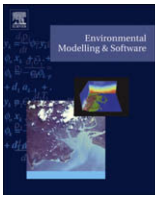
Environmental Modelling & Software 24 (2009) 371–380

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft



Scenario analysis for the role of sanitation infrastructures in integrated urban wastewater management

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ARTICLE INFO

Article history:
Received 24 September 2007
Received in revised form 27 July 2008
Accepted 10 August 2008
Available online 14 October 2008

Keywords:
Model integration
Water quality
Water Framework Directive
Management scenarios
Catchment
Ammonia concentration
Expert knowledge
Sanitation infrastructure control

ABSTRACT

Traditionally, the sanitation infrastructures of most of the Urban Wastewater Systems (UWSs) have been managed individually, without considering the many relationships among the sewer systems, Wastewater Treatment Plants (WWTPs) and receiving waters. The main objective of WWTP management was to comply with the emission limits, without considering the ecological state of the receiving waters. However, the European Union approved the Water Framework Directive (WFD) in 2000 that changes the conventional practice by introducing the integrated approach concept in the hydraulic infrastructure management. The same Directive also promotes the availability and use of decision support tools for water management, specifically where water resources are becoming increasingly scarce. This paper describes the work conducted in the *Besòs* catchment (Catalonia, NE of Spain) in order to deal with this European legislation. A study site was selected to develop an integrated model as a support tool for the UWS management. Specifically, two sewer systems, their WWTPs and a reach of the *Congost* River (a tributary of the *Besòs* River) have been modelled. The selected software to model flow and water quality were Infoworks CS, GPS-X and Infoworks RS for the sewer systems, WWTPs and stream reach, respectively. Besides these, a specific program was developed to be used as a data transfer interface between software. Once this model integration platform was built, and taking into account the expert knowledge of the managers, several management scenarios were defined including some critical events such as industrial spills, rainfall episodes, inhibition of nitrification, WWTP shutdowns, obstruction of a sewer system conduit and episodes of minimum river flow rates as well as potential control actions such as the implementation of storage tanks or the use of bypasses between sewer systems or WWTPs. All these scenarios were modelled and simulated and the results obtained were then analysed, focusing the attention on the river water quality, with the main objective being to gain relevant knowledge to deal with the tested scenarios.

1. Introduction

In the last two decades the facilities for wastewater collection and treatment have spread throughout the majority of European countries and serve a high percentage of the population. However, the management of these sanitation infrastructures has been rarely considered in an integrated way, by taking into account the existing relationships among sewer systems, Wastewater Treatment Plants (WWTPs), receiving waters and other sanitation infrastructures such as storage tanks but rather, on the contrary, considering them as individual and not interrelated systems. The traditional management aims at fulfilling the legal emission limits but usually without bearing in mind the consequences on the receiving waters or on other wastewater facilities. This is usually due to the fact that the sewer system, the WWTP and the receiving water are generally managed by different companies or administrations.

Beck (1976) was one of the first in introducing the concept of a *water quality system*, which includes the integrated management of a water distribution network, sewer system, WWTP and river. However, this idea has not been put in practice until some years ago (in the 1990s), when the technological conditions made it possible to develop it (Butler and Schütze, 2005). These conditions can be divided into three groups:

(i) Improvement of information systems: Geographic Information Systems (GIS), process control systems, data analysis, sensors, communication between computers and other equipment have all greatly improved (Argent, 2004).
(ii) Improvement of simulation tools: New software that can model and simulate water quality in different conditions and

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doi:10.1016/j.envsoft.2008.08.003

environments has appeared (Rauch et al., 2002; Fu et al., 2008) such as deterministic models, geographical information systems, real time control systems or knowledge-based systems.

(iii) Use of Artificial Intelligence (AI) tools in the environmental scope: The AI tools enable the incorporation of expert knowledge in the decision-making processes (Serra et al., 1997; Poch et al., 2004; Denzer, 2005; Gibert et al., 2006; Nguyen et al., 2007; Evers, 2008; Makropoulos et al., 2008).

There are certain pressure elements that are accelerating the change from the individual and separated management model to the integrated management paradigm:

(i) Society demands a high quality environment. The river is an environmental system close to the community and, frequently, highly altered by the human activity, thus requiring a substantial recovery.
(ii) European legislation demands at least a good state of all water bodies, indicates the catchment as the scale for management, and promotes a combined approach of the emission limits values and the recipient quality standards (Water Framework Directive, WFD, 2000/60/CE). Also US regulations such as the Clean Water Act establish a process to facilitate recovery of surface waters not meeting their established water quality standards (Clean Water Act, CWA, public law 107–303, 2002).
(iii) Implementation of Integrated Water Resources Management (IWRM) in compliance with EU water initiative objectives (http://www.euwi.net) and Millennium Development Goals (MDGs, http://www.un.org/millenniumgoals/) targets.
(iv) The increase in the number of management scenarios and their complexity, leading thus to a higher number of relationships among them.

Only integrated water management at river catchment scale can satisfy the current legislation, tackle the high number of scenarios and their complexity and guarantee the water quality demanded by society. River catchments are sometimes divided by different political borders (municipalities, regions and states), making the integrated water management even more difficult. However, the current tendency, promoted by the WFD, is to treat the hydrographic basin as a single area of operations (i.e. hydraulic infrastructures have to be managed in an integrated manner), taking into account the condition of the receiving environment and requiring collaboration between countries within twinned river basins. Integrated management, proposed by the WFD, appears to be a good strategy to improve the catchment water quality but requires a high effort in monitoring, control, and information access among the different managers. For this reason, the development and use of water management tools for decision support (such as deterministic models, geographical information systems, real time control systems or knowledge-based systems), especially where water resources are becoming scarce like in the Mediterranean areas, are necessary to support the management of the three basic elements (sewers, WWTPs and river) of the Urban Water System (UWS) in a global way, by providing integration of different data and information, allowing knowledge management and offering scenario analysis and control actions.

There is a lack of experience in this field because the integrated river basin management is a relatively new concept. However, literature already offers several works describing tools that integrate the three sub-elements of the UWS. In most of these works, sewer, WWTP and river models are used to manage the whole system in an integrated way or to assure a good river water quality (Rauch and Harremoës, 1999; Tomicic et al., 2001; Erbe et al., 2002; Frehmann et al., 2002; Meirlaen et al., 2002; Willems, 2003; Camilleri, 2004; Butler and Schütze, 2005; Vanrolleghem et al., 2005; Matthies et al., 2006; Solvi et al., 2006; Achleitner et al., 2007; Dorner et al., 2007; Letcher et al., 2007; Xu et al., 2007; Benedetti et al., 2007, 2008). The majority of these authors identify the same problems during the construction of the tools:

(i) Different time scales: Simulation time scale for sewer, WWTP and river models can be different for each one and depend on the aim of the simulation (real time control, calibration or evaluation of a perturbation) or the process to be simulated (runoff in the sewer system, nitrification in the WWTP or daily oxygen cycle in the river).
(ii) Adaptation of variables: Traditionally, different state variables have been used to model each sub-system. A case in point would be that organic matter is usually based on the Biologic Oxygen Demand (BOD) in river and sewer models while it is based on the Chemical Oxygen Demand (COD) in WWTP models (Hydromantis, 2003 and Wallingford Software Ltd., 2005).
(iii) Transfer of data among software: The use of different software and models requires using interfaces to facilitate the data transfer process. In this sense, the Open Modelling Interface (the OpenMI) provides a first standard for the exchange of data between different models in water management, even from different computer software and providers (Moore, 2007).
(iv) Calibration: The calibration of an individual model requires sampling campaigns which in turn can increase the economical cost of the projects up to an unachievable level. Besides, when using integrated models, it may be necessary to add a second calibration phase to verify the whole operation of the system.
(v) Uncertainty: When deterministic models are used to simulate water quality, many parameters that describe complex processes must be considered. Usually only the key parameters are calibrated while the default values are used for the other ones. The uncertainty of these results is propagated through the integrated models when each downstream model uses the outputs of the upstream model as inputs.

Some previously published works deal with the above problems but for a very local scenario and are far from a generic solution. Meanwhile, others only partially solve these five problems, and still others have just been tested in only one river basin or for a few scenarios. Finally, only a few have access to an expert knowledge base. Most of the partially successful applications are based on the commercial software (SIMBA, Mouse, Stoat, Aquasim, Mike11, Infoworks or WEST) which points out the complexity and work effort required to obtain a useful model-based integrated tool. Model simplification is a method adopted by some authors to allow for a slight accuracy reduction while saving some computational time.

The main purpose of the paper is to present the development of an integrated water quality model, taking into account the expert knowledge of the managers, and to illustrate its usefulness as a decision support tool for the management of the integrated UWS under different operational situations. The manuscript does not intend to provide a methodology to solve model integration problems but rather to analyse the management of the sanitation infrastructures by considering the river water quality concept, through the simulation of different scenarios presented in the day-to-day operation. The paper illustrates the use of this model-based tool to simulate different scenarios in the selected study site located in the *Besòs* River catchment. In this River catchment, the management of all the sanitation infrastructures is centralized into one single water agency. Thus, the final decision always falls on to this organization which, following the rules promoted by the WFD, wants to include the river water quality concept in its management protocol, in contrast to the management model traditionally based on the WWTP discharge limits of the EU urban wastewater treatment directive (91/271/EEC).

The study site selected includes two sewer systems, two WWTPs and a river reach, as the receiving environment for their wastewater. By analysing the results of the simulated scenarios, relevant and useful knowledge was obtained about the management of the sanitation infrastructures when faced with several real situations which arise in day-to-day operation. This knowledge will enable the final user, for example a water manager, to be provided with the most adequate control strategies to be implemented in those situations where not enough real information or experience is available. This paper is structured as follows: firstly, the study site selection and the modelling of the integrated management of the UWS is explained. Secondly, the UWS models, their integration and use are introduced. Thirdly, the definition of some different management scenarios, including some emergency events, is then described. Fourthly, two specific case studies are discussed in detail as examples of the usefulness of the integrated model-based approach as a support tool and, finally, some conclusions are drawn.

2. Modelling the integrated urban wastewater system

2.1. Study site

As shown in Fig. 1, the *Besòs* River catchment (1039 km^2) is located in Catalonia, NE of Spain. It has a typical Mediterranean hydrological pattern with significant rainfall variability, presenting very low dry water flow rates in summer (near $2\ m^{-3}\ s^{-1}$ at the mouth), but also with flow rates that can increase up to 1000 times in the autumn rainfall period. Further, the flow rates in summer are due exclusively to the WWTP effluents, thus the quality of the treatment facilities discharges becomes critical. This is one of the most populated catchments in this geographic area, with more than two million people connected.

The location of the study site is around the final reach of the *Congost* River (a tributary of the *Besòs* River). The *Congost* River receives, in the study site area of 70 km^2, the discharges of four municipalities: *La Garriga*, with its own sewer system and WWTP, and *Les Franqueses del Vallès*, *Canovelles* and *Granollers*, which all share the sewer system and the WWTP. The total population connected to the study site reaches up to 100,000 inhabitants. Nowadays, there is very high industrial activity in the studied area and all of these industries are connected to the urban sewer systems. The major part of both sewer systems' network is combined (jointly collecting wastewater and rainfall runoff in the same conduits). Both *La Garriga* and *Granollers* WWTPs have a biological wastewater treatment based on an activated sludge system with a modified Ludzack-Ettinger configuration for nitrogen removal. However, the *Granollers* WWTP only performs biological nitrogen removal from May to October due to its current limited capacity. The average influent flow rates for *La Garriga* WWTP and *Granollers* WWTP are around 4000 $m^3\ d^{-1}$ and 23,000 $m^3\ d^{-1}$, respectively. The *Congost* River has an average flow rate (at the starting point of the studied area) of 34,560 $m^3\ d^{-1}$, but this is very irregular due to the variable climate conditions.

2.2. Relationships between the three elements of the UWS: sewer systems, WWTPs and receiving environment

The main pathway for the wastewater from its generation to its discharge at the receiving environment is delimited by the sanitation infrastructures. Generally, the wastewater produced at the study site is channelled through the sewer systems to the respective WWTPs. Then, the treated wastewater is discharged into the *Congost* River. However, under certain conditions, wastewater can reach the receiving environment following alternative routes defined by the relationships between the UWS elements (Fig. 2):

(i) Combined Sewer Overflows (CSO): When the sewer system capacity is surpassed, the wastewater network overflows are discharged directly to the river.
(ii) WWTP bypass: The WWTP influent flow rates are limited to the designed capacities (27,650 $m^3\ d^{-1}$ in *La Garriga* and 76,800 $m^3\ d^{-1}$ in *Granollers*) and, in the biological reactor, 14,000 $m^3\ d^{-1}$ in *La Garriga* and 34,400 $m^3\ d^{-1}$ in *Granollers*, respectively. When the flow rate limitations of the biological reactor are surpassed, the exceeding flow is discharged directly into the river after the primary treatment. The WWTPs were designed to remove at least part of the suspended solids in the case of peak flows due to rain events.
(iii) Bypass from the *La Garriga* WWTP to the *Granollers* WWTP. There is a connection between the two sanitation systems,

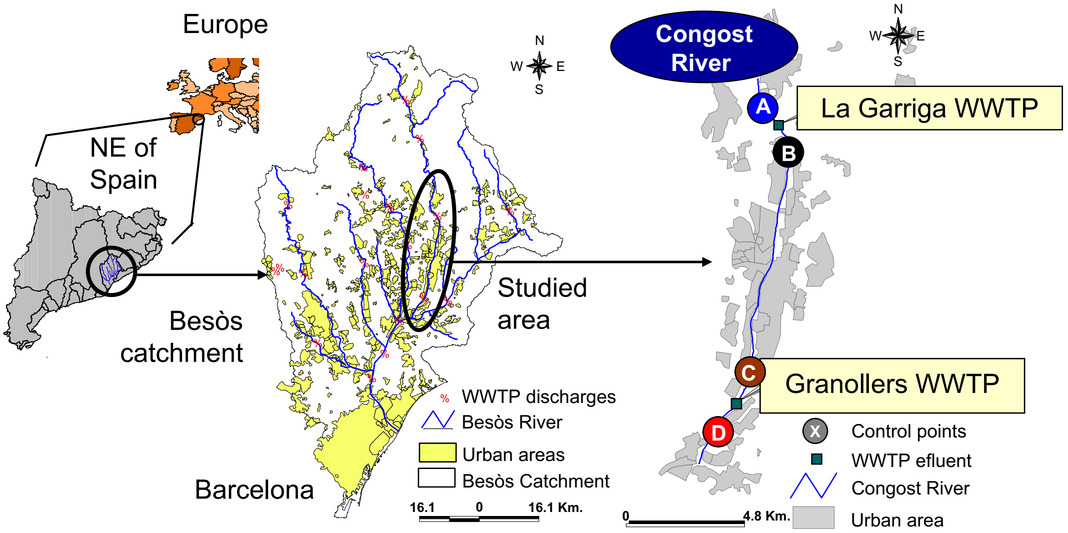

Fig. 1. Study site (*Besòs* River catchment, NE of Spain) (control points: A: upstream *La Garriga* WWTP; B and C: downstream *La Garriga* and upstream *Granollers* WWTP; and D, downstream *Granollers* WWTP).

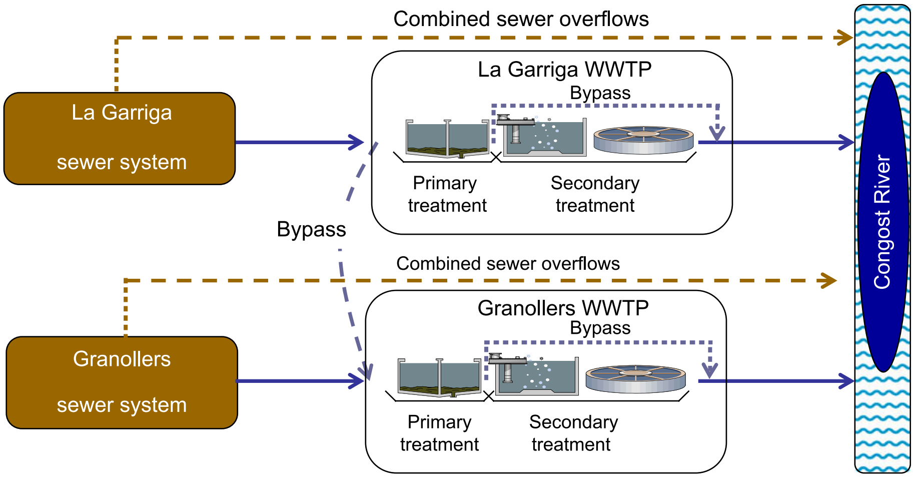

Fig. 2. Relationships between the elements of the UWS.

allowing flow derivations from *La Garriga* to *Granollers* WWTP with a maximum flow rate capacity of 6720 $m^3 d^{-1}$.

Furthermore, there is an important ecological and legal restriction related to the bypasses due to the existence of the minimum ecological river flow rate, which is compulsory to maintain, and which limits the bypassed flow rate in order to guarantee at all times a certain discharge into the river.

2.3. *Physicochemical, hydraulic and biological models*

The models and software packages were selected taking into account that they had to be capable of modelling at least the ammonia concentration, BOD, Dissolved Oxygen (DO) and temperature as water quality parameters as well as the flow rate. Both sewer systems were modelled using InfoWorks CS from Wallingford Software Ltd. (2005). InfoWorks CS manages models of sewer networks, encompassing network data (such as pumping stations, pipes, overflows, storage tanks, etc.), physical data (such as ruggedness coefficient of pipes, gravity or friction factor), chemical data (such as concentrations of ammonium, BOD or COD) and hydraulic data (such as flow, velocity, pressure, etc.). Modelling of soluble pollutants is fully conservative, i.e. Infoworks CS does not consider any interaction between pollutants and their environment or among pollutants, thus no biochemical processes are modelled. However, InfoWorks CS water quality model allows the simulation of the built-up of sediment in the network and the movement of sediments and soluble pollutants through the drainage system during a rainfall event. WWTPs were modelled using GPS-X software (Hydromantis, 2003). GPS-X allows performing both static and dynamic simulations and it is supplied with a library of models covering virtually all the process units, including advanced nutrient removal processes, fixed-film models, anaerobic digestion, secondary settling, primary settling and also models for several sludge operation units (Olsson and Newell, 1999). For the study carried out in this paper, the modelling of pollutants in the biological reactors of the two WWTPs was based on the Activated Sludge Model no. 1 (ASM1) (Henze et al., 1987). Finally, the *Congost* River was modelled using InfoWorks RS from Wallingford Software Ltd. (2005). This software contains a quality simulation engine, separated from the hydraulic engine, which computes concentration using a finite difference approximation of the advection-diffusion equation. Organic matter removal, BOD biodegradation, hydrolysis of organic nitrogen and biological nitrogen removal are the biochemical processes modelled in the river.

The selected models were complex enough to simulate the CSO and the two different possible bypasses and their influence on the water quality. Simulation of the CSO processes is extremely important because the ammonia concentration in the river can increase significantly due to hundreds of discharge points coming from sewer systems. Thus, each overflow structure was connected, during the integration phase, to a point of discharge into the river. For all the models, 1-h time step was selected as the integration time given that this time step is delimited enough to adequately represent the dynamics of the main processes of the real system, such as the rainfall runoff or nitrification. Each model was calibrated with real data from WWTP and with river control stations' historical databases to obtain a reference scenario, representing a quasi-stable situation with an average water quality. Simulated results of each model were adjusted to real data, using mean values of flow, BOD and ammonia for the period 2003–2004.

Specifically, for the sewer systems models, after setting up the physical and geographical information data such as inhabitant equivalents for each sub-catchment, average water consumption, location and quantification of industrial contributions or percentage of soil uses and carrying out the wastewater fractionation, the simulation results using the default model parameters showed a good fit with the experimental data.

On the other hand, calibration of WWTP models involved to modify the following parameters in order to adjust simulated values to real data:

(i) In the influent: soluble inert organic matter (S_I was modified, for example in *Granollers*, from the default value, 30 g COD m^{-3}, to 75 g COD m^{-3} due to the considerable industrial contribution).
(ii) In the reactor: maximum value for the aeration transfer coefficient in the aerobic compartments ($K_{La\ max}$, for example in *Granollers* from the default value, 300 d^{-1}, to 140 d^{-1}), maximum value for the aeration transfer coefficient in the anoxic compartments (from 300 d^{-1} to 240 d^{-1}), half-saturation constant for readily biodegradable substrate (K_S, from 20 g COD m^{-3} to 60 g COD m^{-3}), decay rate for heterotrophic bacteria (b_H, from 0.62 d^{-1} to 0.4 d^{-1}), maximum specific growth rate for autotrophic bacteria ($\mu_{max\ A}$, 0.8 d^{-1} to 0.3 d^{-1}).
(iii) In the secondary settler: sludge volume index (from 150 ml g^{-1} to 160 ml g^{-1}), maximum settling velocity (from 274 m d^{-1} to 200 m d^{-1}) and non-settling fraction (from 0.001 to 0.005).

Finally, in the case of the river model, no modifications from the default parameters were required because once all the morphological data, the initial conditions extracted from river control stations and the data corresponding to the industrial discharges were introduced into the model, the simulated results already presented a good fit with the real data (as an example, the average real values for ammonia and BOD during 2003–2004, 15.7 g m^{-3} and 6 g m^{-3} respectively, are in agreement with the range of variation of the simulated daily results, from 8 g m^{-3} to 17 g m^{-3} for ammonia and from 4 g m^{-3} to 9 g m^{-3} for BOD). Then, using the outputs of each upstream model as the inputs of the downstream models, simulations of the whole system were carried out.

In all simulation studies, dynamic simulations were always performed once a steady state was reached. A 7-day dynamic simulation period was also defined based on the expert criteria so as to take into account the whole weekly variability in wastewater production, including the typical population habits, industrial patterns and weekend effects. This simulation period also enables simulation of rain episodes lasting for more than 24 h and to have enough time to simulate the final effect in the river water of an industrial spill discharged into the sewer system, after going through storage tanks and WWTPs.

Simulation of the flow rate and water quality parameters along the whole integrated urban wastewater system is a complex and time-consuming task due to the number of data transfers needing to be made, especially if these transferences have to be done manually. In order to reduce data transfer time and to reduce the scale and units heterogeneity problem among the elements of the UWS and their possible relationships (sewer systems, WWTPs, overflows, bypass channels and river), a specific software (Data Transfer Software, DTS) was built based on the Delphi programming language. The Open Modelling Interface cannot be used because GPS-X does not yet have a version compliant with the OpenMI standards. DTS enables the automatic transfer of the output files, which cover three basic operations, among the different software packages as shown in Fig. 3:

(i) Transfer of output files from the sewer system model (InfoWorks CS) to the WWTP model (GPS-X).
(ii) Transfer of output files from the WWTP model (GPS-X) to the river model (InfoWorks RS).
(iii) Transfer of output files from the sewer system overflows (InfoWorks CS) to the river model (InfoWorks RS).

The variables considered include flow rate and different quality data (COD, BOD, TSS, NH_4^+, NO_x, TKN and DO). For each one, the necessary mass balances and other computations are performed while time scale and units are converted to the adequate format of the different software involved. Mass balances are necessary for the transfer of output data from the sewer system model to the river model. There are about 85 combined sewer overflows in the studied sewer systems but most of them are discharging to the river almost in the same point. Thus it was required to carry out a mass balance, for each water quality parameter, for those CSOs that could be joined as a previous step to introduce them as a sole input to the river model.

2.4. Geographic Information System

A Geographic Information System (GIS) was constructed to support the visualization and understanding of the simulation results, the relationships among the models, and to have a global picture of the management scenarios, as shown in Fig. 4. The ArcView software package (ESRI, 2005) was selected to develop the GIS model because it allows a direct connection with the InfoWorks

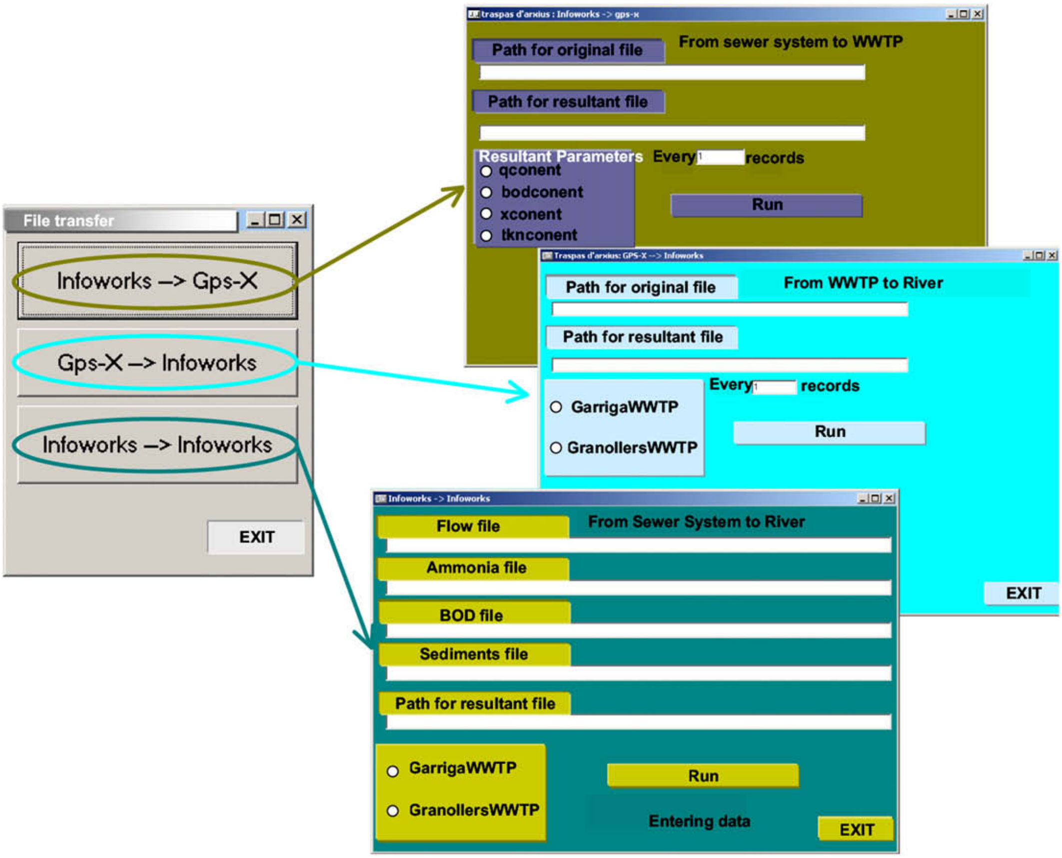

Fig. 3. Main windows of the Data Transfer Software (DTP).

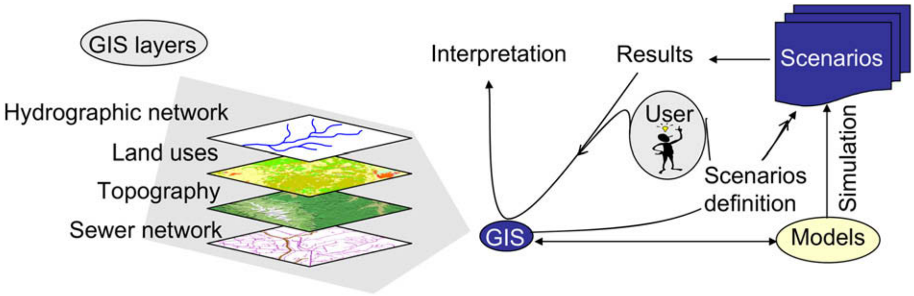

Fig. 4. Scheme of the use of the Geographic Information System (GIS).

CS and InfoWorks RS software, making the transfer of the geographic information easier. Since each geographic layer has associated numerical data, the GIS developed can be used to see any information, in both geographical and numerical formats, concerning the elements of the UWS and the results of the simulations.

3. Results and discussion

3.1. Scenarios definition

Once the data transfer process was automated, various management scenarios were modelled. A reference scenario and modifications of it must enable the definition of specific events including some emergency situations. In order to decide on the number of scenarios to be built and to define their characteristics, expert knowledge was considered to be essential. Therefore, experts from different disciplines (WWTP control and operation, sewer system design and management as well as river water quality control) were consulted by means of personal interviews. These experts mostly belong to the *Consorci per a la Defensa de la Conca del Riu Besòs* (CDCRB), an organization that is responsible of the sewer systems and WWTPs in this area. Taking into account the knowledge of these water managers, some critical management situations and their possible solutions were considered as the scenarios to be simulated.

The scenarios must be defined by considering the water quality as the primary objective at the whole system scale, accepting, in some cases, some minor performance decreases in specific WWTPs or a little water quality worsening in small reaches of the river. The aim of these scenarios was to extract enough knowledge to evaluate the consequences of the introduced modifications on the water quality and quantity. The reference scenario was defined as the more frequent situation, including both domestic and industrial contributions, with an average water quality. The alternative scenarios were designed by introducing modifications, to the reference scenario, in the influent load (increase of population), in the influent flow rate (rain, storms and CSO), in the river water flow rate (minimum river water discharge for ecological activity) or involving industrial spills (highly loaded in organic matter and/or nitrogen), in operational problems (inhibition of nitrification, WWTP shutdowns and obstruction of sewer system conduits) or in control strategies (use of storage tanks or bypasses between WWTPs) (Table 1). As shown in Table 2, 29 scenarios were identified in total by the experts (1 reference scenario and 28 alternative scenarios, including one or more modifications).

The simulation results of the different scenarios were thoroughly analysed and two of them will be presented next as representative case studies to show the advantages and usefulness of the integrated modelling-based approach as a support tool for UWS management. The first case study illustrates the usefulness of the storage tanks while the second one evaluates the use of a flow rate bypass between the two sewer systems as a control strategy for the whole UWS. In both scenarios, uncontrolled industrial spills exist which, depending on the WWTP operational state and hydraulic capacity, can seriously affect its performance. There are two main types of industrial spills depending on the duration of the discharge: concentrated industrial spills (2 days duration, for example in scenarios 11 and 13, with and without bypass of 35% of the influent, respectively) and discrete or punctual industrial spills (a 2 h-industrial discharge event, for example in scenarios 25 and 26, with and without the use of storage tanks, respectively). In all the cases large BOD concentrations and NH_4^+ concentrations are implied and thus, in principle, no toxic substances but instead high organic and nitrogen loads are considered in these scenarios. These two case studies have been selected due to their relevance and because they represent two of the more common situations in sewer system management: discrete industrial spill with or without storage tanks (case study 1) and concentrated industrial spill with or without bypass (case study 2).

3.2. Case study no 1: use of storage tanks in the sewer systems

Using the integrated models and the scenarios no. 1, 25 and 26 in Table 2 (reference scenario, discrete industrial spill into the *La Garriga* sewer system and discrete industrial spill into the *La Garriga* sewer system with the presence of storage tanks), 7-day dynamic simulations were carried out to evaluate the functionality of the storage tanks. Storage tanks were used to achieve the lamination of WWTP influent flow rates, by means of retaining the wastewater in the hours of maximum flow rates and discharging it in the hours of minimum flow rates. Although these storage tanks where originally designed and located to manage CSOs during

Table 1
Modifications incorporated with respect to the reference scenario and scenarios affected

Modification	Type of modification(s) incorporated	Scenarios affected
Influent load	Increase in the wastewater load due to an increase of population	9, 10
Influent flow rate	Increase in the wastewater flow rate due to short or normal rain events	4, 5, 8, 23
	Increase in the wastewater flow rate due to intense rain events	6
River water flow rate	Episodes of water scarcity (minimum river water flow rate for ecological activity)	2, 15, 16, 27, 28
Industrial spills	Increase in the organic and/or nitrogen load due to concentrated industrial spills	11, 12, 13, 14, 15, 16, 20, 21, 22, 23
	Increase in the organic and/or nitrogen load due to discrete industrial spills	25, 26, 27, 28
Operational problems	Inhibition of nitrification	19
	WWTP shutdowns	17, 18
	Obstruction of sewer system conduits	24
Control strategies	Use of storage tanks	3, 4, 6, 7, 10, 12, 22, 23, 26, 28
	Bypasses between WWTPs (different %)	13, 14, 16, 18, 21, 29

Table 2
Complete list and description of scenarios evaluated

Scenario no.	Scenario description
1	Reference scenario (more frequent situation with an average water quality).
2	Minimum flow rate of water in the river (0.01 $m^3\ d^{-1}$).
3	Storage tanks in the sewer systems: 3 tanks in *La Garriga* (total volume of 7000 m^3) and 4 tanks in *Granollers* (total volume of 33,000 m^3).
4	Storage tanks in the sewer systems and rain (1.91 mm/h over 12 h).
5	Rain (1.91 mm/h over 12 h).
6	Storage tanks in the sewer systems and intense rain (3.125 mm/h over 48 h).
7	Storage tanks with a control of the discharge flow to minimize the CSO.
8	Short rain (2 mm/h over 5 h).
9	25% increase of population connected to the sewer systems.
10	25% increase of population and storage tanks.
11	Concentrated industrial spill ($q = 0.03\ m^3\ s^{-1}$, BOD = 9000 g $O_2\ m^{-3}$, $NH_4^+ = 850$ g N m^{-3} for 2 days) into the *La Garriga* sewer system.
12	Concentrated industrial spill into the *La Garriga* sewer system and storage tanks.
13	Concentrated industrial spill into the *La Garriga* sewer system and 35% bypass from *La Garriga* to *Granollers* WWTP.
14	Concentrated industrial spill into the *La Garriga* sewer system and 50% bypass from *La Garriga* to *Granollers* WWTP.
15	Concentrated industrial spill into the *La Garriga* sewer system and minimum flow rate of water in the river.
16	Concentrated industrial spill into the *La Garriga* sewer system, 50% bypass from *La Garriga* to *Granollers* WWTP and minimum flow rate of water in the river.
17	*La Garriga* WWTP switch off.
18	*La Garriga* WWTP switch off and 100% bypass from *La Garriga* to *Granollers* WWTP.
19	Inhibition of nitrification in *La Garriga* WWTP.
20	Concentrated industrial spill ($q = 0.03\ m^3\ s^{-1}$, BOD = 9000 g $O_2\ m^{-3}$, $NH_4^+ = 850$ g N m^{-3} for 2 days) into the *Granollers* sewer system.
21	Concentrated industrial spill into the *Granollers* sewer system and 50% bypass from *Granollers* to *Montornès* WWTP.
22	Concentrated industrial spill into the *Granollers* sewer system and storage tanks.
23	Concentrated industrial spill into *La Garriga* and *Granollers* sewer systems, storage tanks and rain (1.96 mm/h over 48 h.).
24	Conduit obstruction in the *Granollers* sewer system.
25	Discrete industrial spill ($q = 0.003\ m^3\ s^{-1}$, BOD = 9000 g $O_2\ m^{-3}$, $NH_4^+ = 5000$ g N m^{-3} for 2 days and $q = 0.1\ m^3\ s^{-1}$, BOD = 9000 g $O_2\ m^{-3}$, $NH_4^+ = 290$ g N m^{-3} from 9h00 to 11h00) into the *La Garriga* sewer system.
26	Discrete industrial spill into the *La Garriga* sewer system and storage tanks.
27	Discrete industrial spill into the *La Garriga* sewer system and minimum flow rate of water in the river.
28	Discrete industrial spill into the *La Garriga* sewer system, storage tanks and minimum flow rate of water in the river.
29	Maximum bypass from *La Garriga* to *Granollers* WWTP.

rainfall events, they are found to also be appropriate for wastewater lamination in dry weather conditions. This laminated WWTP inflow results in more stable conditions for the WWTP management. The same retention concept can be applied when an industrial spill is dumped into the sewer system, thus smoothing the peak concentrations along the time. Three storage tanks were designed and located in *La Garriga* sewer system, with a total capacity of 7000 m^3, and four in the *Granollers* sewer system, with a total capacity of 33000 m^3. For each storage tank, a pumping system giving a constant discharge flow rate was designed. The constant discharge flow rate was calculated from the analysis of the tanks' influent flow rates profiles and it corresponds with the average tank influent flow rate plus an increment of a 5%. The aim of this 5% increment is to assure absolute emptiness of the tanks in the moments of minimum influent flow rates, as so avoiding the accumulation of water with time.

Fig. 5 illustrates the simulation results for the two scenarios with and without storage tanks and the reference scenario. Fig. 5a allows the comparison of the *Granollers* sewer system effluent flow rate (i.e. the *Granollers* WWTP influent flow rate) for scenario no. 1 (reference) and scenario no. 26 (discrete industrial spill with storage tanks). While the effluent flow rate profile of the reference scenario shows the expected pattern due to the urban and industrial water consumption habits, the control action carried out by the storage tanks results in a lamination of the flow rate in scenario 26, allowing the complete emptiness of the tanks (approximately from 6h00 to 8h00, every day) because, during several hours of minimum wastewater production, the amount of wastewater received was very low. Therefore, the presence of storage tanks leads to a quite constant flow rate. Alternatively, the effect of the storage tanks on the water quality under discrete industrial spill conditions can be observed in Fig. 5b–d. Fig. 5b shows the ammonia concentration of both WWTP effluents. While there is no difference between scenario no. 25 and 26 in *Granollers* WWTP (it is important to note that there is no industrial spill into this sewer system), with the high values of ammonia concentration in the *Granollers* WWTP effluent being due to a non-stable nitrification situation, the use of storage tanks can certainly be noticed in *La Garriga* WWTP. Thus, although the ammonia removal efficiency in *La Garriga* WWTP is very high under normal conditions, the industrial spill causes two peaks of high concentration (maximum values of 16 g N m^{-3} and 21 g N m^{-3}) in scenario 25 (without storage tanks), while in scenario no. 26 these two peaks are considerably smoothed (obtaining only one concentration peak of about 5 g N m^{-3}) thanks to the effect of the storage tanks. Therefore, the implementation of storage tanks allows an ammonium concentration decrease of around 75%. Fig. 5c and d show the simulation results for the ammonia concentration at various locations of the *Congost* River in scenarios 25 (without storage tanks) and 26 (with storage tanks) (see the specific location of the control points in Fig. 1). Fig. 5c shows the expected increase of the ammonia concentration in the river after receiving the *Granollers* WWTP effluent and the peaks caused by the industrial spill after receiving the *La Garriga* WWTP effluent in the scenario without storage tanks. On the other hand, Fig. 5d illustrates that the storage tanks considerably smoothed the ammonia peaks in the river, maintaining the ammonia concentration in the stream reach B-C for almost the entire simulation time under the limit of 1 g N m^{-3} (that has been considered as the maximum allowed N concentration for aquatic life, Prat et al., 2002).

3.3. *Case study no 2: use of bypass between the two sewer systems*

Ammonia concentration at the first reach of the *Congost* River, before receiving the *Granollers* WWTP effluent, is usually lower than the allowed concentration for aquatic life (1 g N m^{-3}) thanks to the high ammonia removal of *La Garriga* WWTP. Therefore, it is a reach with a good water quality and ecological health but passing through a landscape, where urban land uses are predominant, of potentially intense polluting activities. This is a typical case where the system is highly vulnerable to transient pollution events (e.g. industrial spills) and it is necessary to increase the reliability of the wastewater management systems (Beck, 2005). This case study models a situation where a conduit, that allows bypassing wastewater from the end of *La Garriga* WWTP sewer system to the end of *Granollers* WWTP sewer system, contributes to an increase in the reliability of the *La Garriga* WWTP and to minimize the impact of the industrial spill in the first reach of the *Congost* River. It presents a situation with a concentrated industrial spill introduced into the *La Garriga* sewer system, causing a considerable impact on the *La Garriga* WWTP, and the analysis of the scenario without a bypass (scenario no. 11 in Table 2) and with a 35% bypass of the influent flow rate from *La Garriga* WWTP to the *Granollers* system (scenario no. 13 in Table 2). The

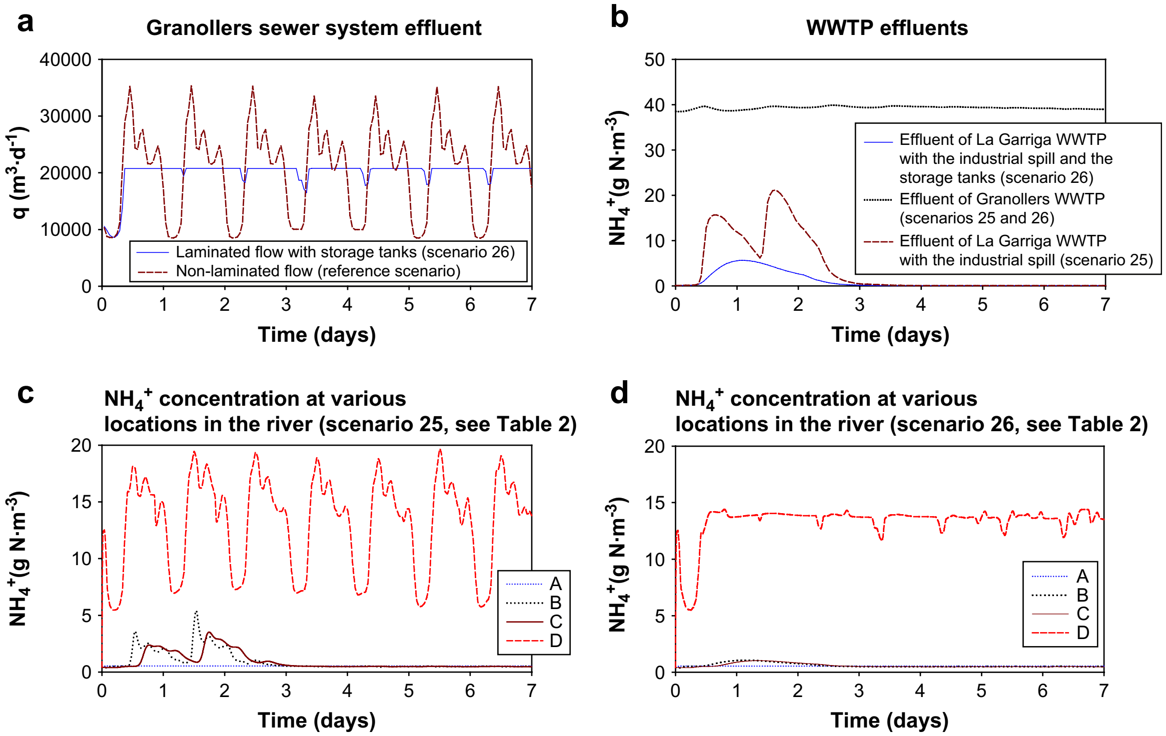

Fig. 5. Simulation results when using storage tanks to laminate the WWTP inflow (a: *Granollers* sewer system effluent; b: WWTP effluents; c: NH_4^+ concentration at various locations in the river for scenario 25; d: NH_4^+ concentration at various locations in the river for scenario 26).

impact of a bypass between the two WWTPs was studied by carrying out a 7-day dynamic simulation with the integrated models.

The results of the two simulated scenarios are presented in Fig. 6. Fig. 6a shows the ammonia concentration in the effluents of *La Garriga* and *Granollers* sewer systems. The effect of the concentrated industrial spill on the *La Garriga* sewer system is highly pronounced. Fig. 6b–d show the differences observed in the WWTP and diverse river locations when considering or not the 35% bypass.

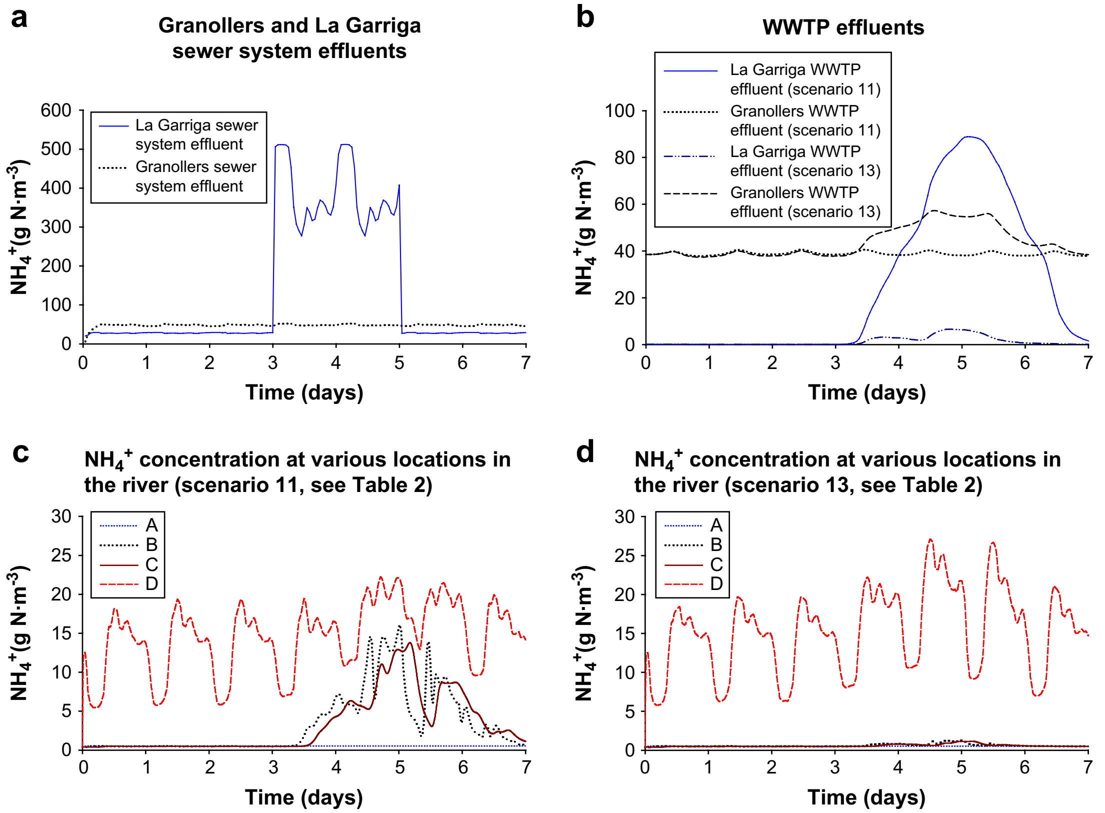

Fig. 6. Simulation results when using a bypass between the two sewer systems (a: *Granollers* and *La Garriga* sewer system effluents; b: WWTP effluents; c: NH_4^+ concentration at various locations in the river for scenario 11; d: NH_4^+ concentration at various locations in the river for scenario 13).

Fig. 6b illustrates how the high ammonia load of the industrial spill affects the nitrification process of *La Garriga* WWTP, giving a maximum concentration peak of 90 g N m^{-3} in *La Garriga* WWTP effluent (scenario no. 11). However, with a 35% of bypass (scenario no. 13), a high ammonia removal efficiency can be kept throughout the simulation time, lowering the peak of ammonium concentration to only 7 g N m^{-3}. Therefore, the use of 35% bypass allows an ammonium concentration decrease of around 90%. Fig. 6c and d shows the ammonia concentration at different river locations (see the specific river locations of the control points in Fig. 1). Whereas the ammonia concentration along the river reach B-C is widely exceeding 1 g N m^{-3} in the scenario without bypass (scenario no. 11, Fig. 6c), it is drastically reduced when there is a bypass of 35% of the wastewater from *La Garriga* to *Granollers* WWTP (scenario no. 13, Fig. 6d). Therefore, bypasses between related sewer systems can be assumed as a good control strategy if the objective is to maintain the ammonia content in a good quality but vulnerable stream reach.

Main conclusions of the other scenarios simulated include: for the case of minimum river flow rate, a significant increase of the ammonia and BOD concentrations in the river is detected; when storage tanks in the sewer systems and rain events are present, a certain dilution effect is detected at the sewer system and WWTP effluents while the stream reach comprised downstream *La Garriga*, i.e. between the two WWTP discharge points, experiences an important increase in the BOD and ammonium concentrations with respect to the reference scenario. This increase is caused by the high impact of the combined sewer overflows since the storage tanks were totally exceeded during the rain episode. These overflows discharge large amounts of untreated wastewater directly to the river, even for a long time after the rain stops. The 25% increase of population affect little the river water quality because the increase in pollutants load can be treated by the WWTPs. In the scenario with a concentrated industrial spill into *La Garriga* sewer system, *La Garriga* WWTP experiences a big impact as does the reach stream quality between the two WWTPs. In this case, a bypass of the 35% from *La Garriga* to *Granollers* WWTP enables to reduce drastically (80%) the ammonium concentration of the stream reach between the two plants while just causing a 5% increase of the concentration downstream *Granollers* WWTP.

Two case studies have been explained in detail, and the other 27 in less detail, although the objective of the manuscript was not to study deeply case by case but rather to illustrate that the use of an integrated model-based approach enables a better management of the sanitation infrastructures, when expert knowledge is used throughout scenario analysis. The integrated approach allows achieving a better river water quality than with an approach based on the management of sewer systems, storage tanks and wastewater treatment plants considered as individual and not interrelated systems.

This integrated model-based tool was tested in a sub-catchment composed of a stream reach, two sewer systems, two WWTPs, all the corresponding spatial information (hydrography, topography, land uses, etc.) and by considering all the options and relationships among the elements of UWS. Then, in order to adapt this tool to the whole catchment, the elements of the rest of the catchment have to be added (other WWTPs, communities, industrial discharges, CSOs, storage tanks, etc.) and their relationships with respect to the existing ones defined. This approach represents an advanced generic solution because it can be applied to any river catchment, for many different scenarios and, compared to other previously published works, involves use and acquisition of expert knowledge in order to handle decision-making in UWS management, in addition to the sole use of mathematical modelling that has been traditionally used.

4. Conclusions

This paper presents a model-based approach as a support tool for the integrated management of sanitation infrastructures. Models for sewer systems, WWTPs and river reaches have been integrated successfully using specifically designed software. Twenty nine scenarios representative of real situations were identified taking into account the experience of the organization that manages the sewer systems and the WWTPs in the studied area and including possible events such as industrial spills, rainfalls, inhibition of nitrification, obstruction of a sewer system conduit and minimum river flow rate as well as possible control actions such as the construction of storage tanks and the use of bypasses between sewer systems or WWTPs. The analysis of the simulated results of several management scenarios, including critical events, enables the acquisition of relevant knowledge about which are good control alternatives when the primary objective is to guarantee a good river water quality and minimum economical cost and/or maximum WWTP efficiency. The use of this integrated model-based approach supports water managers in decision-making about which are good control strategies in every scenario by allowing the simulation of all the alternatives and selecting the one that better fits the manager's primary objectives. The use of complex water quality models to evaluate control alternatives on line in real time control systems is not the best option because the simulation times are too long to give results in a reasonable time. However, the use of offline simulations are a powerful tool to generate information to be used in the decision-making process when expert knowledge is used in the definition of scenarios and interpretation of the simulation results. Indeed scenarios provide a set of control actions to be considered during the management of the infrastructures when a critical situation is detected. Specifically, the paper demonstrates throughout simulation that the construction of storage tanks and the use of bypasses between related sewer systems are useful control actions in order to preserve or increase the river water quality (i.e. ammonium concentration decreases of about 75–90% in the two presented case studies and similar results can be concluded for all the scenarios). The integrated management of the sanitation infrastructures problem, including the river water quality concept, becomes an environmental problem that, in addition to the use of conventional mathematical equations, requires expert knowledge from water managers in order to handle it.

When there are different interests or opposite evaluation criteria among the decision-makers within the UWS, integrated management of UWS should involve a multi-objective decision-making process in order to improve the overall system performance and achieve environmental targets. This decision-making process, which may involve a trade-off between good river quality and low operational costs, can be supported by the knowledge acquired by analysing the different scenario simulation results. The problem becomes even more complex when the active participation of all relevant stakeholders in integrated river basin management, including state agencies, private companies, NGOs, etc. are required to be considered for future management scenarios.

Acknowledgments

Francesc Devesa is pleased to acknowledge the financial support of the Ministry of Education and Science of the Spanish Government. The authors benefited from the partial support of the Spanish research projects DPI2006-15707-C02-01, PET2005_0375 and NOVEDAR (CONSOLIDER-CSD2007-00055). The authors also wish to thank Mr Josep Arràez, Director of the *Consorci per a la Defensa de la Conca del Riu Besòs* (Besòs River Basin Agency), for his confidence in this research and Carles Díez for his collaboration in the development of the data transfer software.

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