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Key words: phosphorus loads, point source, non-point source, land-use, erosion, GIS, Thau lagoon catchment, Mediterranean coast

Abstract

In Thau coastal lagoon, phosphate concentrations have decreased by 89% from 1971 to 1994. The present relatively long term (over 25 years) study compares changes in the contribution of point (PS) and non-point sources (NPS) total phosphorus (P) loads. The analysis of the distribution of the sources in comparison with the changes in the phosphate concentrations in the Thau lagoon aims to point out their relative impact in order to create a sustainable management plan for this system. This is needed, firstly because water quality supports shellfish farming, which is the main economical activity of the basin. Secondly, because the population is planned to increase by 40% between 1995 and 2020 thus leading to an increase of urban pressures. PS P loads, represented by discharges by wastewater treatment plants, have increased by 143% while NPS P loads, both represented by export from lands and loads from non-connected population, have decreased by 64%. Despite important changes in land-use by an exceptional decrease of vineyards areas (−12.5%), domestic effluents main contribute (>60%) to both PS and NPS P loads and seem to be more implicated in the decrease of phosphate concentrations in the Thau lagoon, probably because of the different phosphorus forms engaged.

Introduction

Since the industrial revolution, the N and P contamination of natural systems has been highly correlated with human activities (Vollenweider, 1971). Both industrial, agricultural and sewage from population contribute to the enrichment of natural waters. Furthermore, because of their poor water turnover, Mediterranean coastal lagoons are particularly responsive to fluxes from catchments (Frisoni, 1987). For example, during the 1970s, severe anoxia events and eutrophication occured in French Mediterranean coastal lagoons (Vaulot & Frisoni, 1986). In particular, in 1987 in the Thau lagoon, shellfish farms suffered from considerable losses estimated at 5 million Euro because of these events (Garrabé & Cabassut, 1989). Despite this and the lack of nutrients limiting politics, a 89% decrease of phosphate concentrations occured in the water column of the Thau coastal lagoon between 1971 and 1994 (La Jeunesse, 2001).

This observed trend on phosphate concentrations can be explained both by a new ecological equilibrium in the Thau lagoon and by changes in total phosphorus (P) quantities generated by human activities on the Thau catchment. The study considers the second hypothesis by analysing the changes in point (PS) and non-point source (NPS) P loads produced. PS-P loads studied are represented by loads generated by wastewater treatment plants. NPS-P loads studied are represented by export from lands (both cultivated,

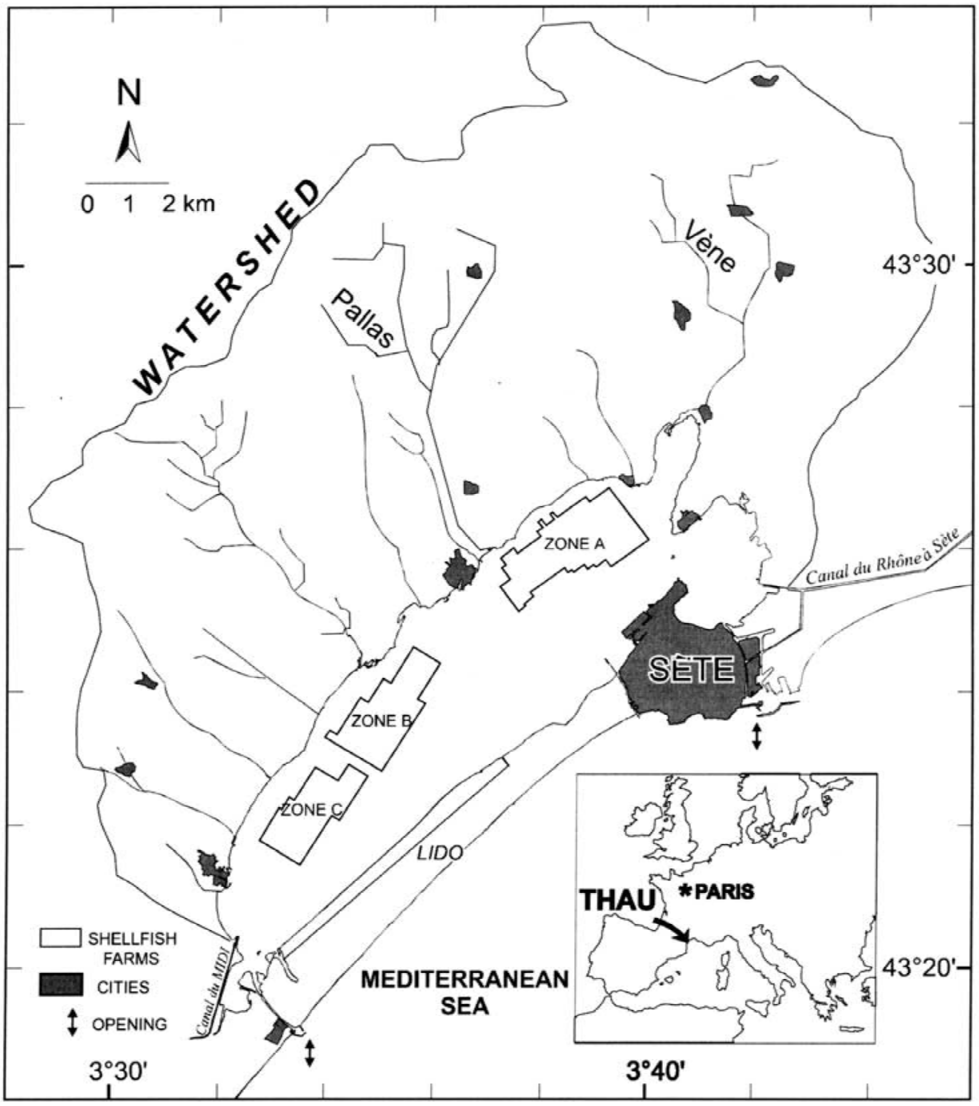

Figure 1. The Thau coastal lagoon and catchment.

non-cultivated and urbanised) and also by loads from the non-connected population. A long-term study is necessary to evaluate the impact of PS and NPS-P loads on the Thau lagoon in order to support decisions for a sustainable management of the system. The latter is required, firstly because water quality has to continue to support shellfish growth and secondly because from the French National Institute of Statistics and Economical Studies a 40% population growth is planned between 1995 and 2020 in the Thau region. In fact, this paper focuses on NPS-P loads and it complements an analysis of PS P loads presented elsewhere (La Jeunesse, 2001). And, even if nitrogen is the first limiting factor of primary production in the Thau coastal lagoon (Vaulot et Frisoni, 1986; Mazouni et al., 1996), the study of nitrogen trend has not already been done. P loads produced by sewage depend on population and on the proportion of effluents treated by wastewater treatment plants. As sewage are discharged directly into rivers in the Thau catchment and because of the Mediterranean weather characteristics impact already described, it is assumed that all wastes should reach the lagoon within a year.

The impact of catchment on P transfer in surface waters depends on regional geology, erodability and land-use (Dillon & Kirchner, 1975), catchment size

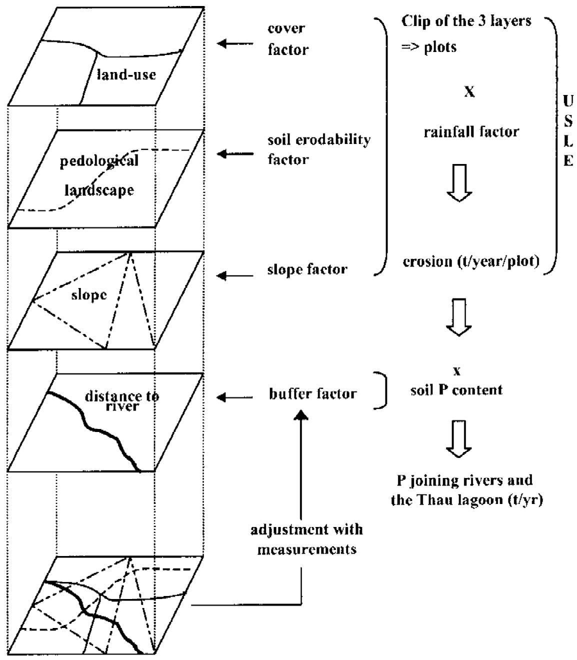

Figure 2. GIS-based P export model principles.

(Bolton & Ward, 1993), shape and topography (Osborne & Wiley, 1988), precipitations (Wichmeier & Smith, 1978) and soil P content (Pote et al., 1996). Interpretation of P transport factors is usually simplified assuming erosion controls particulate P movement and runoff dissolved P movement (Sharpley et al., 1993). Firstly, the Thau catchment is controlled by Mediterranean weather conditions characterized by hot and dry summers and by intense rainfall events where autumn storms can represent up to 75% of the annual rainfalls (Tournoud et al., 1997). Secondly, analysis of P forms in the Thau catchment's soils following the Olsen method (Olsen et al., 1954) show particulate forms represent more than 96% of the P soil content. Hence, not only particulate P is the major proportion (75–90%) of P transported from cultivated land (Sharpley et al., 1987) but also it is mainly exported during the largest storm events (Johson et al., 1976). Thus, it is assumed here that NPS-P loads on the Thau catchment are mainly produced by soils' rainfall-induced erosion.

As required data for export coefficients approaches (Norvell et al., 1979; Reckhow & Simpson, 1980) were not available on the Thau catchment within the study period, a modelisation approach is used. As deterministic models of erosion require too many data usually not available at the catchment scale (Benkhadra, 1997), an empirical erosion model is used: the Universal Soil Loss Equation established by Wischmeier & Smith (1978). This model is linked here to a GIS as it provides (1) large amounts of input data required by the model and reduces uncertainty caused by spatial averaging (Lenzi & Luzio, 1997), (2) identification of environmental sensitive areas and (3) appraising alternative management strategies and programs (Tim et al., 1992).

Because of everything that is said, the objective of the present study is to discuss the contribution of the changes of human activities during the past 25 years on the Thau lagoon's phosphate concentrations. An analysis of land-use change on erosion and phosphorus export will be done. Then, an estimation of the impact of population growth and sewage improvement will be discussed to compare PS and NPS-P load changes and its eventual implication in changes in the Thau coastal lagoon's phosphate concentrations.

Description of the study site

The catchment covers 250 km^2 including a total population of 80 000 inhabitants with half of them concentrated in the city of Sète (Fig. 1). The total population doubles each summer through tourism (SIEE, 1992). As 40% of the catchment is occupied by vineyards, wine and raisin production is the main agricultural activity. Large areas of soil surface remain uncovered, even during the growing season, due to the wide spacing of the plants and weedings. There is only a small industrial activity concentrated in the city of Sète mainly represented by two units of fertilizers production.

The Olsen fraction (bioavailable forms, Oslen et al., 1954) represents in the soil of the Tau catchment 3.10% (±S.D. 1.19%) of P forms and dissolved inorganic phosphorus represents 0.18% (S.D. 0.09%). Therefore, >96% of P element is in particular form. Then, as already observed in other sites (Svendsen et al., 1995), there is no significant relation between P soil content and land-use (ANOVA, p=0.985) or pedological landscape definitions (p=0.3236). Thus, a mean soil P content of 745 ppm (±S.D. 483 ppm) measured on 33 samples collected in July 1998 is used.

The Thau coastal lagoon covers 75 km^2 and it has a mean depth of 4 m with a maximum of 11 m. Its volume approximates 300 Mm^3 and the tide does not exceed 30 cm. It receives freshwater from many small and mostly non-permanent streams from the catch-

Table 1. P loads generated by the population

P loads from sewage	1971	1996
Connected population to a wastewater treatment plant	13%	92%
P loads from connected population (t/yr)	12.4	30.1
P loads from non-connected population (t/yr)	77.0	11.9

ment. Shellfish-farming covers one fifth of the total area with an annual production of shellfish of approximately 15 000 tons (Deslous-Paoli et al., 1998). In the Thau coastal lagoon, shellfish-farming and fishing are the designated priorities because of both exceptional nutritional potentialities of the lagoon and their major economic contribution to the region.

Methods

Annual P loads generated by each inhabitant, resident or tourist, are assessed by multiplying the daily P waste (function of detergent consumption) by 365 days. For the connected population, assessed with water consumers bills, the treatment rate of wastewater treatment plants, differing with process used (activated sludge, natural lagoons...) and chronic dysfunctioning occurring, is implemented to loads generated. P loads from non-connected population are supposed to have no treatment and to contribute entirely to diffuse pollution (La Jeunesse, 2001).

The Universal Soil Loss Equation (USLE, Wischmeier & Smith, 1978) has been implemented to plots resulted from clips between three layers: land-use, pedological landscape and slope (Fig. 2). This permits us to use not average plot values for each factor (respectively C, K and S) of the USLE. The USLE enables us to calculate quantities of sediments exported by erosion from each plot. All the P contained in these sediments is assumed here to be exported. A buffer effect during transfer is assumed here to be proportional to the distance to the river, concept already applied to P transfer on a more humid zone (Lake Geneva sub-catchment: Bouchardy, 1992). Four classes are arbitrarly defined: 0–100 m, 100–200 m, 200–500 m and $>$500 m to which corresponds, respectively, to 80%, 50%, 20% and 0% of P joining the stream.

The rainfall data used are from June 1995 to May 1996, chosen as a mean of average rainfall (a mean of a wet and a dry year). The rainfall intensity factor used resulted in a mean of the factor calculated with the region's rainfalls over 20 years (Pihan, 1979).

ArcInfo and ArcView 3.1 GIS software have been used to manipulate the data in digital form and determine and analyse USLE parameters directly from maps. A Digital Elevation Model has been extracted from the 1:50 000 National Geographical Database, BD-Carto (IGN, National Geographic Institute, 1994), to obtain slopes and superficial hydrosystem covers. Pedological landscape layer was extracted from the 1:250 000 Regional (Languedoc-Roussillon) Database (Robbez-Masson et al., 2000). The land-use is the interpretation of ortho-rectified aerial photographs (IGN) of summer 1971 (1:17 000 black and white paper photographs) and summer 1996 (1:25 000 colour CD-Rom and paper photographs). Ground validations were carried out in 1998 for land-use plots which did not changed between 1996 and 1998. Then, National and Departmental Agricultural Statistics (Recensement Général Agricole: 1970, 1979, 1988; Direction Départementale de l'Agriculture: 1996) indicate the main cultivated areas at a district scale in 1970, 1979 and 1988.

Urban areas are also concerned by runoff due to some wastes and detergents used to clean the cities. P quantities exported are assessed to approximated 2.5 kg P/ha of urban areas/year (Vollenweider, 1971).

Results

The connecting population to a wastewater treatment plant increased from 13% to 92% between 1971 and 1996 (Table 1). Because of this in particular, PS P loads have doubled and NPS P loads have decreased by 85%.

The main evolution of land-use in the Thau catchment is the important decrease of vineyards which represented 48.4% of the catchment (Table 2) in 1971 against 35.6% in 1996. Those 12.5% areas lost have been built upon 4.8% or abandoned (fallow-land and forest-garrigue: 4.6%) and or replaced by cropland

(3.2%). National statistics (Recensement Général Agricole: 1970, 1979, 1988) indicate the decrease of vineyards occurred linearly during the study period (r^2=0.994).

The increase of urbanised areas induced a proportional increase of urban run-off reaching now 6.9 t/yr and representing 10% of the P loads assessed here (Table 5).

The GIS-based erosion model run for 1971 and 1996 estimates an average decrease of 27% in sediments exported from plots by erosion leading to a 21% decrease in P export because of land-use changes (Table 3). The S.D. attached to P export is here due to the S.D. on measurements on soil P content.

The spatial analysis of the contribution of land-uses show the importance of vineyards (Table 2) representing more than 80% of P export both in 1971 and 1996. The decrease of vineyards lead to a decrease in its contribution by 5% replaced by an increase in cropland (mainly wheat) contribution. The spatial analysis of the contribution of pedological landscape importance on P export pointed out 45.1% of vineyards areas on the catchment represent more than 73% of P export (Table 4). This has not changed significantly within the study period. The forest-garrigue cover, which has not significantly changed within the study period either, exports very low P quantities (2–4%) in proportion to its surfaces (>9000 ha). Hence, the vegetation density of forest-garrigue cover represents a high protection against rainfall erosion.

The changes for each source of P load studied and its changes between 1971 and 1996 are presented in Table 5.

Discussion

The assessment of loads coming from the non-connected population are maximum because of the assumption its effluents entirely join superficial hydrosystem. But, in 1996, even if there are no official registration of existing septic tanks and their treatment efficiency, because of the legislation (Directive no. 91/271/), we can assume non-connected houses have their own septic tanks that work accurately (that is to say without any overflowing in the superficial hydrosystem, Philippi et al., 1992). This hypothesis led to an overestimation of NPS-P loads. Without these loads from the non-connected population, the sum of P loads generated by urbanization (the connected population and urban runoff) would be 37 t/yr. Measurements at outlets on the Thau catchment approximate 48 t/yr of total phosphorus (S.D.: 50%, Tournoud et al., 1997). Thus, PS P loads should represent 11 t/yr, that is less than results (18.1 t/yr) of the model developed here. This latest probably overestimates erosion and P export. This can be due, firstly, to an overestimation of erosion with the implementation of the USLE at the plot scale or, secondly, to an underestimation of the buffer coefficients at the catchment scale. The USLE has been established by Wischmeier & Smith (1978) on the basement of available data on 10 000 land-use plots situated in Northern America. This prompts to criticize the universal use of this equation. To discuss the implementation on the Thau catchment, it is possible to compare its results with the available measurements in the Mediterranean agronomical experimentation pilote site situated 30 km close to the Thau catchment (Roujan catchment). Two plots having slopes situated between 5% and 15% have been monitored. Average quantities of sediments eroded during a dry year (1995) are 8.4 t/yr and 30.6 t/yr during a wet year (1997; Andrieux et al., 1998). The implementation of the USLE in 1996 (a humid year), for the same range of slopes, evaluates the average loss to 23 t/yr. Thus, the overestimation does not occur at the plot implementation scale for this range of slopes. But, considering the sensitivity of the USLE to intensive rainfalls and steep slopes (Whischmeier & Smith, 1976), extremes conditions could also generate over-estimations. Then, measurements at the outlet of one Thau sub-catchment (Pallas river, Fig. 1) in 1995 and 1996 shows an export of $3.4.10^3$ t/yr of suspended particulate matter (SPM, Tournoud et al., 1997). This represents an average SPM export of 0.7 t/ha/yr. This is approximately 10 times less than results of the implementation of the model proposed here (Table 3). This means clearly the model could be improved by analysis of buffer capacity of the Thau catchment, in cultivated and natural areas as in rivers beds.

Between 1971 and 1996, the very dynamic changes of land-use do finally not lead to a spectacular change in the export of phosphorus in the Thau catchment. If the model answered to the assumption of the implication of these changes in the general decrease of P loads in the catchment, stronger impacts on erosion could have been expected. In fact, the implementation assumes all the variables remain constant except land-use. These assumptions probably obscured some changes in important variables as fertilization and agricultural techniques. But, on this semi-long term study period, it seems difficult to approach fertilization

Table 2. Evolution of land-use and total phosphorus losses

Cover	1971			1996		
	Surfaces (ha)	% Watershed	% of TP Exported	Surfaces (ha)	% Watershed	% of TP Exported
Vineyards	13 471	48.4	**91.6**	9983	35.9	**83.6**
Forest-Scrub	9094	32.7	**2.4**	9246	33.3	**3.5**
Fallow-Land	1580	5.7	**0.3**	2696	9.7	**0.7**
Urban areas	1213	4.4	–	2548	9.2	–
Cropland	860	3.1	**2.3**	1756	6.3	**8.1**
No Cover	495	1.8	**2.3**	399	2.0	**2.9**
Orchards	179	0.6	**0.9**	208	1.4	**1.0**
Quarries	70	0.3	**0.2**	65	0.2	**0.2**
Marshy Land	834	3.0	–	736	2.0	–

Table 3. Results of the GIS-based total phosphorus export model

	A (t/ha/yr)		TP (kg/ha/yr)		TP (t/yr)	
	Average	S.D.	Average	S.D.	Sum	S.D.
1971	11.5	37.2	1.9	7.1	23.0	14.9
1996	8.4	20.2	1.5	5.6	18.1	11.7

as far as nutrients stocks in soils have been constituted because of fertilization at least since the 1950s with demonstrated impacts until 60 cm deep (Comlan, 1996); which thus could not significantly decrease without any strong decreases in fertilization during many years. Then, agricultural practices are very difficult to generalize at the catchment scale and could be tackled only with many field studies. Despite all these things, on one hand, the present study pointed out the necessity of a fine identification of land-use and, on a second hand, it firstly indicated some clear 'critical source areas' (Gburek et al., 1996) within the Thau catchment. Between 1971 and 1996, changes in the two main human activities of the Thau catchment, wine production and urbanization, have provided a 42% decrease of P loads production. Despite exceptional loss of vineyards, the main quantities lost are because of the improvement of sewage collection and treatment. But, the most important change between 1971 and 1996 is probably the new distribution of PS and NPS. NPS were representing 90% of loads entering the lagoon in 1971 and 55% in 1996, with 67% due to non-connected population in 1971 and 18% in 1996, or probably less, as explained above. Furthermore, erosion from lands contribute only by 27% to P loads entering the lagoon. In addition, P quantities (mainly particulate) generated by erosion are only half as bioavailable than those from sewage which is mainly composed of dissolved inorganic phosphorus (Dorioz et al., 1997, 1998). Because of all is said, P loads from erosion of agricultural and natural lands are less implicated is the availability of phosphorus quantities in the Thau lagoon than loads from sewage. Then, it is necessary to consider inputs to the lagoon especially with regard to urbanization pressures given the population growth predicted by 2020 in the Thau catchment as in coastal zones in general (La Jeunesse et al., 1999).

In the Thau coastal lagoon–catchment system, phosphate concentrations have decreased by 89% between 1971 and 1994, thus much more than the decrease of P loads generated on the catchment. Either the assessement of P loads produced by the catchment has underestimated the decrease or some other variables are controlling changes in P availability in the lagoon. In fact, shellfish farms stocks have more than doubled between 1970 and 1995 (Deslous-Paoli et al., 1998), with an important increase of requirements leading to a decrease of the Thau lagoon eutrophisation (Deslous-Paoli et al., 1998). Then, even if nowadays because of legislation the two fertilizers units of the Sète city do not discharge any waste in

Table 4. Phosphorus critical source areas analysis on vineyards areas

Pedological landscale type	Silt (%)	K factor	% of the catchment	% of vineyards	1971 contribution of P export (%)	% of vineyards	1996 contribution to P export (%)
1	59.0	0.44	**5.6**	8.3	**15.8**	9.0	**22.3**
2	44.6	0.31	**12.2**	22.0	**11.6**	23.9	**19.0**
3	29.4	0.12	**10.2**	14.2	**16.3**	11.6	**10.1**
4	29.3	0.12	**17.1**	22.9	**31.1**	22.8	**21.7**
		TOTAL	**45.1**		**74.8**		**73.1**

The K factor depends on the composition of the upper soil's layer (sand, clay, silt and organic matter) but is much more linked to the proportion of silt (Wischmeier & Smith, 1978). For more information about the 24 pedological landscape types describing the Thau catchment upper soil's layer, see Robbez–Masson et al. (2000).

Table 5. Contribution of point (PS) and non-point sources (NPS) to TP (P) loads

Total Phosphorus (t)	Type of pollution	1971	% of total	1996	% of total	Changes (%) 1971–1996
Connected population	**PS**	**12.4**	**10**	**30.1**	**45**	143
Non-connected population	NPS	77.0	67	11.9	18	−85
Cultivated and natural lands	NPS	23.0	20	18.1	27	−21
Urbanised areas	NPS	3.3	3	6.9	10	109
TOTAL	**NPS**	**103.3**	**90**	**36.9**	**55**	−64
	TOTAL	**115.7**		**67.0**		**−42**
Changes in the Thau lagoon phosphate concentrations (1971–1994)						**−89**

the Thau coastal lagoon, as the legislation date back to the 1970s, the possible changes during this period should be studied.

Conclusion

The changes in both PS and NPS-P loads provided a 42% decrease of quantities entering the lagoon. The loss of vineyards areas on the Thau catchment, a high erosion risk culture, contributed to the general decrease. Despite these changes in land-use, the decrease of P loads is mainly due to the improvement of collection and treatment of sewage. Moreover, the impact of reducing NPS-P loads generated by erosion could be delayed because of a different bioavailability between P forms export by soil erosion and those from sewage (i.e. particulate and dissolved forms). Therefore, long term studies on catchment are valuable in indicating the ranking of impact by different nutrient sources on water quality. This confirms the importance of the accuracy of land-use cover for which data from aerial photographs represent a good approach. And, the GIS tool used for the study is now available to provide a management support as it pointed out criticize sources areas because of urbanization and pedological landscape characteristics. However, to produce more accurate estimates of quantities exported and also in order to have a better predictive capability, the model developed here requires buffer analysis of both sediments and P transfer as a study of changes in fertilization. Then, a 40% population growth is planned between 1995 and 2020 in the Thau region. This will induce an increase in urban pressures and surely a decrease of arable and natural lands. Thus, considering the distribution of PS and NPS-P loads, it is necessary to manage population growth and sewage without affecting shellfish farm requirements and causing eutrophication problems as those occurring in the 1970s. The GIS based model developed here is valuable for improving and accomplishing the Thau Integrated Coastal Zone Management cooperative initiatives as far as it has described critical source areas. It is considered that the main objective should be to maintain in the lagoon water phosphate concentrations at a level similar to the present one which finally shows a good equilibrium between the shellfish farms' requirements and preventing anoxia events.

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