Chemical Engineering Journal 142 (2008) 135–146

Chemical Engineering Journal

www.elsevier.com/locate/cej

Review

Evaluation of WWTP discharges into a Mediterranean river using KSOM neural networks and mass balance modelling

Esther Llorens, Frédérik Thiery, Stéphane Grieu *, Monique Polit

ELIAUS Laboratory, Université de Perpignan, 52 Avenue Paul Alduy, 66860, Perpignan, France

Received 26 July 2006; received in revised form 7 September 2007; accepted 20 November 2007

Abstract

The water quality of the Têt River, referred to nutrients compounds, is lower than the expected. Its management must be largely improved. The present work takes part in a global effort of development and evaluation of reliable and robust tools, with the aim of allowing the control and supervision of its lowland area (at the south Mediterranean coast of France). A simplified model, based on mass balances, has been developed to estimate nitrogen and organic matter concentrations in the stream and to describe the river water quality. Kohonen self-organizing maps (KSOMs) were used to deal with missing data. This kind of neural networks proved to be very useful to predict missing components and to complete the available database, describing the chemical quality of the river and the WasteWater Treatment Plant (WWTP) outflows. The simulation model also proved to be a good tool for the system evaluated. The results it provided reveal the high impact of the WWTPs located along the studied area, due to malfunction and tourism activities.

Keywords: WWTP; River; Kohonen self-organizing maps; Mass balance; Missing data; Nitrogen; DOC

1. Introduction

Since many years, the management of hydraulic resources, the efficiency of WasteWater Treatment Plants (WWTPs) and the protection of environment are major concerns. Industry executives and scientists agree that poor resources management, on quantitative as well as qualitative levels, and WWTP malfunction usually have negative impacts both on environmental well-being (fauna and flora) and on human health. One of the key effects is the poor water quality.

In the last decades water quality of European aquatic systems has especially deteriorated and it is now one of the most serious problems to solve. Rivers have suffered a nutrient enrichment (nitrogen and phosphorus) due to large nutrient discharges from human activities (i.e. effluents from WWTPs), which leads to losses of river functionalities [1–4]. As rivers cannot assimilate all nutrients, these are transported downstream affecting, at the last, the coast ecosystems. As a consequence, nitrogen has become the major contributor to coast marine ecosystems pollution [5]. Moreover, the situation in Mediterranean regions is critical [6], due to the scarcity of water (related with the deep seasonality of river flows) and high tourism impacts (i.e. high density of population placed in the lowland river basins or in the coast increases the demand for water resources and the quantity of wastewater generated).

The European Water Framework Directive (WFD) ([7]/60/EC) appeared as an attempt to face the situation. One of its principal objectives was to achieve a good health of waters by 2015. According to this goal, the WFD establishes a set of steps to follow.

The present paper is a contribution in the Têt River studies, focused in one of these steps: estimation and identification of point pollution sources and evaluation of their impacts to the river. In this sense, the present work takes part in a global effort of development and evaluation of reliable and robust tools [8], with the aim of preparing the control and supervision of the lowland area of the Têt River. This area is affected by one tributary and two WWTPs. As they seem to be the main nitrogen and organic matter pollution sources, the main purpose is to estimate the concentrations of these nutrients in the river and to evaluate their impact to the river chemistry health.

As a lot of Mediterranean coastal rivers, the hydrological system of the Têt River presents periods of low water level, interspersed by brief and violent flash-floods, essentially due to rain

* Corresponding author. Tel.: +33 4 68 66 22 02; fax: +33 4 68 66 20 87.
E-mail address: grieu@univ-perp.fr (S. Grieu).

1385-8947/$ – see front matter
doi:10.1016/j.cej.2007.11.027

[9,10]. This type of Mediterranean river merits further research with independent models [11,12]. River water quality models have been used extensively in research as well as in design and assessment of water quality measurements. The application of mathematical models begins with the initial studies of oxygen depletion, due to organic waste pollution. Since then, models have been constantly refined and updated to solve new and emerging problems. They seek to describe the constituent spatial and temporal changes.

Components or state variables have been gradually incorporated into models over the past seven decades, following the evolution of water quality problems. Water quality models characterize among others oxygen household, nutrients and eutrophication, toxic materials, and so on. The complexity covers a broad range from the simple Streeter-Phelps model [13] with two state variables to QUAL2 and similar tools describing O, N and P cycling with about 10 or more state variables [14], to ecosystem models that consider suspended solids, several classes of algae, zooplankton, invertebrates, plants, and fish [15–17,33]. The model choice depends on many different factors such as the objectives of the analysis, as well as data and time availability [18–20].

Fundamental phenomena encountered in complex physical systems as rivers (high number of parameters, high number of dependencies, uncertainty of measured data, incomplete information and unknown input–output arrangement of parameters) can also be handle using AI-based models for water quality. Their versatile applicability was demonstrated by examples of practical use [21,22].

Within the framework of our study about the river water quality, existing water quality models are not totally adequate for the Têt River. A simplified mathematical model, based on mass balances and on the STREAMES European project works, was developed to estimate nutrient concentrations in the stream and to describe the river water quality. However, the application of mathematical models for river water quality as support tools is often limited by the availability of reliable data [34].

The processing of data which contain missing values is a complicated and always awkward problem, especially when the data come from real-world contexts. Most of the statistical software simply suppresses incomplete observations. It has no practical consequence when the data are very numerous. But if the number of remaining data is too small, it can remove all significance to the results. To avoid suppressing data in that way, it is possible to replace a missing value by the mean value of the corresponding variable. Nevertheless, mean imputation might not be useful when the data sets have large variances as they do not produce any variance among the imputed values and also do not represent reality [23]. Kohonen self-organizing maps were used to estimate missing data [24,25].

The paper presents both developed methodologies (maps and model) and results related to the nitrogen and organic matter compounds. These results were used to run the STREAMES EDSS [6] in order to corroborate the results and determine the instream problems of the Têt River.

2. Study area

2.1. The Têt River

The Têt River catchment's area is located in the Pyrénées-Orientales department, south of France. The river has a total length of 120 km and drains a catchment's area of about 1380 km^2 (Fig. 1). It originates in the Carlit Mountain, in the eastern part of the French Pyrenees and discharges into the Mediterranean Sea. We distinguish two quite different parts:

- The upstream part comprises the origins of the Têt River until the dam at Vinça (about 75 km). Its average altitude is about 1026 m and its average slope, about 22.6°.

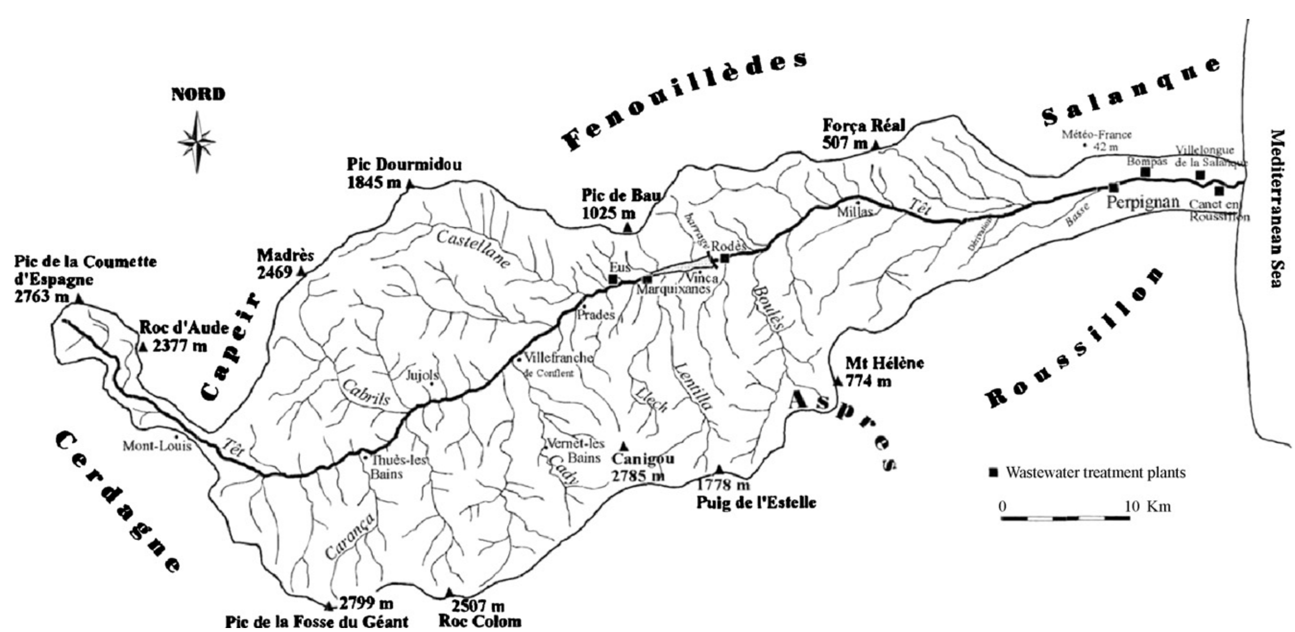

Fig. 1. The Têt River catchment's area [35].

- The downstream part is the river from the city of Vinça to Canet-en-Roussillon, which is close to the river mouth into the Mediterranean sea (about 45 km). The average altitude of this part is about 280 m and the average slope, about 8.9°.

The study part of the river covers the last 14 km of the downstream, with tourism as major economic activity. It is affected by one tributary (La Basse) and two WWTPs, at Perpignan and Canet-en-Roussillon [26]. Perpignan has a current population of about 120,000 in the city proper and 250,000 in the metropolitan area. The town of Canet-en-Roussillon is a seaside resort and its population considerably increases during the summer period (12,000 inhabitants in winter, more than 70,000 in summer).

The weather is globally hot, with dry summers, mild and humid winters and just a few rainy days during the year.

2.2. The Perpignan's WWTP

The WWTP at Perpignan was built to treat the urban wastewater of 160,000 inhab.-eq. from six towns: Bompas, Canohès, Perpignan, Saint-Estève, Le Soler and Toulouges. This WWTP has a biological Biocarbone treatment for organic matter elimination and nitrification processes.

The Biocarbone process is a down-flow filter whose immersed and aerated material supports a fixed film biomass. It removes the BOD_5 (the biochemical oxygen demand of wastewater occurring over a 5-day-period) and operates like a filter due to the material grain size which captures suspended solids. Nutrients are added to the mills' wastewater as it moves toward the biofilter. The oxygen essential to all biological aerobic activities is supplied by air diffusers which blow up air into the material. This system ensures an exceptionally high oxygen transfer. The diffused air rises to the liquid flow, continuously loosening most of the filter bed. In this way, the suspended solids contained in the wastewater securely penetrate the filter bed and are trapped in a layer of the supporting material located under the air diffusers. The biocarbone biofiltration process was developed by OTV (France), which holds the worldwide patent.

The WWTP at Perpignan does not have technology for actively removing nitrogen or phosphorus. It only entails a nitrification process. However, a partial denitrification results from the organic matter removal process. Finally, average value of bypassed water is about 25%.

2.3. The Canet-en-Roussillon's WWTP

The Canet-en-Roussillon's WWTP was built to treat the domestic wastewater of 75,000 inhab.-eq. from two towns: Canet-en-Roussillon (about 12,000 inhab.) and Saint Nazaire (about 2500 inhab.). It is a low influent discharges WWTP based on an activated sludge process (Henze et al. [27]).

The activated sludge process is a biological method of wastewater treatment that is performed by a variable and mixed community of microorganisms in an aerobic aquatic environment. These microorganisms derive energy from carbonaceous organic matter in aerated wastewater for the production of new cells in a process known as synthesis. Simultaneously, it releases energy through the conversion of this organic matter into compounds that contain lower energy, such as carbon dioxide and water, in a process called respiration. As well, more microorganisms produce energy by converting ammonia nitrogen to nitrate nitrogen in a nitrification process. This consortium of microorganisms, the biological component of the process, is known collectively as activated sludge. The overall goal of the activated sludge process is to remove substances that have a demand for oxygen from the system. This is accomplished by the metabolic reactions (synthesis–respiration and nitrificaction) of the microorganisms, the separation and settling of activated sludge solids to create an acceptable quality of secondary wastewater effluent, and the collection and recycling of microorganisms back into the system or removal of excess microorganisms from the system.

The plant consists of parallel treatment modules, where denitrification and biological dephosphatation are done in addition to the organic matter removing. Its module structure permits to adapt its operation to seasonal population variations. As for the Perpignan's WWTP, it has no technology for actively removing nitrogen or phosphorus. It only entails a nitrification process. However, again, a partial denitrification results from the organic matter removal process. Finally, average value of bypassed water is about 50%.

3. Materials and methods

3.1. Experimental data

All the experimental data, used in the present study, have been collected by the CEFREM (Centre de Formation et de Recherche sur l'Environnement Marin) laboratory from Perpignan University. Its main objective is to quantify the impact of the Têt River on the sea mouth.

3.2. The Kohonen self-organizing map (KSOM)

The KSOM is a neural network based on unsupervised learning [28,29].

3.2.1. Network structure

The Kohonen self-organizing map consists of a regular, usually two-dimensional, grid of neurons called output neurons. Each neuron i is represented by a weight, or model vector, $m_i = [m_{i1}, \ldots, m_{in}]^T$ where n is equal to the dimension of the input vectors. The set of weight vectors (code-vectors) is called a code-book [24].

The neurons of the map are connected to adjacent neurons by a neighbourhood relation, which dictates the topology of the map. Usually rectangular or hexagonal topology is used.

Immediate neighbours belong to the neighbourhood N_i of the neuron i (Fig. 2). The topological relations and the number of neurons are fixed before the training phase allowing the configuration of the map. The number of neurons may vary from a few dozens up to several thousands. It determines the granularity of the mapping, which affects the accuracy and generalisation capability of the KSOM.

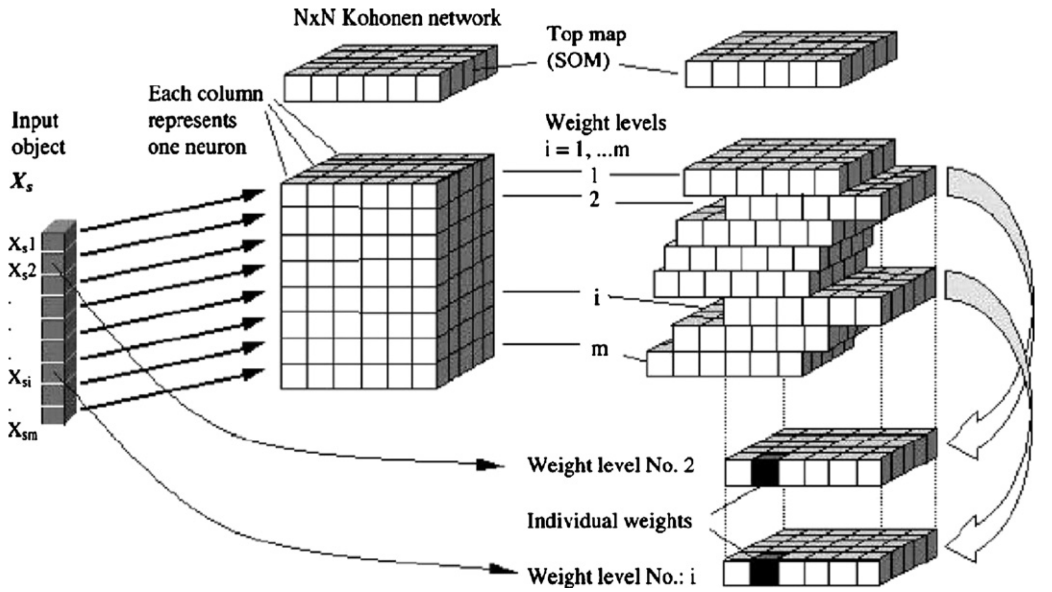

Fig. 2. Kohonen network structure [36].

3.2.2. Kohonen training algorithm

The Kohonen training algorithm is a simple procedure which consists of randomly selecting a training pattern, determining the winning node, updating the weights of all nodes (code-book) within the winning neighborhood, and modifying the training parameters [29].

In determining the winning unit, a certain distance metric is used, and the node that obtains the minimum distance relative to the current training pattern is referred to as the winning unit (the best matching unit). Changes in the weights will subsequently involve only nodes in the region surrounding this winning unit. The most common metrics used are the Euclidean distance, the Manhattan distance, and the cosine of the angle of the current input vector and each nodes weight vectors. The neighborhood size is decreasing in value as the number of training cycles increases. This winning neighborhood is the set of nodes surrounding the winning unit which will undergo weight update. Outside nodes in the map will not change their weights. Meanwhile, the winning unit would depend on the presented training pattern, the winning neighborhood moves around the map throughout the training phase.

The neighborhood size is typically denoted by a "radius", which is the number of "hops" from one node to another. In a rectangular map, the radius between a given node and all its eight direct neighbor nodes is 1. Its distance to the 16 next nearest nodes has a radius of 1, and so on. There are no hard and fast rules as to the initial value of the neighborhood size. But setting it initially to be equal to the size of longest map dimension (height or width of map in terms of number of nodes) is appropriate.

3.2.3. Adaptation of the Kohonen algorithm to estimate missing values in a data set

The observations are real-valued p-dimensional vectors to be clustered into n classes. When the input is an incomplete vector x, the set M_x of the missing components numbers is first defined. M_x is a sub-set of $\{1, 2, \ldots, p\}$. If $C = (C_1, C_2, \ldots, C_n)$ is the set of code-vectors (named code-book) at this stage, the winning code-vector $C_{i_0(x,C)}$ related to x is computed by setting:

$$i_0(x,\ C) = arg\min_i ||x - C_i|| \tag{1}$$

where the distance $||x - C_i||^2 = \sum_{k \notin M_x} (x_k - C_{i,k})^2$is computed with the components present in vector x. One can use incomplete data in two ways [30]:

(i) Incomplete data are used during the construction of the code-vectors. Update (the winning one and its neighbours) only affects the components present in the observation. $C^t = (C_1^t, C_2^t,\ \ldots,\ C_n^t)$ is the code-vector at time t and if a randomly chosen observation x^{t+1} is drawn, the code-vectors are updated by setting:

$$C_{i,k}^{t+1} = C_{i,k}^t + \varepsilon(t)(x_k^{t+1} - C_{i,k}^t) \tag{2}$$

for $k \notin M_x$ and j neighbour of $i_0(x^{t+1}, C^t)$. Otherwise:

$$C_{i,k}^{t+1} = C_{i,k}^t \tag{3}$$

The sequence $\varepsilon(t)$ is [0,1]-valued with $\varepsilon(0) \approx 0.5$ and converges to 0 as *1/t*. After convergence, the classes are defined by the nearest neighbour method.

(ii) Enough data are available to avoid using incomplete vectors to build the map. We classify incomplete vectors after the map is built by allocating them to the class with the nearest code-vector for the distance restricted to non-missing components.

Whatever the method used to deal with missing values, one of the most interesting properties of the algorithm is that it allows an a posteriori estimation of the missing values. If M_x is the set of missing component numbers for the observation x, and if x is classified in class i, for each index k in M_x, one estimates x_k by:

$$\hat{x}_k = C_{i,k} \tag{4}$$

Because in the end of the learning, the Kohonen algorithm uses no more neighbours, the code-vectors are asymptotically near the mean values of their classes. Therefore, this method consists in estimating the missing values of a variable by the mean value of its class.

3.2.4. Quantization error

Quantization error of an input vector is defined as the difference between the input vector and the closest codebook vector. For a set of input vectors, one can reflect on the similarity of the input data set and the KSOM by investigating the distribution of the quantization errors. The range of quantization error tells the smallest and the largest amount of error. Thus, the evaluation of a trained map quality can be done by calculating the average quantization error over the input samples.

3.3. The mass balance model

A simplified mathematical model based on mass balances was developed to estimate nutrient concentration in the Têt River and to describe its water quality.

3.3.1. Mass balances

A mass balance is an account of material entering and leaving a system. The main particularity of the mass balances is that they assume the conservation of mass principle (i.e. matter cannot disappear or be created). Taking into account this principle, the mass that enters a system must either leave the system or accumulate within the system, i.e. $E + G = S + A$, where E denotes what enters to the system, G denotes the production term, S denotes what leaves the system and A denotes accumulation within the system. G and A may be negative or positive.

Mass balances have been used to design chemical reactors, to analyse alternative processes in production of chemicals, in pollution dispersion modelling, etc. Although they are often developed for total mass crossing the boundaries of a system, they can also focus on one element (i.e. carbon) or one chemical compound (i.e. ammonium).

In the present study, the system is the lowland of Têt River. The model is focused on different chemical compounds, considered as indicators of water pollution.

3.3.2. The model structure

In order to represent the system as accurate as possible, it is divided into seven subsystems according to both WWTPs at Perpignan and at Canet-en-Roussillon and to sample or split point locations (Fig. 3).

The inputs, outputs and retention processes for nutrients are described in a mass balance environment for each subreach and define compartment (Fig. 4). The characteristics of one compartment may be different from the characteristics of the other ones. The most noticeable differences concern their self-purification capabilities and their lengths.

The first compartment takes into account all the upstream flows. The second one allows quantifying the Basse impact (R_{Basse}), which is the river main affluent, on the main stream. In this compartment some water is taken for agriculture activities and domestic use (S_0). Compartments 3 and 6 describe subreaches where WWTPs of Perpignan and Canet-en-Roussillon, respectively dump into the river. Their lengths are considered to be negligible. Both compartments allow quantifying the impact of plants discharges into the river. Two inputs into the river can be considered for the plants: E_P and E_C (the resulting water of depuration processes) for effluents and B_P and B_C (on raining days and/or when wastewater flow is so high that WWTP cannot treat all the incoming water) for bypasses.

Compartments 1, 2, 3, 4 and 6 do not make possible to appreciate the self-purification process because lengths of compartments 1, 2, 3 and 6 are too small and because minimal distance for nutrient assimilation corresponds to compartment 4 length. On the opposite, compartments 5 and 7 integrate this process. Experimental data analysis (on sample or split points $R_{Têt}$, R_3 and R_4) made possible to extract self-purified parameters in these compartments. The self-purification process concerns both ammoniacal nitrogen and phosphates, in compartment 5,

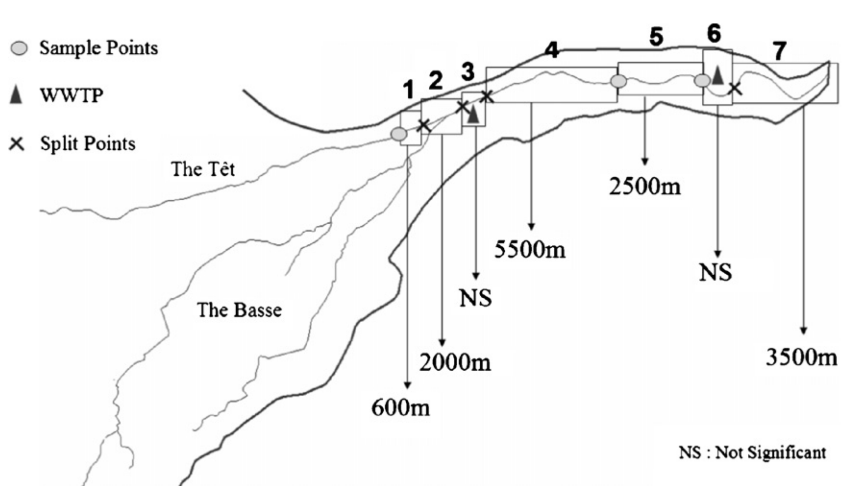

Fig. 3. The study area and the seven subsystems according to WWTPs at Perpignan and at Canet-en-Roussillon and to sample and split point locations.

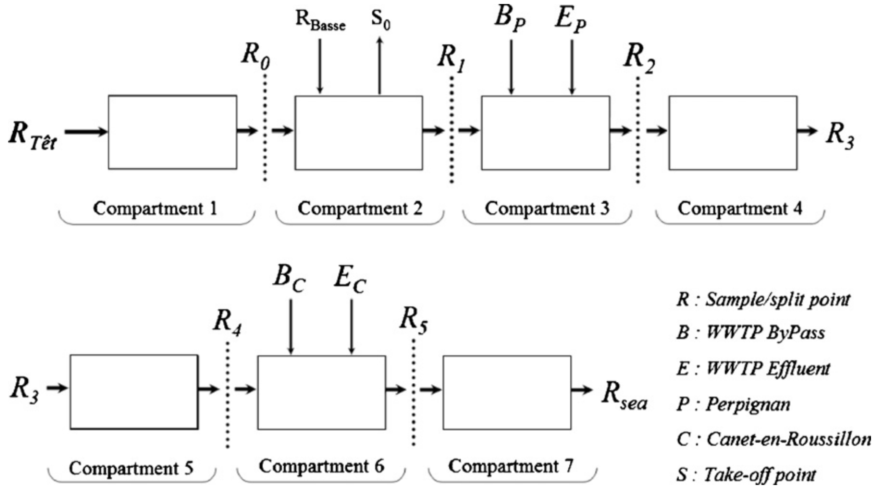

Fig. 4. Model structure, where, R is a sample or a split point into the Têt River or La Basse tributary, S refers to the Têt water taking, B is the WWTPs' bypass, E is the WWTPs' effluent, P refers to the WWTP at Perpignan and C refers to the WWTP at Canet-en-Roussillon.

whereas in compartment 7, it only concerns phosphates, due to Canet-en-Roussillon WWTP discharges. A similar methodology can be efficiently used, after updating, for all Mediterranean rivers.

In all of them it is considered that there is no accumulation, taking the term A as zero. In reference of the production term G, this is zero where nutrient retention processes are not considered. The consideration of the nutrient retention existence in each compartment is the result of the treatment of some Têt experimental data [9], in order to represent the processes within the river as accurately as possible. Where the stream experiments nutrient processes, G is composed by self-depuration equations developed for nutrient compounds within the STREAMES European project [3], and have been adapted to the Têt River. The equations that sum up the model are the following ones (5–7):

$$\sum_1^m Q_s = \sum_1^n Q_e \tag{5}$$

$$C_{s,i} = \frac{\sum_1^n (Q_e \times C_{e,i})}{\sum_1^m Q_s} \tag{6}$$

$$C_{s,j} = \frac{\sum_1^n (Q_e \times C_{e,j}) - G_{k,j}}{\sum_1^m Q_s} \tag{7}$$

where, for each subsystem, n is the number of inputs, m the number of outputs, Q_e is the input flow, and Q_s is the output flow, C_s refers to the input concentration, C_e refers to the output concentration, i refers to the compound of dissolved organic carbon (DOC), nitrites or nitrates, and j to the compound of phosphate or ammonium, k is the compartment number and G refers to the nutrient retention ($G \neq 0$ if $k = 5$ and $j =$ phosphates or ammonium and if $k = 7$ and $j =$ phosphates).

The production term G is described by Eq. (8) and characterizes the nutrient retention process and the self-purification phenomenon for nitrogen and phosphorus compounds:

$$G = \frac{C_e \times Q_e \times d}{\mathrm{Sw}} \tag{8}$$

where d and Sw, in meters, respectively represent the compartment length and the “uptake length”.

The uptake length Sw is only valid for Mediterranean rivers and is calculated for each considered chemical compound. Eq. (9) is an example of calculation for ammonium:

$$\begin{aligned}\log \mathrm{SwNH_4} = {} & 3.9175881 + 0.46175449 \log \mathrm{PST} \\ & + 0.56760408 \log \mathrm{QST} \\ & + 0.38058059 \log \mathrm{NO_3ST}\end{aligned} \tag{9}$$

where, $SwNH_4$ is the uptake length for NH_4^+ (m), PST the phosphorus concentration (mg P–PO_4/l), QST the river discharge (l/s) and NO_3ST the NO_2^- concentration (mg NO_3/l).

Let us notice that even if this study is focused on nitrogen, phosphorus calculation is necessary to solve the Eq. (9).

3.4. Linking KSOM with the mass balance model

In order to face the limited reliable data and the data missing (filling out the existing gaps in the database), KSOMs were used. The provided data completed the available database, which was after used by the mass balance model as input data. These data were related to the river and either the bypass or effluent of both Perpignan's and Canet-en-Roussillon's WWTP.

3.5. The STREAMES project and EDSS

Streams in developed regions are under significant stress due to nutrient enrichment. Humans affect streams by changing land uses in the catchment or modifying the landscape in ways that increase the nutrient transport to surface waters. By directly dumping urban or industrial sewage (point sources) into the stream and modifying the streams themselves, they reduce river ability to respond to increased nutrient discharges. Whereas these processes operate at diverse scales, from within stream processes to watershed processes, stream managers are often constrained to act at the reach scale. The goal of the European Commission's project STREAMES (Stream Reach Manage-

Table 1
KSOM grids sizes and training epochs

Location	Season	Optimal grid size	Average quantization error	Optimal number of epochs
WWTP of Perpignan (bypass/effluent)	Summer	11 × 5	2.419	500
	Winter	10 × 5	2.673	450
WWTP of Canet-en-Roussillon (bypass/effluent)	Summer	9 × 5	1.987	450
	Winter	8 × 5	2.038	450
Têt River (sample point $R_{Têt}$)	Summer	10 × 6	1.602	300
	Winter	9 × 6	1.793	300

ment: An Expert System) has been to develop a tool to help streams managers in two ways: first, to evaluate sources and magnitudes of nutrient (nitrogen and phosphorus) discharges affecting the stream reach of interest and, second, to decide of the best strategy to ameliorate that part of the stream, with special emphasis on actions directed towards increasing nutrient retention within the stream [2,31].

The developed STREAMESS EDSS is a useful tool, especially developed for Mediterranean area, able to integrate point and non-point pollution to help water managers on decision making processes related to the river water domain. It provides three types of outputs: diagnosis, actions and prognosis [6].

3.6. KSOM results

Ten KSOM have been trained using available and complete data characterizing the WWTPs of Perpignan and Canet-en-Roussillon and the chemical state of the Têt river at the sample point $R_{Têt}$, for various days of winter and summer of year 2001. Table 1 summarizes the optimal size of its output layer for each network and the optimal number of epochs carried out during its training phase, in order to obtain the weakest average quantization error and thus the best training process. By means of remaining complete data, a testing phase allowed to validate the networks learning phase and to highlight their generalization capabilities.

Table 2 presents the results of the missing (and needed) components estimation for incomplete days of February (winter) and June (summer) 2001, using the ten trained KSOM neural networks. The result units were modified according to their use in of the mass balance model. Predicted components are displayed in grey and available components in the database are displayed in white. The analysis of the data provided by the KSOM reflects a strongly fitting between the nutrient data for the Têt river and the WWTP of Perpignan (both effluent and bypass) and its historical pattern, accordingly to the season. However, the situation is different for the results of the effluent of the WWTP of Canet-en-Roussillon. Ammonium and nitrates data fit moderately with the winter pattern. The same occurs for total phosphorus in summer. Although, the error rate is so small that data are considered accurate enough to be used in the mathematical model.

3.7. Estimation of the nitrogen and organic matter concentrations

Some relevant results, basically related to the stream flow and to the dissolved organic carbon (DOC), ammonium (NH_4), nitrites (NO_2) and nitrates (NO_3) concentrations instream, were obtained from the running of the mass balance model. DOC concentration is used to quantify organic carbon loads and is directly calculated from biochemical oxygen demand (BOD) and/or chemical oxygen demand (COD) concentrations. These data allowed the estimation of nitrogen, organic matter concentration and the flow rate within the studied reach (the lowland of the Têt River) for February (winter) and June (summer) of 2001.

Both months were considered the best to observe the WWTP impacts to the river water quality due to their different climate behaviours. High river flow rate dependence of meteorology (the average flow rate in the ending of winter is 7217 ± 159 l/s and in the beginning of summer, 1788 ± 236 l/s) corroborates it. This situation is typical of the Mediterranean area.

Average flow rates along the river site are represented in the Fig. 5, where the distance index refer to the compartment outputs of the model (except point 1, which refers to the sample point $R_{Têt}$). The darker line represents the winter and the lighter line, the summer. The entrance of the WWTP of Perpignan (Pp) outflows can be clearly observed and even, the opposite effects of La Basse and water extraction. However, the input of the WWTP of Canet-en-Roussillon (Pc) is difficult to see since its outflows are very low in comparison with the stream flow.

The average nitrogen concentrations of the river water along the study stream are represented in the Fig. 6. The Pp seems to have a greater negative impact to ammonium, ammonia and nitrites concentrations than the Pc, as it treats more water. How-

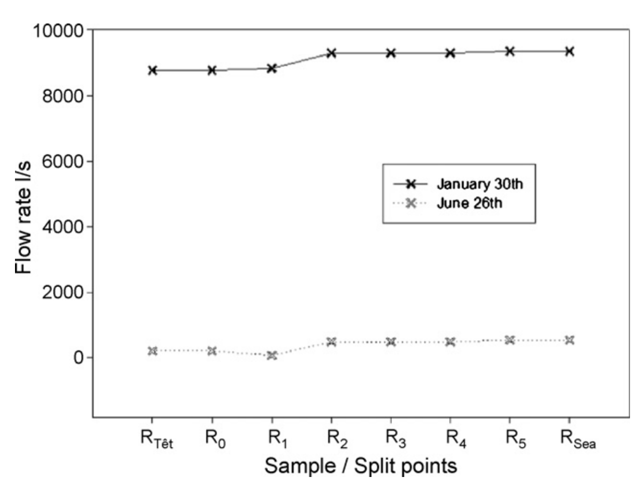

Fig. 5. Flow values along the study site for both seasons.

Table 2
Results for the missing components estimation (in grey: predicted components, in white: available components)

Effluent for the WWTP of Perpignan (Ep)								
Day	02.06.01	02.13.01	02.20.01	02.27.01	06.06.01	06.12.01	06.19.01	06.26.01
Flow (m^3/d)	36837	38824	37291	36730	36530	39505	41044	35437
NH4 (mg/l)	39.2	18.8	35.4	27	44.5	28.5	28	32.3
NO2 (mg/l)	0.85	0.5	1.13	0.2	1.2	0.63	0.5	1.3
NO3 (mg/l)	2	4	3.2	2.2	1.1	2.8	2.8	3.5
TP (mg/l)	1.4	0.6	1.8	0.4	2.1	1.5	1.5	1.8
BOD (mgO_2/l)	28	27	25	21	19	22	20	20

Bypass for the WWTP of Perpignan (Bp)								
Day	02.06.01	02.13.01	02.20.01	02.27.01	06.06.01	06.12.01	06.19.01	06.26.01
Flow (m^3/d)	0	440	0	0	0	0	0	0
NH4 (mg/l)	0	56	0	0	0	0	0	0
NO2 (mg/l)	0	0.02	0	0	0	0	0	0
NO3 (mg/l)	0	0.8	0	0	0	0	0	0
TP (mg/l)	0	9.4	0	0	0	0	0	0
BOD (mgO_2/l)	0	246	0	0	0	0	0	0

Effluent for the WWTP of Canet-en-Roussillon (Ec)								
Day	02.06.01	02.13.01	02.20.01	02.27.01	06.06.01	06.12.01	06.19.01	06.26.01
Flow (m^3/d)	1701	1510	1604	1651	1530	1624	1525	1725
NH4 (mg/l)	1	4.4	1.33	1.33	1.16	1.33	1.16	3
NO2 (mg/l)	1	0.6	0.33	0.33	2.12	0.33	2.12	1
NO3 (mg/l)	5	5.2	0.64	0.64	1.42	0.64	1.42	4
TP (mg/l)	4	2.7	1.7	1.7	1.9	1.7	1.9	5
BOD (mgO_2/l)	10	5	5	3	6	4	5	4

Bypass for the WWTP of Canet-en-Roussillon (Bc)								
Day	02.06.01	02.13.01	02.20.01	02.27.01	06.06.01	06.12.01	06.19.01	06.26.01
Flow (m^3/d)	1668	1902	1736	1512	2746	2191	2245	2868
NH4 (mg/l)	50	50.5	48.2	50.2	45	49	40	43
NO2 (mg/l)	0.03	0.03	0.02	0.03	0.05	0.01	0.05	0.01
NO3 (mg/l)	0.14	0.14	0.2	0.1	0.02	0.02	0.02	0.22
TP (mg/l)	9.7	9.7	8.6	9.7	7.5	7.5	9	9
BOD (mgO_2/l)	160	218	162	197	263	263	294	284

Têt River ($R_{Têt}$)								
Day	02.06.01	02.13.01	02.20.01	02.27.01	06.06.01	06.12.01	06.19.01	06.26.01
Flow (m^3/d)	756000	645408	743040	438048	135648	95040	20736	19008
NH4 (mg/l)	0.06	0.06	0.05	0.06	0.03	0.03	0.03	0.09
NO2 (mg/l)	0.07	0.03	0.07	0.03	0.09	0.07	0.09	0.14
NO3 (mg/l)	4	3.5	3.37	4.32	5.1	5.82	6.38	5.91
PO4 (mg/l)	0.18	0.18	0.18	0.18	0.24	0.16	0.23	0.17
DOC (mgC/l)	2.04	2.1	2.19	1.95	1.7	1.98	2.17	2.58

ever, the situation for nitrates is different, as the Basse impact, due to industrial rejects, is higher than the impact of both WWTP. Even, it is possible to see in Figs. 5 and 6 that the outflows of Pp and Pc contribute to the river nitrate dilution. All of these cases can be especially observed during summer conditions, when water discharge is lower and a higher part of the flow down of WWTPs is the effluent and bypass of both WWTPs. The effect of their outflows is magnified by low stream flow rate.

To sum up on one hand, in concentration terms, the Pp contributes to the increase ammonium and nitrite concentrations within the river, meanwhile its impact on nitrates is very small or even positive. These conclusions lead to think that the nitrification processes in the Pp are partial and they should be improved to reduce its impact to the river. On the other hand, the major impact of the Pc is on ammonium terms. But, in water quality terms the conclusions change due as people usually refer to qualitative measures rather than quantitative ones.Meanwhile, the river water quality [32] is in the Very Good category for nitrates in both seasons and the very good (in winter)/good (in summer) category for nitrites along the study site, the situation is very different for ammonium and ammonia. In both cases the quality before the Pp outflows is very good. After them, it becomes very bad for ammonia in both seasons and for ammonium in summer.

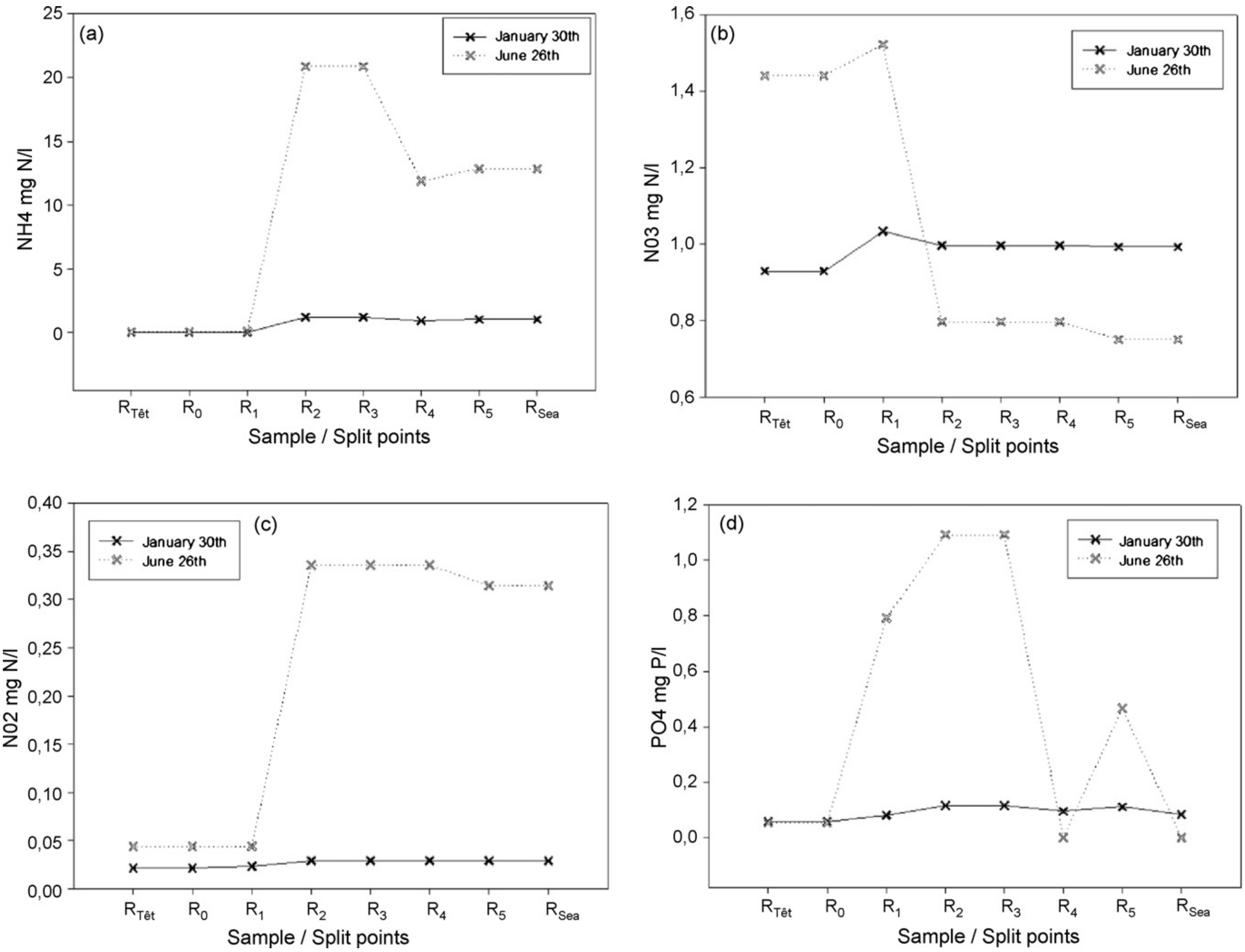

Fig. 6. (a) Ammonium concentrations along the study site. (b) Nitrates concentrations along the study site. (c) Nitrites concentrations along the study site. (d) Phosphates concentrations along the study site.

In winter the water quality for ammonium after the Pp is moderate. So, these values corroborate the greater impact of Pp on river water quality in reference with ammonium and ammonia compounds.

Finally, the average DOC concentrations in the river water along the study site are represented in the Fig. 7. The impact of both WWTPs to the Têt River during the summer season is clear, comparing the season values. However, the average flows and DOC concentrations of the effluent and bypass of the Pp are maintained along the time. This led us to think that the high impact of Pp on summer is basically due to the low stream flow, which intensifies the effects of Pp outflows. Related to the Pc, the effluent is maintained along the seasons (flow and DOC). For the bypass it is a bit different because while the flow only experiments a very small increment (10 l/s), the DOC concentrations increase an average of 5.19 mg C/l. The increment of the DOC concentrations seems to be the result of the tourism activities in the town of Canet-en-Roussillon. In water quality terms, only the Pc contributes to the change from Very Good to Moderate category value in summer. In winter, neither of WWTPs contributes to a change of the quality category, which is Very Good in all 14 km of the study site. So, in both quantitative and qualitative terms of organic matter, the Pc has higher negative effects to the river chemical health, especially in summer.

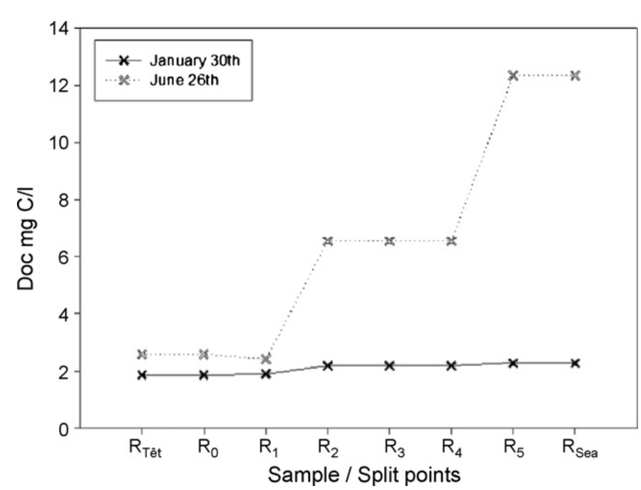

Fig. 7. DOC concentrations along the study site.

Table 3
Results from the EDSS running for each compartment

Problem	Season	Compounds 1 and 2	Compound 3	Compound 4	Compound 5	Compound 6	Compound 7
Eutrophication	Winter	No	No	No	No	No	No
	Summer	Low	No	No	No	No	No
Excess of nitrogen	Winter	No	Moderate ammonium	Moderate ammonium	No	No	No
	Summer	No	Ammonia[a] (Severe ammonium)	Ammonia[a] (Severe ammonium)	Ammonia[a] (Moderate ammonium)	Ammonia[a] (Severe ammonium)	Ammonia[a] (Severe ammonium)
Organic matter pollution	Winter	No	No	No	No	No	No
	Summer	No	No	No	No	Severe	Severe

[a] Ammonia higher than 0.02 mg/l.

3.8. Estimation of the river problems according to the nutrient concentrations

The obtained results from the simulation model were used to run the STREAMES EDSS [6] with the aim of corroborate the above commented assumptions and determine the instream problems of Têt River. The interest of the present study is focused on the diagnosis output, which supplies a list of the main problems affecting the studied stream reach.

The system was run for all compartments of the model. According to the results (Table 3), the river does not have problems of eutrophication. A low eutrophication only is diagnosed in summer in the first subreach, due to the phosphorus concentration of the tributary La Basse. The river recovers quickly after this point.

Related to the nitrogen problems, the impact of the Pp (in the comp. 3) on ammonium excess is evident. Luckily, the river recovers in winter thanks to its self-depuration capacity. But, the situation is different in the summer period, where an important amount of ammonia (very dangerous for fish population) due to the physico-chemical characteristics of the river water (pH, temperature and ammonium concentration) was diagnosed in the study area. In this case the contribution of Pc maintains and even deteriorates the situation. The self-depuration capacity of the river is not able to solve the problem, only to reduce its degree.

Finally, the river does not experiment organic matter pollution in winter. However, the contribution of Pc in organic matter seems to be very important as the EDSS diagnoses severe organic matter pollution in summer after its outflows. In this case the river has not the capacity of recovering before it is flowing into the Mediterranean Sea.

4. Conclusion

As a lot of Mediterranean rivers, the water quality of the Têt River has to be largely improved and better monitored. In this sense, a tool has been developed and is presented in this paper, based on both Kohonen self-organizing maps and simulation mass balance modelling, to estimate nutrient concentrations in the stream and to describe the river water quality. The study area, where the major economic activity is tourism, covers the last 14 km of the river (from Perpignan to Canet-en-Roussillon) and is affected by one tributary and two WWTPs.

On one hand, Kohonen self-organizing maps were first used to face the limited reliable data and to fill out the existing gaps in the available database related to the chemical state of the river and the WWTP operation. This kind of neural network proved to be very useful for estimating missing values in a database, using available values by means of a training phase, independently of the nature of the studied system (i.e. river, WWTP outflows . . .). The results obtained using KSOM, in order to avoid the data missing, can be considered as satisfactory in spite of the system complexity and strong non-linearity.

On the other hand, a simplified simulation model based on mass balances has been developed and proved to be an efficient diagnostic tool. It allowed efficiently estimating the nitrogen, the organic matter and the flow concentrations within the lowland of the Têt River. Completed data from months February (winter season) and June (summer season) of 2001 has been used to highlight the WWTPs impacts to the river water quality according to different meteorological features.

Finally, the results obtained from the simulation model were used to run the STREAMES EDSS with the aim to corroborate the assumptions and determine the instream problems of the Têt River.

After these interesting preliminary results, future works will focus on modelling all the Têt River catchment area and improving the simulation model taking into account new parameters impacting the ecological and chemical states of the Têt River. The developed model will also be integrated in a global tool allowing the control and supervision of the Têt River catchment area, with the aim of improving its water quality.

Acknowledgements

The authors wish to thank Dr. W. Ludwig and Dr. J. Garcia-Esteves for providing experimental data, which have been used in the development of the tool presented in this paper.

References

[1] O. Sterba, J. Mekotova, M. Krskova, P. Samsonova, D. Harper, Floodplain forests and river restoration, Global Ecol. Biogeograph. Lett. 6 (1997) 331–337.

[2] J. Comas, E. Llorens, E. Martí, M.A. Puig, J.L. Riera, F. Sabater, M. Poch, Knowledge acquisition in the STREAMES project: the key process in the environmental decision support system development, AI Commun. 16 (2003) 253–265.

[3] E. Llorens, Desenvolupament d'un sistema expert com a eina per a una millor gestió de la qualitat de les aigües fluvials, Thesis dissertation, Universitat de Girona, DL 2004, ISBN: 84-688-8628-9 (2004).

[4] E. Martí, J. Aumatell, Ll. Godé, M. Poch, F. Sabater, Nutrient retention efficiency in streams receiving inputs from wastewater treatment plants, J. Environ. Qual. 33 (2004) 285–293.

[5] R.W. Howarth, Human acceleration of the nitrogen cycle: drivers, consequences, and steps toward solutions, Water Sci. Technol. 49 (2004) 7–13.

[6] E. Llorens, J. Comas, M. Poch, E. Martí, M.A. Puig, J.L. Riera, F. Sabater, D. Pargament, M. Pusch, M. Venohr, P. Vervier, Integrating point and diffuse pollution in an EDSS for stream management at reach scale, Proceedings of the EWA Conference Nutrient Management, European Experiences and Perspectives (Aquatech 2004), EWA Eur. Water Assoc. (2004) 159–182.

[7] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy, Official Journal L327, 2000-10-23, P0001.

[8] S. Grieu, A. Traoré, M. Polit, J. Colprim, Prediction of parameters characterizing the state of a pollution removal biologic process, Eng. Appl. Artif. Intell. 18 (2005) 559–573.

[9] W. Ludwig, P. Serrat, L. Cesmat, J. Garcia-Esteves, Evaluating the impact of the recent temperature increase on the hydrology of the Têt river (southern France), J. Hydrol. 289 (2004) 204–221.

[10] J. Guillén, F. Bourrin, R. Buscail, A. Palanques, P. Puig, X. Durrieu de Madron, Comparison of sediment dynamics during "wet" and "dry" storm events on the Têt Prodelta, Geophys. Res. Abs. 7 (2005) 71–74.

[11] M. Alvarez Cobelas, C. Rojo, D.G. Angeler, Mediterranean limnology: current status, gaps and the future, J. Limnol. 64 (2005) 13–29.

[12] M. Plus, I. La Jeunesse, F. Bouraoui, J.M. Zaldivar, A. Chapelle, P. Lazure, Modelling water discharges and nitrogen inputs into a Mediterranean lagoon: Impact on the primary production, Ecol. Model. 193 (1–2) (2006) 69–89.

[13] W.H. Streeter, E.B. Phelps, A study of the pollution and natural purification of the Ohio River, U. S. Public Health Service, Public Health Bull. 146 (1925).

[14] L.C. Brown, T.O. Barnwell, The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual, Report EPA/600/3-87/007, U.S. EPA, Athens, USA (1987).

[15] R.H. Boling, R.C. Petersen, K.W. Cummings, Ecosystem modeling for small woodland streams, in: B.C. Pattern (Ed.), Systems Analysis and Simulation in Ecology, vol. 3, Academic Press, New York, USA, 1975, pp. 183–204.

[16] J.H. Wlosinski, G.W. Minshall, Predictability of stream ecosystem models of various levels of resolution, in: T.D. Fontaine, S.M. Bartell (Eds.), Dynamics of Lotic Ecosystems, Ann Arbor Science, Chelsea, MI, USA, 1983, pp. 69–86.

[17] M. Matthies, J. Berlekamp, S. Lautenbach, N. Graf, S. Reimer, System analysis of water quality management for the Elbe river basin, Environ. Model. Software 21 (9) (2006) 1309–1318.

[18] R.B. Ambrose, T.O. Barnwell, S.C. McCutcheon, J.R. Williams, Computer models for water quality analysis, in: L.W. Mays (Ed.), Water Resources Handbook, McGraw-Hill, New York, 1996.

[19] B. Grizzetti, F. Bouraoui, G. De Marsily, G. Bidoglio, A statistical method for source apportionment of riverine nitrogen loads, J. Hydrol. 304 (1–4) (2005) 302–315.

[20] B. Crabtree, A.J. Seward, L. Thompson, A case study of regional catchment water quality modeling to identify pollution control requirements, Water Sci. Technol. 53 (10) (2006) 47–54.

[21] F.H. Schulze, H. Wolf, H.W. Jansen, P. van der Veer, Applications of artificial neural networks in integrated water management: Fiction or future? Water Sci. Technol. 52 (9) (2005) 21–31.

[22] G. Parkin, S.J. Birkinshaw, P.L. Younger, Z. Rao, S. Kirk, A numerical modelling and neural network approach to estimate the impact of groundwater abstractions on river flows, J. Hydrol. 339 (1–2) (2007) 15–28.

[23] R.J.A. Little, D.B. Rubin, Statistical Analysis with Missing Data, John Wiley, New York, 2002.

[24] O. Simula, E. Alhoniemi, J. Hollmén, J. Vesanto, Analysis of complex systems using the self-organizing map, in: Proceedings of 4th International Conference on Neural Information Processing (ICONIP'97), Dunedin, New Zealand, 1997, pp. 1313–1317.

[25] O. Simula, J. Vesanto, E. Alhoniemi, J. Hollmén, Analysis and modeling of complex systems using the self-organizing map, in: N. Kasabov, R. Kozma (Eds.), Neuro-Fuzzy Techniques for Intelligent Information Systems, Physica-Verlag, 1999, pp. 3–22.

[26] F. Thiery, S. Grieu, A. Traoré, M. Estaben, M. Polit, Neural networks for estimating the efficiency of a WWTP biologic treatment, Front. Artif. Intell. Appl.: Artif. Intell. Res. Dev. 131 (2005) 25–32.

[27] M. Henze, C.P.L. Grady, W. Gujer, G.v.R. Marais, T. Matsuo, Activated Sludge Model No.1, IAWQ, London, 1987.

[28] S. Grieu, F. Thiery, A. Traoré, T.P. NGuyen, M. Barreau, M. Polit, KSOM and MLP neural networks for on-line estimating the efficiency of an activated sludge process, Chem. Eng. J. 116 (2006) 1–11.

[29] Y-S.T. Hong, M.R. Rosen, R. Bhamidimarri, Analysis of a municipal wastewater treatment plant using a neural network-based pattern analysis, Water Res. 37 (2003) 1608–1618.

[30] M. Cottrell, P. Ibbou, P. Letrémy, P. Rousset, Cartes auto-organisées pour l'analyse exploratoire de données de visualisation, Journal de la Société Française de Statistique 144 (2003) 67–106.

[31] F. Sabater, E. Marti, C. Voreadou, P. Vervier, A.G. Solimini, I. Roda, J.L. Riera, M. Pusch, M.A. Puig, M. Morais, S. Gafny, Q. Comas, T. Battin, STREAMES, a multidisciplinary project to develop an Expert System for stream management in human-altered streams: current status of research activities, in: Science in Support of European Water Policies, Sustainability of Aquatic Ecosystem, Stresa, Italy, 2002.

[32] SEQ-EAU Version 2. Système d'Evaluation de la Qualité de l'Eau des Cours d'Eau, 2003. http://www.eaurmc.fr/.

[33] P. Cianchi, S. Marsili-Libelli, Integrated software platform for water quality management, in: Proceedings of 4th International Symposium on Sys-

tems Analysis and Integration Assessment in Water Management, Ghent, Belgium, 2000.
[34] T. Deksissa, J. Meirlaen, P.J. Ashton, P.A. Vanrolleghem, Simplifying dynamic river water quality modelling: a case study of inorganic nitrogen dynamics in the Crocodile River (South Africa), Water, Air Soil Pollut. 155 (1–4) (2004) 303–320.
[35] P. Serrat, W. Ludwig, B. Navarro, J.L. Blazi, Spatial and temporal variability of sediment fluxes from a coastal Mediterranean river: the Têt (France), Earth Planet. Sci. 333 (2001) 389–397.
[36] F. Marini, J. Zupan, A.L. Magri, Class-modeling using Kohonen artificial neural networks, Anal. Chim. Acta 544 (2005) 306–314.