fields like planning, ecology, economics and biology in past years such as Carpenter 1998, Wilson 2010, and Mouri 2011. Urban streams represent, thus, opportunities for studying disturbance of the ecosystems processes and related water quality variation and contribute to more effective landscape management (Paul, 2001) being the assessment of the water quality resulting from LULC change a critical challenge to environmental scientists (Wilson, 2010).

Portugal has experienced in the last 40 years a rapid economic development and urban population growth which has outpaced, in many cases, the construction of environmental infrastructure designed to contain the effects of pollution generated by the increasing population namely lack of connection to sewage networks, of water treatment plants or of a holistic and effective environmental planning.

The Cértima catchment is part of the bigger Vouga river Basin in central Portugal. Its main river, the Cértima, drains an area of about 535 km^2 occupied mainly by forest and agricultural areas (around 90% of the total area) urban areas (roughly 9%) and surface water bodies making up the rest of the catchment. Pateira de Fermentelos, a lagoon of variable area according to the seasons, reaching a maximum of 5 km^2 during winter, and considered by many as the largest natural lagoon of the Iberian Peninsula, sits at the end of the Cértima catchment, one of the most polluted in Portugal and in Europe, and shows serious ecological threats and problems, namely eutrophisation. Eutrophisation is a process which derives from the excessive increase of the quantity of nutrients in a water mass, namely a lake, which in turn give way to the proliferation of phytoplankton and aquatic plants that start to filter the sunlight and eventually blocking it completely from the layers of water underneath, aided by the increase in sediments which concur to the same outcome. These processes increase the sedimentation rate and the lake starts to narrow and eventually can disappear (Ramade, 2005). This phenomenon was classified by the International Lake Environment Committee (ILEC) as one of the major risks affecting lakes and reservoirs all over the planet (Lagha, 2012). Nitrate (N), phosphorus (P) and suspended sediments (SS) are three of the most common parameters used to evaluate streams water quality and water quality variations related to mixed agricultural and urban settings found in literature (Mouri, 2011; Schaffelke, 2012; Wilson, 2010; Pratt, 2012). The impact of the particular phosphorus and nitrogen on eutrophisation is a complex process depending largely on the stream hydrodynamics, season, and capacity of the suspensions to yield or fixate the phosphate and nitrogen ions as well as the capacity of the algae to utilize the nutrients from the sediments (Dorioz, 1998).

In this study we assess the extent to which historical urbanization patterns evolution impacted on surface water quality in the Cértima catchment, focusing on the Pateira de Fermentelos lagoon which lies at the end of the catchment. We apply a spatially explicit watershed model, Soil and Water Assessment Tool (SWAT 2009), to estimate the contribution of nutrients and sediments yielded by the changing land cover. To this end we use a previously built and calibrated SWAT model for the period 1980-1990. Afterwards we used multitemporal cartography of the urban areas of 2006 and 1975 to rebuild the model, keeping all the remaining data inputs the same. Finally we gathered the simulated data of the pollution levels of the Pateira de Fermentelos lagoon for the three moments and quantified the impacts of the urbanization processes on water quality, by differentiating the contributions of urban, agricultural and forestry areas. We also expect to show the potential benefits of crossing the use of SWAT modelling with multitemporal cartography in helping to monitor, assess and plan the urban expansion with regards to improving the water quality in water masses and catchments.

METHODS

Experimental Set-Up

The Soil and Water Assessment Tool (SWAT) is designed to assess the land management practices on water

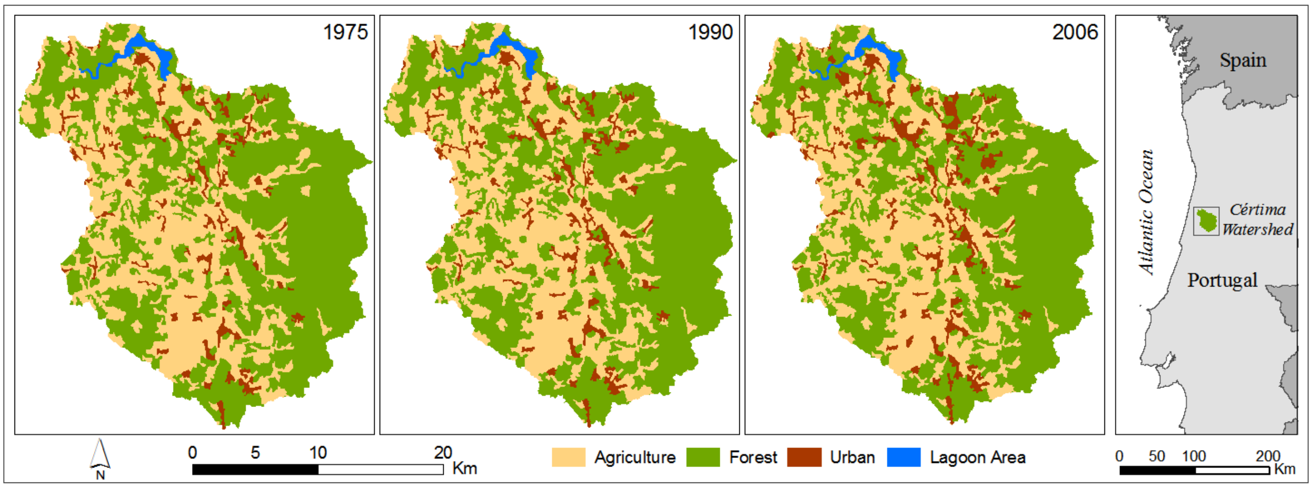

Figure 1 - Evolution of the Land Cover in the Cértima catchment across the time span

resources and pollution loading in watersheds and large river basins over long periods of time. SWAT operates on a daily time-set basis but can be cumulated to obtain monthly or annual outputs. The model uses a command structure to route runoff and nonpoint source pollutants through a watershed. SWAT is divided into several subcomponents which encompass hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. SWAT model requires numerous data which encompasses land use, soil, elevation, precipitation, temperature, humidity, stream flow, and water quality input to facilitate surface water flow and quality modelling (Arnold *et al.,* 1998). In this study, we employed SWAT version 2009.93.5.

The model was built up using: topography (SRTM90; Jarvis *et al.*, 2006), land use (CLC, 2006), vegetation cover (FAOSTAT, 2012), soil types (SROA, 1970) and daily meteorology (IM, 2012; SNIRH, 2012). The calibration was made for a 6 year period (starting in September 1977 and ending in October 1984), using the available hydrological data (SNIRH, 2012) for 2 gages (Vila Nova de Monsarros e Ponte de Águeda).

Gathering and execution of multitemporal historical cartography

To achieve the best possible representation of the land use and land cover of the three chosen moments, 1975, 1990 and 2006, several different methods were followed. Firstly we already had the land use and land cover for 1990 as the model was built to simulate that time period – a set of generalizations and groupings of classes based in the CORINE Land Cover (CLC - EEA) map of 1990. So, to allow the minimum possible change in the model, apart from the urban areas expansion, we used the urban areas of the 2006 CLC map and superimposed it to the land use map of 1990. This way we discarded all the information regarding the other classes of 2006 the idea being to avoid any other interference in the model apart from urban expansion. For the 1975 land use map there was no CLC map available, as the watershed lies 20km away from the coast, beyond the buffer for the CLC of 1975. The solution here was to use the 1990 CLC map as a base. To create the 1975 urban areas we used military cartography from the 1970's, and clipped the parts of the 1990 urban areas polygons which were not urban in the military cartography. To fill the voids created by the clippings we extended the polygons representing the different land covers in the direction they were at the contact point with the original 1990 urban areas.

Running the SWAT model for the three moments

Two models were recreated from the 1990 model to represent the years 1975 and 2006. All the main inputs, constants, parameters, and databases were equal. The simulation running period was also the same, as well as the weather inputs, so virtually being 3 simulations for the same time step. It is the same as assuming that the weather patterns would be repeated for all the time steps. This was done, again, to avoid any interference in the model so the changes in the results could be explained exclusively by the more or less soil occupation by urban areas. It is useful to keep in mind, though, that there are some changes in the models which imply a deviation from the expected results as simply a process of varying the amount of urban expansion. First, forestry and agricultural areas decrease their soil occupation areas across the time steps in a disproportional way, so, for example, forest loses much more area both in absolute terms and in percentage than all the agricultural areas. Second, as all the areas increase or decrease their occupation over time they also sit in different proportions on the various classes of soil and slopes, affecting the processes by which SWAT calculates the outputs.

Table 1. Land Cover change across the time span

	1975		1990		2006	
Land Cover area	***ha***	***%***	***ha***	***%***	***ha***	***%***
Urban	2923	5,6	3393	6,4	4480	8.5
Agricultural	18335	34,8	18157	34,5	17926	34,1
Vineyard	8923	17,0	8836	16,8	8764	16,7
Pasture	4903	9,3	4853	9,2	4771	9,1
Corn	1786	3,4	1773	3,4	1740	3,3
Potatoes	1634	3,1	1618	3,1	1590	3,0
Oats	1090	2,1	1078	2,0	1060	2,0
Forestry	31368	59,6	31076	59,1	30220	57,4
Cértima Watershed	52626	100	52626	100	52626	100

Calculating pollution outputs and the urban contribution

The output values for N, P and Organic N were calculated by multiplying the average output of the different land covers, given in weight per area per time lapse, by the area of each of the land covers thus getting a quantity of weight per time lapse, adjusted to tons per year. This way, we got the precise amount each land cover contributed to the overall nutrient loading. The Total Suspended Sediments (TSS) output values had to be indirectly calculated because SWAT computes a concentration instead of weight or weight per area output. Basically, the average runoff at the end of the watershed, which corresponds to Pateira de Fermentelos, was multiplied by the concentration of TSS at the same spot, thus getting a quantity of weight per time lapse, adjusted to tons per year.

Observation values

There was a need to gather observations of pollutant levels for comparison with the modelled values, so as to test the effects of the land use changes on one hand, and to get an idea of the accuracy of the model itself regarding water quality. Observation values of the Cértima watershed are sparsely available both in spatial and temporal terms. There are no official values for the watershed as a whole in the River Basin Management Plan of the Vouga River, the administrative plan which covers the Vouga river basin and its sub-basins, including the Cértima watershed, as it is divided in sub-basins bigger than Cértima. A way to circumvent this obstacle was to gather readings from the SNIRH (National Water Resources Information System) gages along the Cértima catchment. Apart from the fact that the only two nearby gages were located upstream of the Pateira de Fermentelos and downstream of the point the river Águeda, from another watershed, joins the Cértima river, thus definitely compromising a reliable comparison. There were several other problems: no readings for 1975 for any of the considered pollutants; very few readings for N

Table 2. Nutrients and TSS exports across the time span from the model outputs

	1975	1990		2006	
Exports	***ton***	***ton***	***%****	***ton***	***%****
N of NO3	293	318	8,4	369	25,9
P	49	49	-0,2	49	-0,7
Organic N	153	153	0,02	153	-0,2
TSS	23404	22954	-1,9	21967	-6,1

**growth relative to 1975 values*

and P in 1990, 4 each, and 2006, 10 and 13 respectively; comparatively more readings for TSS, 12 and 70 for the 1990 and 2006 periods, but no values for the exact years, so the values are an average of the two years before and after the time step; no Organic N readings or other readings which indirectly could allow a calculation for any of the years. Trying to complement and enrich this information we then looked for readings in other sources, having finally used two master thesis, Silva, 2008 and Ferreira, 2007 about the water quality of the Cértima watershed. In total we gathered 21 readings spread across the four pollutants for 2006 and none for 1990 or 1975. We then averaged all the readings for each parameter and covered all four for the years 1990 and 2006.

Results

The results are presented in two steps: first the variation of the areas of the different land covers across the three moments; second the impact the variation had on the emission of pollutants and resulting water quality levels at the Pateira de Fermentelos.

Table 1 shows that urban areas went from occupying 2923 ha of the watershed in 1975 (5,6% of the total) to 3393 ha (6,4%) in 1990 and finally to 4480 ha (8,5%) in 2006. This represents a growth rate of over 53% between 1975 and 2006. On the other hand, agricultural and forestry land cover decreased their percentage of occupied area, 34,8% to 34,1% and 59,6% to 57,4% respectively for the years 1975 and 2006. The agricultural crops all decreased their areas at a rate of -2,7%, apart from vineyard which decreased 1,8% between 1975 and 2006.

Table 2 shows model outputs 293 tons of N in 1975, increasing to 318 tons in 1990 and 369 tons in 2006. The growth of the N exported was thus 25,9%. The exports of P and Organic N, on the other hand, showed a decrease, even if small, of about 0,7% and 0,2% respectively between 1975 and 2006. The amount of TSS exports went from 23404 tons in 1975 to 21967 tons in 2006 with a decrease of 6,1%.

Table 3 - Nutrients and TSS exports across the time span from observations

	1975	1990		2006	
Exports	***ton***	***ton***	***growth %****	***ton***	***growth %****
N of NO3	n/a	324	n/a	409	n/a
P	n/a	30	n/a	43	n/a
Organic N	n/a	n/a	n/a	348	n/a
TSS	n/a	4746	n/a	4777	n/a

**growth relative to 1975 values*

Table 4 - Nutrients exports by Land Cover type in 2006 from the model outputs

	Urban	*Agriculture*	*Forest*	*Cértima Watershed*
ton/year				
N of NO3	209	88	71	368
P	2	45	2	49
Organic N	7	139	7	153
Kg/ha/year				
N of NO3	45	5	2	7
P	0,5	3	0,1	0,9
Organic N	1,6	7,7	0,2	2,9

For control values (Table 3), unfortunately, there were no observations that could indicate the amounts of N, P, Organic N or TSS exports for 1975. For N the modeled values were similar to those observed: 318 tons modeled versus 324 tons observed in 1990 and 369 tons modeled versus 409 tons observed in 2006. The observations confirm the exports increase tendency from 1975 to 2006 that the modeled results show. For P, only the values of 2006, 49 versus 43 tons, were similar, with a much greater difference in 1990, 49 versus 30 tons. The observations show, thus, a steep increase from 1990 to 2006, contradicting the results of the model which indicate the exports suffer a minor decrease. For Organic N there is only one observation value for 2006. It shows a great difference, more than the double of the modeled result. Unfortunately there is no other observed value for the other moments so as to compare the growth tendency of the exports. Finally the observed exports of the TSS are almost a fifth of those modeled both in 1990 and 2006, which indicates an important deviation from observed values but, on the other hand, shows a certain degree of proportionality between them. The growth rates are also very similar: slight decrease both in the modeled and in the observations values.

Exports by land cover (Table 4) were also calculated for the three moments. We use here the year 2006 values of total export per year, for better assessment of the present levels of pollution, and the values of export per area per year, which is roughly steady along the time steps. There are no values for TSS as the model database concerning the TSS doesn't disaggregate the results by land cover. Clearly, the biggest contribution of N exports per area per year, by a very large margin, is the urban land cover with 45 kg/ha/year against 5 from agriculture and only 2 from forest. In absolute terms the exports of the urban areas, with 209 tons/year represented almost 57% of the total while in 1975 they accounted for only 45%. As for P and Organic N, the biggest exports contributor both in absolute and in per area per year terms is the agricultural land cover with 92% and 90% of the total exports respectively.

CONCLUSION

Results show an increase of the nutrient pollutants reaching the Pateira de Fermentelos lagoon by more than 25% between 1975 and 2006. At the same time there was a reduction of TSS exports by 6,1% in the same period.

The exports of nitrates are strongly positively correlated to the expansion of urban areas which can be easily related to the fact that the urban areas, although occupying a significantly small portion of the catchment, export a much larger quantity of nitrate per area than agricultural or forestry areas. On the other hand, the exports of P and Organic N suffer almost no variation or only a slight decrease, explained by the fact that, although the agricultural areas are by far the biggest per area contributors of the exports of both these nutrients, the agricultural areas suffer a relative smaller proportional reduction in area compared to the increase of urban areas. The TSS exports show a steady decrease, which can be explained by the increase of impervious areas which inherently yield much less sediments than the agricultural or forestry soil.

Overall the results were confirmed by the observations but in some cases they were contradicted, although the small number and the short time span of the observed readings might have a great influence in the accuracy of the assumed values. Similar studies like Paul, 2001, Wilson, 2010, Mouri, 2011 or Dixon & Earls, 2012 also point to the same results

The approach we followed overlooks the impact of the population variation, both in absolute numbers and in density, on the pollution levels. Taking it as another variable would improve the accuracy of the model and, most importantly, its resemblance with reality.

This study clearly shows the potential benefits of crossing the data outputs of a calibrated SWAT model with multitemporal land use cartography aiming at studying and understanding the impacts of urbanization evolution patterns on water quality, and can be further developed to become a relevant tool in the assessment and implementation of environmental planning.

ACKNOWLEDGEMENT

We thank the Centre for Environmental and Marine Studies (CESAM) at the University of Aveiro for facilitating this research. This study has been developed within the context of the Iberian Trans-boundary Water Management (IB-TWM) project, funded by the Fundação para a Ciência e a Tecnologia (FCT; PTDC/AAC-AMB/104301/2008) and the Fundo Europeu de Desenvolvimento Regional (FEDER; FCOMP-01-0124-011867-FEDER).

LITERATURE CITED

Arnold, J. G., *et al.*, 1998. Large area hydrologic modelling and assessment part i: model development. *Journal of the American Water Resources Association*, 34, 73–89.

Bouzid-Lagha, S. & Djelita, B., 2011. Etude du phénomène d'eutrophisation dans le Barrage de Hammam Boughrara (Wilaya de Tlemcen, Algérie). *Hydrological Sciences*, 57(1), 186-201.

Braga, B.P.F., 2001. Integrated Urban Water Resources Management: a challenge Into the 21st Century. *International Journal of Water Resources Development*, 17(4), 581-599.

Carpenter, S. R., *et al.*, 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, 8, 559–568.

CLC. 2006. CORINE Land Cover 2006. Instituto Geográfico Português (IGP), Lisbon.

Dixon, B. & Earls, J., 2012. Effects of urbanization on streamflow using SWAT with real and simulated meteorological data. *Applied Geography*, 35, 174-190.

Dorioz, J. M., *et al.*, 1998. Proprietes physico-chimiques et biodisponibilite potentielle du phosphore particulaire selon l'origine des sediments dans un bassin versant du lac Leman (France). *Water Research*, 32(2), 275-286.

Elnaboulsi, J. C., 2011. An efficient pollution control instrument: the case of urban wastewater pollution. *Environmental Modeling & Assessment*, 6(4), 343-358.

FAOSTAT. 2012. FAO Statistical Databases & Data-sets. Food and Agriculture Organization (FAO) of the United Nations. Available at: http://faostat.fao.org/default.aspx. Accessed 3 December 2012.

Ferreira, R. S. V., 2007. Avaliação hidroquímica e da qualidade da água na bacia do rio Cértima (Portugal). Master thesis, University of Aveiro, Aveiro, Portugal. 119p.

Global Water Partnership – Technical Advisory Committee (GWP-TAC), 2000. Integrated water resources management. TAC Background Paper No. 4. GWP, Stockholm, Sweden.

IM. 2012. Instituto de Meteorologia. Available at: www.meteo.pt. Accessed December 2012.

Jarvis, A., H.I. Reuter, A. Nelson and E. Guevara. 2006. Hole-filled seamless SRTM data V3. International Centre for Tropical Agriculture (CIAT), Cali. Available at: http://srtm.csi.cgiar.org. Accessed 15 October 2012.

Medema, W., *et al.*, 2008. From premise to practice: a critical assessment of integrated water resources management and adaptive management approaches in the water sector. *Ecology and Society*, 13(2): 29.

Mouri, G., *et al.*, 2011. Spatial and temporal variation in nutrient parameters in stream waterin a rural-urban catchment, Shikoku, Japan: Effects of land cover and human impact. *Environmental Management*, 92, 1837-1848.

Paul, M. J. & Meyer, J. L., 2001. Streams in the urban landscape. *Annual Review of Ecology, Evolution, and Systematics*, 32, 333-365.

Pratt, B. & Chang, H., 2012. Effects of land cover, topography, and built structure on seasonal water quality at multiple spatial scales. *Hazardous Materials*, 209-210, 48-58.

Schaffelke, B., *et al.*, 2012. Water quality in the inshore Great Barrier Reef lagoon: Implications for long-term monitoring and management. *Marine Pollution Bulletin*, 65, 249-260.

Silva, M. H. M. P., 2008. Avaliação e monitorização integrada do estado da qualidade da água do rio Cértima. Master thesis, University of Aveiro, Aveiro, Portugal. 128p.

SNIRH. 2012. Sistema Nacional de Informação de Recursos Hídricos (SNIRH). Available at: http://snirh.pt. Accessed October 2012.

SROA. 1970. Carta de solos de Portugal, volume I: classificação e caracterização morfológica dos solos – 6th Edition. Serviço de Reconhecimento e de Ordenamento Agrícola, Secretaria de Estado da Agricultura, Ministério da Economia, Lisbon.

WFD. 2013. Water Frame Directive (WFD). Available at: http://ec.europa.eu/environment/water/water-framework/. Acessed February 2013.

Wilson, C. & Weng, Q., 2010. Assessing Surface Water Quality and Its Relation with Urban Land Cover Changes in the Lake Calumet Area, Greater Chicago. *Environmental Management*, 45, 1096-1111.