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INTEGRATED MANAGEMENT OF URBAN WASTEWATER SYSTEMS: A MODEL-BASED APPROACH

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Integrated management of urban wastewater systems: a model-based approach

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That Mr. Pau Prat Busquets has done the work presented in this thesis, **"Integrated management of urban wastewater systems: a model-based approach"**, under our supervision. The thesis is submitted as part of the requirements to obtain a doctoral degree in Experimental Sciences and Sustainability.

We sign and submit the present certificate to the Faculty of Sciences at the University of Girona for any intents and purposes for which it may be used.

Girona, November 2011

Joaquim Comas Matas Lluís Corominas Tabares

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ABSTRACT

Since the publication of the Water Framework Directive, urban wastewater systems have to be considered as single operating units. That is a difficult task. Managers have to understand the interactions between systems, which have rarely been taken into account. Efforts to meet WFD objectives have been focused on the integrated modeling of the UWS, which at least take into account sewer systems, wastewater treatment plants and receiving water bodies as final receptors of the treated wastewater.

Integrated models of urban wastewater systems have not been successfully applied due to bottlenecks, but some experiences and case studies have suggested the adoption of simplified numerical models. Models can help to better understand the interrelations within the system itself. Hence, integrated models play an important role in exploring the vast range of available management strategies to confront problematic situations. The current state of the art in modeling has reached a point where it is feasible to construct a model that provides a reasonable level of resolution.

The study presented in this thesis involves the development and implementation of a new method to find the best operational strategies from an integrated model of the urban wastewater system to overcome typical problematic scenarios posted in the Besòs River basin case study.

First, the analysis of these scenarios was conducted based on global sensitivity analysis (GSA) and multi simulations were launched by means of Monte Carlo simulations. Such analyses contribute to identifying the most sensitive parameters for each problematic scenario simulated and, from those sensitive parameters, which key parameters could help to overcome the problem posted as soon as possible. The results of GSA are provided by box plots and descriptive statistical techniques. A table summarizing those key parameters is presented.

Once the sensitive parameters are selected for each scenario, a second iteration of multi simulations was done. In the Monte Carlo method the model is fed with different combinations of these sensitive parameters. By using economical and environmental criteria, a best parameter combination could be found, to discard from all simulations, a Pareto Front was conducted followed by one screening. For each problematic scenario a combination of set points, which contribute to improve almost all criteria, have been found and are presented.

The model has provided a lot of valuable information that can be used to pursue the integrated management objectives. Sensitive parameters together with best management strategies were integrated as a simple rule-based system. The full implementation and application of this method is presented for practice in WEST but can be used in any other simulation platform.

The final results conclude that the method can improve management practices in real cases.

RESUM

Des de la publicació de la directiva marc de l'aigua les conques fluvials s'han de gestionar de forma integrada, com a conseqüència, els sistemes urbans d'aigües residuals han de ser considerats coma a una sola unitat de gestió. Els responsables de les diferents infraestructures de sanejament han de tenir en compte les relacions existents entre les diferents unitats, que massa sovint s'han ignorat. Alguns dels esforços per a garantir la directiva marc s'han centrat en l'ús de models matemàtics que integren les següents infraestructures: els sistemes de clavegueram, les estacions depuradores d'aigües residuals i les masses d'aigua receptores de les aigües residuals un cop tractades.

Aquests models integrats rarament han estat aplicats en casos reals, la seva complexitat i característiques prevenen el seu ús, no obstant, alguns casos d'estudi i exemples suggereixen l'ús de versions més simplificades d'aquests models per representar els sistemes urbans. Els models ajuden a entendre millor les interrelacions entre les diferents unitats, per tant, poden ser molt útils per trobar noves estratègies de gestió i així superar situacions adverses. El desenvolupament actual dels models i l'estat de la tecnologia han arribat a tal punt que permeten construir de forma menys complicada models integrats amb un bon grau de resolució.

El treball presentat en aquesta tesi comprèn el desenvolupament de la implementació d'una nova metodologia per tal de trobar millors estratègies de gestió dels sistemes urbans a partir de models integrats, i així trobar solucions davant d'escenaris problemàtics de la Conca del Riu Besòs.

En primer lloc, s'ha dut a terme un estudi de les diferents situacions problemàtiques basat amb una anàlisi de sensibilitat, utilitzant la metodologia Monte Carlo s'han dut a terme simulacions múltiples. Entre altres objectius, aquesta anàlisi serveix per identificar quins són els paràmetres d'operació més sensibles per a cada situació simulada, i a la vegada, identificar quins són els més importants. Els resultats de l'anàlisi de sensibilitats han estat presentats utilitzant diagrames de caixa i tècniques estadístiques descriptives. Els paràmetres més sensibles s'han resumit en una taula.

Un cop identificats els paràmetres sensibles per cada situació, s'ha dut a terme una segona interacció de simulacions múltiples. El mètode Monte Carlo llança diferents simulacions utilitzant diferents configuracions dels paràmetres sensibles. Utilitzant criteris econòmics i ambientals, ha estat possible identificar quines són les simulacions que donen millors resultats, per descartar entre les simulacions primer s'han identificat les solucions Pareto, i seguidament s'han triat les que presenten millors resultats. Finalment s'ha trobat una combinació de consignes per a cada situació que en la major part dels casos milloren tots els criteris d'avaluació.

El model integrat ha aportat informació que pot ser utilitzada per aconseguir els objectius perseguits per la directiva marc de l'aigua. Els paràmetres més sensibles, juntament amb les millors pràctiques de gestió identificades han estat integrades en forma de control a la plataforma de simulació WEST.

Els resultats finals conclouen que la metodologia presentada pot ser utilitzada per trobar millors pràctiques de gestió utilitzant models integrats.

CONTENTS

CHAPTER 1

INTRODUCTION

1. Introduction

1.1 Problem statement

The Water Framework Directive[1] (WFD) establishes a legal framework to protect and restore clean water across Europe and ensure its long-term and sustainable use. The directive establishes an innovative approach for water management based on integrated river basin management (IRBM), the natural geographical and hydrological units, and sets specific deadlines for member states to achieve ambitious environmental objectives for aquatic ecosystems. The directive addresses inland surface waters, transitional waters, coastal waters and groundwater.

The traditional management of wastewater infrastructures aims to meet legal emission limits, but usually without taking into account the consequences for the receiving waters or any other wastewater facilities. This is usually due to the fact that the sewer system (SS), the wastewater treatment plants (WWTP) and the receiving water bodies (RWB) are generally managed by different companies or administrations. This directive has introduced a crucial change in river basin management, from emission-based regulations to an immission-based approach. It is the status of water bodies that will decide pollution permissions to be set in the catchment.

This approach introduces a higher degree of complexity during the selection of IRBM strategies due to the interactions at different spatial and temporal scales between the infrastructures of the urban wastewater systems (UWS). All the infrastructures making up the UWS, i.e., the WWTP and the SS, have to be included in the evaluation and decision processes during wastewater management. There is a need to redesign the old facilities, construct more efficient treatment systems and add other infrastructures like storm tanks.

However, this is not an easy task, and moreover, a reliable analysis of the UWS will involve other challenges such as: offering reliable prediction of the UWS taking into account the multiplicity of interactions among the different infrastructures (and models) in which is comprised; reducing the number of operational strategies to solve UWS problems using either previous experiences or expertise; dealing with multiple objectives and multiple performance measures; identifying both strong and weak points of the different operational strategies; and including uncertainty/risk during the evaluation procedure to see how it can affect the decision-making process.

For all the above, it will be necessary to develop new methods and decision tools to support the decision-making process from a reliable point of view and at the same time achieve the objectives demanded by the WFD.

1.2 Hypothesis

Integrated models that include at least the SS, WWTP and RWB have been developed in order to manage the UWS as a whole. Complex numerical modelling techniques are able to represent the whole system but require long calibration procedures and high computational capabilities. These models can be used to improve the performance of

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[1] Its official title is 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.

UWS design or operation. Some experiences and case studies have suggested the adoption of simplified integrated numerical models of the UWS (Freni *et al.,* 2010; Fu *et al.,* 2008; Solvi *et al.,* 2006; Vanrolleghem *et al.,* 2005a).

Simplified integrated numerical models also results in a better understanding of the interrelations within the system itself. Models can be used to test scenarios in order to evaluate future events (e.g. sewer system collapse), or to assess certain measures intended to improve the performance of the system (e.g. increased hydraulic load to the WWTP or in-stream aeration of the river).

We state that by using simplified integrated models it is possible to improve the integrated management of UWS. Such approach allows to efficiently simulate and analyze the behavior of the integrated system and to find best operational strategies for day to day management. At the same time models can provided useful information for manager and stakeholders involved in decision processes.

1.3 Contributions

The main contribution of this thesis is the development and application of a model-based approach to find the best management strategies to confront problematic situations in an integrated way. An integrated model was first developed based on Devesa's (2005) case study. That model considered two SS, two WWTP, storage tanks, a connection channel between systems, and a river. We have taken a step further than Devesa (2005) and have integrated the model into a single modeling platform, which has been used to simulate typical problematic scenarios posted on the system and to assess its performance using nine evaluation criteria, including environmental and economic aspects.

The model has provided a lot of valuable information that can be used to pursue the integrated management objectives. Important operational parameters and good management strategies for the UWS control have been identified and integrated as a simple rule-based system to improve overall management of the system. The full implementation and application of this method is presented for practice in WEST but can be used in any other simulation platform.

All the work presented in this thesis has been presented at international conferences and published in the following journal articles:

Model-based knowledge acquisition in Environmental Decision Support System for wastewater integrated management (2010). Prat, P., Benedetti, L., Corominas, L., Comas, J., Poch, P. Accepted for publication in Water Science and Technology.

Global sensitivity analysis of a sewers-WWTPs-river integrated model for the development of a supervisory system at river basin scale (2009). Benedetti, L., Prat, P., Nopens, I., Poch, M., De Baets, B. and Comas, J. Water Science and Technology. 60 (8) 2035-2040.

Role Playing Games: A Methodology to Acquire Knowledge for Integrated Water River Management (2009). Prat, P., Aulinas, M., Turon, C., Comas, J and Poch, M. Water Science and Technology. 59 (9) 1809-1816.

1.4 Outline

The present thesis is structured as follows:

In **Chapter 2**, the urban wastewater system (UWS) is introduced, the main elements and processes within the system (SS, WWTP and RWB) are described, and the main interactions between those elements are pointed out. Following that, there is a section devoted to the legislative framework of urban wastewater systems. Afterwards, a brief review of the integrated modeling of UWS is presented, starting with models for single processes of the UWS, and finally introducing integrated modeling challenges. In **Chapter 3** the objectives of this thesis are presented.

Chapter 4 offers a full description of the method developed in this thesis. The first part introduces typical problematic scenarios to be modeled and the approach followed for global sensitivity analysis (GSA), and the second part presents how to identify best management strategies. **Chapter 5** introduces the case study, followed by the integrated model developed and a description of each part. Finally, it identifies the key elements of the case study for each step of the method.

The results of the method developed are contained in **Chapters 6** and **7**. In **Chapter 6**, the results of the GSA are presented with the main outcomes. A table summarizes the overall results of that chapter. In **Chapter 7**, the results of the second part of the method are presented. A management strategy has been chosen for each scenario. Finally, overall strategies have been introduced as a rule-based system. **Chapter 8** provides a general discussion, presenting implications, possibilities and future work on the method.

Chapter 9 presents the conclusions drawn for the results of the thesis, **Chapter 10** provides the references, and finally an **Annex** is provided with the model layout and extended results from Chapters 5 and 6.

CHAPTER 2

URBAN WASTEWATER SYSTEM

2. Urban wastewater system

2.1 Description

The term urban wastewater system (UWS) refers to the different elements or infrastructures that convey, transport and treat wastewater coming from different sources, until it is discharged to a water body or re-used.

Normally a UWS consists of a sewer system (SS), wastewater treatment plants (WWTP) and receiving water bodies (RWB). Other infrastructures considered within these units include storm tanks, connection channels between infrastructures, pumping stations, manholes, and combined sewer overflows (CSO).

Two main objectives frame the UWS: (1) Flood prevention in constructed areas, and (2) preventing discharges of wastewater without treatment.

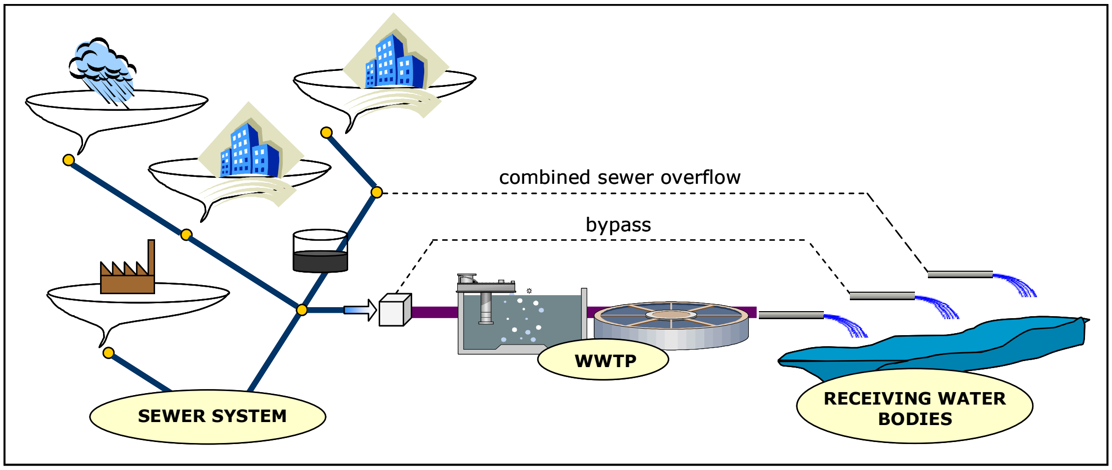

Figure 2.1. Urban Wastewater System (adapted from Devesa, 2005)

2.1.1 Sewer Systems

Sanitary SS are underground closed systems composed of intercepting sewers, networks of pipes, pumping stations, manholes and other items, which transport domestic, commercial, and industrial wastewater, and limited amounts of infiltrated groundwater and stormwater, to treatment or disposal.

The earliest sewers were built to collect and transmit urban stormwater to the nearest watercourse. Later, sanitary sewage from houses was discharged into large storm drains, converting them into combined sewers. When it was recognized that environmental problems were associated with the discharge of untreated sewage to receiving water, overflow points were designed into the sewer system, and new sewers were constructed to intercept and convey dry-weather flows to treatment facilities, while CSO were diverted directly to receiving water (Torno, 1975). Nowadays separate systems have been constructed for sanitary and stormwater flows.

Most SS have been designed to transport wastewater in dry-weather flow, when all the wastewater is treated, but during storm weather flow sewer system capacities are exceeded and CSO are lposted in the system. CSO are major sources of urban water pollution (Andrés-Doménech *et al.,* 2010).

Different SS configurations have been designed to overcome storm weather flows, ranging from separate sewer systems to the development of green stormwater infrastructure (GSI). Both approaches seek the best management practices to avoid mixing dry weather flow with the stormwater flow.

Recent studies have demonstrated that a separate system is not always the best option to assure receiving water quality (De Toffol *et al.,* 2007). Separate systems avoid CSO because dry weather flow is conducted through different conduits. However, the pollutants conveyed by stormwater flow are directly discharged into the RWB unless a mitigation measure is added (Mannina and Viviani 2009). Here, on-site stormwater pretreatment methods like sand filters, bioretention facilities, permeable pavement, green roofs, rainwater harvesting and bioretention planters under drains play an important role. However, those systems are not enough to remove micro pollutants, or to deal with large quantities of nitrogenous and phosphorus compounds that will finally arrive at the RWB (Kus *et al.,* 2010; Weyrauch *et al.,* 2010).

Storage facilities like tanks and detention basins are certainly the most widely used measures to control CSOs (Andrés-Doménech *et al.,* 2010). Barcelona has nine tanks and two detention basins with a total volume of 492,200 m^3 (Malgrat Bregolat *et al.,* 2004). Germany considers combined sewer detention tanks (CSDT) to be an essential part of the sewer system (Kowalski *et al.,* 1999). In France many catchments are served by underground settling basins (Faure *et al.,* 2005). Tanks retard the waste in the sewage system and prevent water pollution during storm rainfall events. Besides, tanks can be used to control WWTP inflows. By improving the integrated operation of the sewer system and the WWTP, critical concentrations can be avoided, and the wastewater flow rate can be made smoother. With a correct tank volume, good levels of wastewater treatment efficiency can be achieved (Seggelke *et al.,* 2005).

2.1.2 Wastewater Treatment Plants

WWTP are key elements in the UWS because it is not permitted to discharge wastewater to the RWB without treatment. The configuration and composition of the treatment plants will depend on current and future treatment needs and the stringent discharge requirements of the place where the they are located (Tchobanoglous *et al.,* 2003). The first WWTP were focused on reducing organic and suspended solids. Later on, in accordance with more restrictive legislation and the general needs of society, WWTP evolved into complex systems able to treat almost any kind of pollutant present in wastewater (Clara *et al.,* 2005). Municipal wastewater is mostly treated in biological WWTP. They should ensure a certain degree of pollution removal within legislative limits on water discharge while, at the same time, keeping construction, operating cots and footprint to a minimum (Flores-Alsina 2008; De Gussem *et al.,* 2011).

WWTP have become complex systems to operate, manage and assess. Processes within WWTP are characterized by intrinsic unsteadiness and the system remains in the non-linear operation state. In order to meet the effluent specifications to minimize the impact on the receiving media, and because more knowledge is available for WWTP, a lot of research has been conducted to improve their performance. The most important work has focused on the activated sludge system as the technology usually applied to WWTP

(Sànchez *et al.,* 1994; Martinez *et al.,* 2006; Marti *et al.,* 2008). Other works analyzed the best operational strategies of the plant-wide WWTP process (Mark *et al.,* 1998; Pfister *et al.,* 1998; Tränckner *et al.,* 2007; Flores-Alsina *et al.,* 2010). Finally, simulation works have become important elements to analyze best configurations and operational strategies. Mathematical modeling research has also paid attention to the operational problems of microbiological origin and some attempts to model these matters were performed (Gernaey *et al.,* 2004; Dalmau, 2009).

2.1.3 Receiving Water Bodies

RWB are creeks, streams, rivers, lakes, estuaries, groundwater formations, or other bodies of water into which surface water and/or treated or untreated wastewater are discharged, either naturally or in man-made systems (McMillin *et al.,* 2006). Rivers are the most frequent sinks for urban wastewater.

RWB are normally also natural resources for drinking water and irrigation. For these reasons water must be returned to the RWB, with an acceptable levels of quantity and quality maintained. Traditionally wastewater has been discharged into RWB without treatment, upholding the idea of river self-purification. Once the bad effects of those management strategies had been recognized, solutions were adopted to reduce the pollution. The discharge of treated wastewater will have to fulfill certain concentrations and flow limits, depending on current legislation and the wastewater's final use.

End-of-pipe limits can strongly determine wastewater treatment strategies. These limits can be set by (1) emission-based regulations, defining effluent standard characteristics based on effluent concentrations on individual pollutants or groups (Tilche and Orhon, 2002) or (2) immission-based regulations, defining environmental water quality strategies based on ecosystem-based quality objectives (Gabriel and Zessner, 2006).

The water quality of the RWB is not only determined by the inputs into the system, but also by the physical transport and exchange processes and the biological, biochemical or physical conversion processes taking place between the water column and the sediments.

The RWB is clearly influenced by a vast range of parameters, and several factors should be looked at when judging the water quality. The combination of several criteria leads to a classification of the river as having very good, good, mediocre, deficient and bad environmental quality according to the European WFD.

2.1.4 Interactions between different units of the Urban Wastewater System

The different units of the UWS are related in several ways (Figure 2.1). These interactions (SS-WWTP, SS-RWB, WWTP-RWB) are defined by water flows, water quality and backwater effects. Some of these interactions are obvious, e.g., CSO put in the sewer system can cause oxygen depletion in rivers (Rauch and Harremoës, 1996), or WWTP can contribute to eutrophication in rivers (Llorens *et al.,* 2008).

For other interactions the cause-effect relationship is difficult to determine. Every change of quality in an upstream compartment (SS or WWTP) will have a more or less pronounced effect on the downstream compartment (WWTP or RWB), e.g., chemicals added to the sewer system have an impact on the performance of the WWTP (Gutierrez *et al.,* 2010). Table 2.1 summarizes the effects of key contaminants on the water quality on receiving waters. More information about the interactions between these elements is given in Lijklem *et al.* (1993), Meirlaen (2002) and Aulinas (2009).

Table 2.1. Impacts of key contaminants on receiving waters (Lijklema *et al.,* 1993).

Contaminant	Environmental effects	Ecological impacts[1]	Affected water use[2]
OXYGEN DEMAND			
COD from CSO	DO reduction	3,4	A,B,D,E
WWTP	Biomass accumulation	1,2,7	A
NH_4 from CSO	DO reduction	3,4	A,B,D,E
WWTPs		1,2,7	A
NUTRIENTS			
N_{tot} from CSO and surface runoff	Enrichment	1,2,4,7	A,B,C,D,E
P_{tot} from CSO and surface runoff	Enrichment	1,2,4,7	A,B,C,D,E
TOXICANTS			
NH_4 (+temp. +pH)	Toxicity	2,3,4	D
Metals – Acute	Toxicity	2,3,4,7	D
- Cumulative	Toxicity	2,3,4,7	D
Organic micropollutants (cumulative)	Toxicity	2,3,4	D
HYGIENE			
Fecal bacteria	Public health Biomass	1,2,7	A,B,D
PHYSICAL			
Temperature	Temp.rise + long-term change	1,2,5,6	D
Suspended solids	Blanketing + harm to fish	4,6	A,B,C,D,E,F
Flow	Washout; morphology changes	2,4,7	D
Chloride	Excess dissolved solids	2,5,7	A,D,F

[1] The ecological impacts noted refer to ecosystem characteristics: 1. Energy dynamics; 2. Food web; 3. Biodiversity; 4. Critical species; 5. Genetic diversity; 6. Dispersal and migration; 7. Ecosystem development

[2] Beneficial receiving water uses affected by contamination are coded as follows: A- Water supply; B – Bathing; C – Recreation; D – Fishing; E – Industrial water supply; F – Irrigation.

Managing the UWS in an integrated way makes it possible to take into consideration these relationships. New management strategies arise to overcome typical problematic situations and improve the quality of receiving water bodies. For example, WWTP capacity can be enhanced if influent characteristics are known in advance (Pfister *et al.,* 1998; Ahnert *et al.,* 2009;). If a WWTP is overloaded, then alternative strategies can be used, e.g., when feasible, wastewater can be sent to storage tanks, or bypassed to another system.

2.2 Legislative framework of urban wastewater systems

As already mentioned in the introduction, since the publication of the Water Framework Directive (WFD) (CEC (2000)), the UWS have to be considered as single operating units whose main objectives are to improve all the water bodies in Europe by 2015:

- Good ecological status, based on environmental quality standards which might differ from member states (Kallis and Butler, 2001).

- Good chemical quality status based on emission limit values.

Before the WFD, other directives had been published in Europe to improve the water quality of European rivers. Directive 91/271/EEC concerning urban wastewater treatment sets clear infrastructure targets for wastewater treatment for all European urban settlements according to different classes of receiving waters sensitivity. And Directive 96/61/EC on Integrated Pollution Prevention and Control was developed to apply an integrated environmental approach to the regulation of certain industrial activities.

The WFD coordinates the application of all European Union water-related legislation and marks an important trend towards an ecosystem based-approach for water policy and water resources management. Each authority is responsible for preparing and implementing a river basin management plan (RBMP) to achieve good environmental quality. According to the WFD, an RBMP should have been available as of 22 December 2009 in all river basin districts. However, there have been serious delays in some parts of the EU. Spain has 25 river basin districts, and at the time of writing this thesis the only RBMP adopted and published refers to the RBMP from internal basins of Catalonia[2].

Legislation similar to the WFD exits in other countries: the Clean Water Act (CWA) or the Federal Water Pollution Control Act in the USA (33 U.S.C. 1251 *et seq*., 1972), or the amended Water Law in 2002 in China (GB 3838-2002, China State Environmental Protection Administration, 2002) (Wang *et al.,* 2008). The aim of these directives is to improve the water status for a variety of users and uses, including bathing, outdoor recreation, industry and drinking. There are parallels between those directives and the WFD in terms of objectives, implementation and IRBM approach (Hoornbeek, 2004).

An IRBM approach considers traditional solutions, but emphasizes non-structural solutions (management and governance) and incorporates systematic management methods (Ravesteijn and Kroesen, 2007) to improve water resources management in river basins. One of the major advantages of using an integrated approach lies in the ability to evaluate the performance of the urban wastewater system directly. The consideration of the UWS as a unit and the emission-immission WFD approach increase the degrees of freedom for wastewater management (Solvi, 2007). Legislation is the way to move from individual management of the different units of UWS to an integrated approach.

Despite this, however, the evolution of water policy and management shows that IRBM has not been effectively implemented, it has only been used to heuristically identify opportunities for water system integration and wastewater recycling. The implementation of the WFD has been, and still is, a major challenge. Moreover IRBM is required for effectively improving human health and hygiene, reducing environmental and economic impacts, and improving water resource independency (Wang *et al.,* 2008; Hering *et al.,* 2010; Lim *et al.,* 2010).

2.3 Modeling of integrated Urban Wastewater System

After publication of the WFD, the interest in integrated modeling of UWS has increased. Integrated modeling means identifying the entire river basin as a single model. The challenge is not only to model individual processes but also their interactions. The

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[2] http://ec.europa.eu/environment/water/participation/map_mc/countries/spain_en.htm

model should take into account processes developed at different degrees and time series. Modeling the activated sludge in a WWTP is not the same as the effect of uncontrolled spills on the activated sludge; the model needs a different degree of process detail.

Constructing a single model of all UWS processes is a tedious task, it does not make proper use of existing models, does not provide the flexibility to try alternative models of individual processes, and is complex for the model itself (Blind and Gregersen, 2005). Different variables are considered for each single infrastructure with different time resolutions (Table 2.2). The complexity of the total UWS prevents a single linkage of the existing detailed deterministic models of the individual sub-system to an entity (Rauch *et al.,* 2002). The model should be as detailed as necessary and as simple as possible to achieve the best objective-driven results.

Table 2.2: Comparison of state variables used in models of the different subsystems of an urban catchment (Rauch *et al.,* 1998).

Sewer System		**Wastewater Treatment Plant**		**River**	
Flow Rate		Flow Rate		Flow Rate	
Total Suspended Solids		Total Suspended Solids		Total Suspended Solids	
BOD	Particular Soluble	COD	Inert soluble (SI) Soluble readily biodegradable (SS) Inert particulate (XI) Slowly biodegradable (XS) Heterotrophic biomass (XBA) Autotrophic biomass (XBA)	BOD	Slowly biodegradable Readily biodegradable Sediment oxygen demand
Total (Kjeldahl) Nitrogen		N	Ammonium (SNH) Nitrate (SNO) Soluble biodegradable (SND) Inert soluble (SNI) Slowly biodegradable (XND)	N	Ammonium Nitrite Nitrate Kejldahl
		Dissolved oxygen		Dissolved oxygen	
Total Phosphate				Phosphate	Inorganic Organic
Fecal coliforms				Fecal coliforms Chlorophyll a pH	

Various kinds of models, more or less complex in structure, exist for the different elements of the UWS. The current modeling platforms allow UWS to be integrated in a single modeling package. They can be conceptual models describing underlying concepts of processes, or exact mathematical equations for physical or chemical processes. They can also be empirical models, like black-box models built on existing data and not relying on knowledge of the system functioning itself. Stochastic models include the description of intrinsic randomness of processes within the system.

2.3.1 Sewer System models

Several models are capable of simulating the different flows and processes within the SS, from run-off modeling coming from rain events to sulfide productions inside the collection system. To name just a few, Muschalla *et al.* (2006) present a detailed hydrological deterministic rainfall-runoff model and a pollution load model, SMUSI 5.0, that computes the dominant characteristics for the assessment of the effect of overflow structures on RWB. Mannina and Viviani (2010) present a mathematical model for the evaluation of the pollution load in sewers. Sharma *et al.* (2008) present a mathematical model which takes into account the hydraulics and the biochemical transformation processes to describe the temporal and spatial variations of sulfide in sewer systems.

There are also commercial modeling software packages such as Storm Water Management Model (SWMM, (Huber 2001), HydroWorks/InfoWorks CS (Wallingford Software Ltd., 1995), HYPOCRAS (Bertrand-Krajewski 1993), MouseTrap/Mike Urban (Crabtree *et al.,* 1995) or KOSIM (ITWH 2000). Final objectives will determine which model to use.

2.3.2 Wastewater Treatment Plant models

WWTP models have been widely developed. There are a lot of mathematical models to design, assess, predict and control plant-wide operations and processes inside WWTP (activated sludge, anaerobic digestion), or models for operational problems of microbiological origin. Gernaey *et al.* (2004) presented a state of the art of treatment plant modeling and simulation, with an overview of the most frequently applied models. They concluded that the activated sludge model family (ASM) (Henze *et al*., 2000) by the International Water Association (IWA) provides researchers and managers with a standardized set of models, which are mainly applicable to municipal wastewater systems, and these can be easily adapted to specific situations such as the presence of industrial wastewater.

Commercial platforms are available for WWTP, for example WEST (mikebydhi.com) uses the IWA ASM model family. GPS-X (Hydromantis, Hamilton, Canada) is a modular multi-purpose computer program for the modeling and simulation of municipal and industrial wastewater treatment plants. SIMBA® (GmbH, Magdeburg, Germany) is also used for modeling and dynamic simulation for a plant-wide system or parts of it.

2.3.3 Receiving Water Bodies models

For receiving waters there are different models depending on which is the final water body to be modeled. In this case we will focus on river models. Rivers are key elements of the UWS since the WFD pursues improvement in the ecological and chemical status of RWB. Modeling the river will indicate the best management practices to improve the river quality, but a lot of parameters are difficult to model, such as the ecological status of the river. Hence, typical river modeling focuses on the hydraulics. The first approaches tried to understand the behavior of rivers and predict the consequences of change. Since then, models have been constantly refined and updated to meet new and emerging problems, mainly focused on flooding problems, or incoming pollution. The selection of the river model will depend mainly on the objectives of the analysis, data and time availability.

Computer-based numerical models are used to simulate hydrological processes and water quality within the basin and can be useful tools for organizing basin data in a structured and readily accessible manner. Examples of river models are:

- RWQM1 (Reichert *et al*., 2001) was developed within the IWA task force to be compatible with the existing ASM (Henze, *et al*., 2000). Model state variables are of the same kind as in the ASM models.

- Infoworks River System (Wallingford Software) is a 1D and 2D hydraulic tool for river modeling. Some of the examples that the tool treats are conservative pollutants, salt, sediment, coliforms, temperature, phytoplankton, and macrophytes.

- QUAL 2K A Modeling Framework for Simulation River and Stream Water Quality, is a river and stream water quality model that is intended to represent a modernized version of the QUAL2E (or Q2E) model. QUAL2K model has two main modules: Hydrodynamic and Water Quality (Chapra *et al.*, 2006).

Nowadays there is a wide range of river models with different approaches. Recent studies have focused on the relationship between flow and ecological response as presented in Hughes and Louw (2010). Aguiar *et al.* (2010) present a predictive modeling approach to macrophyte communities as a tool for water quality assessment. (Macrophytes were recognized as biological quality elements for the implementation of the WFD.)

2.3.4 Integrated modeling challenges

The current state of the art of environmental modeling and software engineering has reached a point where it is possible to construct an integrated model of the UWS with a reasonable level of resolution. Model applications are performed according to the purpose they are meant for. The integrated model can be used to test scenarios in order to evaluate future impact, e.g., future housing construction, or to assess certain measures intended to improve performance of the UWS, evaluate operating strategies, identify the origin and quantity of pollution reaching the receiving river and so on.

However, the complexity of the systems themselves makes the integrated modeling of UWS difficult (Rauch *et al*., 2002). Several challenges are being addressed.

Transfer of data among software. Models can be integrated sequentially and in parallel. In the first approach, each part of the UWS is simulated itself, and one after the other during the whole simulation period. The output of one model is the input for the following model. Since they are different models, some modifications of the input are necessary before use. The main advantage is that already developed complex and precise models for the UWS can be used. However, it is time consuming, it is not possible to see back effects of the models, and time scales are also different. All UWS are interrelated, so a CSO in the SS directly affects the river (Benedetti, 2006).

Integrated control strategies for which information from more than just one part of the urban wastewater system is used require a parallel approach. In this approach, simultaneous simulations in every unit are performed for every time step, making it possible to evaluate system feedback effects like backwater or real-time control (RTC) strategies (Erbe and Schütze, 2005).

One of the most challenging tasks in constructing an integrated model is the incompatibility of the state variables for a single model. State variables of WWTP modeling are not the same for the SS (Table 2.2). Traditionally, different state variables have been used to model each sub-system. One example is organic matter, which is usually based on the BOD in river and sewer models, but on COD in WWTP models. Transformers are needed to link the different models and keep mass balances closed.

Integrated modeling includes processes with **time dynamics** from seconds to days and months (e.g., dissolved oxygen in the WWTP, runoff in the sewer system, nitrification in the WWTP, or daily oxygen cycle in the river). It has a significant influence on the choice of numerical algorithms, simulation time, and simulation precision. Depending on the goal of the study (RTC, calibration, or evaluation of a perturbation), the simulation settings will change.

Once an integrated model is constructed, there is still complexity that relies on the **calibration** and **validation** of those models. Experimental campaigns may become huge as there is both a temporal and a spatial dimension to consider. Other aspects to consider are **error propagation** and **uncertainty** due to the fact that integrated modeling is composed of sub-models representing the different elements making up the UWS. The errors and uncertainties produced in one sub-model propagate to the following ones depending on the model structure, the estimation of parameters, and the availability and uncertainty of measurements in the different parts of the system (Freni *et al.,* 2009).

Despite recognition of the necessity of modeling the UWS since Beck (1976), who introduced the concept of integrated management, the first attempts at modeling UWS were made by Crabtree *et al.* (1996), Fronteau *et al.* (1997), Carstensen (1998) and Schütze *et al.* (1999a). Besides, integrated modeling has rarely been applied due to the overall complexity of the system as well as the lack of field data required for reliable model application (Freni *et al.,* 2011).

Nowadays it is more common to use platform programs with models of the different elements of the UWS already developed. So the adaptation of the output is overcome, and simulations are usually faster and able to study other modeling characteristics like overall uncertainty, sensitivity analysis (SA), or control strategy analysis. The tendency is to develop integrated models via simulation packages, rather than linking existing models, since it is very difficult to reconcile them. Examples of simulation packages are WEST (Vanhooren *et al.,* 2003), City Drain (Achleitner *et al.,* 2007), SYNOPSIS (Schütze *et al.,* 1999a) or OPEN-MI which connects models that already exist in different software (Blind and Gregersen, 2005), SIMBA (GmbH, Magdeburg, Germany) and AQUASIM (Reichert, 1994).

2.4 Current use of models within Urban Wastewater Systems

2.4.1 Real Time Control

Real time control (RTC) plays an important role when minimizing the impact of the urban water on the receiving media. RTC tries to optimize the performance of the UWS and minimize the pollution going to the RWB. Optimizing the UWS requires less investment costs, such as avoiding extra storage volume or updating the WWTP, and tries to make optimal uses of the existing facilities in the catchment (Vanrolleghem *et al.,* 2005).

Traditionally, RTC strategies were initially developed for a single element of the UWS (normally either the sewer system or the WWTP). The tendency now is to shift towards integrated control as proposed by Schütze *et al.* (1999b). RTC strategies have been evaluated by using simulation, which is a cost-effective tool that optimizes storage volume or evaluates several system configurations. Several RTC strategies have been defined according to Vanrolleghem *et al.* (2005a):

- Volume-based RTC is the most frequently used strategy since it is based on SS and WWTP flow optimization to improve wastewater storage in tanks or on SS to prevent CSO discharges. Flows are measured by level sensors, rainfall intensity, and online data, and expected flows are measured using weather and radar predictions, which have become more reliable in recent years.

- Pollution-based RTC aims to reduce pollutant discharge from the CSO and WWTP outflow to the receiving media.

- Immission-based RTC takes into account the receiving water body quality to choose the best management practices (Rauch and Harremoës 1999; Erbe *et al.*, 2002; Vanrolleghem *et al.*, 2005a).

The RTC approach has been demonstrated by Schilling *et al.* (1996), Schütze *et al.* (2004) and Schroeder and Pawlowsky-Reusing (2005). However, few full-scale, real-time control applications have been implemented. Some examples include Pleau *et al.* (2005) and Schroeder and Pawlowsky-Reusing (2005), who installed control systems in sewer systems in Québec and Berlin, respectively. Even so, it has to be pointed out that the optimal management of components of the UWS does not necessarily yield the optimum performance of the entire system (Butler and Schütze, 2005; Rauch *et al.,* 2002).

2.4.2 Scenario Analysis and Sensitivity Analysis

Scenario analysis provides valuable help in finding solutions for UWS system to investigate design and operational management through simulation. They can be used to test scenarios and evaluate future impacts, e.g., population increases (Fu *et al.*, 2009a), evaluate several operating and control strategies using immission-based criteria (Meirlaen 2002; Vanrolleghem *et al.*, 2005a; Butler and Schütze, 2005; Devesa *et al.*, 2009), identify the major pressures and impacts (Benedetti *et al.*, 2008a), and design WWTP (Benedetti *et al.*, 2010).

On the other hand, sensitivity analysis (SA) aims to establish the relative importance of initial conditions, model parameters, and input factors involved in the model. This type of analysis identifies the factors affecting the model performance most. SA also helps to identify which inputs cause major uncertainties.

2.4.3 Environmental Decision Support Systems

Environmental decision support systems (EDSS) have been presented as promising tools to overcome management problems in UWS by suggesting operational procedures to be applied. EDSS are multi-level, knowledge-based computer systems that improve the decision consistency and quality by offering criteria for the evaluation of various alternatives or by justifying the decisions made (Fox and Das, 2000). The EDSS initially developed (Guariso and Werthner, 1989; Kamimura *et al.*, 1996; Stephanopoulos, 1999) has proven to be a promising tool when dealing with complex systems. The EDSS of UWS will help to manage the system as a single operating unit, also considering the interactions between wastewater infrastructures, to finally improve the RWB.

One bottleneck of EDSS is the knowledge-based construction, which is a key element of these systems since it confers the EDSS with the ability to emulate human reasoning. Hence, special attention has to be paid during the knowledge acquisition step. A variety of methods were used for the development of a knowledge base for a real EDSS. Conventional knowledge acquisition methods like literature reviews or interviews with managers or stakeholders were used first. Multivariate statistical/data mining techniques have been widely used as unbiased methods in the analysis of complex data, extracting significant information. These techniques can be used to unravel the natural association between samples or variables highlighting information not available at first glance. AI methods have been used for automatic knowledge acquisition (Chen *et al.,* 2008).

DSS have been developed for a variety of purposes and several methods have been presented to develop them properly (Poch *et al.,* 2004; Giupponi, 2007; Makropoulos *et al.,* 2008; Lautenbach *et al.,* 2009). Examples of DSS for UWS management include: MULINO (Giupponi, 2007), ELBE-DSS (Lautenbach *et al.*, 2009), UWOT (Makropoulos *et al.*, 2008), E2 (Argent *et al.,* 2009) and Manzanares DSS (Paredes *et al.,* 2010).

Despite the fact that EDSS have been used in theory to solve environmental problems, rarely have they been applied in complex domains where a policy-making community is involved. EDSS are difficult to implement and complicated for non-expert users, who do not trust the system since it operates in a “black-box” mode (Hamouda *et al.*, 2009).

Only a few DSS are in actual use: atl_EDAR (Turon *et al.,* 2009), Québec SS (Pleau *et al.,* 2005) and Berlin SS (Schroeder *et al.,* 2005). They use simple robust tools to deal with problems in single wastewater infrastructures.

Knowledge coming from integrated modeling will help to better construct the knowledge base of EDSS and make it more prone to a real application.

CHAPTER 3

OBJECTIVES

3. Objectives

The main objective of this thesis is to gain expert knowledge through mathematical models of the UWS to improve river water quality through the integrated management of the different wastewater elements. The achievement of this objective requires definitions of the following sub-objectives:

A) To develop a method to find better integrated operational strategies of the UWS when facing different problematic situations in the system.

   1. To develop a model that considers all the elements of the UWS.
   2. To define the key elements to control the performance of the system (i.e., evaluation criteria, operational parameters).
   3. To find better combinations of set points for the relevant control parameters.

B) To apply the method in the case study of *El Consorci per a la Defensa de la Concal del riu Besòs* (Besòs River Basin Agency).

   1. To identify typical problematic scenarios from this case study.
   2. To recommend better operational strategies for the different scenarios analyzed.

CHAPTER 4

KNOWLEDGE ACQUISITION METHOD

4. Knowledge acquisition method

A method has been developed to acquire knowledge from an integrated model of the UWS. The goal is to improve performance of the UWS by preparing for anticipated conditions that affect the operation and management of the entire municipal wastewater system, while recognizing that severe, unmanageable events and conditions are likely to occur.

The main idea behind the method is to find the best operational strategies for the UWS under study. The method has been simplified enough to be used, either for a whole UWS, or to test just a part of it, like a WWTP or the lamination of wastewater contained in storage tanks. The discovered management strategies will support and help managers in the day-to-day management of the UWS and will help to overcome problematic situations.

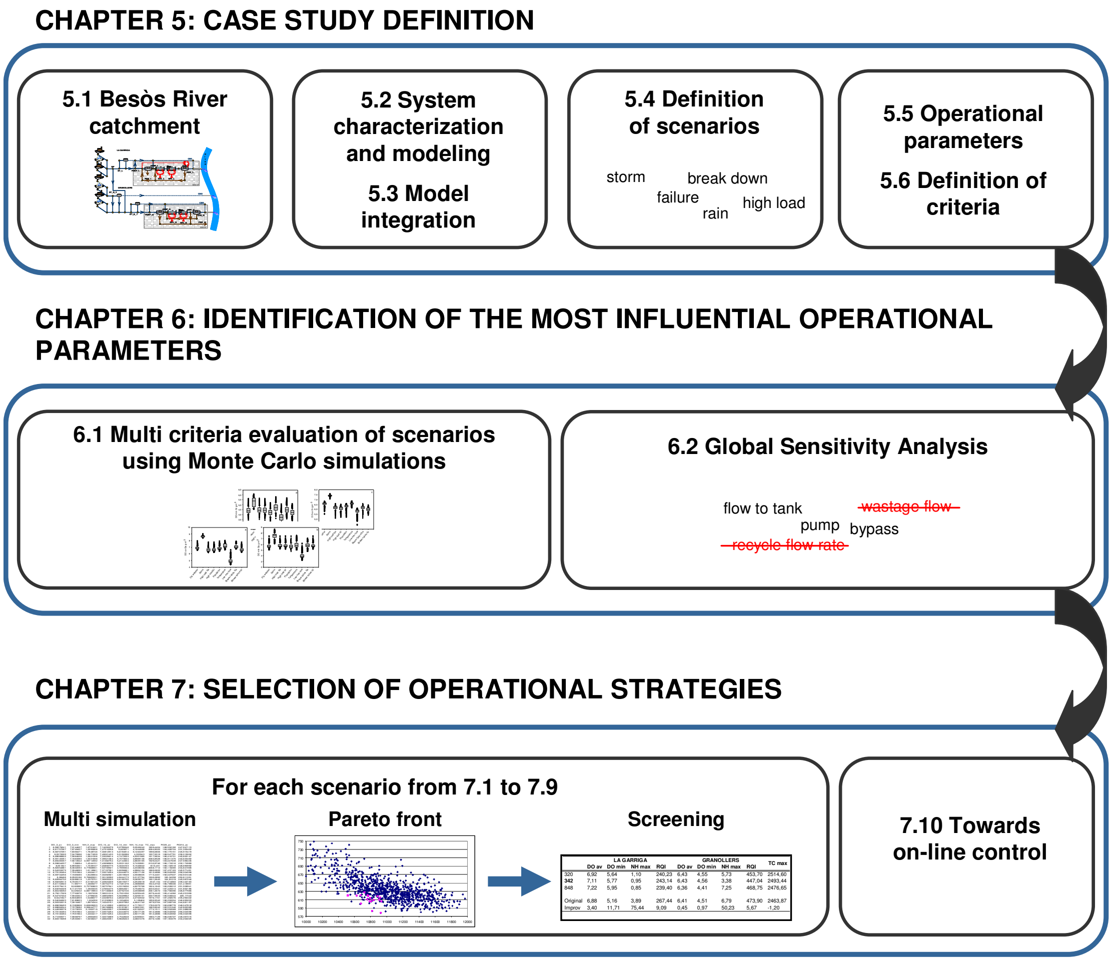

Figure 4.1: Methodology flow diagram.

4.1 Model build-up

The method presented here has been developed for simple application in any UWS. The first step will be the selection of the models of each element of the UWS and the construction of an integrated model for the whole UWS under study. As presented in Chapter 2, a lot of models are available, and several platforms for model integrations are also in use. The objectives of the study will determine the level of model resolution and complexity. This is a key step since the overall method for knowledge acquisition is focused on the model characteristics. Hence, it is clear that if the model does not represent the system, the results will be useless.

4.2 Scenario Analysis

To study the system, several scenarios built from the case study should be modeled and evaluated with multiple criteria. These scenarios could range from reference scenarios, when the system performs properly, to rain events or other scenarios that are typical from the case study. The next section describes scenarios that could be considered for a proper scenario analysis.

4.2.1 Scenarios

Reference scenario: After the model is built up, the steady state situation represents the reference scenario. The reference scenario uses the same operational strategies as the case study and will be used for comparison with and evaluation of the remaining scenarios.

Dry weather: This scenario applies the reference scenario characteristics in order to improve the operational strategies under normal conditions, when the overall systems perform properly and there are no problems on the system.

Storm: The intensity, duration, and frequency of rain occurrences are important weather conditions that must be quantified in this scenario. Historical data offers some insight. Different kinds of rain storms should be analyzed since they could require different management strategies. Obviously, an average rain intensity of 20 mm in one day is not the same as the same average in one hour.

The objective of this scenario is to properly manage the wastewater facilities, like storage tanks, a bypass between WWTP and any other infrastructure that could help to confront a wet weather event, reduce CSO, and treat as much water as possible to finally improve RWB.

High load: River basins could be characterized by a strong industrial presence; hence, uncontrolled discharges of industrial wastewater could be common. The objective of this scenario is to simulate these discharges, which can overload the system. According to the industrial discharges, the organic load could be twice the original or even more. If different industrial parks or different industries are present in the UWS, this scenario could be taking into account all industrial discharges, the worst cases, or just one of them.

Population: This scenario refers to population changes. The population can change due to seasonal variability, during weekends or summers. The scenario increases or decreases the quantity of domestic water that is generated in the catchment. Its purpose is to push the urban water system to the limits and to analyze how the system minimizes the impact on the river. This scenario is also useful to study future needs of the basins. Data that predict a population increase are easily available and can be used to study how the system will perform with current characteristics.

Temperature: WWTP models are normally constructed considering the kinetic parameter value at 20ºC, which is the default value. In that scenario a situation where the wastewater temperature differs from that temperature can be studied, e.g., a decrease or increase of 5ºC between summer and winter. At different temperatures biological parts of the treatment reach different treatment yields. Kinetic parameters can be calculated by applying the Arrhenius equation (Hu et al., 2007). The use of this equation requires a set of default parameters and the values of the Arrhenius constant (θ) for each model parameter.

$$k_1 = k_2 \cdot \theta^{(T_1 - T_2)} \quad \textbf{(Eq. 4.1)}$$

Low river flow: In some regions, like the Mediterranean, streams are characterized by irregularity of flow with harsh hydrological fluctuations, presenting very low rates in summer, but also with flow rates that can increase up to 1000 times in the autumn rainfall period (Munné and Prat, 2011). The objective of this scenario is to simulate a scenario of low river flow. During low river flow events, WWTP effluents provide the vast part of the river flow, hence WWTP produce a higher impact on the RWB since there is no dilution effect, and the WWTP should increase treatment yield.

Failures: Mechanical problems could be in any part of the system. These problems can range from collapse in the sewer system, to pump failures at the WWTP. The objective of this scenario is to find treatment alternatives to overcome those problems. According to the case study, problems more likely to happen should be identified.

In this section the main problems of the UWS have been presented. However, historical data, or expert interviews regarding the case study can contribute to extend those scenarios and point out other problems for each particular UWS.

4.2.2 Parameters

The objective of the method is to find operational strategies to overcome a problem in the system. An operational strategy can be defined as a combination of model parameters and their set point. These operational parameters might change according to model construction. However, important operational parameters that should be taken into account are:

1. Flow limitation parameters
    a. Flow to primary or secondary treatment which will determine the WWTP capacity.
    b. Underflow rates from settlers.
    c. Recirculation flow rates.
    d. Any pump or splitter considered in the sewer system or the WWTP, i.e., flow limitations which determine the amount of flow going to each part of the system, to storage tanks, or to the WWTP.

2. Control parameters
    a. Those parameters that refer to local controls located in the system, i.e., DO controllers, sludge controllers or nitrate controllers.
    b. Control of storage tanks, filling and emptying patterns.

4.2.3 Evaluation criteria

To evaluate the operational strategies several criteria have to be defined. The suggested criteria include environmental and economic aspects, which are immission-based criteria according to WFD.

Environmental criteria:

A river quality index (RQI $g \cdot m^{-3}$) has been defined to find the best emission-based strategies. The RQI has been adapted from the effluent quality index (EQI, in kg pollution units d^{-1}) developed in Copp (2002), as a weighted average sum of the following components:

$$RQI = DQO + 30 \cdot (X_{ND} + S_{NH}) + 10 \cdot (NO_3 + NO_2) + 30 \cdot TP + 2 \cdot DBO \quad \textbf{(Eq. 4.2)}$$

where:

X_{ND} is particulate biodegradable organic nitrogen ($g\ N \cdot m^{-3}$)
S_{NH} is $NH_4^+ + NH_3$ nitrogen ($g\ N \cdot m^{-3}$)

RQI has to be calculated in the RWB downstream any WWTP.

Within environmental criteria can also be included minimum and maximum DO concentration downstream of the WWTP. Maximum NH_4 concentrations are also considered in order to avoid peak ammonia effluents at the sampling points. RQI considers average, not maximum, concentrations, but high concentrations of ammonia can be toxic for a wide range of microorganisms in water bodies (Dodds and Welch, 2000).

Economic criteria:

Economic criteria indicate the economic efficiency of the UWS, which should include all accounted costs. The evaluation of costs for UWS is very complex. Costs can differ among countries or regions because of different conditions. To overcome that complexity, different cost indexes have been studied (Benedetti *et al.*, 2008b; Vrecko *et al.*, 2007).

It is suggested to use the operational cost model included in the WEST model library. That model defines a total cost (TC) which takes into account aeration cost (AC), pumping cost (PC) and sludge cost (SC):

$$TC\ \left(€ \cdot d^{-1}\right) = AC + PC + SC \quad \textbf{(Eq. 4.3)}$$

The AC is calculated from the energy needed for aeration in the aerobic tanks of the WWTP by multiplying with an aeration cost factor (F_AC). The aeration energy is derived from the oxygen transfer coefficient (Kla):

$$E_{aer}\left(kWh \cdot d^{-1}\right) = 24 \cdot \int \sum_{i=1}^{10} (\alpha \cdot k_{La}^{2} + \beta \cdot k_{La} + \gamma) \cdot dt \quad \textbf{(Eq. 4.4)}$$

where α, β and γ are empirical factors of the second order relationship between Kla and energy.

$$\alpha = 0.0003$$
$$\beta = 0.1479$$
$$\gamma = -1.4731$$

$$AC\left(€ \cdot d^{-1}\right) = f_{mix} \cdot E_{aer} \quad \textbf{(Eq. 4.5)}$$

where $f_{mix} = 0.07$ is the cost factor for aeration (euro·kW^{-1}).

PC is calculated from the pumping energy of the different pumps within the UWS. The pumping energy is derived from the flow rate, multiplying with a pumping cost factor (F_PC).

$$E_{pump}\left(kWh \cdot d^{-1}\right) = f_{Q} \cdot \int \sum_{i=1}^{2} Q_{W,i} \cdot dt \quad \textbf{(Eq. 4.6)}$$

$$PC\left(€ \cdot d^{-1}\right) = f_{pump} \cdot E_{pump} \cdot 10^{-3} \quad \textbf{(Eq. 4.7)}$$

Where $f_{pump} = 0.07$ is the cost pump factor (euro·kW^{-1}).

The SC is calculated from the total amount of sludge that is produced in the WWTP by multiplying with a pumping sludge cost factor:

$$M_{sludge}\left(kg \cdot d^{-1}\right) = \int \sum Q_{W,i} \cdot TSS_{W,i} \cdot dt \quad \textbf{(Eq. 4.8)}$$

$$SC\left(€ \cdot d^{-1}\right) = f_{sludge} \cdot M_{sludge} \cdot 10^{-3} \quad \textbf{(Eq. 4.9)}$$

Where $f_{sludge} = 0.57$ is the sludge cost factor (euro·kg^{-1}) for the amount of final disposal sludge, that is, sludge being dewatered or/and digested.

The operational cost model does not exactly reproduce the overall operational cost in a UWS (Olsson, 2005), but gives a good estimation of the cost and an idea about how to save costs by avoiding the most expensive processes.

4.3 Sensitivity Analysis

The objective of this step is to identify which operational parameters influence the model behavior most, and consequently, the overall system performance.

4.3.1 Multi simulations

Monte Carlo (MC) simulations are a way to carry out probabilistic analysis based on multi simulations using as input random numbers and observing which fraction of the numbers obey some property or properties. This method is commonly used when the model is complex, non-linear, or involves uncertain parameters, and the uncertainty propagation is analyzed.

In this work a Monte Carlo method has been adapted from (Rousseau *et al*., 2001) in order to find good operational strategies for the case under study and using the model as follows:

First of all, probability distribution information is assessed for each variable in the system. In that case variables are operational parameters of the model. The MC engine randomly selects a value for each operational parameter and for every simulation from the appropriate probability density function (PDF) with a Latin hypercube sampling (LHS) technique (Helton and Davis, 2003). After multiplying simulations, the MC engine produces a range of values for the operational parameters that cover the PDF. All these simulations are independent and the deterministic model solves each single simulation. The outputs of the MC simulations are the criteria to evaluate the system's performance (4.2.3 Evaluation criteria).

Different distributions are available within the PDF. Here it is suggested to use triangular distributions, since uniform distributions with the same minimum and maximum contain lees information than triangular ones. However, the distribution method and the solver should be chosen according to the objectives of the study.

The number of the MC simulations will also vary according to operational parameters included in the study. A trade-off should be established between the computational time and the number of simulations to achieve proper results. The formula in the paper cited by the authors Morgan and Henrion (1990) can be used: N>p*(1-p)*(2/delta_p)^2 where N is the required number of samples, p the percentile to be estimated and delta_p the desired percentile precision at a confidence level of 95%. The outputs of the MC simulations are the criteria to evaluate the system's performance (4.2.3 Evaluation criteria).

4.3.2 Global Sensitivity Analysis

Sensitivity analysis (SA) evaluates the system behavior and the confidence in the model in reaction to changes in the input, the initial conditions and parameters. Changes in the model input, the initial conditions and parameters can lead to either no change or extreme changes in the model behavior. Global sensitivity analysis (GSA) allows ordering by importance the strengths and relevance of the inputs in determining the variation in the outputs.

In that case, model outputs are the criteria used to evaluate the system performance, and model inputs are operational parameters. Knowing most sensitive parameters will help managers face problematic situations. They will know which key parameters have to be modified to improve the RWB.

MC results have to be post-processed to calculate the partial correlation coefficients (PCC) for a multi-linear regression. The PCC are the measure of linear dependence between an output variable and a parameter in the case where the influence of the other parameters is eliminated. PCC are an alternative to regression analysis. When the variables within the sample are independent, standard regression coefficient (SRC) and PCC are equal, but SRC characterize the effect on the output variable that results from perturbing an input variable by a fixed fraction of its standard deviation. PCC characterize the strength of the linear relationship between an input and output variable after a correction has been made for the linear effect of the other input variables (Helton and Davis, 2003). The parameters could be judged as sensitive or not on the basis of the calculation of the t-static on the PCC, which allows the parameters to be classified as significant at the 5% level with a t-static larger than 1.96 (Morrison, 1984).

The goal of the sensitivity analysis is to identify the most sensitive parameters, which will then be considered in the next step of the method. Non-sensitive parameters will not be taken into account and the default value will be used for that given scenario. A screening of the parameters can be performed by not including parameters not sensitive for more than two criteria in the latter step.

4.4 Best management strategy

This is the final step of the proposed method, and the objective is to identify the best management. If MC simulations are run, it is possible to identify which combination of operational parameters results in better RWB quality, based on the predefined criteria.

4.4.1 Multi simulations

A second iteration of multiple simulations has to be performed, in the same way as in the experiments defined in the previous step, only for the sensitive parameters selected from the GSA. The same amount of MC simulations has to be launched only for sensitive operational parameters with the same triangular distribution using LHS, the same criteria and steady state and dynamic conditions. For the unselected parameters the reference values will be used.

Leaving out non-sensitive parameters leads to exploring in better detail the parameter space since there are fewer combinations of possible set points. This heuristic optimization method is robust, simple to implement and user friendly (there are no special algorithm settings, except deciding the size of the sample). Other advantages are:

1. It can be used as a preliminary step to locate interesting parts of the parameter space to be explored with other methods.

2. The (multi-criteria) objective function does not need to be defined up front, which allows different functions to be applied to the same set of simulations, avoiding the re-running of the optimization each time the function is changed.

4.4.2 Pareto front and screening

The goal of this step is to identify which is the best solution from the MC simulations. The complexity arises since multiple criteria conflict across a high-dimensional problem space. Therefore, the MC simulation evaluations are screened in such a way that for a given combination of set points there is no other possible combination that improves at least one criterion without worsening at least another. Hence, a Pareto Front of solutions is obtained. A Pareto solution has the characteristic that one criterion cannot be improved without worsening a different one (Muschall *et al.*, 2008). To reduce the extension of the Pareto Front another screening is performed by leaving out all parameter combinations which are worse than 50% of all sets for at least one criterion, thus focusing on the “compromise” area in the trade-off between performance criteria.

Hence one should notice that any combination of set points which is a Pareto solution and surpasses the screening is better for all criteria in the simulation, but this does not ensure being better than using the reference combination of set points. In the latter case, for any combination of problematic scenarios one cannot ensure to fulfill the screening of 50% since the current problematic scenario faced by the system could require more investment (increase of the economic criteria) in order to discharge within legal emission limits.

CHAPTER 5

CASE STUDY DEFINITION

5. Case study definition

5.1 Besòs River catchment

Located in Catalonia, NE of Spain, the Besòs River catchment has 1039 km^2. It is framed between the coastal and pre-coastal ranges, although most of its surface is within the Vallès depression. The length of the main rivers and streams is around 180 km, and they flow in a NE-SW direction. The Besòs River, which gives the name to the basin, flows from the confluence of two of its main tributaries, the Mogent and the Congost. It has a length of about 18 km to its mouth located in the north part of the city of Barcelona. It is one of the most populated catchments in the area, with more than two million people connected to the system.

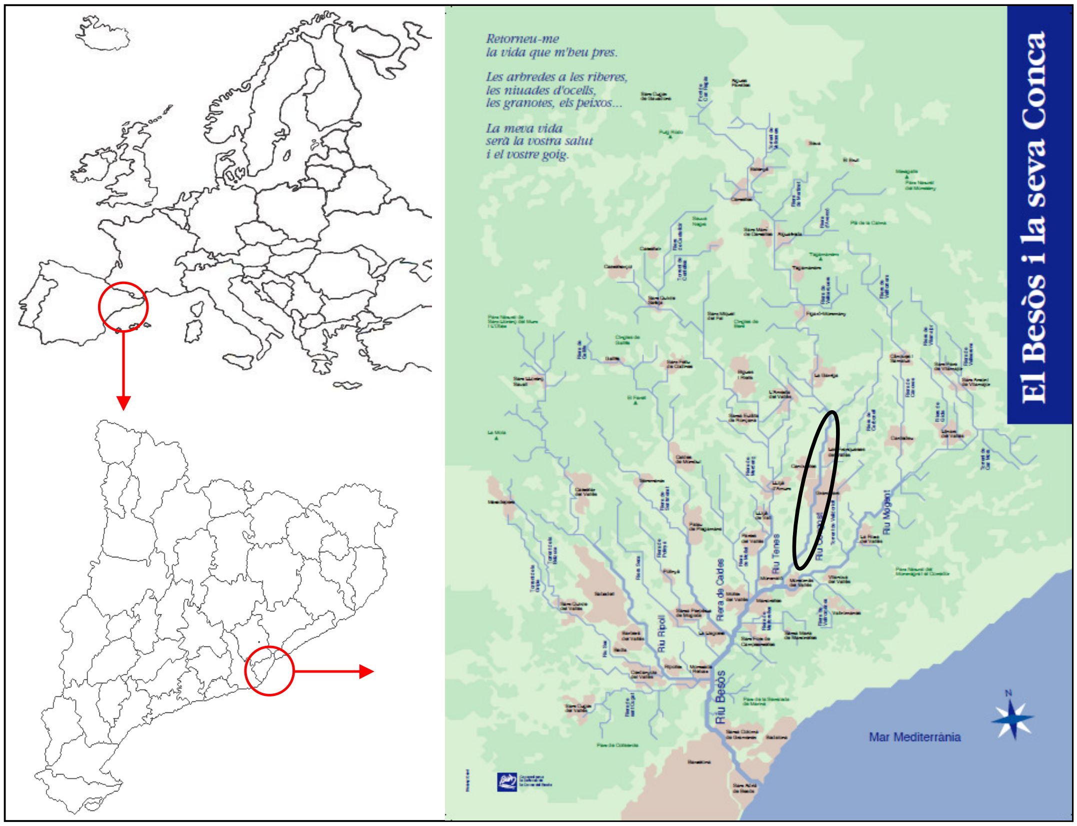

Figure 5.1. Besòs river catchment (adapted from Besòs website[3]).

The case study was conducted at the final reach of the Congost River. In the study site area of 70 km^2 the river receives the discharge of four municipalities: La Garriga, with its own sewer system and the La Garriga WWTP, and Les Franqueses del Vallès, Canovelles and Granollers, which all share a sewer system and the Granollers WWTP. The total population connected is about 100,000 inhabitants. The two WWTP, La Garriga and Granollers, discharge treated water at different locations of the Congost River. The system is managed by the Besòs River Basin authority, the *Consorci per la Defensa de la Conca del Besòs* (CDCB).

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[3] http://www.besos.cat/

5.2 System characterization and modeling

The software WEST (mikebydhi.com), version 3.7.6 is used as a modeling and simulation platform. It is presented in more detail in Vanhooren *et al.* (2003) and Claeys *et al.* (2007). Its main applications are dynamic modeling and simulation for water-related processes (i.e., for municipal wastewater treatment modeling, river water quality) that can be represented by differential algebraic equations.

WEST is divided into three main interfaces:

- Model editor. WEST incorporates a range of already developed models. They are hierarchically structured and the user is allowed to change existing models and create new ones if required. Models are described in a high-level object-oriented declarative language: model specification language (MSL).
- The configuration builder is the place to graphically construct the model. The user selects most appropriate components to construct the system under study (e.g., settler, sewer, biological reactor and so on). For each component the user can select, from a list of models, the one that fits the system best. Once the model is set up it is necessary to compile it, which means that it will be written in MSL by extracting the relevant equations from the model base. The MSL file is then parsed into low-level C-code, which in its turn is compiled to an executable WEST® model library (WML-file), which can be loaded in the experimentation builder.
- The experimentation environment enables the user to conduct different experiments, scenario analysis, sensitivity analysis and optimal experimentation design on compiled models. In this environment the user also defines the parameters of the model (e.g., sewer system slope, settler volume) and the place to run the experiments. The environment also allows for the graphical presentation of the results.

WEST presents the following models: KOSIM model (ITWH, 2000) for simulations of dry weather generation, rainfall-surface runoff and transport in the sewer system; IWA standard activated sludge models (ASM1, ASM2, ASM2d, ASM3, (Henze *et al.,* 2000) for WWTP processes; and the river water quality model (RWQM1), (Reichert *et al.,* 2001). Those models provide good accuracy of the processes that they represent and can be linked in the configuration builder allowing an integrated model (sewer system, WWTP and river) to be constructed in a single platform. WEST links the state variables, processes and parameters between the different sub-models. Besides, WEST is a user-friendly platform with reasonable calculation times. WEST was also chosen for the Tornado engine which allows different kinds of experiments, i.e., Monte Carlo simulations, to be performed in a reasonable time scale.

5.2.1 Sewer System

Processes within the different elements of the sewer systems (pipes, urban catchments, storage tanks) are represented by the KOSIM modeling tool (ITWH, 2000), whose mathematical equations were adapted by Meirlaen (2002) and Solvi (2007). Table 5.1 summarizes the processes represented within the KOSIM-WEST.

Table 5.1. Modeled processes in KOSIM-WEST (from Solvi (2007)).

Subsystem	Water	Pollutants
	DW (Dry Weather)	
Atmosphere	Evaporation	
Surface		Accumulation
Sewer network	DW flow[*]	DW pollution[*] Pollutant transport Sedimentation Resuspension
	WW (Wet Weather)	
Atmosphere	Rain[*]	
Surface	Runoff generation[*]	Wash off
Sewer network	DW flow[*]	DW pollution generation[*]
	Mixing DW and WW flow and pollution storage[*] Combination and splitting[*]	
		Sedimentation Resuspension

[*] Processes considered within this work.

The processes considered in this work have been adjusted according to the case study and are described in the following paragraphs. The rest of processes were kept at default values.

5.2.1.1 Urban Catchment

Domestic and industrial communities are represented within the urban catchment model. These units produce the domestic and industrial wastewater entering the sewer system and involves the processes contained in Table 5.1. They are also used to define the sub-catchment characteristics, the area surrounding the community, the potential evaporation and the impervious and pervious surfaces. Modeled pollutants introduced to the catchment are soluble and particulate COD, ammonia, TN and TP.

Catchments are also used to introduce the rain as input data in a simple time-rain vector format. As it rains the same all over the catchment, the spatial distribution of rainfall is uniform. The effective rain entering the sewer system depends on the area connected in each urban catchment as well as pervious and impervious surfaces. The model considers all those processes but for this case example they were kept at default values.

Our case study is divided into two sub-catchments, La Garriga and Granollers. For La Garriga, three different catchments were defined, one domestic and two industrial. For Granollers four different catchments were defined, two domestic and two industrial. Information contained in the model was updated from Devesa (2005) and IDESCAT (2009) (Table 5.2).

Table 5.2. Characteristics of urban catchment.

	SEWER SYSTEM						
	LA GARRIGA (SS 1)			**GRANOLLERS (SS 2)**			
Catchment	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	Dom[1]	Ind[2]	Ind	Dom	Ind	Dom	Ind
Flow pattern number	3	3	3	3	3	3	3
Infiltration	0,11	0,11	0,11	0,1	0,1	0,1	0,1
Infiltration pattern number	1	1	1	1	1	1	1
Mean_S(COD_part)	290	500	500	290	400	290	750
Mean_S(COD_sol)	290	500	500	290	400	290	750
Mean_S(H2O_sew)	1000000	1000000	1000000	1000000	1000000	1000000	1000000
Mean_S(NH4_sew)	70	15	15	60	50	60	2
Mean_S(PO4_sew)	6	4	4	10	10	10	2
Mean_S(TN_sew)	40	20	20	40	90	40	20
Mean_S(TP_sew)	8	5	5	12	12	12	12
Pollution pattern number	3	3	3	3	3	3	3
Population density EI/Km^2	11993	56700	1133	22456	78100	60658	208300
Start day	2	2	2	2	2	2	2
Total area (ha)	125	60	30	150	40	100	40
Tourist end	300	300	300	300	300	300	300
Tourist pollution	1	1	1	1	1	1	1
Tourist start	162	162	162	162	162	162	162
Tourist water	1	1	1	1	1	1	1
Wastewater PerIE m^3/dia	0,24	0,07	0,07	0,18	0,05	0,18	0,05
We factor	0.7	0.7	0.7	0.7	0,7	0,7	0,7
We pollution	0.5	0.5	0.5	0.5	0.5	0,5	0,5

[1] Domestic
[2] Industry

The habitants (population density EI/km^2), water consumption for habitant (wastewater per EI m^3/day) and the total area (ha) will determine the amount of dry weather flow entering to the system. The model considers low wastewater production during weekends by multiplying flow by a factor (We factor for less or more water production during the weekend; We pollution for less or more pollution during the weekend). Wastewater pollution is determined according to the characteristics defined in the urban catchment model (Mean_S(COD_part), Mean_S(NH4_sew), Mean_S(TN_sew) and Mean_S(TP_sew)). Since wastewater production is not the same during the entire day, the model offers different pollution patterns (flow pattern number, pollution pattern number).

5.2.1.2 Sewer pipes

The sewer system is represented by tanks in series without considering chemical processes (e.g., degradation) in the structure. Pipes are represented as well mixed tanks (black-box models) with some physical characteristics considered: slope, length, diameter and pipe roughness. The sewer system has been represented as linear tanks in series where the input of the downstream tank is the output of the previous tank. This hydrological modeling approach leads to a low calculation time and higher calculation stability and provides a good overview of the model structure. However, this model cannot represent backwater effects. Sediment transport is not considered.

The concrete sewer system of La Garriga has a total length of 6.3 km, with diameters between 30 and 60 cm. On the other hand, the concrete sewer system of Granollers has a total length of 22 km, with diameters between 20 and 130 cm. It has been also considered storage tanks that in the same time are used to model the CSO. And a connection channel between the La Garriga SS to the Granollers SS.

Storage tanks are key elements in integrated management since they allow some wastewater to be retained when the system is overloaded and they help to reduce CSO. Tanks in the sewer network are placed off line, and only excess water goes to the tank. Tanks are represented according to storm water tank pumped out model. There is a pump that sends the wastewater to the WWTP, and it starts at the same time water is filling the tank. Water inside the tanks is supposed to be well mixed. Once the tank is full and it has exceeded the pump capacity, water is discharged as CSO to the river.

There are three tanks in the system: one in the SS La Garriga with a volume of 7000 m^3 and two placed in Granollers, with volumes of 7000 and 28,000 m^3, respectively. Pumped out flow is set at 3000 m^3/day. Their volume was chosen according to Devesa (2005), and although they do not exist in reality, plans have been made to build them.

The bypass between the La Garriga SS and the Granollers SS is used in case the La Garriga WWTP is overloaded. In that case some wastewater is sent to the Granollers WWTP, which has much more treatment capacity. This bypass is modeled as an SS pipe.

5.2.2 Wastewater Treatment Plants

5.2.2.1 La Garriga WWTP

The La Garriga WWTP is situated at the right bank of the Congost River, within La Garriga township. It treats domestic and industrial wastewater collected from La Garriga and part of Ametlla del Vallès. This WWTP was extended in 2000 with a biological wastewater treatment based on an activated sludge system with a modified Ludzack-Ettinger configuration for nitrogen removal.

Figure 5.2. La Garriga WWTP.

The wastewater treatment line is based on a primary treatment with a capacity of 27,480 $m^{3\cdot}d^{-1}$ with an underflow of 50 m^3/day in the reference case modeled by the primary Otterpoh Freund model (Otterpohl and Freund, 1992) with a total volume of 795 m^3.

The primary treatment is followed by a biological reactor with an inflow limit of 13,994 $m^3 \cdot d^{-1}$. The biological treatment is based on a plug-flow activated-sludge model based on ASM2d. The biological tank is divided into two compartments, an anoxic one of 480 m^3 and an aerobic one of 2400 m^3. There is a cascade control for DO and ammonia. Diffusers provide aeration with a set point for the proportional-integral controllers at 1.5 $g \cdot m^{-3}$. Internal recirculation is 15,000 $m^3 \cdot d^{-1}$, controlled by anti windup saturation controller for nitrate concentrations in the anoxic reactor. The external recirculation is 150% on the inflow set by constant ratio control.

The final step is a secondary settler modeled after a secondary clarifier model based on Takács (Takács *et al.,* 1991), which has an underflow of 50 $m^3 \cdot d^{-1}$ in the reference case with a surface area of 628 m^2. Underflow is sent to the primary treatment, where the sludge mixed is extracted and sent to the sludge treatment line.

The main design parameters of the La Garriga WWTP are summarized in Table 5.3.

Table 5.3. Main characteristics of the La Garriga WWTP

Parameter	**Design value**
Daily flow	7000 $m \cdot d^{-1}$
Inflow BOD	250 g $O_2 \cdot m^{-3}$
Inflow TSS	200 $g \cdot m^{-3}$
Outflow BOD	< 25 g $O_2 \cdot m^{-3}$
Outflow TSS	< 35 $g \cdot m^{-3}$
Equivalent inhabitants	29,000 EI
Installed power	425 Kw
Surface area	13,500 m^2

5.2.2.3 Granollers WWTP

The Granollers WWTP is situated on the left bank of the Congost River within Granollers township. It treats domestic and industrial wastewater collected from Granollers, Canovelles and Les Franqueses del Vallès. This WWTP was extended in 1998 with a biological wastewater treatment based on an activated sludge system with a modified Ludzack-Ettinger configuration for nitrogen removal.

Figure 5.3. Granollers WWTP

The wastewater treatment line is based on a primary treatment with a capacity of 76,800 m^3·d^{-1} with an underflow of 600 m^3·d^{-1} in the reference case, modeled by the primary Otterpoh Freund model (Otterpohl and Freund, 1992) with a total volume of 4623 m^3.

The primary treatment is followed by a biological reactor with an inflow limit of 3440 m3·d^{-1}. The biological treatment is based on a plug-flow activated-sludge model based on ASM2d. The biological tank is divided into two compartments, an anoxic one of 648 m^3 and another aerobic one of 4064 m^3. There is a cascade control for DO and ammonia. Diffusers provide aeration with a set point for the proportional-integral controllers at 1.5 g·m^{-3}. Internal recirculation is 21,600 m^3·d^{-1}, controlled by an anti windup saturation controller for nitrate concentrations in the anoxic reactor. After the reactors there is a 10 m^3 deoxygenation tank from which 1500 m^3·d^{-1} of sludge are extracted.

The final step is a secondary settler modeled by secondary clarifier Takács model (Takács *et al.,* 1991) with an underflow of 500 m^3·d^{-1} and a surface area of 1414 m^2. External recirculation is 28,800 m^3·d^{-1} sent to the aerobic reactor.

Main design parameters of the La Garriga WWTP are summarized in Table 5.4.

Table 5.4. Main characteristics of the Granollers WWTP.

Parameter	**Design value**
Daily flow	25,000 m·d^{-1}
Inflow BOD	650 g O_2·m^{-3}
Inflow TSS	550 g·m^{-3}
Outflow BOD	< 25 g O_2·m^{-3}
Outflow TSS	< 35 g·m^{-3}
Equivalent inhabitants	128,000 EI
Installed power	780 Kw
Surface area	30,000 m^2

5.2.3 River

The modeled section of the Congost River has a length of 15 km, most of which passes through a highly altered environment and the villages of La Garriga, Les Franqueses del Vallès, Canovelles, Granollers, where it has been channeled, and Montornès del Vallès. Congost flows into the Mongent River, and both are tributaries of the Besòs River, the main water body of the catchment.

Figure 5.4: Congost River downstream from the La Garriga WWTP

The Congost River has a typical Mediterranean hydrological pattern with significant rainfall variability: very low dry water flow rates in summer, near 2 m^3s^{-1} at the mouth, and also flow rates that can increase up to 1000 times in the autumn rainfall period. Furthermore, the flow rates in summer are due exclusively to the WWTP effluents, thus the quality of the treatment facility discharges becomes critical.

Information about the river has been extracted from Devesa (2005) and from the automatic control station located in La Garriga (BE5001037 and EA037) owned by the Catalan Water Agency (Agència Catalana de l'Aigua, ACA), the station can be consulted online.

The hydrological model River Water Quality Model nº1 (RWQM1) (Reichert *et al.,* 2001) was chosen since it is available within the WEST model library and also because a hydrological approach makes the integrated model consistent. The RWQM1 model was developed for easy integration with the ASM family. The model state variables are of the same kind as in the ASM models: organic material, organisms (bacteria, algae and consumers), nutrients, oxygen and inorganic materials. Bacterial concentration, pH equilibrium reactions, precipitation and predation are processes that can be described within RWQM1.

The approach followed in the river model is the same one adopted in the sewer system: completely mixed tanks in series where the output of the previous tanks is the input of the following one rather than using full St.Venant equations for energy and momentum conservation.

The 15 km of the Congost River have been divided into 18 tanks in series. For each tank the length of the channel according to the river sections described in Devesa (2005) have been defined.

5.3 Model integration

Three models have to be linked to have the UWS in a single simulation environment. The relations between models have always been a bottleneck due to heterogeneous scales, different quality parameters, objectives and degrees of complexity between processes. A connector is needed to transfer the state variables from one model to the state variables of the destination model in a proper way.

Vanrolleghem *et al.* (2005b) summarized the main problems:

- Some state variables used in one model do not exist in the next connected model.
- The “meaning” of a state variable in one system may not hold for the other system (e.g., components can be considered as inert in one system but may be biodegradable in another).
- The elemental composition of a component in one model may not be identical for the connected model and in some instances, the elements considered are not the same (e.g., in ASM3 COD, N and charge are considered whereas in ADM1 COD, C and N are taken into account).

Vanrolleghem *et al.* (2005b) developed a continuity-based interfacing method (CBIM) based on algebraic transformation equations on a Petersen matrix description of two models to be linked. Therefore it is possible to maintain the continuity of elements C, H, N, P, O, charge and COD, while the linked models remain unaltered. So any model expressed via the Petersen matrix can be linked. This method was used by Benedetti (2006) and Solvi (2007) and has been used in this work since the models used are already linked.

The solver was chosen according to Benedetti *et al.* (2008a). That paper suggests the use of advanced solvers which often show a better performance. Numerical settings have to be carefully selected to minimize the time required to run a single simulation. The integrated method chosen was CVODE (Hindmars *et al*., 2005), solver accuracy of 10^{-5} and output frequency was set to 5 minutes (Claeys *et al* 2006).

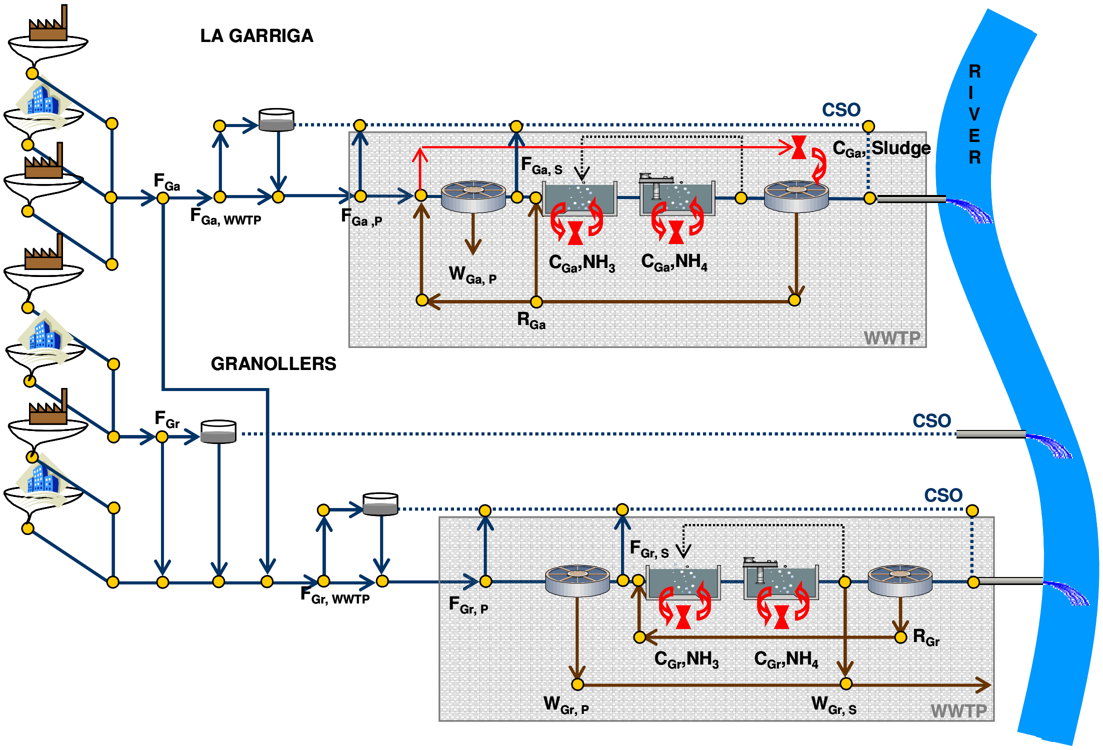


Figure 5.5: Main elements of the integrated model. Main layout of the integrated model is presented in Annex 1

5.4 Definition of scenarios

Scenarios considered for the knowledge acquisition are the scenarios presented in Devesa (2005) which were validated by experts from CDCB. Those scenarios have been created from the reference case.

Dry weather: Scenario that refers to the reference case, no perturbations posted on the system.

Storm: This scenario includes rain posted in the system in May 2010. River flow was taken from the Catalan Water Agency (*Agència Catalana de l'Aigua*) and rain intensity was taken from the Catalan Meteorological Service website (*Servei Meteorológic de Catalunya*). In this scenario, the river reaches high flows up to 5 m^3/s which is a significant high from medium value, 0.4 m^3/s due to rain. Rainfall has an average intensity of 2.2 mm/h, and it rains intermittently for almost three days.

High load La Garriga: The Besòs River basin is characterized by strong industrial presence. In that scenario, the COD concentration at the industry located in the La Garriga has been doubled for the following two days.

High load Granollers: The same scenario as high load La Garriga but in the Granollers system. The COD concentration in the two industries located in Granollers has been doubled for the following two days.

Population: This scenario increases the quantity of domestic wastewater that is generated in the catchment. The population has been increased according to the data provided in the official statistics website of Catalonia (IDESCAT), which predicts an augment of the population of around 18.5% by 2021 in that region. The population has increased from 11,993 to 14,215 inhabitants in La Garriga. In Granollers there are two communities, one has increased from 22,455 to 26,614 inhabitants and the other has increased from 60,658 to 71,896 inhabitants.

Low river flow: The objective of this scenario is to simulate a week of low river flow. The average Congost River flow is 0.4 m^3/s, and for that scenario it was decreased to $0.01 m^3 \cdot s^{-1}$ considering the data coming from the control station that the Catalan Water Agency has located upstream of the Congost River (aforament – La Garriga EA037, ACA).

Blower failure La Garriga: A mechanical problem related to the blower has been considered at La Garriga WWTP. The maximum K_La was reduced by 85% to mimic mechanical problems with a blower at La Garriga for the following two days.

Blower failure Granollers: The same mechanical problem posted in La Garriga is now posted in Granollers, the maximum K_{La} was reduced by 50% to mimic mechanical problems with a blower for the following two days.

Temperature: In this scenario a situation were the wastewater temperature is 15ºC is simulated according to temperature differences between summer and winter. Kinetic parameters at 15ºC are presented in Table 5.5

Table 5.5: Kinetic parameters at 20ºC and an example at 15ºC.

Temperature		**θ**	**20ºC**	**15º**
Maximum specific hydrolysis rate	K_h	3	1.041	2.454
Heterotrophic organisms				
Maximum growth rate of XOHO	μ_H	6	1.072	4.238
Rate constant for fermentation / Maximum specific fermentation growth rate	q_{fe}	3	1.072	2.119
Decay rate for XOHO	b_H	0.4	1.072	0.283
Phosphorus accumulating organisms (PAO)				
Rate constant for SVFA uptake rate (XPAO,storage)	q_{PHA}	3	1.041	2.454
Rate constant for storage of XPAO,PP	q_{PP}	1.5	1.041	1.227
Maximum growth rate of XPAO	μ_{PAO}	1	1.041	0.818
Decay rate for XPAO	b_{PAO}	0.2	1.072	0.141
Rate constant for Lysis of XPAO,PP	b_{PP}	0.2	1.072	0.141
Rate constant for respiration of XPAO,Stor	b_{PHA}	0.2	1.072	0.141
Autotrophic organisms				
Maximum growth rate of XANO	μ_{AUT}	1	1.111	0.591
Decay rate for XANO	b_{AUT}	0.15	1.116	0.087

Main characteristics of scenarios are summarized in Table 5.6.

Table 5.6: Main characteristics of scenarios simulated.

Name	**Characteristics**
Dry weather	Dry-weather flow conditions and no perturbations are generated in the system
Storm	3 mm/h 2 days, an increase of river flow
High load Ga	Increase of COD, 2 days
High load Gr	Increase of COD, 2 days
Population	From 11,993 to 14,215 PE in the La Garriga, and from 83,113 to 98,508 PE in the Granollers
Temperature	From 20ºC to 15ºC at WWTP, and from 15ºC to 10ºC at river water during a week
Low river flow	River flow from 0.4 $m^3 \cdot s^{-1}$ to 0.01$m^3 \cdot s^{-1}$ during a week
Blower failure La Garriga	Maximum KLA of 50 d^{-1} for 2 days
Blower failure Granollers	Maximum KLA of 150 d^{-1} for 2 days

5.5 Operational parameters

Model parameters according to model construction are summarized in Table 5.7 and represented in Figure 5. The minimum, maximum and default values refer to the triangular distribution of the PDF for the later analysis.

Table 5.7: Model parameters

Short name	Description	Unit
F_{Ga}	Flow going to La Garriga, overflow is bypassed to Granollers system	$m^3 \cdot d^{-1}$
$F_{Ga, WWTP}$	Flow going to La Garriga WWTP, overflow is bypassed to tank in La Garriga	$m^3 \cdot d^{-1}$
F_{Gr}	Flow going to Granollers WWTP, overflow is bypassed to a bigger tank in Granollers	$m^3 \cdot d^{-1}$
$F_{Gr, WWTP}$	Flow going to Granollers, overflow is bypassed to small tank in Granollers	$m^3 \cdot d^{-1}$
$F_{Ga, P}$	Flow going to primary settling La Garriga, overflow goes to river	$m^3 \cdot d^{-1}$
$F_{Gr,P}$	Flow going to primary settling Granollers, overflow goes to river	$m^3 \cdot d^{-1}$
$F_{Ga,S}$	Flow going to activated sludge La Garriga, overflow goes to river	$m^3 \cdot d^{-1}$
$F_{Gr,S}$	Flow going to activated sludge Granollers, overflow goes to river	$m^3 \cdot d^{-1}$
$W_{Ga, P}$	Wastage flow rate of primary settler La Garriga	$m^3 \cdot d^{-1}$
$W_{Gr, P}$	Wastage flow rate of primary settler Granollers	$m^3 \cdot d^{-1}$
$W_{Ga, S}$	Recycle flow rate after secondary treatment La Garriga	$m^3 \cdot d^{-1}$
$W_{Gr,S}$	Wastage flow rate of secondary treatment Granollers	$m^3 \cdot d^{-1}$
R_{Gr}	Recycle flow rate of secondary settler Granollers	$m^3 \cdot d^{-1}$
$C_{Ga,}$Sludge	Ratio between settled activated sludge and recycle flow La Garriga	
$C_{Ga,}$ NH_4	NH_4 set-point of the DO cascade controller La Garriga	$g \cdot m^{-3}$
$C_{Gr,}$ NH_4	NH_4 set-point of the DO cascade controller Granollers	$g \cdot m^{-3}$
$C_{Ga,}$ NO_3	NO_3 set-point of the internal recirculation controller La Garriga	$g \cdot m^{-3}$
$C_{Gr,}$ NO_3	NO_3 set-point of the internal recirculation controller Granollers	$g \cdot m^{-3}$

5.6 Definition of criteria

The criteria presented in Chapter 4 at two sampling points have been used: downstream La Garriga WWTP and downstream Granollers WWTP (Table 5.8).

Table 5.8: Criteria considered.

Description of the criteria	LA GARRIGA	GRANOLLERS	
Dissolve oxygen average	DO av Ga	DO av Gr	$gO_2 \cdot m^{-3}$
Dissolve oxygen minim	DO min Ga	DO min Gr	$gO_2 \cdot m^{-3}$
Ammonia maxim	NH_4 max Ga	NH_4 max Gr	$gN \cdot m^{-3}$
River Quality Index	RQI Ga	RQI Gr	Kg pollutant
Total cost	TC		€

With reference to TC, which is an integration of AC, PC and SC the following specifications have been considered:

- No changes were introduced to AC.
- Pumps considered within the model are the ones described in Table 5.8.

- The sludge factor considered in the OperatinalCost model is 0.57 Euros·kg^{-1}. This factor is for sludge that has been dewatered and digested. Since sludge treatment has not been considred in the UWS, sludge factor reduction has been considered in order to adjust SC. Otherwise the vast part of the energy consumption will come from sludge production. In that way AC represents 50%, PC is 30% and SC is 20% (CEDEX, 2008).

Table 5.8: Pumped flow in the integrated model

PUMP	Localization
Pump 1	Flow bypassed from SS La Garriga to SS Granollers
Pump 2	Pumped flow of storage tank La Garriga to La Garriga WWTP
Pump 5	Internal recirculation of La Garriga
Pump 6	External recirculation of La Garriga
Pump 7	Pumped flow of storage tank 1 Granollers to Granollers WWTP
Pump 8	Pumped flow of storage tank 2 Granollers to Granollers WWTP
Pump 11	Internal recirculation of Granollers WWTP
Pump 12	External recirculation of Granollers WWTP
Pump waste 1	Pumped sludge waste La Garriga
Pump waste 2	Pumped sludge waste Granollers

5.7 Reference scenario

The following graphics describe wastewater generated in both systems, La Garriga and Granollers, according to criteria selected and for the different problematic scenarios described. Figure 5.6 refers to the scenarios dry weather, temperature, population and low river flow that are posted in one week. Figure 5.7 refers to the scenarios dry weather, storm, high load La Garriga, high load Granollers, and blower failure La Garriga and blower failure Granollers which are posted during the following two days.

From the figures it can be deduced that storm scenarios improve for all criteria, because it produces a dilution affect on the river (Figure 5.7a and 5.7b). However, the other scenarios produce a bad impact on the RWB for some criteria, i.e., low river flow for DO av Ga (Figure 5.6a) or temperature for NH_4 max Gr (Figure 5.6e).

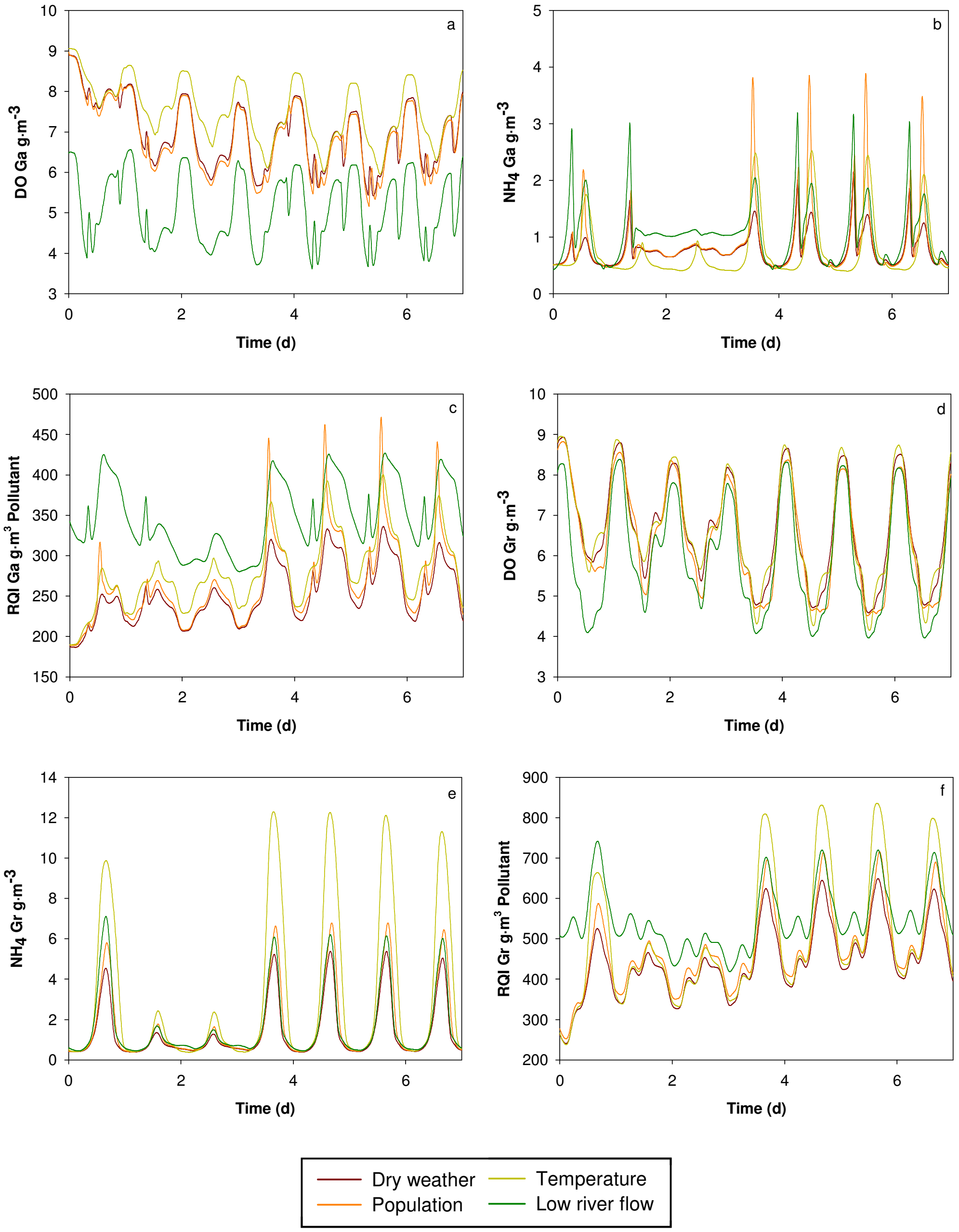


Figure 5.6: Criteria for scenarios: dry weather, temperature, population and low river flow.

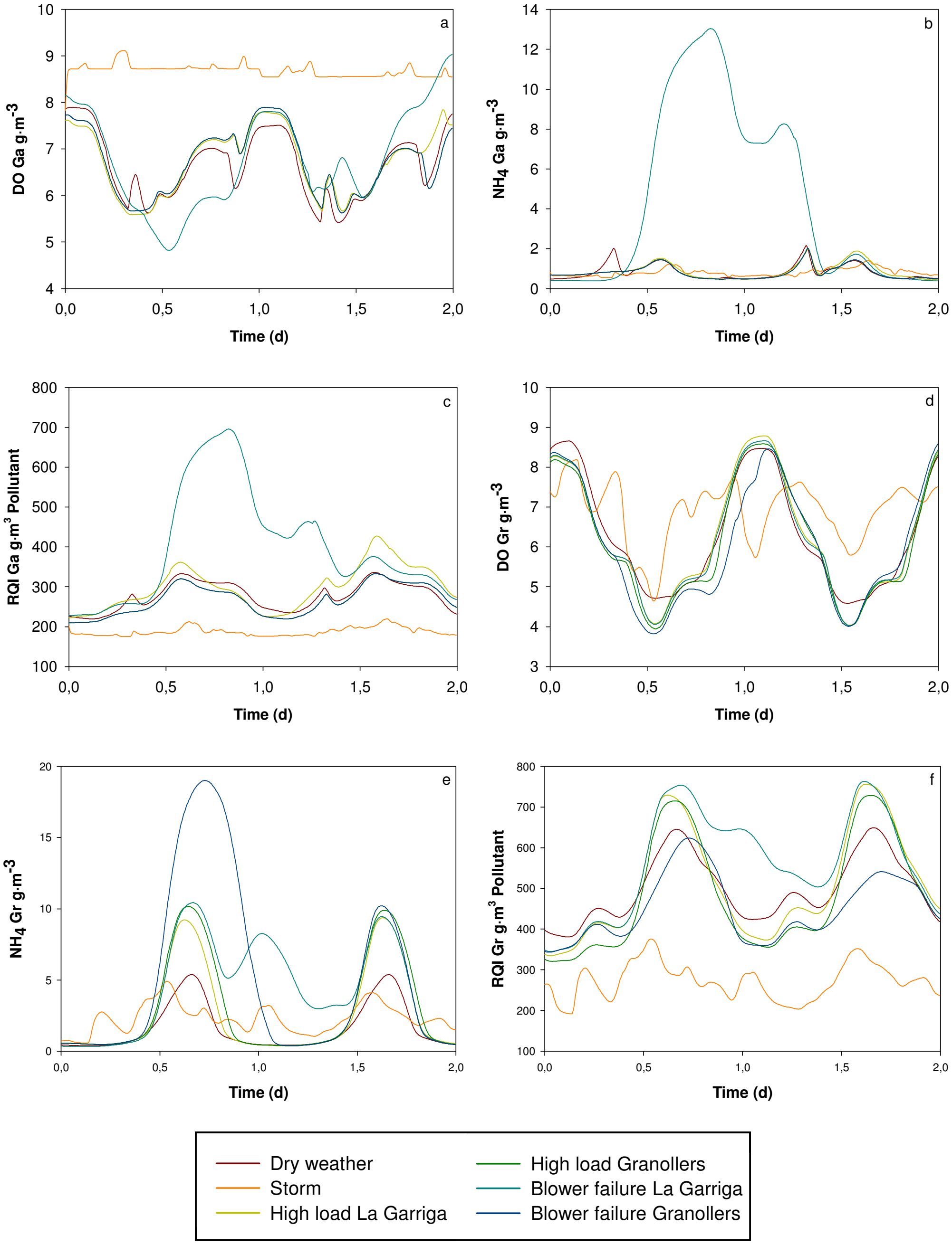


Figure 5.7: Criteria for scenarios: dry weather, storm, high load La Garriga, high load Granollers, blower failure La Garriga and blower failure Granollers.

CHAPTER 6

IDENTIFICATION OF THE MOST INFLUENTIAL OPERATIONAL PARAMETERS

6. Identification of the most influential operational parameters

One issue which has not been addressed yet in integrated management of UWS, is to evaluate the sensitivity of operational parameters of the SS and WWTP on the RWB quality, under different perturbations. Therefore, the objective of this chapter is to present the results of section **4.3 Sensitivity analysis**, quantify the importance of operational parameters for integrated management of urban wastewater systems using Monte Carlo (MC) simulations and Global Sensitivity Analysis (GSA). The outcome of the analysis is information that can help managers changing the right parameters to handle with disturbances in the UWS.

6.1 Multi criteria evaluation of scenarios using Monte Carlo simulations

Following the method presented in chapter 4, the nine scenarios have been simulated 1000 times, changing the model parameters using LHS sampling at each iteration. The values to define the triangular distributions for each parameter are presented in Table 6.1.

Table 6.1. PDF distribution for model parameters.

Short name	Unit	Lower bound	Ref value	Upper bound	Default
F_{Ga}	$m^3 \cdot d^{-1}$	5000 *12000*[*]	10000 *27648*	15000 *100000*	27648
$F_{Ga, WWTP}$	$m^3 \cdot d^{-1}$	5000 *10000*	10000 *27648*	15000 *75000*	27648
F_{Gr}	$m^3 \cdot d^{-1}$	6000	12000	25000	30000
$F_{Gr, WWTP}$	$m^3 \cdot d^{-1}$	25000 *38000*	35000 *76800*	46000 *15000*	76800
$F_{Ga, P}$	$m^3 \cdot d^{-1}$	10000	27648	50000	27648
$F_{Gr,P}$	$m^3 \cdot d^{-1}$	38400	76800	153600	76800
$F_{Ga,S}$	$m^3 \cdot d^{-1}$	70000	14500	30000	14500
$F_{Gr,S}$	$m^3 \cdot d^{-1}$	25000	46000	75000	46000
$W_{Ga, P}$	$m^3 \cdot d^{-1}$	20	50	150	50
$W_{Gr, P}$	$m^3 \cdot d^{-1}$	250	600	1800	600
$W_{Ga, S}$	$m^3 \cdot d^{-1}$	50	100	300	200
$W_{Gr,S}$	$m^3 \cdot d^{-1}$	250	500	1500	500
R_{Gr}	$m^3 \cdot d^{-1}$	10000	28800	57760	28800
$C_{Ga,}$Sludge		0.2	1.5	3	1.5
$C_{Ga,}$ NH_4	$g \cdot m^{-3}$	0.2	1	3	1
$C_{Gr,}$ NH_4	$g \cdot m^{-3}$	0.2	1	3	1
$C_{Ga,}$ NO_3	$g \cdot m^{-3}$	0.2	1	3	1
$C_{Gr,}$ NO_3	$g \cdot m^{-3}$	0.2	1	3	1

[*] Values in italics refer to PDF for the storm scenario experiment.

PDF have been defined according to system characteristics (default parameters) and scenario characteristics (maximum flow per day, capacity of the different parts of the plant, and capacity of the storage tanks). Hence, for storm scenarios different distributions have been assigned to the parameters that limit the wastewater that goes to both WWTPs, La Garriga and Granollers (F_{Ga}, $F_{Ga,\ WWTP}$ and $F_{Gr,\ WWTP}$). During a storm scenario more wastewater enters the UWS and distributions have to be readjusted.

The results of the MC simulations are presented as box plots for the selected variables. These box plots provide the inter-quartile ranges (difference between first and third quartile) and the minimum and maximum values for each criteria. These indicators are used i) to evaluate the observed variability in the variables caused by changes in the operational parameters and ii) to identify opportunities for improvement. Figures 6.1, 6.2, 6.3 and 6.4 show the box plots for the different variables and Table 6.2 summarizes the information of all the box plots.

6.1.1. Variability of parameter combinations to average and minimum DO

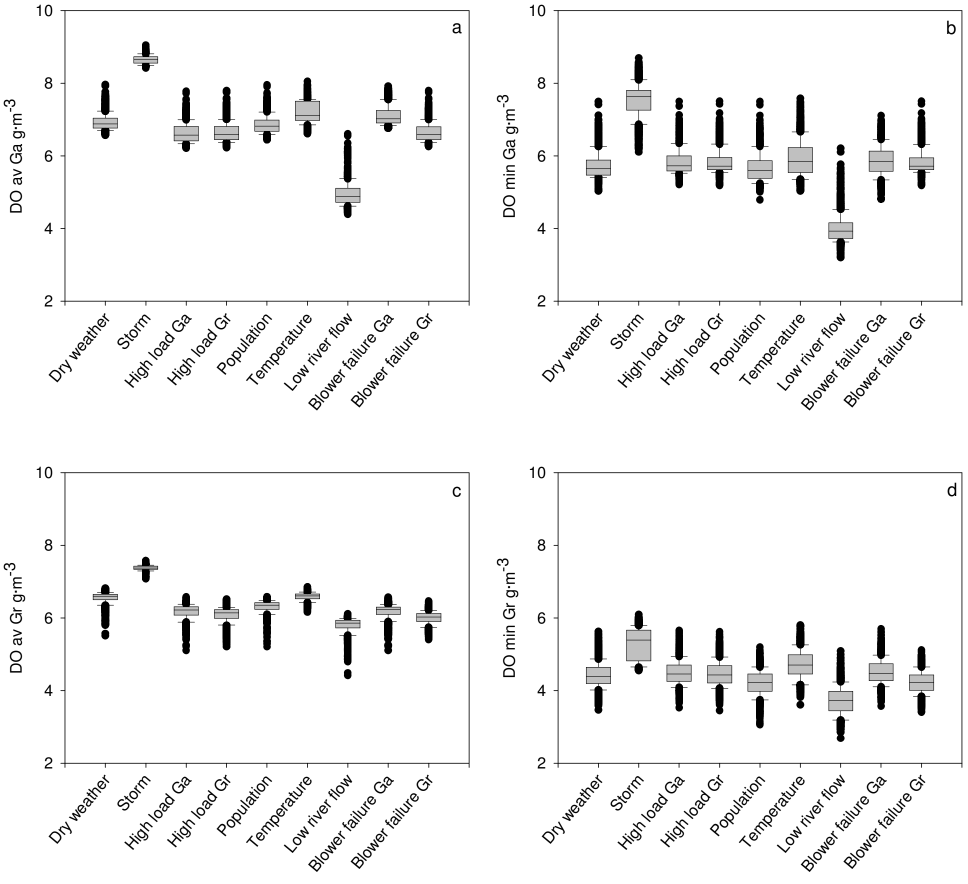


Figure 6.1: Box plot for DO criteria. (a) DO av Ga, (b) DO min Ga, (c) DO av Gr and (d) DO min Gr.

For the average DO concentrations the inter-quartile ranges between scenarios are similar both in la Garriga and Granollers (Figure 6.1a and 6.1c). This means that the different combinations of operational parameters do not contribute to significant changes in the DO concentration in the river. In la Garriga, a longer distribution of outliers is observed at the top of the box plots. In Granollers, the longest distribution of outliers is found at the bottom. Therefore, there is more room for improvement in La Garriga and attention should be paid in Granollers to not reach low DO values in the river. On the other hand, box plots of minimum DO concentration (Figure 6.1b and 6.1d) present larger inter-quartile ranges, indicating that the minimum DO concentration variable is more sensitive than the average DO concentration to changes in parameters.

Several scientific studies suggest that 4 $gO_2 \cdot m^{-3}$ is the minimum amount to ensure good ecosystem quality (FWR, 1998). In la Garriga, the only problematic situation is low river flow, which can lead to values lower than 4 $gO_2 \cdot m^{-3}$. In Granollers, all the scenarios except for the storm scenario reach values below the limit, with low river flow being the most problematic scenario again.

6.1.2. Variability of parameter combinations to ammonia maximum concentrations

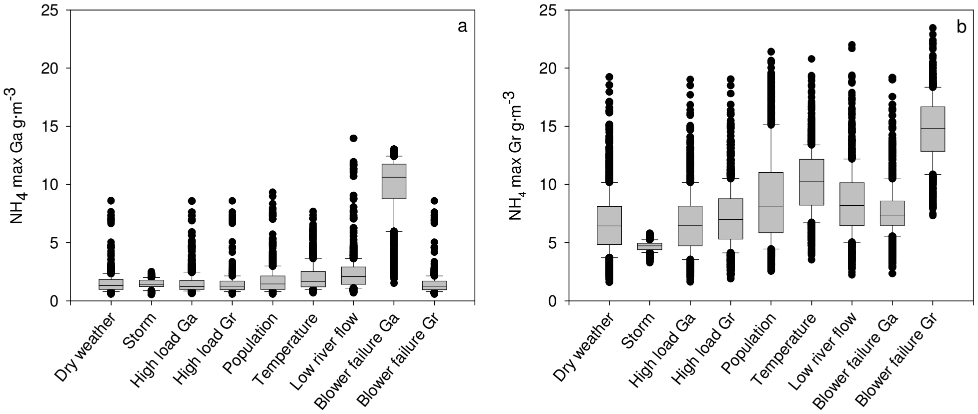


Figure 6.2: Box plot for NH_4 criteria. (a) NH_4 max Ga and (b) NH_4 max Gr.

Box plots of NH_4^+ maximum concentrations show that the inter-quartile ranges between scenarios are much larger in Granollers than in la Garriga (Figure 6.2b and 6.2a). The short outlier distribution below the box plots reflects that avoiding ammonia peaks is not easy, which can be explained by the limited nitrification capacity of the WWTPs.

NH_4^+ concentrations higher than 5 $gN \cdot m^{-3}$ are toxic for the river fauna (Hellawell, 1986; Dodds and Welch, 2000). Therefore, the most problematic situation is having a blower failure in the WWTP. In this situation there is lack of dissolved oxygen to nitrify and large amounts of nitrogen are discharged to the river. Even though the inter-quartile range is large, only outliers go below the limit.

6.1.3. Variability of parameter combinations to RQI

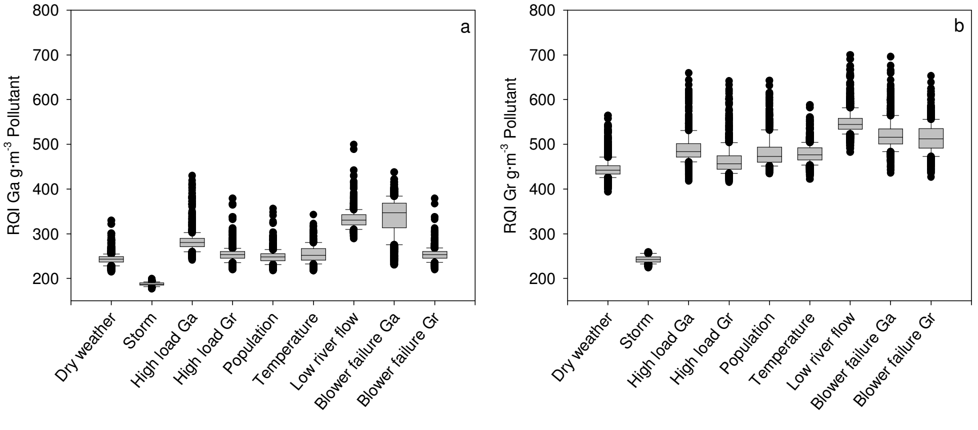


Figure 6.3: Box plot for RQI criteria. (a) RQI Ga and (b) RQI Gr.

Box plots of the RQI (Figure 6.3a 6.3b) show that the inter-quartile ranges between scenarios are similar in Granollers and la Garriga. This can be partially explained by the fact that the RQI is a lumped variable. The box plots presented indicate that the RQI would be difficult to decrease (poor distribution at the bottom of the figure) but management strategies can increase the RQI (bigger distribution at the top).

The RQI values in Granollers are much larger than in la Garriga because the RQI Gr takes into account the pollution coming from la Garriga and the discharge from the Granollers WWTP (which is larger than la Garriga). The storm perturbation leads to very low RQI values explained by the large dilution capacity of the river.

6.1.4. Variability of parameter combinations to total costs

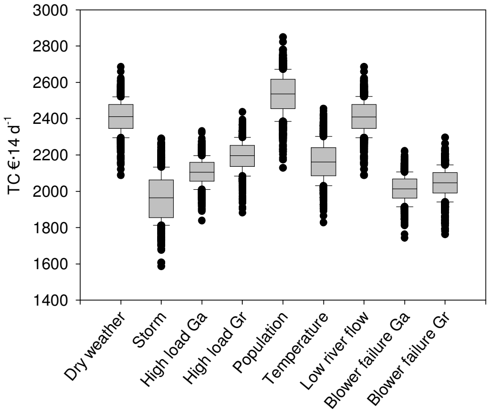


Figure 6.4: Box plot for TC criteria.

Box plots for TC are similar (in terms of inter-quartile range and difference between maximum and minimum values, see Table 6.1). However, the median values for the scenarios are quite different (from 1933 €·$14d^{-1}$ to 2520 €·$14d^{-1}$).

The most expensive scenarios are dry weather, increase of population and low river flow. For reference and low river flow the box plots have the same patterns because the changes were only introduced in the river and not in the sewer system or the WWTP. The population increase scenario means more domestic water treated and hence increased costs. In the storm scenario more water is also treated but it is the cheapest. This scenario increases pumping costs but decreases sludge and aeration costs due to the dilution effect. In the case of blower failures, aeration does not work for two days, therefore, aeration costs decrease and, consequently, the TC does too.

The results from the box plot, together with the values of Table 6.2 suggest that there are some management strategies that could help to improve the criteria for the problems posted. According to the operational parameters tested, the criteria presents different values. Since there are 18 parameters, identifying the most sensitive parameters will help to improve the performance of the system and eventually improve the RWB quality.

Table 6.2: Mean and standard deviation of the criteria for the different scenarios

		Dry weather	Storm	High load Ga	High load Gr	Population	Temperature	Low river flow	Blower La Garriga	Blower Granollers
DO av Ga	Median	6,86	8,65	6,57	6,57	6,80	7,12	4,87	7,01	6,57
$g \cdot m^{-3}$	p75 – p25	0,27	0,18	0,38	0,35	0,30	0,52	0,39	0,37	0,35
	Max – min	1,36	0,66	1,64	1,31	1,30	1,35	2,16	1,13	1,13
DO min Ga	Median	5,64	7,63	5,71	5,71	5,59	5,82	3,92	5,84	5,72
$g \cdot m^{-3}$	p75 – p25	0,41	0,55	0,42	0,34	0,47	0,71	0,47	0,58	0,35
	Max – min	2,40	2,57	2,23	1,97	2,23	2,46	2,85	2,26	2,15
NH_4 max Ga	Median	1,27	1,40	1,28	1,21	1,43	1,72	1,99	10,66	1,22
$g \cdot m^{-3}$	p75 – p25	0,81	0,63	0,80	0,66	1,06	1,31	1,45	3,09	0,68
	Max – min	6,87	1,94	11,58	6,61	6,87	5,87	10,74	11,39	6,81
DO av Gr	Median	6,58	7,37	6,22	6,14	6,36	6,61	5,84	6,19	6,04
$g \cdot m^{-3}$	p75 – p25	0,15	0,08	0,21	0,25	0,20	0,12	0,21	0,18	0,21
	Max – min	0,98	0,56	1,46	1,33	1,43	0,68	1,72	1,37	1,07
DO min Gr	Median	4,35	5,03	4,44	4,43	4,19	4,71	3,70	4,43	4,24
$g \cdot m^{-3}$	p75 – p25	0,46	0,86	0,45	0,47	0,51	0,52	0,54	0,46	0,43
	Max – min	2,01	1,53	2,18	2,13	2,31	2,19	2,37	1,91	1,75
NH_4 max Gr	Median	6,83	4,57	6,76	7,30	8,62	10,72	8,36	7,67	15,02
$g \cdot m^{-3}$	p75 – p25	3,57	0,63	3,81	3,59	5,41	3,67	3,62	2,50	3,74
	Max – min	17,14	2,68	15,37	17,91	21,23	15,01	20,01	18,12	17,09
TC	Median	2398,79	1933,50	2100,25	2189,63	2520,43	2166,14	2404,31	1979,39	2017,47
€.14d^{-1}	p75 – p25	114,34	199,44	94,27	102,98	140,32	148,44	118,60	79,45	98,02
	Max – min	542,69	623,02	478,20	553,45	712,81	654,93	619,96	425,60	477,88
RQI Ga	Median	242,95	186,94	280,98	253,00	247,51	252,53	330,79	346,45	253,10
Kg pollutant	p75 – p25	12,23	5,28	19,76	13,68	13,53	24,14	21,45	57,20	14,22
	Max – min	72,00	23,26	254,40	85,45	75,46	95,24	141,12	174,08	88,02
RQI Gr	Median	443,68	243,95	486,26	458,25	474,82	479,42	545,33	523,49	514,97
Kg pollutant	p75 – p25	21,29	11,03	31,01	31,47	36,08	30,51	24,98	32,90	43,95
	Max – min	168,51	37,02	223,52	235,71	213,63	140,53	228,17	245,62	214,35

6.2 Global Sensitivity Analysis

6.2.1 Results of Global Sensitivity Analysis

The last section provided information about how different combinations of parameters resulted in variability in the evaluated criteria. In this section, the goal is to identify which parameters are generating more variability in the criteria, i.e., which parameters are more sensitive to the different scenarios.

The aim of this section is not to discuss in detail each ranking but to provide guidelines for interpreting the obtained results. The following tables summarize the ranking of the most sensitive parameters for each scenario and criteria evaluated in la Garriga (Table 6.3.1) and in Granollers (Table 6.3.2). These tables include only the parameters that obtained a *t*PCC value larger than 1.96 after running the GSA. The larger the *t*PCC, the more sensitive the parameter is. Empty boxes mean that the multi linear regression model resulted in an R^2 smaller than 0.7, and for these cases the tPCC are not valid measures of sensitivity. For example, this happens in the reference scenario for the criteria $NH_{4,max,Gr}$, or in the case of temperature for the DO concentrations and the RQI in La Garriga. Regarding the TC criteria, good linear regressions have been found for all scenarios except for the storm event.

Bold values were obtained using multi linear regression and grey values were calculated applying ranked multi linear regression. The sign of the *t*PCC indicates whether the linear relationship between the parameter and the variable is positive or negative. Only the ranking in the high load La Garriga scenario is further explained. For that case (Table 6.3.1), the RQI_{Ga} can be improved by decreasing F_{Ga} (i.e., send more wastewater to Granollers), $C_{Ga,\ NH4}$ (increase aeration capacity) and $F_{Ga,\ WWTP}$ (send more wastewater to the tank in la Garriga) or by increasing $C_{Ga,\ Sludge}$ (adjust wastage to maintain sludge retention time). In the case of $DO_{av,Ga}$, it can be improved by also decreasing $C_{Ga,\ NH4}$ and F_{Ga}. Increasing $F_{Ga,WWTP}$ results in better $DO_{av},_{Ga}$. However, this change has a negative effect on the RQI_{Ga} described before. This indicates that a change in one parameter can positively affect one variable but can have a negative affect on another, and trade-off situations appear.

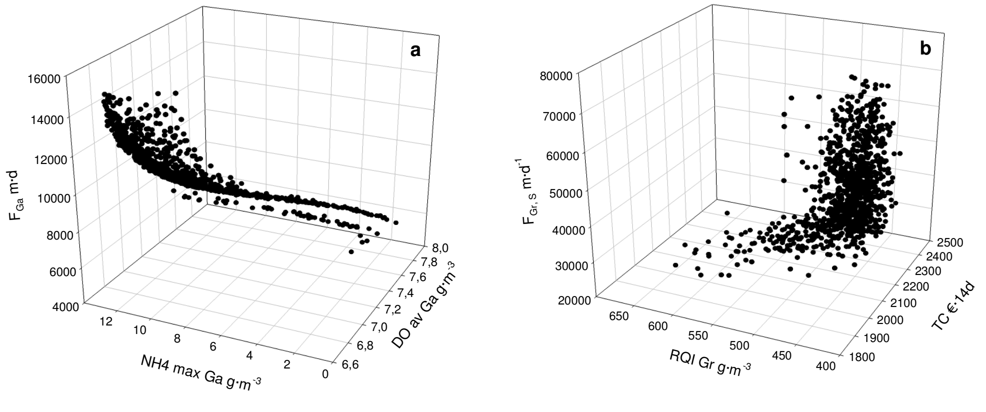


Figure 6.5: (a) Relation between $F_{Gr,\ S}$, NH_4 max G DO Gr and TC for high load Granollers scenario and (b) Relation between R_{Gr}, TC and RQI for the low river flow scenario.

Figure 6.5 presents (a) the relation between flow to the La Garriga system (F_{Ga}), ammonia max concentration ($NH_{4\ max\ Ga}$) and DO av ($DO_{av\ Ga}$) in La Garriga and, in the case of blower failure, in La Garriga and (b) the relation between recycle flow to secondary treatment in Granollers WWTP ($F_{Gr,\ S}$), TC and RQI for Granollers (RQI_{Gr}) in case of high load Granollers.

Figure 3-a clearly defines a pattern between the parameter and the two criteria: decreasing the flow to the La Garriga system secondary treatment will lead to better ammonia and DO concentrations in the WWTP effluent. In that case the relation is clear since the flow to the La Garriga system will decrease and less wastewater will reach that point. Figure 3-b shows how improving the RQI in Granollers requires more flow to secondary treatment and consequently increased expenses. The RQI will decrease since more wastewater will be treated and the WWTP effluent will improve.

Finally, from Tables 6.2.1 and 6.2.2. it can be seen that the criteria in the La Garriga system can only be modified for operational parameters within the same system. However, this is different in the case of the Granollers system. Although most of the sensitive operational parameters are from the Granollers system, other parameters from La Garriga also appear to be sensitive (F_{Ga}, $F_{Ga,\ WWTP}$ and $C_{Ga}\,NH_4$). F_{Ga} determines the wastewater bypassed to Granollers; the other two influence upstream pollution (la Garriga), which is also reflected downstream (Granollers).

Table 6.3.1 Most sensitive parameters for each criteria and scenario in La Garriga, including total cost

	Reference		**Storm**		**High load La Garriga**		**High load Granollers**		**Population**		**Temperature**		**Low river flow**		**Blower La Garriga**		**Blower Granollers**	
	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC
RQI Ga	F_{Ga}	18,83	**F_{Ga}**	**15.45**	F_{Ga}	18.54	F_{Ga}	19.29	F_{Ga}	19.77					**F_{Ga}**	**20.20**	F_{Ga}	19.09
	C_{Ga}, NH$_4$	5,98	**$F_{Ga,S}$**	**-10.64**	C_{Ga}, NH$_4$	7.22	C_{Ga}, NH$_4$	5.39	C_{Ga}, NH$_4$	4.07					**$F_{Ga, WWTP}$**	**4.00**	C_{Ga}, NH$_4$	5.34
	$F_{Ga, WWTP}$	3,17	**$F_{Ga, WWTP}$**	**5.42**	$F_{Ga, WWTP}$	4.38	$F_{Ga, WWTP}$	4.57	$F_{Ga, WWTP}$	3.33							$F_{Ga, WWTP}$	4.69
			C_{Ga}, NH$_4$	**3.77**	C_{Ga},Sludge	-4.04												
			$F_{Ga, P}$	**-3.76**														
DO av Ga	F_{Ga}	-13,90	**F_{Ga}**	**-19.33**	**C_{Ga}, NH$_4$**	**-14.86**	**C_{Ga}, NH$_4$**	**-14.32**	F_{Ga}	-15.30			C_{Ga}, NH$_4$	-15.00	**F_{Ga}**	**-20.67**	C_{Ga}, NH$_4$	-15.08
	C_{Ga}, NH$_4$	-13,45	**$F_{Ga, WWTP}$**	**-3.62**	**F_{Ga}**	**-12.79**	**F_{Ga}**	**-12.83**	C_{Ga}, NH$_4$	-12.14			F_{Ga}	-11.08			F_{Ga}	-13.10
	$F_{Ga, WWTP}$	5,00	**C_{Ga}, NH$_4$**	**-3.36**	**$F_{Ga, WWTP}$**	**2.12**	**$F_{Ga, WWTP}$**	**2.26**	$F_{Ga, WWTP}$	4.86			$F_{Ga, WWTP}$	6.45			$F_{Ga, WWTP}$	2.92
													C_{Ga},Sludge	-2.06				
DO min Ga	**F_{Ga}**	**-17,20**	**F_{Ga}**	**-14.74**	F_{Ga}	-17.73	F_{Ga}	-17.75	**F_{Ga}**	**-17.79**			F_{Ga}	-15.99	F_{Ga}	-18.60	F_{Ga}	-17.61
	C_{Ga}, NH$_4$	**-6,26**	**$F_{Ga, WWTP}$**	**-12.93**	C_{Ga}, NH$_4$	-9.20	C_{Ga}, NH$_4$	-9.69	**C_{Ga}, NH$_4$**	**-6.24**			$F_{Ga, WWTP}$	-9.83	$F_{Ga, WWTP}$	-8.66	C_{Ga}, NH$_4$	-9.65
	$F_{Ga, WWTP}$	**-5,54**			$F_{Ga, WWTP}$	-4.60	$F_{Ga, WWTP}$	-2.54	**$F_{Ga, WWTP}$**	**-5.61**			C_{Ga}, NH$_4$	-6.51			$F_{Ga, WWTP}$	-2.64
NH$_4$ max Ga	C_{Ga}, NH$_4$	16,79	**F_{Ga}**	**17.82**	C_{Ga}, NH$_4$	15.69	C_{Ga}, NH$_4$	17.36	C_{Ga}, NH$_4$	16.35	**$F_{Gr,P}$**	**16.93**	C_{Ga}, NH$_4$	17.10	**F_{Ga}**	**19.63**	C_{Ga}, NH$_4$	17.25
	$F_{Ga, WWTP}$	8,43	**$F_{Ga,S}$**	**-8.05**	F_{Ga}	10.13	F_{Ga}	8.63	$F_{Ga, WWTP}$	9.19	**$F_{Ga, P}$**	**9.98**	$F_{Ga, WWTP}$	8.78	**$F_{Ga, WWTP}$**	**4.34**	F_{Ga}	8.48
	F_{Ga}	8,26	**$F_{Ga, WWTP}$**	**5.37**	$F_{Ga, WWTP}$	6.68	$F_{Ga, WWTP}$	7.75	F_{Ga}	8.45	**$F_{Ga,S}$**	**-3.87**	F_{Ga}	7.27			$F_{Ga, WWTP}$	7.83
			$F_{Ga, P}$	**-2.70**	C_{Ga},Sludge	-4.56					**F_{Gr}**	**3.84**						
			C_{Ga}, NH$_4$	**2.41**							**R_{Ga}**	**-2.67**						
											F_{Ga}	**-2.15**						
TC	**R_{Gr}**	**11,92**			**R_{Gr}**	**12.57**	**C_{Gr}, NO$_3$**	**11.59**	**R_{Gr}**	**9.87**	**R_{Gr}**	**10.39**	**R_{Gr}**	**11.78**	**R_{Gr}**	**12.76**	**R_{Gr}**	**12.35**
	C_{Gr}, NO$_3$	**8,32**			**C_{Gr}, NO$_3$**	**8.89**	**R_{Gr}**	**9.70**	**C_{Gr}, NO$_3$**	**8.14**	**C_{Ga}, NH$_4$**	**10.01**	**C_{Gr}, NO$_3$**	**8.43**	**$W_{Gr,S}$**	**8.68**	**$W_{Gr,S}$**	**8.15**
	C_{Ga},Sludge	**7,79**			**$W_{Gr,S}$**	**8.45**	**$W_{Gr,S}$**	**7.98**	**$W_{Gr,S}$**	**7.15**	**C_{Gr}, NO$_3$**	**8.61**	**C_{Ga},Sludge**	**7.74**	**C_{Gr}, NO$_3$**	**8.61**	**C_{Gr}, NO$_3$**	**7.95**
	$W_{Gr,S}$	**7,18**			**C_{Ga},Sludge**	**8.14**	**C_{Ga},Sludge**	**7.36**	**$F_{Gr, WWTP}$**	**6.75**	**$W_{Gr,S}$**	**7.91**	**$W_{Gr,S}$**	**7.10**	**C_{Ga},Sludge**	**5.08**	**C_{Ga},Sludge**	**7.65**
	C_{Ga}, NH$_4$	**5,76**			**$F_{Gr,S}$**	**4.18**	**C_{Ga}, NH$_4$**	**5.60**	**$F_{Gr,S}$**	**6.47**	**C_{Ga}, NO$_3$**	**6.20**	**C_{Ga}, NH$_4$**	**5.76**	**C_{Ga}, NO$_3$**	**5.08**	**C_{Ga}, NH$_4$**	**5.80**
	$F_{Gr,S}$	**4,69**			**C_{Ga}, NO$_3$**	**3.36**	**$F_{Gr,S}$**	**4.31**	**C_{Ga}, NH$_4$**	**6.07**	**C_{Ga},Sludge**	**4.08**	**$F_{Gr,S}$**	**4.73**	**F_{Ga}**	**4.78**	**$F_{Gr,S}$**	**4.26**
	C_{Ga}, NO$_3$	**4,37**			**$W_{Gr, P}$**	**1.96**	**C_{Ga}, NO$_3$**	**4.08**	**C_{Ga},Sludge**	**5.94**	**$F_{Gr,S}$**	**3.05**	**C_{Ga}, NO$_3$**	**4.46**	**$F_{Gr,S}$**	**4.27**	**C_{Ga}, NO$_3$**	**4.16**
	$F_{Gr, WWTP}$	**2,06**					**$F_{Gr, WWTP}$**	**2.14**	**C_{Ga}, NO$_3$**	**4.30**	**$F_{Ga, WWTP}$**	**-2.74**	**$F_{Gr, WWTP}$**	**2.03**	**C_{Ga}, NH$_4$**	**2.23**		
									F_{Ga}	**2.39**								

Table 6.3.2 Most sensitive parameters for each criteria and scenario in Granollers

	Reference		**Storm**		**High load La Garriga**		**High load Granollers**		**Population**		**Temperature**		**Low river flow**		**Blower La Garriga**		**Blower Granollers**	
	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC	Parameter	*t*PCC
RQI Gr	$F_{Gr, WWTP}$	17.61			$F_{Gr, WWTP}$	16.39	$F_{Gr, WWTP}$	17.41					$F_{Gr, WWTP}$	15.34	$F_{Gr, WWTP}$	14.34	**$F_{Gr, WWTP}$**	**17.92**
	$F_{Gr,S}$	-7.71			$F_{Gr,S}$	-7.05	$F_{Gr,S}$	-7.46					C_{Gr}, NO_3	-8.47	F_{Ga}	9.35	**$F_{Gr,S}$**	**-5.11**
	C_{Gr}, NO_3	-4.52			C_{Gr}, NO_3	-6.68	F_{Gr}	3.48					$F_{Gr,S}$	-7.44	$F_{Gr,S}$	-6.82	**F_{Ga}**	**-4.26**
	F_{Gr}	3.39			F_{Gr}	3.21	$W_{Gr, P}$	-2.86					$W_{Gr,S}$	-3.07	C_{Gr}, NO_3	-5.49	**C_{Gr}, NO_3**	**-3.50**
	$W_{Gr,S}$	2.64			C_{Ga}, NH_4	2.38	C_{Gr}, NO_3	-2.85					F_{Gr}	2.77	F_{Gr}	2.64	**$W_{Gr, P}$**	**-3.27**
					$W_{Gr, P}$	-2.23	R_{Gr}	-2.00							$F_{Ga, WWTP}$	2.03	**F_{Gr}**	**2.61**
																	$W_{Gr,S}$	**-2.53**
DO av Gr	F_{Ga}	15.06					F_{Ga}	14.80	F_{Ga}	16.66	**F_{Ga}**	**16.94**	F_{Ga}	16.06			**F_{Ga}**	**16.33**
	$W_{Gr,S}$	8.26					$W_{Gr,S}$	9.76	$W_{Gr,S}$	7.83	**$W_{Gr,S}$**	**8.82**	$W_{Gr,S}$	7.26			**$W_{Gr,S}$**	**10.63**
	$W_{Gr, P}$	5.88					$W_{Gr, P}$	4.75	$W_{Gr, P}$	4.78	**$W_{Gr, P}$**	**6.27**	$W_{Gr, P}$	5.01			**$W_{Gr, P}$**	**5.02**
	C_{Gr}, NH_4	-5.01					C_{Gr}, NH_4	-4.63	C_{Gr}, NH_4	-3.26	**R_{Gr}**	**2.66**	C_{Gr}, NH_4	-4.57			**$F_{Gr, WWTP}$**	**-3.20**
	$F_{Gr, WWTP}$	3.10					$F_{Gr, WWTP}$	-2.64	$F_{Gr,S}$	2.24	**C_{Ga}, NH_4**	**-2.02**	$F_{Gr, WWTP}$	4.11				
	R_{Gr}	2.35											R_{Gr}	2.28				
	C_{Ga}, NH_4	-1.97											$F_{Gr,S}$	2.26				
DO min Gr	$F_{Gr, WWTP}$	-15.07			**$F_{Gr, WWTP}$**	**-15.28**	**$F_{Gr, WWTP}$**	**-15.70**			**$F_{Gr, WWTP}$**	**-16.39**			**$F_{Gr, WWTP}$**	**-14.98**	**$F_{Gr, WWTP}$**	**-18.17**
	F_{Ga}	8.05			**F_{Ga}**	**7.90**	**F_{Ga}**	**8.10**			**$W_{Gr,S}$**	**7.51**			**F_{Ga}**	**8.20**	**F_{Ga}**	**8.68**
	$W_{Gr,S}$	6.21			**$W_{Gr,S}$**	**6.66**	**$W_{Gr,S}$**	**6.12**			**F_{Ga}**	**7.02**			**$W_{Gr,S}$**	**6.45**	**$W_{Gr,S}$**	**3.56**
	C_{Gr}, NH_4	-5.15			**C_{Gr}, NH_4**	**-5.45**	**C_{Gr}, NH_4**	**-4.99**			**$W_{Gr, P}$**	**2.01**			**C_{Gr}, NH_4**	**-5.93**	**$F_{Ga, WWTP}$**	**3.45**
	$F_{Ga, WWTP}$	2.90			**$F_{Ga, WWTP}$**	**2.43**	**$F_{Ga, WWTP}$**	**3.36**			**$F_{Ga, WWTP}$**	**2.01**			**$F_{Ga, WWTP}$**	**2.72**	**$W_{Gr, P}$**	**2.31**
					$W_{Gr, P}$	**2.00**					**C_{Gr}, NO_3**	**2.00**						
NH_4 max Gr			**$F_{Gr,S}$**	**-15,83**	$F_{Gr, WWTP}$	17.72	$F_{Gr, WWTP}$	18.61			$F_{Gr, WWTP}$	17.48					$F_{Gr, WWTP}$	18.62
			$F_{Gr, WWTP}$	**10,95**	$F_{Gr,S}$	-5.29	$F_{Gr,S}$	-4.66			$W_{Gr,S}$	9.27					F_{Ga}	-6.14
			$F_{Ga,S}$	**-3,17**	$W_{Gr,S}$	4.36	$W_{Gr,S}$	4.34			F_{Gr}	3.80					$W_{Gr, P}$	-3.06
			$F_{Ga, WWTP}$	**1,97**	C_{Gr}, NH_4	4.21	F_{Gr}	3.22			$F_{Gr,S}$	-3.49					F_{Gr}	2.88
					F_{Gr}	2.87	C_{Gr}, NH_4	2.79			R_{Gr}	-2.66					$F_{Gr,S}$	2.46
											F_{Ga}	-2.01					$W_{Gr,S}$	-2.35

6.2.2 Most sensitive parameters

Following the method proposed in chapter 4, most sensitive parameters were selected according to their ranking for the different criteria. Table 6.4 summarizes the parameters that are sensitive for more than two criteria, or that ranked 1st or 2nd for one variable. These parameters will be used for MC simulation in step **4.4 Best management strategy**.

Table 6.4 Parameters selected for best management strategy.

	Dry weather	Storm	High load Ga	High load Gr	Pop	Tem	Low river flow	KLA Ga	KLA Gr
$C_{Ga,}$ NH_4	√	√		√	√	√	√	√	√
$C_{Gr,}$ NH_4	√	√	√	√	√		√		
$C_{Ga,}$ NO_3						√			
$C_{Gr,}$ NO_3	√	√	√	√	√	√	√		
$W_{Ga,\ P}$									
$W_{Gr,\ P}$			√	√	√	√			√
$W_{Gr,S}$	√		√	√	√	√	√	√	√
R_{Ga}									
R_{Gr}	√	√	√	√	√	√	√	√	√
$F_{Ga,S}$		√	√						
$F_{Gr,S}$	√	√	√	√	√	√	√	√	√
$F_{Ga,\ P}$									
$F_{Gr,P}$									
$C_{Ga,}$Sludge			√			√	√		
F_{Ga}	√	√	√	√	√	√	√	√	√
$F_{Ga,\ WWTP}$	√	√	√	√	√	√	√	√	√
F_{Gr}							√		
$F_{Gr,\ WWTP}$	√	√	√	√	√	√	√	√	√

Table 6.4 shows that five parameters are sensitive in all scenarios, and that four parameters refer to hydraulic conditions of the WWTP: i) flow to the La Garriga (F_{Ga}); ii) flow to the La Garriga WWTP ($F_{Ga,\ WWTP}$); iii) flow to the Granollers WWTP ($F_{Gr,\ WWTP}$); and iv) flow to secondary treatment at the Granollers WWTP ($F_{Gr,S}$). These parameters determine the WWTP treatment capacity and for that reason they are sensitive: by sending more flow to secondary treatment, more wastewater is treated and river quality improves. However, exceeding that capacity can result in a wash off problem and consequently decrease the evaluation criteria.

The last sensitive parameter in all the scenarios is the wastage flow rate from the secondary settler in the Granollers WWTP (R_{Gr}). This flow is the external recirculation at the WWTP. Recycle flow rates in the WWTP are normally 1.5 times greater than influent flow, and are the main contributors to pumping costs. Wastage flow rates and recycle flow rates are relevant parameters because they determine the hydraulic retention and the solid retention times, which are important design parameters for the activated sludge process (Tchobanoglous *et al.,* 2003).

A few parameters are also repeated in almost all the scenarios: ammonia controllers in both WWTPs, the La Garriga and Granollers ($C_{Ga,NH4}$, $C_{Gr,NH4}$), which determine the nitrification yield in the WWTPs; nitrate controllers in Granollers ($C_{Gr,NO3}$), which determine the internal recirculation in the Granollers WWTP; and the wastage flow after the secondary treatment in the Granollers WWTP ($W_{Gr,S}$), which contributes to sludge costs.

Some other parameters are important depending on the problematic scenario posted. The wastage flow from the primary settler in the Granollers WWTP ($W_{Gr,P}$) is sensitive in four scenarios and sludge control in the La Garriga WWTP ($C_{Ga,Sludge}$) is sensitive in three scenarios. Flow to secondary treatment at the La Garriga WWTP ($F_{Ga,S}$) is only sensitive in the storm and high load La Garriga scenarios. As explained previously, flow to secondary treatment determines the WWTP capacity. During storm events more wastewater enters the system and it is necessary to improve the treatment yield of the WWTP, as in the case of high load La Garriga where it is also necessary to improve the treatment yield because the wastewater is more polluted than reference case. This parameter is not sensitive in the other scenarios because there are other flow limitations located before the WWTP, i.e. F_{Ga} and $F_{Ga,WWTP}$. The nitrate controller at the La Garriga WWTP ($C_{Ga,NO3}$) is only sensitive in the case of the temperature scenario: anaerobic treatment at lower temperatures has slower reaction rates and it is necessary to readjust the nitrate controller. Flow to Granollers system (F_{Gr}) is only sensitive in the case of the low river flow scenario. This parameter limits the flow that keeps going to the Granollers system and overflow is bypassed in the smaller tank located in Granollers.

Finally four parameters are not significant in any scenario. The first is flow to primary treatment in both WWTPs ($F_{Ga,P}$ and $F_{Gr,P}$). Primary treatments have much more capacity than secondary treatments and their capacities could be exceeded only in the case of big storms. Another is wastage flow from primary treatment at La Garriga WWTP ($W_{Ga,P}$), which is very small ($50\ m^3 \cdot d^{-1}$) and does not significantly affect WWTP operational conditions. And the last is the recycle flow rate in the La Garriga WWTP (R_{Ga}), which is also conditioned by the sludge controller in the sane plant ($C_{Ga,Slduge}$).

6.3 Concluding remarks

In this chapter the results of the multi simulations have been presented in two different parts. The first is the multi criteria evaluation of the different scenarios posted. A PDF has been defined for the operational parameters. This function is the same for all scenarios except for the storm event, which presents a different distribution for the four parameters that refer to hydraulic conditions of the system. The results of the multi simulations have been presented in a box plot. This analysis provides the variability caused by the combinations of operational parameters tested and identifies opportunities for improvement. The storm scenario has the best evaluation criteria; low river flow, blower failure in La Garriga, and blower failure in Granollers are the worse scenarios.

The second part presents the results of the GSA and the most sensitive parameters. The results of the GSA have been presented in Tables 6.3.1 and 6.3.2. These tables present the sensitivity of one operational parameter to one criteria for each scenario simulated. Managers of the UWS can use these tables to improve the UWS performance. The result of the GSA also identifies the most sensitive parameters. Five operational parameters were sensitive in all scenarios. Four parameters were not sensitive in any scenario and the rest were sensitive depending on the scenario posted. Finally, overall results suggest that improvements in UWS management can be achieved by selecting the best operational strategies.

CHAPTER 7

SELECTION OF OPERATIONAL STRATEGIES

7. Selection of operational strategies

In the previous chapter GSA was used to identify most sensitive operational parameters under different problematic scenarios. Finding a good combination of these parameters will overcome the scenario posted and will improve the RWB quality. Therefore, the objective of this chapter is to present the results of section **4.4 Best operational strategy**. For each scenario steps **4.4.1 Multi simulations** and **4.4.2 Pareto front and screening** of the method were performed.

Following the method presented in chapter 4, the nine scenarios have been simulated 1000 times again, changing at each iteration only the most sensitive parameters using the same sampling and distribution as GSA (Table 6.1). For not sensitive operational parameters the reference values were used.

The Pareto front and screening were used to select best results from the 1000 simulations according to the evaluation criteria. The results of the screening are a table with better operational strategies tested within the MC experiment. The manager of the UWS should choose one of the strategies proposed. For simplification in practice it has been selected one strategy that improves environmental rather than economic criteria. This strategy has been used to rerun the problematic scenario and check the percentage improvement achieved. These results are presented graphically. The figures also show the thresholds proposed by the Urban Pollution Management (UPM) Manual (FWR, 1998), for minimum dissolved oxygen (DO) of 4 $mg \cdot l^{-1}$, and maximum ammonia (NH_4) concentration of 3.5 $mg \cdot l^{-1}$(red line). All the proposed strategies are compared to the use of current management set points (reference situation). In the reference cases, the storage tanks and the bypasses are not used, except for the storm scenario.

Finally, the selected strategies have been incorporated into the WEST modelling platform as a simple rule-based control system, which is able to identify the current scenario posted and apply the correct operational strategy to improve overall operation for the Besòs case study.

7.1 Dry weather

The Pareto front has reduced the extension from 1000 to 898 simulations, and only three simulations have overcome the screening (Table 7.1). The strategy that improves current management is 860 and model behavior using this strategy is presented in Figure 7.1.2.

Figure 7.1.1 shows the flow distribution in La Garriga (a) and in Granollers (b). Solid lines refer to the total flow that reach each subsystem (before any bypass or storage tank) and doted lines refer to the flow reaching the La Garriga and Granollers WWTPs. The grey area is the volume of wastewater bypassed from La Garriga to Granollers, and the blue area indicates the volume sent to the storage tanks.

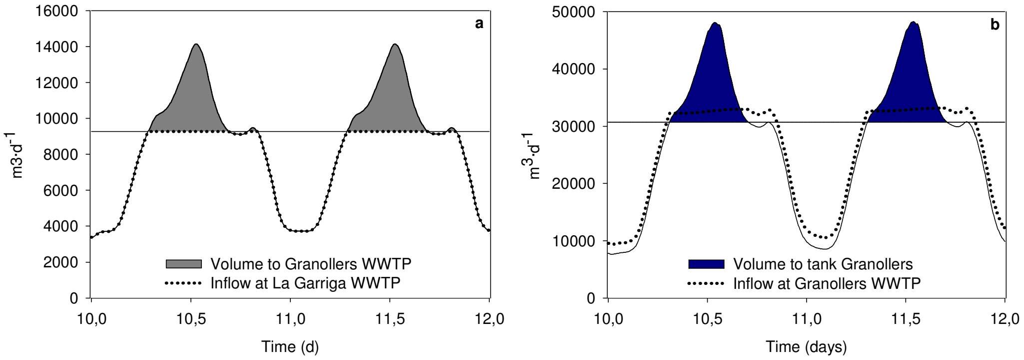


Figure 7.1.1: Dry weather scenario flow distribution in La Garriga (a) and in Granollers (b).

In that case, the tank located in La Garriga is not used and the bypass to the Granollers system is working during daily flow peaks (Figure 7.1.1a: grey area), decreasing the load in the La Garriga WWTP. The tank located in Granollers is filled during daily peaks (Figure 7.1.1b). With the proposed strategy all wastewater in the system receives primary and secondary treatment.

Table 7.1. Criteria values for the dry weather scenario.

	LA GARRIGA				GRANOLLERS				TC
	DO av	DO min	NH_4 max	RQI	DO av	DO min	NH_4 max	RQI	
177	7.03	6.07	0.62	242.47	6.59	4.62	2.41	423.51	2367.45
352	6.94	5.72	0.83	237.25	6.58	4.82	2.69	428.66	2369.69
860	7.11	5.69	1.09	237.74	6.61	4.89	4.20	423.00	2374.26
Reference	6.97	5.42	2.15	252.16	6.64	4.59	5.38	446.98	2322.15
% Improv.	2	5	49	6	-1	7	22	6	2

This strategy improves all the criteria in La Garriga, and the criteria DO_{min}, $NH_{4,\ max}$, and RQI in Granollers compared to the reference situation. However, TC slightly increases because the cost of bypassing is added to the treatment costs. The DO_{av} in Granollers remains similar. Although ammonia peaks in Granollers are smoothed, in some cases they still are over 3.5 $mg \cdot l^{-1}$ (Figure 7.1e).

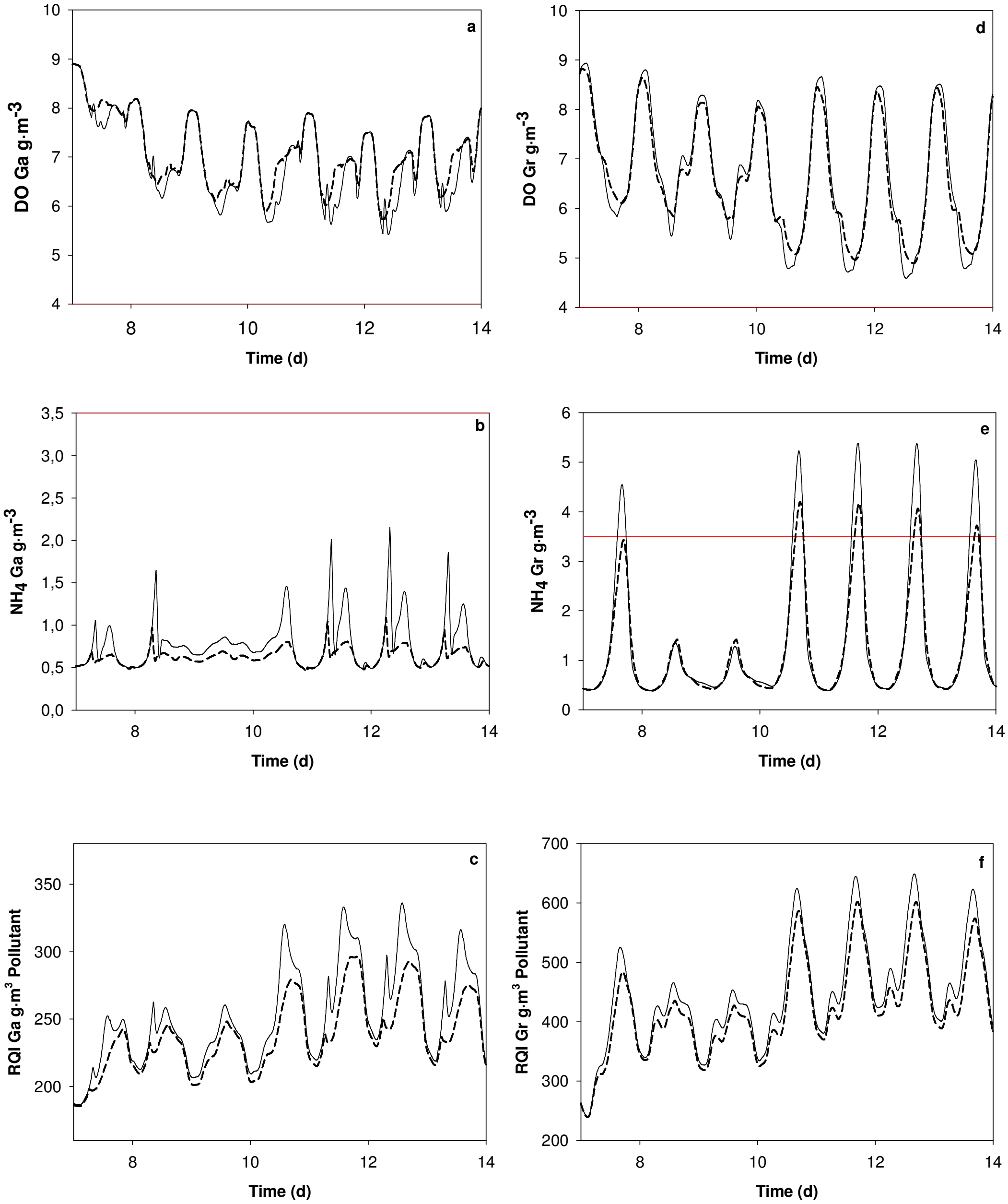


Figure 7.1.2: Dry weather scenario model behavior, solid line reference configuration, and discontinuous line best strategy. (a) DO Ga, (b) NH_4 Ga, (c) RQI Ga, (d) DO Gr, (e) NH_4 Gr and (f) RQI Gr.

7.2 Storm

The Pareto front has reduced the extension from 1000 to 767 simulations, and only two simulations have overcome the screening (Table 7.2). The strategy that improves current management is 74 and model behavior using this strategy is presented in Figure 7.2.2.

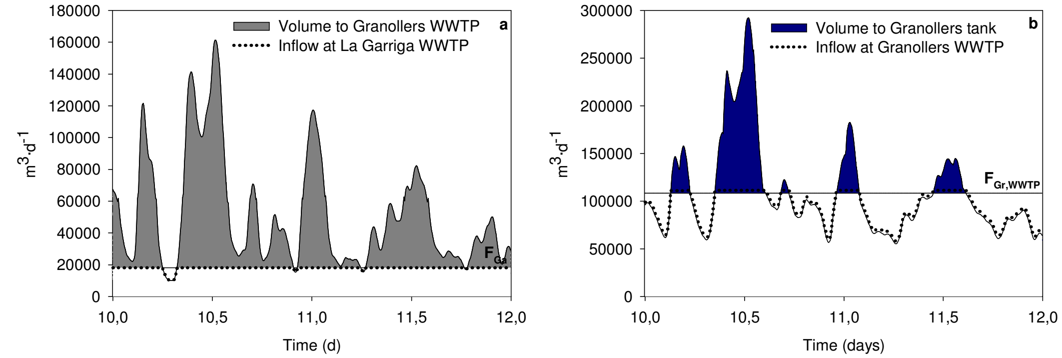


Figure 7.2.1: Storm scenario flow distribution in La Garriga (a) and in Granollers (b).

Like in the dry weather scenario, the tank located in La Garriga is not filled and the bypass to the Granollers system is activated (Figure 7.2.1a). The tank in la Garriga is not used because its volume is small (7,000 m^3) and when this capacity is exceeded river discharges occur. This is more prone to happen during a storm event. On the other hand, the tank in Granollers is used (see Figure 7.2.1b). This strategy also maximizes the volume of wastewater receiving secondary treatment in both WWTPs and increases the aeration supply by decreasing the ammonia controller set points.

Table 7.2. Criteria values for the storm scenario.

	LA GARRIGA				GRANOLLERS				TC
	DO av	DO min	NH_4 max	RQI	DO av	DO min	NH_4 max	RQI	
74	9.00	8.59	0.56	179.28	7.51	5.08	3.99	235.75	1927.30
539	8.70	7.98	1.24	184.98	7.43	5.77	4.36	240.73	1795.79
Reference	8.73	7.76	1.40	186.89	7.33	4.64	4.90	256.05	1812.91
% Improv.	3	11	60	4	3	10	19	8	-6

Table 7.2 shows that all the criteria improve in La Garriga and Granollers except TC. The strategy selected increases aeration and sludge costs compared to the reference case. The main improvement is with $NH_{4\,max}$ in the La Garriga system (up to 60% decrease). The ammonia and RQI peaks are smoothed as illustrated in Figure 7.2.2c and 7.2.2f. The improvement of RQI results from the reduction of the BOD, TSS and NO3 besides NH_4^+.

Further analysis of this scenario shows that with the strategy selected, the CSOs in the La Garriga posted using the reference parameter values disappear, and the CSOs in Granollers are decreased in magnitude but not completely avoided (see annex A3).

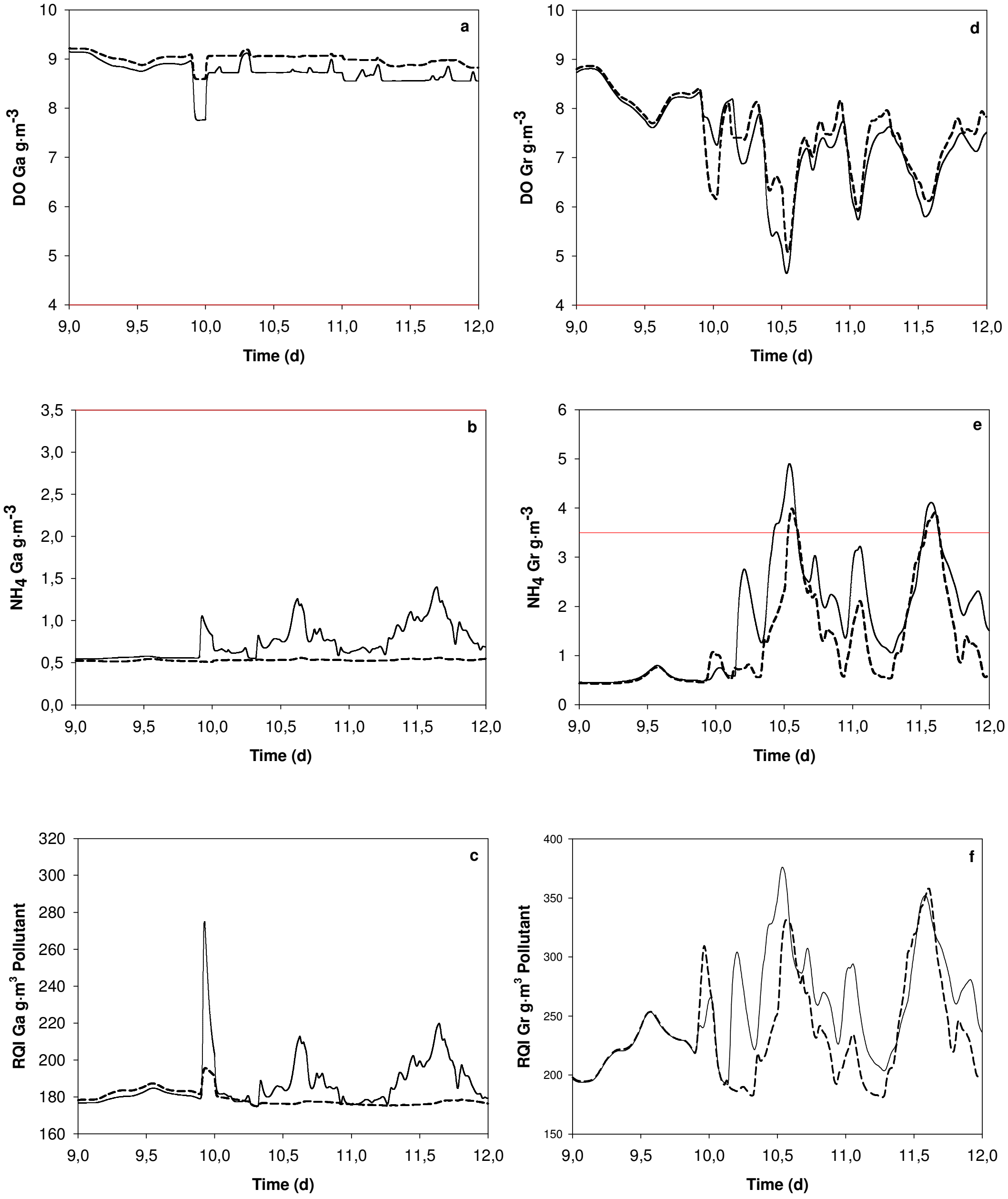


Figure 7.2.2: Storm scenario model behavior, solid line reference configuration, and discontinuous line best strategy. (a) DO Ga, (b) NH_4 Ga, (c) RQI Ga, (d) DO Gr, (e) NH_4 Gr and (f) RQI Gr.

7.3 High load La Garriga

The Pareto front has reduced the extension from 1000 to 746 simulations, and 20 simulations have overcome the screening (Table 7.3). The strategy that improves current management is 258 and model behavior using this strategy is presented in Figure 7.3.2.

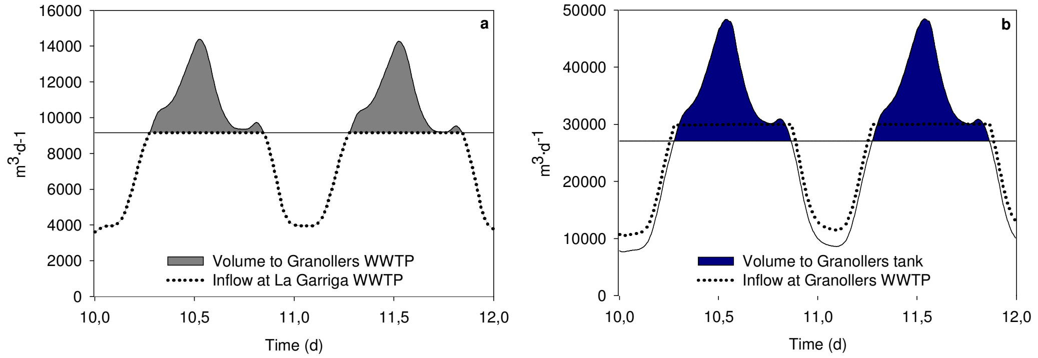


Figure 7.3.1: High load La Garriga scenario flow distribution in La Garriga (a) and in Granollers (b).

Like in the dry weather and storm scenarios the tank located in La Garriga is not used, and the bypass to Granollers works during daily peak flows (Figure 7.3.1a). The tank in Granollers receives more wastewater than in the dry weather scenario. External recycle in the La Garriga decreases ($C_{Ga,Sludge}$). The new strategy promotes the growth of microorganisms to handle the increased load. Even though wastage remains constant, the decreased set point of external recycle compensates for that growth.

Table 7.3: Criteria values for high load La Garriga.

	LA GARRIGA				GRANOLLERS				TC
	DO av	**DO min**	**NH_4 max**	**RQI**	**DO av**	**DO min**	**NH_4 max**	**RQI**	
15	7.00	6.15	0.79	262.12	6.24	4.95	3.00	448.46	2061.80
42	6.91	6.24	0.79	257.74	6.24	4.96	3.14	442.52	2045.47
44	6.90	5.90	0.92	278.54	6.42	5.16	3.36	461.65	2071.96
79	7.33	6.78	0.94	273.83	6.22	4.57	5.20	469.70	2067.76
100	7.38	6.90	0.88	269.24	6.25	4.67	6.17	480.03	2066.98
101	7.02	5.91	0.96	271.35	6.26	4.48	6.37	473.59	2099.23
143	6.99	5.90	0.96	274.72	6.33	4.95	4.11	470.65	2028.64
178	6.74	6.10	0.85	275.85	6.26	4.86	2.48	458.39	2073.91
199	6.66	5.94	0.93	278.09	6.23	4.56	4.82	467.72	2100.13
224	6.68	5.81	0.91	272.20	6.25	4.58	3.81	466.66	2074.26
238	6.73	6.08	0.95	262.76	6.33	5.18	1.93	447.24	2011.01
258	6.91	5.86	1.14	272.03	6.42	5.32	2.56	444.08	2072.32
263	6.76	5.72	1.13	276.39	6.26	4.85	3.43	465.75	2062.84
340	6.69	5.79	0.93	274.21	6.23	4.71	5.12	484.83	2065.97
519	6.60	5.88	1.27	273.75	6.35	5.18	3.28	453.78	2085.69
638	6.61	5.90	1.06	269.21	6.25	5.00	2.18	460.43	2061.67
829	6.99	5.91	0.89	273.24	6.32	5.03	1.97	460.30	2084.40
882	6.77	6.13	0.79	260.37	6.50	5.53	3.04	433.89	2077.37
956	6.96	6.15	0.78	262.41	6.24	4.83	3.46	471.11	2072.73
957	7.33	6.85	0.95	275.87	6.27	4.84	3.18	461.54	2043.45

	LA GARRIGA				GRANOLLERS				TC
	DO av	DO min	NH_4 max	RQI	DO av	DO min	NH_4 max	RQI	
Reference	6.73	5.59	1.97	298.64	6.25	4.03	9.37	512.59	2058.343
% Improv.	3	5	43	9	3	32	73	13	-1

This strategy clearly smoothes the organic shock posted, and improves all criteria. In this scenario RQI in both points, downstream La Garriga and Granollers, have improved and ammonia concentrations are kept at lower values (Figure 7.3.2b and e).

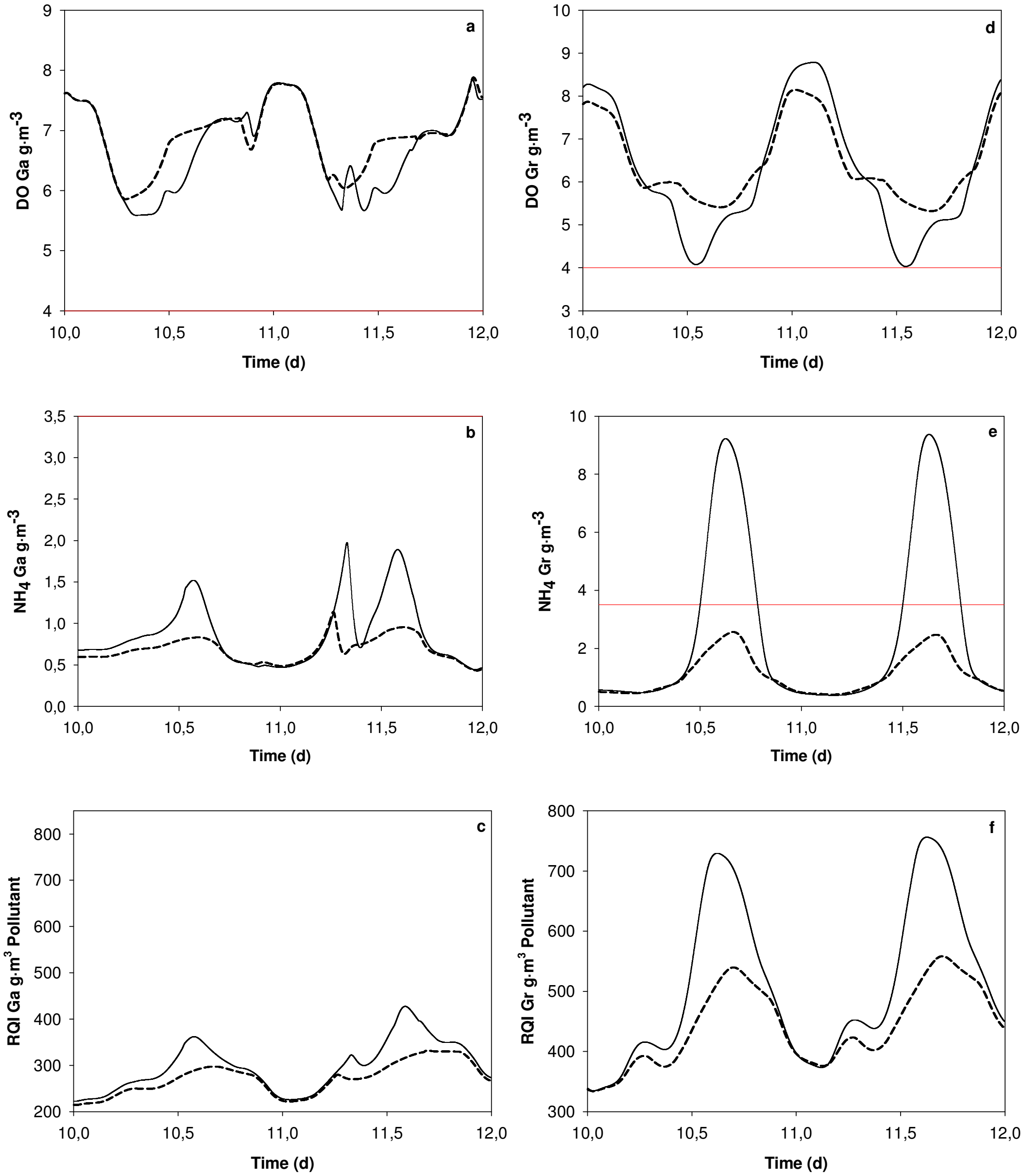


Figure 7.3: High load La Garriga scenario model behavior, solid line reference configuration, and discontinuous line best strategy. (a) DO Ga, (b) NH_4 Ga, (c) RQI Ga, (d) DO Gr, (e) NH_4 Gr and (f) RQI Gr.

7.4 High load Granollers

The Pareto front has reduced the extension from 1000 to 750 simulations, and 16 simulations have overcome the screening (Table 7.4). The strategy that improves current management is 149 and model behavior using this strategy is presented in Figure 7.4.2.

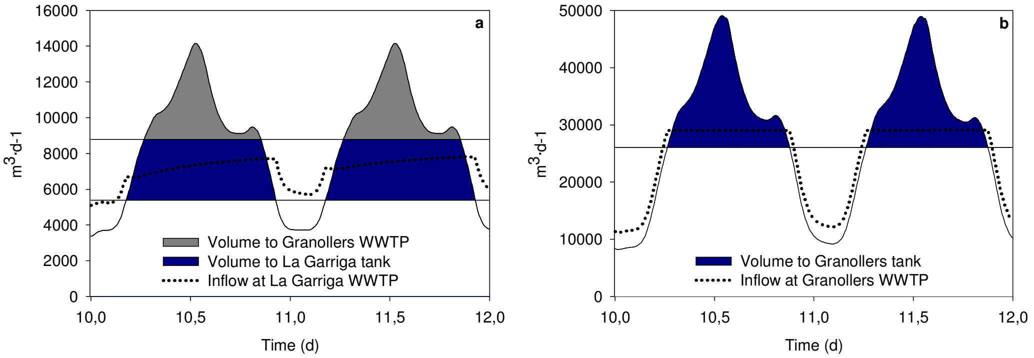


Figure 7.3.1: High load Granollers scenario flow distribution in La Garriga (a) and in Granollers (b).

In that case, the strategy selected fills the tank located in La Garriga and it also activates the bypass to Granollers (Figure 7.3.1a). Although the problem is posted in Granollers, the bypass to the Granollers system increases. However, it also sends more wastewater to the Granollers tank. There is a significant increase of the recirculation flow rate in the Granollers WWTP (R_{Gr}) to assimilate the increase of load at the influent, and an increase of the wastage flow rate after secondary treatment ($W_{Gr,S}$).

Table 7.4: Criteria values for high load La Garriga.

	LA GARRIGA				GRANOLLERS				TC
	DO av	**DO min**	**NH_4 max**	**RQI**	**DO av**	**DO min**	**NH_4 max**	**RQI**	
29	6.68	5.88	0.90	242.62	6.24	4.99	2.53	427.23	2085.93
149	7.15	6.59	0.60	244.65	6.45	5.40	3.47	426.99	2024.84
182	6.65	5.76	0.99	246.82	6.27	4.94	3.74	428.70	2183.76
184	7.05	6.24	0.69	233.88	6.24	5.10	3.95	427.19	2100.13
218	6.66	5.96	1.17	242.99	6.20	4.94	4.05	437.46	2147.30
262	6.87	6.04	0.75	238.78	6.40	5.37	2.41	414.10	2094.70
295	6.90	5.81	1.09	250.84	6.19	4.83	3.65	433.12	2154.03
321	6.95	6.25	0.72	253.00	6.26	4.67	5.58	440.86	2183.83
376	7.00	5.97	0.90	246.10	6.23	5.03	2.20	426.49	2105.40
436	7.34	6.48	0.65	233.47	6.19	5.03	2.73	420.96	1999.95
489	6.65	5.73	1.09	250.05	6.14	4.52	5.61	446.42	2185.85
548	6.97	6.44	0.64	251.11	6.33	4.92	5.04	448.25	2068.28
819	6.77	6.03	0.83	237.92	6.19	4.92	2.81	425.08	2146.61
884	6.96	6.26	0.72	250.87	6.15	4.62	4.87	443.17	2099.42
929	6.71	5.77	0.82	247.84	6.23	4.89	3.90	431.52	2165.50
982	6.81	5.96	0.78	241.04	6.25	5.10	2.12	421.48	2077.68
Reference	6.73	5.63	2.01	267.21	6.13	3.95	10.16	487.08	2119.988
% Improv.	6	17	70	9	5	37	66	12	5

Without any exception, all the criteria have ameliorated, and improvements over 50% have been achieved for ammonia max in both sampling points (Table 7.4). Although DO av criteria improve the least, DO depletion has been avoided (Figure 7.4 a and d).

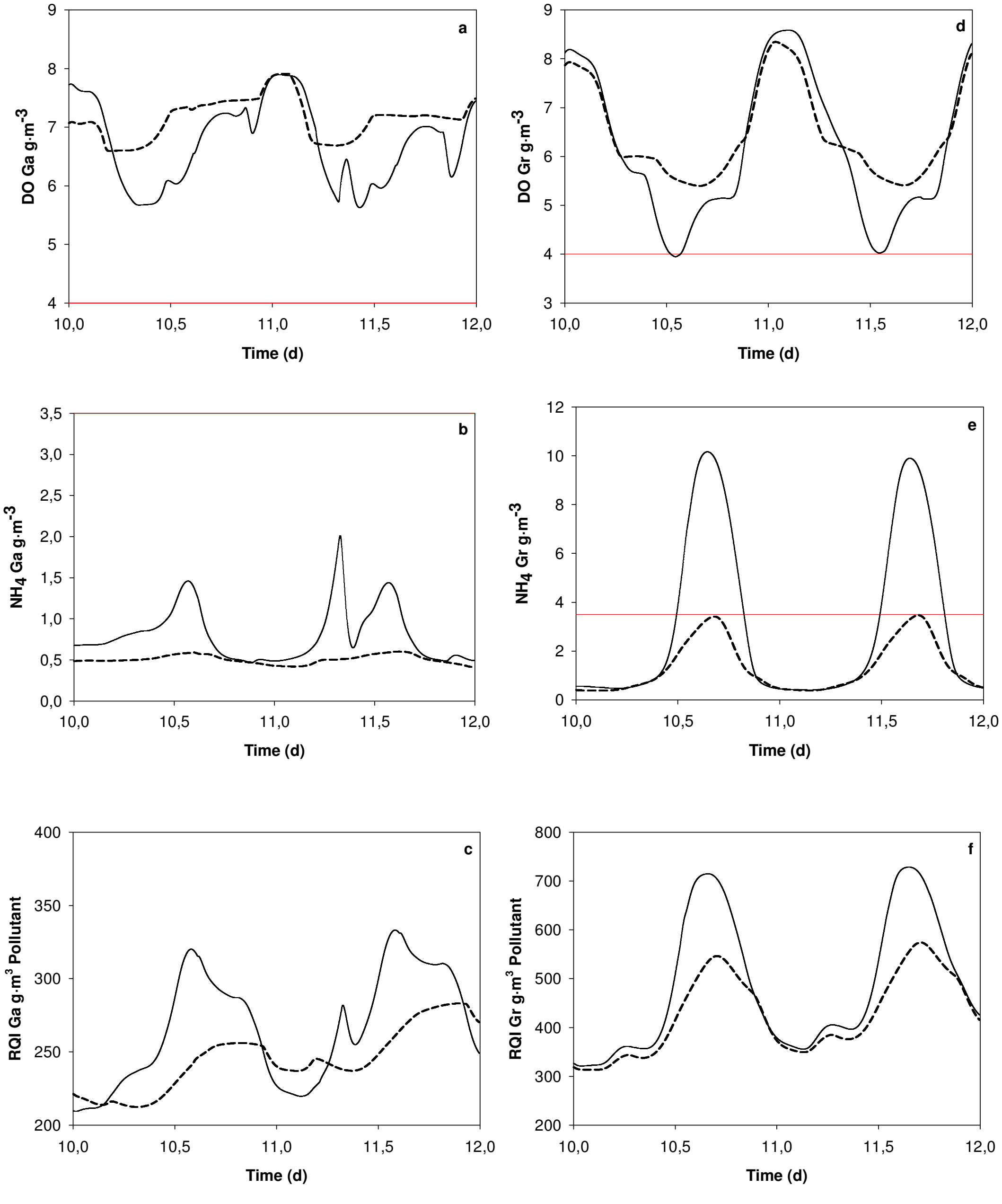


Figure 7.4: High load Granollers scenario model behavior, solid line reference configuration, and discontinuous line best strategy. (a) DO Ga, (b) NH_4 Ga, (c) RQI Ga, (d) DO Gr, (e) NH_4 Gr and (f) RQI Gr.

7.5 Increase of population

The Pareto front has reduced the extension from 1000 to 924 simulations, and three simulations have overcome the screening (Table 7.5). The strategy that improves current management is 342 and model behavior using this strategy is presented in Figure 7.5.2.

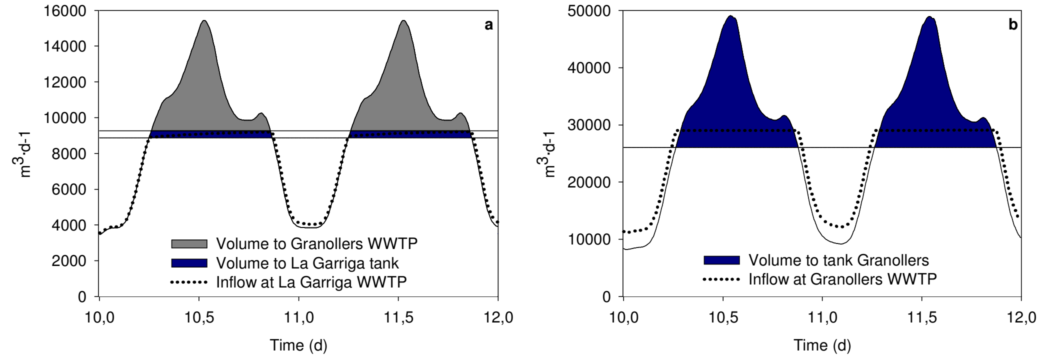


Figure 7.5.1: Increase of population scenario flow distribution in La Garriga (a) and in Granollers (b).

As in the previous scenarios, the strategy selected uses the tank located in La Garriga and activates the bypass to Granollers (Figure 7.5.1a). But on this occasion, the tank is partially filled since the strategy does not send too much water. Again the tank in Granollers is filled in a way similar to the previous scenarios. The strategy increases the wastage flow rate from the primary settler ($W_{Gr,P}$) and the set point for the ammonia controller both operational parameters in the Granollers WWTP, decreasing aeration supply.

Table 7.5: Criteria values for increase of population.

	LA GARRIGA				**GRANOLLERS**				**TC**
	DO av	**DO min**	**NH_4 max**	**RQI**	**DO av**	**DO min**	**NH_4 max**	**RQI**	
320	6.92	5.64	1.10	240.23	6.43	4.55	5.73	453.70	2514.60
342	7.11	5.77	0.95	243.14	6.43	4.56	3.38	447.04	2493.44
848	7.22	5.95	0.85	239.40	6.36	4.41	7.25	468.75	2476.65
Reference	6.88	5.16	3.89	267.44	6.41	4.51	6.79	473.90	2463.87
% Improv.	3	12	76	9	1	1	50	6	-1

In this case, improvement cannot be achieved for both DO_{av} and DO_{min} in Granollers (Table 7.5). The strategy is a bit more expensive, but ammonia concentration and RQI improve largely in both WWTPs, 76% in the La Garriga and 50% in Granollers. The strategy selected is the only one which totally avoids any ammonia violation limits downstream of the Granollers WWTP (Figure 7.5e).

Despite both WWTPs are working close to their limits, and in this scenario the WWTPs are pushed even more, there is still room for improvement.

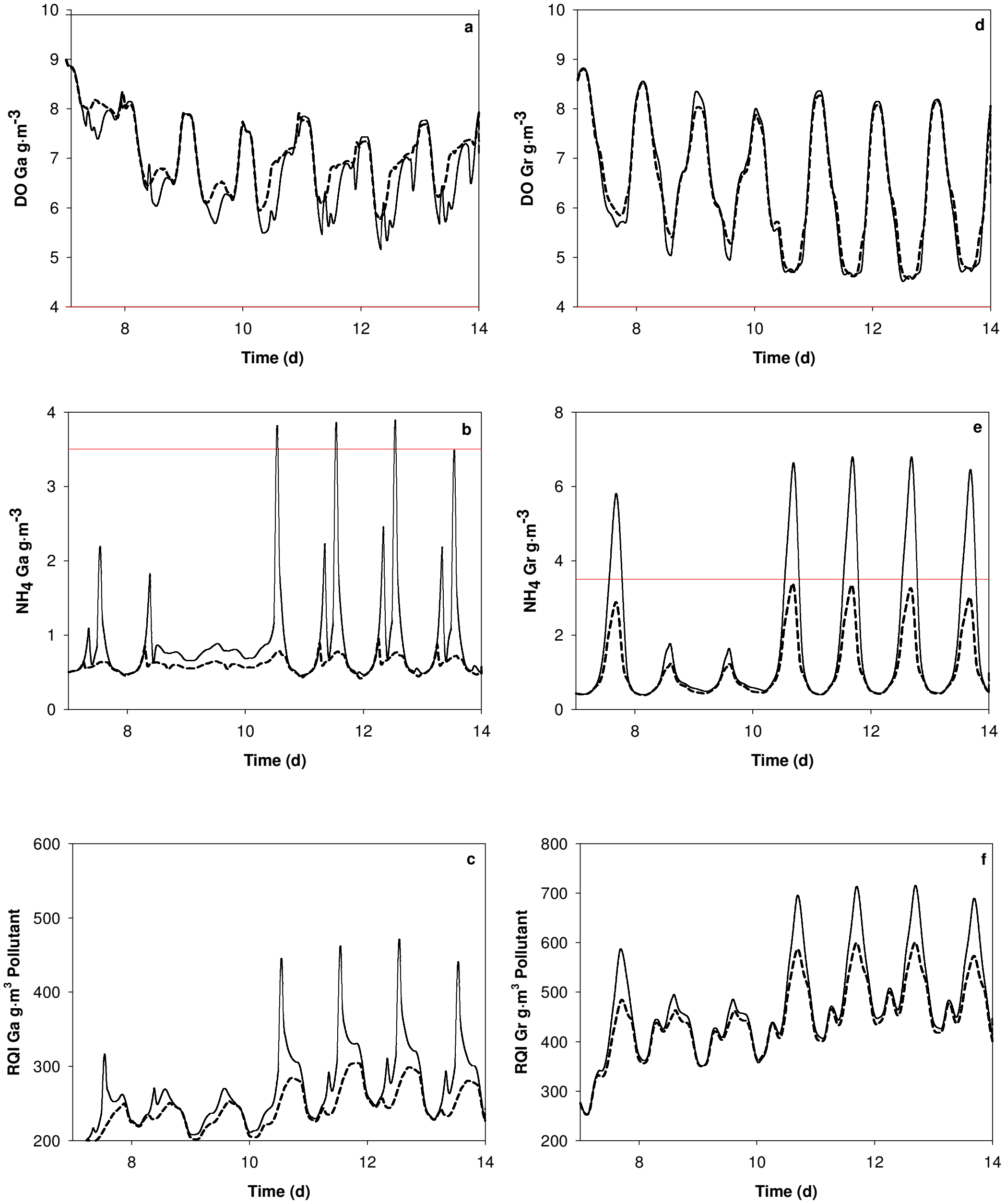


Figure 7.5: Increase of population scenario model behavior, solid line reference configuration, and discontinuous line best strategy. (a) DO Ga, (b) NH_4 Ga, (c) RQI Ga, (d) DO Gr, (e) NH_4 Gr and (f) RQI Gr.

7.6 Temperature

The Pareto front has reduced the extension from 1000 to 730 simulations, and only one simulation has overcome the screening (Table 7.6). The strategy that improves current management is 513 and model behavior using this strategy is presented in Figure 7.6.2.

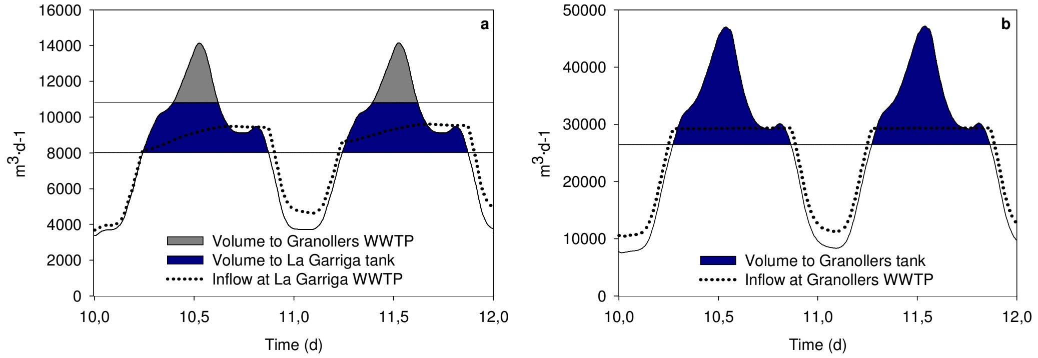


Figure 7.5.1: Temperature scenario flow distribution in La Garriga (a) and in Granollers (b).

Just one strategy has been found from the method. It uses the tank in La Garriga, the bypass to Granollers (Figure 7.6.1a) and the tank in Granollers (Figure 7.6.1b). It is the only scenario that increases the set point for the nitrate controller in the La Garriga WWTP ($C_{Ga,NO3}$) to improve the denitrification process and increase the set point for the sludge controller in the same plant ($C_{Ga,Sludge}$). No other significant changes have been proposed for the other parameters.

Table 7.6: Criteria values for temperature.

	LA GARRIGA				GRANOLLERS				TC
	DO av	**DO min**	**NH_4 max**	**RQI**	**DO av**	**DO min**	**NH_4 max**	**RQI**	
513	7.16	5.84	1.14	252.20	6.67	5.47	5.15	436.62	2084.59
Reference	7.52	5.95	2.52	280.05	6.65	4.15	12.30	500.52	2115.82
% Improv.	-5	-2	55	10	1	32	58	13	2

Table 7.6 shows that the only strategy found decreases the DO_{av} and DO_{min} in the La Garriga system, but DO concentrations do not go below 4 $gO_2 \cdot m^{-3}$. On the other hand, the strategy improves the rest of the evaluation criteria (Figure 7.6). The decision to select this strategy or not will rely on the UWS experts who will finally decide what is better for the system.

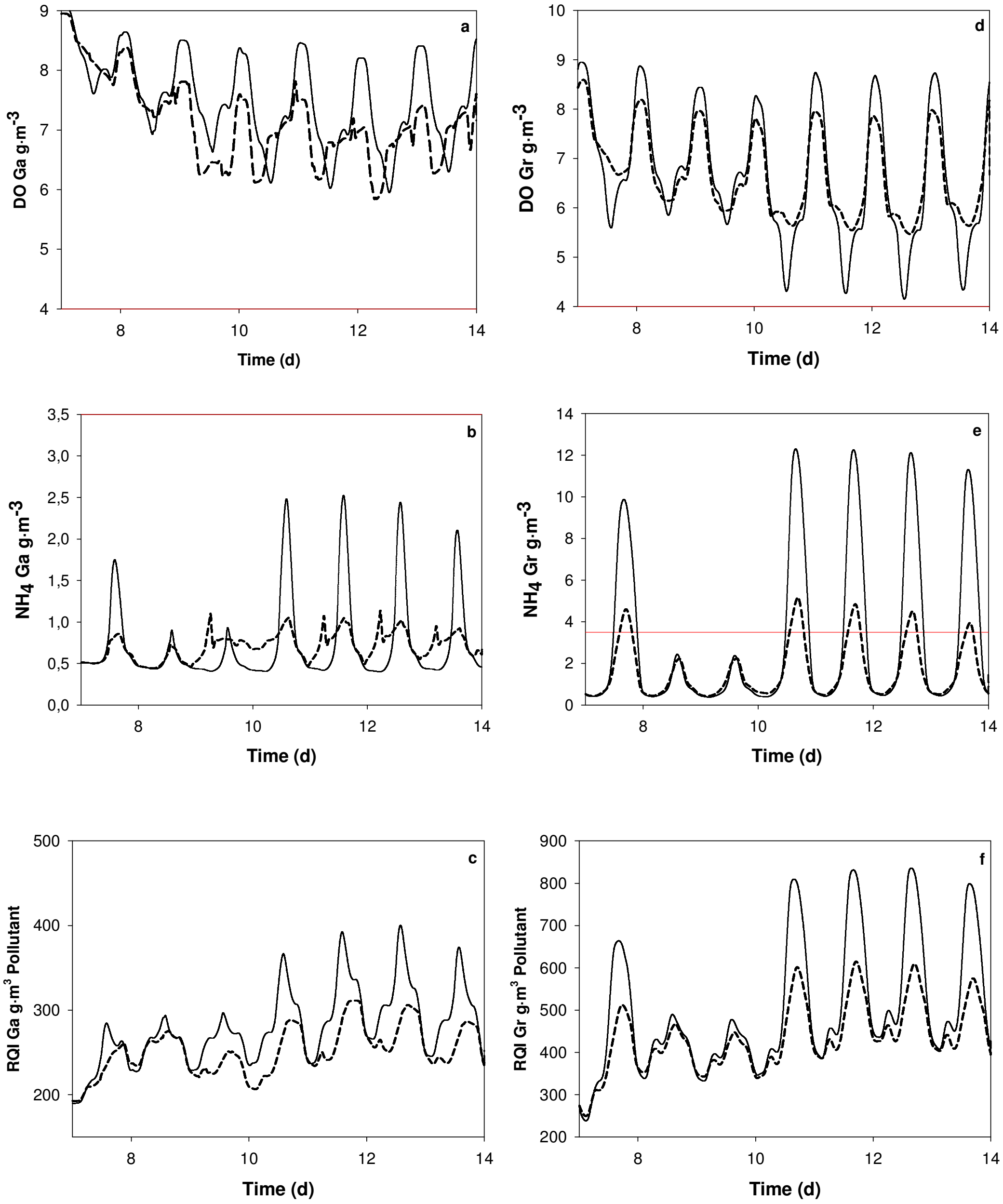


Figure 7.6: Temperature scenario model behavior, solid line reference configuration, and discontinuous line best strategy. (a) DO Ga, (b) NH_4 Ga, (c) RQI Ga, (d) DO Gr, (e) NH_4 Gr and (f) RQI Gr.

7.7 Low river flow

The Pareto front has reduced the extension from 1000 to 869 simulations, and five simulations have overcome the screening (Table 7.7). The strategy that improves current management is 78 and model behavior using this strategy is presented in Figure 7.7.2.

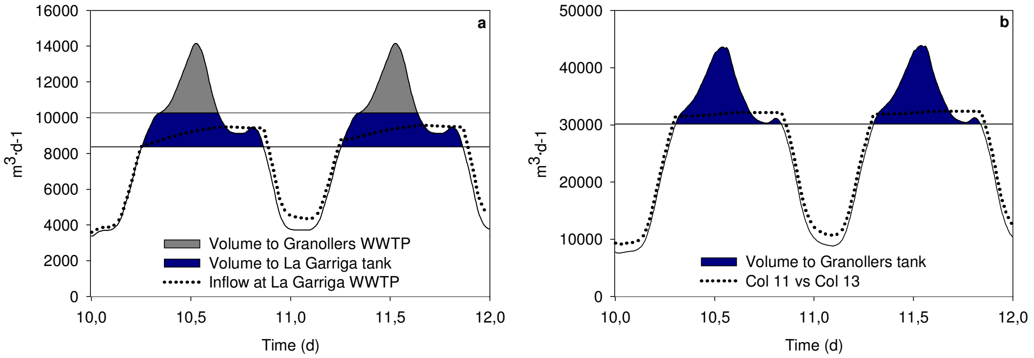


Figure 7.6.1: Low river flow scenario flow distribution in La Garriga (a) and in Granollers (b).

The strategy selected for this scenario presents behavior similar to the temperature scenario. The strategy makes use of both tanks in La Garriga and Granollers, and also activates the bypass from one system to the other (Figure 7.6.1). This is the only scenario that uses the small tank located upstream of the Granollers system (not shown in Figure 7.6.1). Aeration in both systems is slightly increased.

Table 7.7: Criteria values for low river flow.

	LA GARRIGA				GRANOLLERS				TC
	DO av	**DO min**	**$NH_{4,max}$**	**RQI**	**DO av**	**DO_{min}**	**NH_4 max**	**RQI**	
78	5.15	4.06	1.13	325.14	5.88	4.31	5.16	515.29	2375.70
247	5.16	3.93	1.70	322.24	5.86	4.12	4.81	529.81	2364.14
455	4.88	4.06	0.98	326.30	5.91	4.17	4.80	530.90	2375.60
462	4.90	4.08	1.07	316.99	5.86	4.34	2.81	516.22	2355.16
753	4.91	4.03	1.06	320.64	5.86	3.88	7.06	543.04	2376.58
Reference	5.10	3.62	3.19	347.55	5.92	3.96	7.11	550.78	2322.06
% Improv.	1	13	65	7	-1	9	28	7	-2

Table 7.7 shows that $NH_{4,max}$ in la Garriga and Granollers improves by 65 and 28% respectively. DO average values remain similar, but the minimum values improve by 13% in la Garriga and 9% in Granollers. The increase in the aeration energy results in higher total costs. Figure 7.7 shows that ammonia peaks are smoothed. However, it has not been possible to reduce them below 3.5 $gN \cdot m^{-3}$.

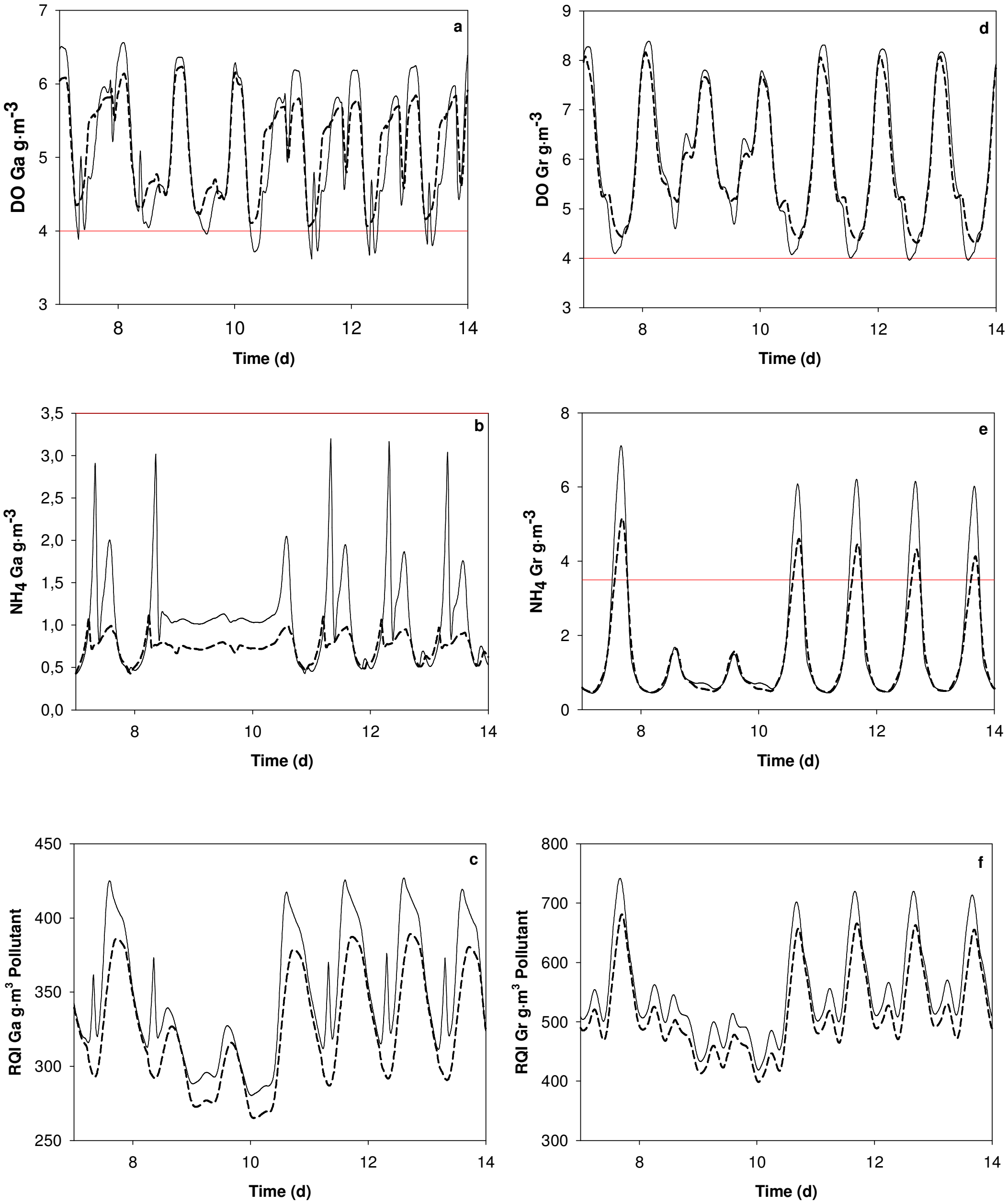


Figure 7.7: Low river scenario model behavior, solid line reference configuration, and discontinuous line best strategy. (a) DO Ga, (b) NH_4 Ga, (c) RQI Ga, (d) DO Gr, (e) NH_4 Gr and (f) RQI Gr.

7.8 Blower failure in La Garriga

The Pareto front has reduced the extension from 1000 to 992 simulations, and 10 simulations have overcome the screening (Table 7.8). The strategy that improves current management is 848 and model behavior using this strategy is presented in Figure 7.8.2.

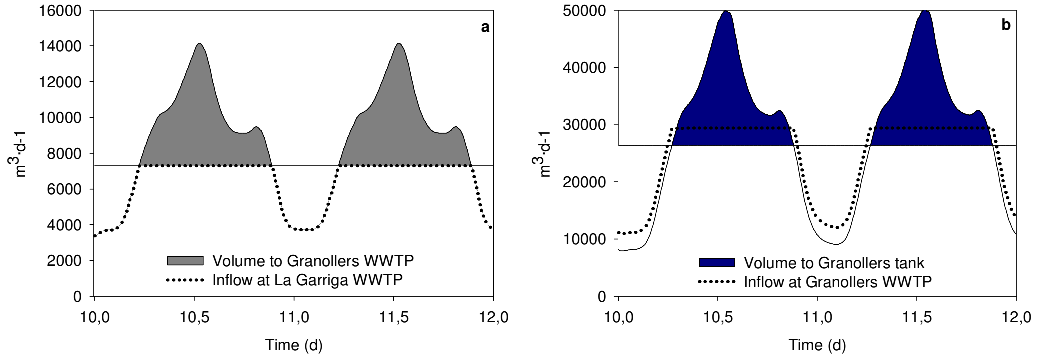


Figure 7.8.1: Blower failure La Garriga scenario flow distribution in La Garriga (a) and in Granollers (b).

The La Garriga WWTP has a mechanical problem and only partially works. To overcome that situation wastewater is sent to the Granollers WWTP (Figure 7.8.1a) and to the tank in Granollers. Although the problem is posted in La Garriga, it does not use the tank located in the same place, but it sends more wastewater to Granollers than other scenarios do. The set point for the wastage flow rate after secondary treatment ($W_{Gr,S}$) has significantly increased, which causes a flow reduction to the secondary settler.

Table 7.8: Criteria values for blower failure in La Garriga

	LA GARRIGA				GRANOLLERS				TC
	DO av	DO min	NH_4 max	RQI	DO av	DO min	NH_4 max	RQI	
141	7.23	6.26	7.85	304.47	6.33	5.16	4.56	474.94	1934.04
161	7.18	5.96	9.73	326.03	6.23	4.85	5.73	499.41	1973.51
193	7.03	5.93	10.18	340.76	6.22	4.83	6.09	502.44	1950.05
668	7.12	5.89	10.24	334.38	6.23	4.87	6.02	499.46	1952.13
718	7.10	5.99	9.82	332.14	6.21	4.69	5.97	504.40	1956.01
727	7.24	6.04	9.22	317.71	6.28	5.06	5.33	487.90	1963.34
807	7.29	6.30	7.44	297.74	6.25	5.00	4.34	479.07	1925.75
848	7.57	6.45	5.81	273.85	6.39	5.36	3.32	455.02	1946.60
929	7.16	5.94	9.87	328.33	6.20	4.87	5.65	493.92	1923.45
938	7.46	6.31	7.16	288.56	6.27	5.09	3.97	467.55	1972.60
Reference	6.77	4.82	13.04	398.95	6.22	4.03	10.43	566.15	1969.34
% Improv,	12	34	56	32	3	33	68	20	1

The proposed strategy largely improves all the criteria. DO_{min} and $NH_{4,max}$ are the criteria with greatest improvement (Table 7.8). However, Figure 7.8b shows that ammonia peaks reach values over $3.5 gN \cdot m^{-3}$. The strategy selected clearly helps to overcome the problem posted.

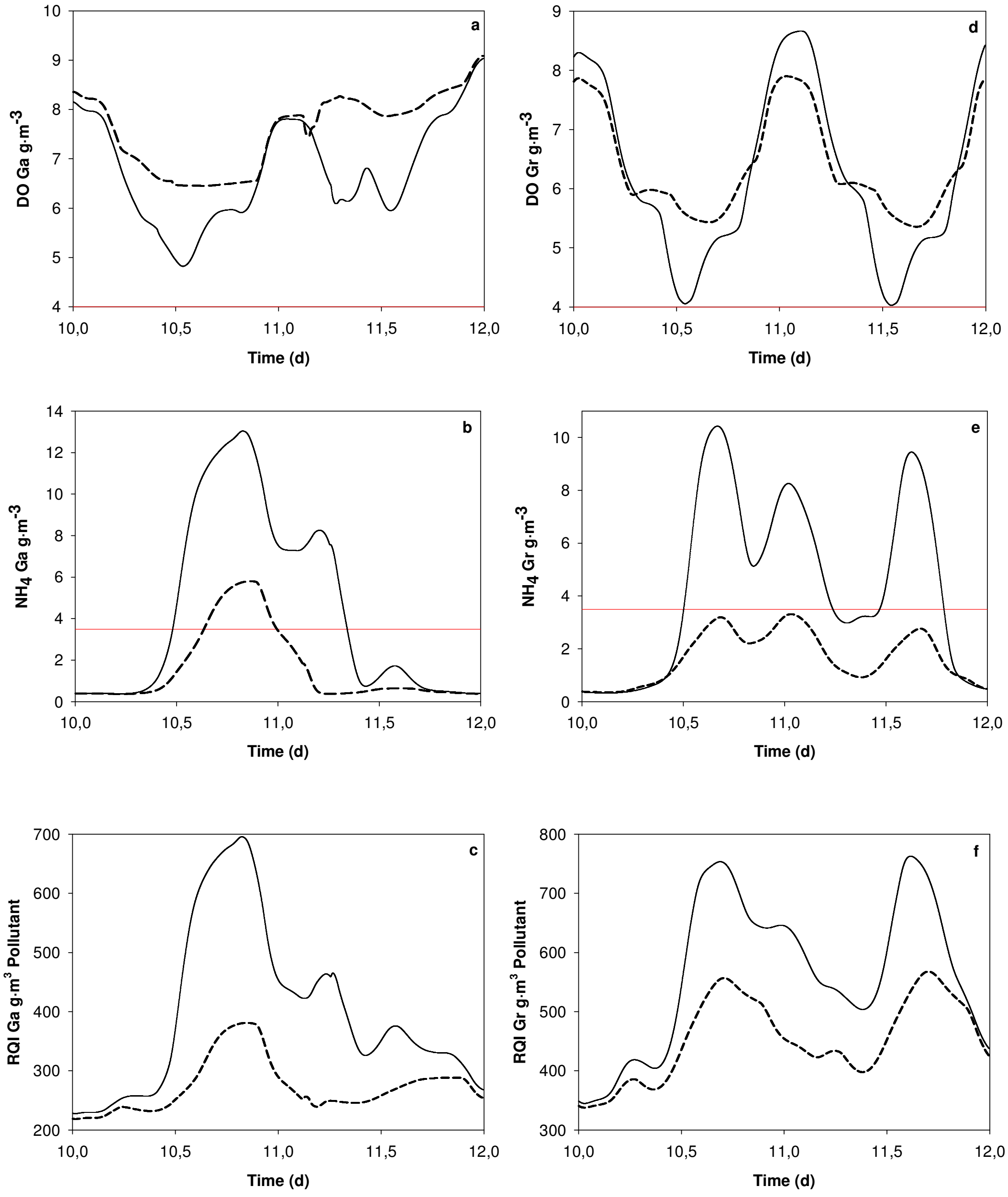


Figure 7.8: Blower failure in La Garriga scenario model behavior, solid line reference configuration, and discontinuous line best strategy. (a) DO Ga, (b) NH_4 Ga, (c) RQI Ga, (d) DO Gr, (e) NH_4 Gr and (f) RQI Gr.

7.9 Blower failure in Granollers

The Pareto front has reduced the extension from 1000 to 852 simulations, and 19 simulations have overcome the screening (Table 7.9). The strategy that improves current management is 817 and model behavior using this strategy is presented in Figure 7.9.2. In this case the problem presented before is posted in Granollers.

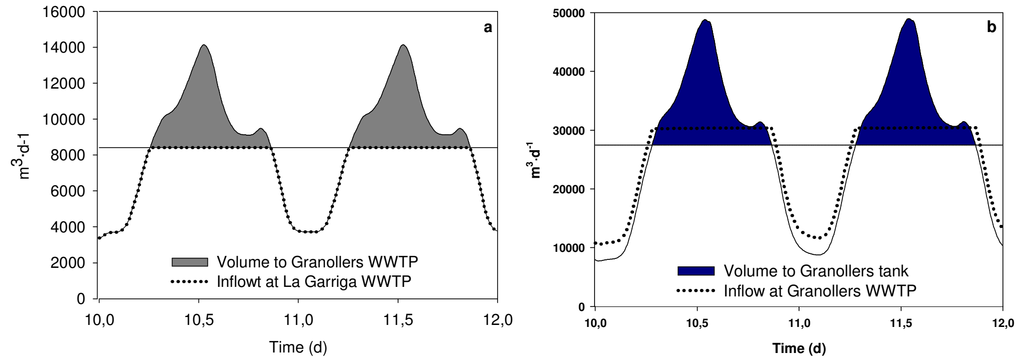


Figure 7.9.1: Blower failure Granollers scenario flow distribution in La Garriga (a) and in Granollers (b).

In that case, the tank located in the La Garriga is not used, the bypass to Granollers works during daily peak flows (Figure 7.9.1a), and the tank in Granollers is filled (Figure 7.9.1b). Wastage flow from the primary settler in the Granollers WWTP ($W_{Gr,P}$) increases, sending less wastewater to the secondary treatment. The external recirculation in the same plant (R_{Gr}) has decreased.

Table 7.9: Criteria values for blower failure in Granollers WWTP.

	LA GARRIGA				GRANOLLERS				TC
	DO av	DO min	NH_4 max	RQI	DO av	DO min	NH_4 max	RQI	
156	6.64	5.88	1.03	243.03	6.08	4.65	10.27	465.98	1995.13
217	6.96	6.12	0.68	237.40	6.06	4.54	11.39	474.64	2007.54
309	6.87	5.91	0.76	243.38	6.05	4.44	12.62	485.00	1971.61
322	6.69	5.79	0.75	248.49	6.06	4.28	14.54	503.70	2013.29
370	6.92	5.97	0.92	245.19	6.14	4.68	10.69	468.90	1966.27
385	6.77	5.78	0.94	247.43	6.07	4.69	9.75	466.56	1933.05
434	6.62	5.73	0.94	248.08	6.05	4.42	13.17	492.63	2001.09
496	6.77	5.97	0.81	240.14	6.09	4.68	8.81	458.43	1949.60
541	6.98	6.44	0.84	228.39	6.05	4.55	10.19	460.62	1992.56
576	6.76	6.03	0.84	237.98	6.33	4.88	8.08	445.12	1979.36
590	7.10	5.95	0.79	251.43	6.05	4.33	14.97	507.68	1999.51
598	7.18	6.17	0.72	242.88	6.07	4.53	12.05	480.78	2003.34
688	6.95	6.35	0.69	251.54	6.18	4.33	14.47	504.52	2006.93
691	6.59	5.76	0.80	246.89	6.39	4.93	8.33	448.87	2010.51
698	6.68	5.74	1.04	249.41	6.06	4.58	11.76	481.82	2004.63
817	7.19	6.11	0.74	246.41	6.14	4.74	8.02	453.12	1784.20
853	6.96	6.44	1.21	234.08	6.20	4.67	9.27	452.22	1994.71
904	6.68	5.96	1.01	240.88	6.19	4.70	9.90	460.77	1995.94
922	6.67	5.82	0.93	244.61	6.21	4.84	8.14	449.08	1938.27
Reference	6.73	5.63	2.01	267.22	6.02	3.82	19.01	557.58	1968.77
% Improv.	7	9	63	8	2	24	56	19	10

This strategy results in better evaluation criteria than the reference, except DO_{av} in Granollers, which improves 2%. However, ammonia peaks downstream of Granollers reach values over 3.5gN·m^{-3}, which can not be avoided with the new strategy (Figure 7.9e).

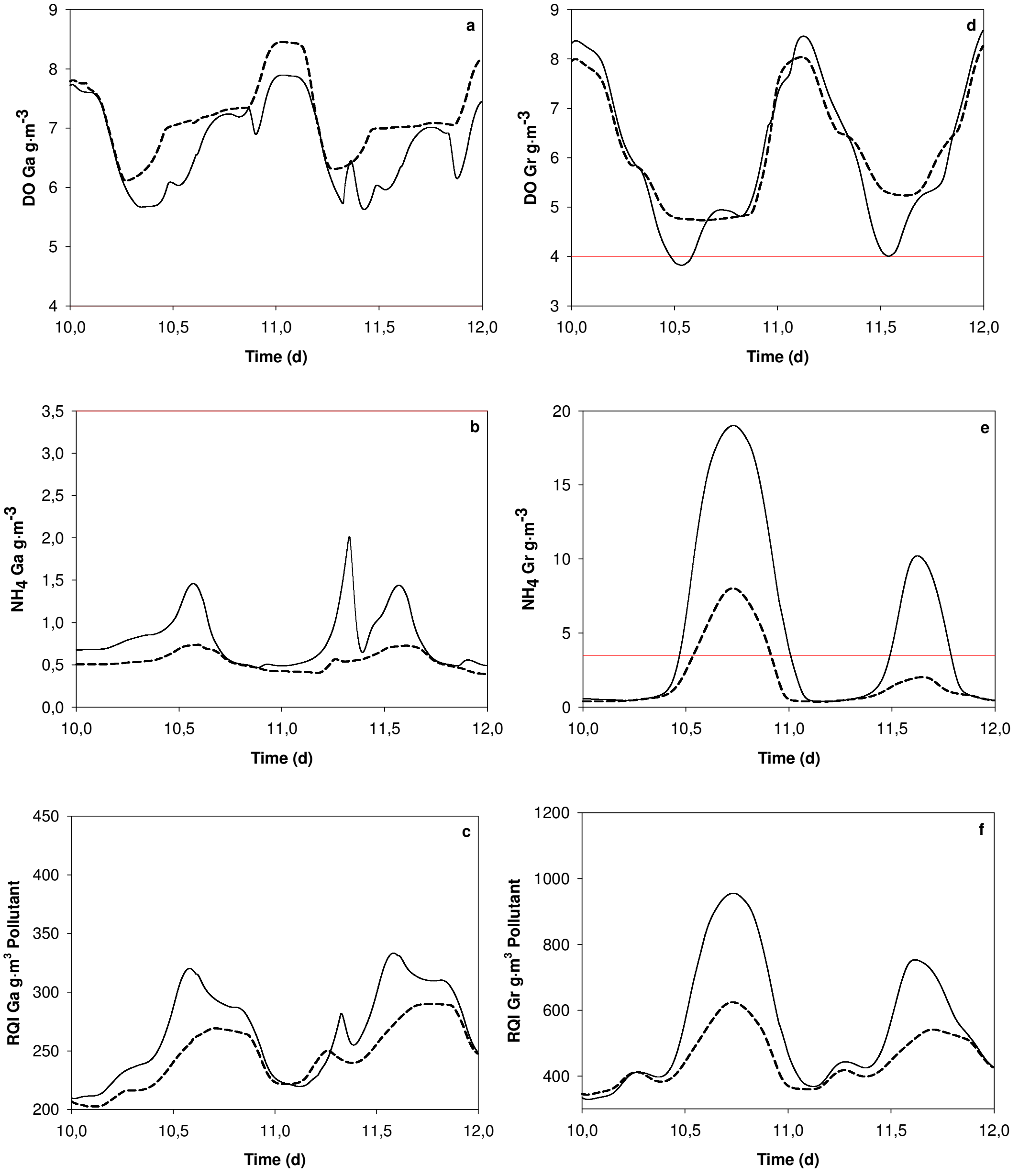


Figure 7.9: Blower failure in Granollers scenario model behavior, solid line reference configuration, and discontinuous line best strategy. (a) DO Ga, (b) NH_4 Ga, (c) RQI Ga, (d) DO Gr, (e) NH_4 Gr and (f) RQI Gr.

Table 7.10: Selected operational strategies for each scenario.

	Original	**Dry weather**	**Storm**	**High load La Garriga**	**High load Granollers**	**Population**	**Temperature**	**Low river flow**	**Blower failure La Garriga**	**Blower failure Granollers**
		860	74	258	149	342	513	78	848	817
C_{Ga}, NH_4	1	0.71	0.49	1	0.40	0.63	0.92	0.67	0.90	0.46
C_{Gr}, NH_4	1	0.75	0.69	1.26	0.83	1.71	1	0.61	1	1
C_{Ga}, NO_3	1	1	1	1	1	1	1.93	1	1	1
C_{Gr}, NO_3	1	1.70	0.90	1.93	0.54	1.85	1.36	1.63	1	1
$W_{Ga, P}$	50	50	50	50	50	50	50	50	50	50
$W_{Gr, P}$	600	600	600	603.00	747.94	1295.92	483.29	600	600	1569.29
R_{Gr}	28800	23566.40	28800	36702.00	45694.00	45246.30	28962.10	17316.10	38184.70	14669.00
R_{Ga}	200	200	200	200	200	200	200	200	200	200
$W_{Gr,S}$	500	1064.47	703.37	953.77	1353.95	474.22	724.61	1034.77	1206.09	493.34
$F_{Ga,S}$	14500	14500	25172.60	24725.60	14500	14500	14500	14500	14500	14500
$F_{Gr,S}$	46000	70723.80	66284.80	40677.70	55575.10	58175.90	35839.90	58160.00	31787.00	42255.30
$F_{Ga, P}$	27648	27648	27648	27648	27648	27648	27648	27648	27648	27648
$F_{Gr,P}$	76800	76800	76800	76800	76800	76800	76800	76800	76800	76800
C_{Ga},Sludge	1.5	1.5	1.5	0.97	1.5	1.5	2.16	1.75	1.5	1.5
F_{Ga}	27648	9263.70	18204.80	9167.12	8784.06	9271.28	10809.90	10275.10	7294.20	8420.36
$^*F_{Ga, WWTP}$	27648	10840.30	22161.90	13775.80	5392.56	8869.17	8022.13	8374.66	10728.60	9526.84
$^*F_{Gr}$	30000	30000	30000	30000	30000	30000	30000	11990.20	30000	30000
$F_{Gr, WWTP}$	76800	30708.10	108264.00	27070.90	26055.30	31796.50	26431.10	30130.50	26417.10	27469.40

*In order to use the tank located in the La Garriga system, the flow that goes to the system needs to be bigger than the flow that goes to the La Garriga WWTP ($F_{Ga}>F_{Ga,WWTP}$).

7.10 Towards on-line control

Current management of the UWS could be improved by introducing dynamic set points. The procedure proposed here is based on applying a better combination of the operational parameters for each scenario. A simple knowledge base composed of a set of if-then rules was implemented in the WEST modeling platform. By receiving information from the current conditions of the system, the control will decide which operational strategy set has to be applied. This rule-based control system has been compared with the reference situation.

Table 7.11. Main rules for the control.

Scenario	Rule
Storm	Rains over 1.2 mm for more than 1 hour.
High load La Garriga	DQO over 1100 for more than 3 hours.
High load Granollers	DQO over 1150 for more than 3 hours.
Increase of population	Maximum domestic wastewater flow is greater than 9000 $m^3 \cdot d^{-1}$ in La Garriga and 23000 $m^3 \cdot d^{-1}$ in Granollers.
Temperature	Wastewater temperature is below 15ºC.
Low river flow	River flow under 0.02 $m^3 \cdot s^{-1}$ for more than 6 hours.
Blower failure in La Garriga	Kla at aerobic reactor decrease below 60 d^{-1} for more than 1 hour.
Blower failure in Granollers	Kla at aerobic reactor decrease below 150 d^{-1} for more than 1 hour.
Dry weather	When any other rule is not applied.

Table 7.11 summarizes the rules applied for the on-line control. The rules have been defined with a threshold value for rain intensity, DQO, flow, river flow or Kla, and minimum duration time. This time is important since it will determine when the rule starts. Daily flow characteristics can reach DQO peak concentrations up to 1100 $g \cdot m^{-3}$ for a short moment, so the minimum duration time will distinguish between a normal situation and the problematic scenario. The rules will have to be adjusted according to the case study and the UWS characteristics.

The rule-based control receives information coming from the rainfall data, the wastewater characteristics in the sewer system, river flow information, and control information, and therefore, identifies which operational strategy set should be applied (Figure 7.10).

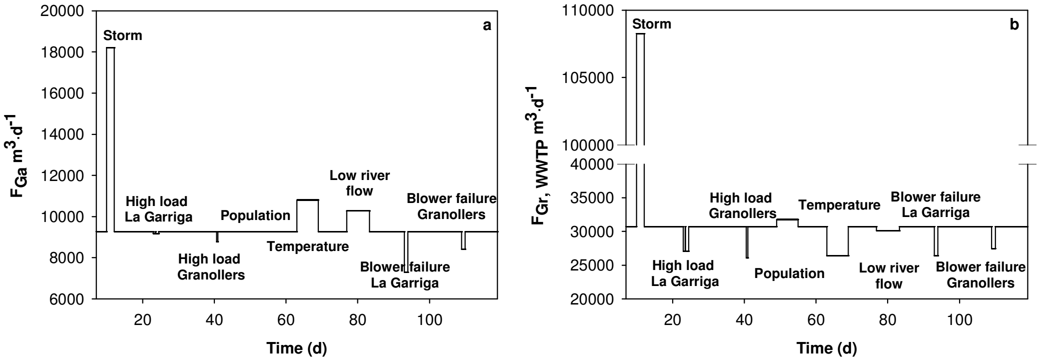


Figure 7.10. F_{Ga} (a) and $F_{Gr, S}$ (b) set points value for the different scenarios.

Figure 7.10 shows the results of the implementation of the rule-based control. The system must identify each scenario and apply the desired combination of operational strategies. Table 7.12 summarizes, as in the first part of the chapter, the percentage of improvement of the same evaluation criteria, when the set points had the same value, no matter which scenario is posted (Reference) and using better operational parameters (Better).

Table 7.12. Criteria values for all scenarios

	LA GARRIGA					TC
	DO av	**DO min**	**NH_4 av**	**NH_4 max**	**RQI**	
Reference	7.13	3.72	0.79	7.60	256.54	21826.74
Better	7.25	4.07	0.63	4.73	238.51	21850.19
% Improv.	2	10	21	38	7	-1

	GRANOLLERS				
	DO av	**DO min**	**NH_4 av**	**NH_4 max**	**RQI**
Reference	6.77	3.52	1.35	20.34	450.88
Better	6.73	4.64	0.97	9.21	411.90
% Improv.	-1	32	28	55	9

Using better operational strategies for each scenario, the system improves for all criteria except for DO in Granollers and TC. However, minimum DO concentrations improve, 10% in La Garriga and 32% in Granollers, and one can ensure the DO will ameliorate. These results are in agreement with what has been presented in the previous section, where dry weather, low river flow and temperature scenarios follow a similar pattern with DO concentrations. The dry weather scenario is the most common situation in this simulation, and thus smoothes the DO improvement coming from the rest of the scenarios. No difference with the TC can be appreciated.

Table 7.13. Percentiles for the criteria.

REFERENCE						
	LA GARRIGA			GRANOLLERS		
Percentile	**DO av**	**NH_4 av**	**RQI**	**DO av**	**NH_4 av**	**RQI**
5	5.52	0.44	185.46	4.56	0.42	248.18
25	6.31	0.56	219.42	5.87	0.51	387.12
50	7.20	0.70	245.34	6.72	0.66	441.80
75	7.95	0.85	283.75	7.88	1.13	512.50
95	8.85	1.32	352.06	8.60	4.91	659.38

BEST MANAGEMENT STRATEGY						
	LA GARRIGA			GRANOLLERS		
Percentile	**DO av**	**NH_4 av**	**RQI**	**DO av**	**NH_4 av**	**RQI**
5	5.73	0.45	184.17	5.38	0.42	247.20
25	6.57	0.54	211.58	5.96	0.49	367.62
50	7.19	0.60	231.59	6.59	0.69	410.26
75	8.04	0.67	258.31	7.55	1.17	452.01
95	8.96	0.79	303.55	8.28	2.35	560.26

Table 7.13 also summarizes the percentiles for the different criteria. From the table it can be concluded that the system will improve its overall quality with better operational

strategies. Again, for the DO lower percentiles are better in the best management strategies, which is in accordance with the DO min criteria.

The time violation is summarized in the Table 7.14. They have been reduced with the best operational strategies. For DO, despite better concentration not being achieved, the time violation has disappeared and the time violations of ammonia concentration has largely decreased, from 12.10 d^{-1} to 1.01 d^{-1} (Table 7.14).

Table 7.14. Time violation in days.

	LA GARRIGA		GRANOLLERS	
	DO av	**NH_4 av**	**DO av**	**NH_4 av**
Reference	0.80 d^{-1}	0.60 d^{-1}	0.83 d^{-1}	12.10 d^{-1}
Best management	0.00 d^{-1}	0.29 d^{-1}	0.00 d^{-1}	1.01 d^{-1}

Figure 7.10 shows the results of the implementation of the rule-based control. The system must identifies each scenario and apply the desired combination of operational strategies. The following table 7.12 summarizes, as in the first part of the chapter, the percentage of improvement on the same evaluation criteria, when the set-points had the same value, no matter which scenario is posted (Reference) and, using better operational parameters (Better).

Table 7.12. Criteria values for all scenarios

	LA GARRIGA					TC
	DO av	**DO min**	**NH_4 av**	**NH_4 max**	**RQI**	
Reference	7.13	3.72	0.79	7.60	256.54	21826.74
Better	7.25	4.07	0.63	4.73	238.51	21850.19
% Improv.	2	10	21	38	7	-1

	GRANOLLERS				
	DO av	**DO min**	**NH_4 av**	**NH_4 max**	**RQI**
Reference	6.77	3.52	1.35	20.34	450.88
Better	6.73	4.64	0.97	9.21	411.90
% Improv.	-1	32	29	55	9

Using better operational strategies for each scenario, the system improve for all criteria except for DO in Granollers and TC. However, minimum DO concentrations improve, 10% in the La Garriga and 32% in Granlloes and hence, one can ensure the DO will ameliorate. These results are in agreement with what have been presented in the previous section, where dry weather, low river flow and temperature scenarios follow a similar pattern with DO concentrations. Dry weather scenario is the most common situation in this simulation, and thus smooth the DO improvement coming from the rest of the scenarios. No difference with the TC can be appreciated.

Table 7.13 also summarizes the percentiles for the different criteria. From the table it can be concluded that, with better operational strategies the system will improve its overall quality. Again, for the DO lower percentiles are better in the best management strategies which is in accordance with the DO min criteria.

Table 7.13. Percentiles for the criteria

	ORIGNIAL					
	LA GARRIGA			GRANOLLERS		
Percentile	**DO av**	**NH_4 av**	**RQI**	**DO av**	**NH_4 av**	**RQI**
5	5.52	0.44	185.46	4.56	0.42	248.18
25	6.31	0.56	219.42	5.87	0.51	387.12
50	7.20	0.70	245.34	6.72	0.66	441.80
75	7.95	0.85	283.75	7.88	1.13	512.50
95	8.85	1.32	352.06	8.60	4.91	659.38

	BEST MANAGEMENT STRATEGY					
	LA GARRIGA			GRANOLLERS		
Percentile	**DO av**	**NH_4 av**	**RQI**	**DO av**	**NH_4 av**	**RQI**
5	5.73	0.45	184.17	5.38	0.42	247.20
25	6.57	0.54	211.58	5.96	0.49	367.62
50	7.19	0.60	231.59	6.59	0.69	410.26
75	8.04	0.67	258.31	7.55	1.17	452.01
95	8.96	0.79	303.55	8.28	2.35	560.26

The time violation is summarized in the following table 7.14. They have been reduced with the best operational strategies. For DO, despite no better concentration is achieved, the time violation have disappeared and regarding ammonia concentration, its time violations has largely decreased, from 12.10 d^{-1} to 1.01 d^{-1} (Table 7.14).

Table 7.14. Time violation in days.

	LA GARRIGA		GRANOLLERS	
	DO av	**NH_4 av**	**DO av**	**NH_4 av**
Reference	0.80 d^{-1}	0.60 d^{-1}	0.83 d^{-1}	12.10 d^{-1}
Best management	0.00 d^{-1}	0.29 d^{-1}	0.00 d^{-1}	1.01 d^{-1}

7.11 Concluding remarks

In this chapter detailed results of the best operational strategy have been presented, showing how they can improve the river quality in terms of the evaluation criteria.

The objective of this chapter was to find better operational strategies to support the managers of the UWS, to choose between operational alternatives to overcome the scenarios studied. The presented method has found at least one better operational strategy for each problematic scenario. For some scenarios—high load La Garriga, high load Granollers, blower failure in La Garriga, and blower failure in Granollers—there are more operational strategies that improve evaluation criteria. However, when presenting just one strategy, like in the case of temperature scenario, it is possible that the strategy does not improve all the criteria and then a conflict of interest arises. Therefore, together with the results of the GSA, alternative solutions can be presented to overcome the scenario posted. Besides, the case of temperature is not a limiting time problem, and further studies should be done, such as increasing the number of MC shots, to finally find several strategies.

Looking at overall strategies leads to the conclusion that they follow a similar pattern. The bypass from La Garriga to Granollers (F_{Ga}) is always activated, the blower failure in La Garriga being the scenario that bypasses more water. In the same way, the bigger tank in Granollers is always in use. The tank located in La Garriga is only used in the high load Granollers, increase of population, temperature, and low river flow scenarios. The smaller tank located in Granollers is only used in the low river flow scenario. The other operational parameters change in order to readjust sludge retention times, recirculation flow rates and wastage flow rates.

Finally, one should notice that the reference values of the set points, settled according to domain experts of the case study, are good enough to almost overcome the scenarios tested. This is a consequence of the good operational strategy practices that the managers of the Besòs River Basin have accumulated over the years. Nevertheless, it has been demonstrated that it is possible to improve the operational strategies, and to improve the river quality, by using currently available facilities.

CHAPTER 8

DISCUSSION

8. Discussion

The goal of this chapter is to discuss some important aspects related to the developed method and the results. Limitations and future work issues are addressed here.

8.1 Modelling

Several modelling approaches have been developed in the last decade to describe the hydrological and biochemical behavior of the different elements of the UWS (sewer systems, wastewater treatment plants and river). It is possible to find very detailed models of the UWS. However, the uses of simplified models (especially for the sewer system and river) offer good accuracy at acceptable computational cost. In this thesis a simplified hydrological modeling approach was adopted for the sewer system as in Meirlaen (2002) and in Solvi (2007). This simplified approach is good enough to answer the general questions posted in this thesis. If greater level of detail is required to address a new problematic situation (e.g., selection of better location for a storm water tank), more detailed models would be needed (e.g., using SWMM) and effort would have to be made to calibrate and validate it. In this study a rough calibration of the model was conducted to adjust the predictions obtained in the work by Devesa (2005).

Nevertheless, the results obtained depend strongly on the models selected. There are some clear limitations to the units that require more detailed process descriptions, i.e. storage tanks are considered to be well mixed and non-reactive, sewers pipe models are simulated using a set of tanks in series, and backwater effects are not considered. Therefore, the results obtained have to be properly framed within the goals of this thesis.

8.2 Evaluation criteria

To evaluate operational strategies it is important to properly define the criteria at the beginning of the study in accordance with the goal. The more criteria, the better the description of the process performance, but the decision-making becomes more complex. Generally, the environmental (dissolved oxygen, ammonia concentration and RQI) and economic (TC) criteria used in this thesis are already complex enough to generate interesting trade-off situations. To manage UWSs immission-based criteria as defined by the WFD have been used.

8.3 Sensitive analysis

Sensitivity analysis was performed after running Monte Carlo (MC) simulations. A crucial step when defining the MC experiments is the selection of type and ranges of the probability density functions (PDFs) of the parameters. Very little knowledge is available to properly define these PDFs and therefore rough assumptions are made. The knowledge from experts and the limited capacity of the actuators have been used to select the PDFs in this study. Again, the results depend on this selection and further research should be conducted to verify the effect of the PDFs on the outcomes of the study.

The number of MC simulations is defined according to the model construction, the computational cost and the number of input factors. A test was run to find the optimum number of Monte Carlo shots. Table 8.1 shows the results of the sensitivity analysis in the dry weather scenario evaluated for 125, 250, 500, 1000 and 1500 MC shots.

Table 8.1: Sensitive parameter for different numbers of Monte Carlo shots.

Simul time (minutes)		$C_{Ga,}$ NH$_4$	$C_{Gr,}$ NH$_4$	$C_{Ga,}$ NO$_3$	$C_{Gr,}$ NO$_3$	$W_{Ga, P}$	$W_{Gr, P}$	$W_{Gr,S}$	R_{Ga}	R_{Gr}
136	**125**	√			√			√		√
181	**250**	√	√		√			√		√
284	**500**	√	√		√			√		√
542	**1000**	√	√		√			√		√
840	**1500**	√	√		√			√		√

		$F_{Ga,S}$	$F_{Gr,S}$	$F_{Ga, P}$	$F_{Gr,P}$	$C_{Ga,}$Sludge	F_{Ga}	$F_{Ga,}$ WWTP	F_{Gr}	$F_{Gr,}$ WWTP
	125		√				√	√		√
	250		√				√	√		√
	500		√				√	√		√
	1000		√				√	√		√
	1500		√			√	√	√	√	√

The results in table 8.1 show that the sensitive parameters are the same from 250 up to 1000 simulations. In the case of 1500 shots two additional parameters become sensitive. The more MC shots the more parameters present *t*PCC values larger than 1.96, and therefore become sensitive (Table 8.2) according to the screening method described in section 4.3.2. The very conservative number of 1000 MC shots was selected to make sure that the whole space was explored at a reasonable computational time (1 second per simulated day). Then, the same number of MC shots was run in the selection of best management strategies.

Table 8.2: Number of model parameters with *t*PCC larger than 1.96 for number of simulations.

***t*PCC**	**125**	**250**	**500**	**1000**	**1500**
	23	32	38	44	53

8.4 Best management strategies

The proposed method was applied to single problematic situations. However, it is also possible to find combinations of two or more problems happening at the same time. Given an example of two problematic situations (1 and 2), five different solutions can be applied to solve them:

1. Use the best strategy of problematic scenario 1.
2. Use the best strategy of problematic scenario 2.
3. Apply the entire method to find the new best strategy for the combination.
4. Average values obtained from options 1 and 2 for parameters that are sensitive in both options and maintain reference values for the rest.
5. Keep the reference values.

In order to validate the different options six combinations of scenarios have been analyzed for the five options mentioned just before.

1. Blower failure La Garriga and storm.
2. Blower failure Granollers and storm.
3. High load La Garriga and temperature.
4. High load Granollers and temperature.
5. Low river flow and blower failure La Garriga.
6. Low river flow and blower failure Granollers.

Only the results from the combinations "blower failure in La Garriga (Ga)" + "storm" (Table 8.3); and "low river flow" + " blower failure in Granollers" (Table 8.4) are shown here. The other results are summarized in Annex 4.

For "blower failure in La Garriga (Ga)" + "storm": The system is pushed even more to the limit with this combination of scenarios. Table 8.3. shows the criteria values for the different options. The best strategy for blower failure in La Garriga cannot be used because it has a negative impact on Granollers. This strategy sends water to the Granollers system, and since a storm is posted there, Granollers becomes overloaded (39% worse NH4max). The remaining strategies show good performance. With the "new best" strategy improved results are obtained for Granollers and with the "best storm" and "average" options better results are observed for la Garriga.

Table 8.3. Criteria values for the different options in case of blower failure in La Garriga (Ga) and storm.

	LA GARRIGA				GRANOLLERS				TC
	DO av	**DO min**	**NH_4 max**	**RQI**	**DO av**	**DO min**	**NH_4 max**	**RQI**	
Best storm	8.90	8.62	0.87	177.65	7.13	4.78	4.11	235.82	2114.15
Best blower Ga	9.15	8.90	0.55	174.89	6.80	4.59	6.09	305.80	1750.37
New best	8.56	8.20	1.33	189.41	7.10	5.44	3.80	240.23	2005.38
Average	9.04	8.59	0.62	175.37	6.99	4.76	4.42	253.72	1982.12
Reference	8.70	7.81	1.41	187.99	6.97	4.72	4.37	253.62	1997.86
				% Improvement					
Best storm	2.35	10.35	38.13	5.50	2.28	1.28	6.06	7.02	-5.82
Best Ga	5.18	13.93	60.70	6.97	-2.50	-2.64	-39.27	-20.57	12.39
New best	-1.60	4.95	5.31	-0.75	1.79	15.32	13.17	5.28	-0.38
Average	3.85	9.93	56.01	6.71	0.24	0.95	-1.12	-0.04	0.79

For “low river flow” + ” blower failure in Granollers”: In this case, the results obtained for the four options are very similar. All the options maximize the use of the storage tanks. The limiting factor would be the TC, which improves by almost 10% in “best blower Gr” and “new best” (Table 8.4).

Table 8.4. Criteria values for the different options in case of low river flow and blower failure in Granollers (Gr).

	LA GARRIGA				GRANOLLERS				TC
	DO av	**DO min**	**NH_4 max**	**RQI**	**DO av**	**DO min**	**NH_4 max**	**RQI**	
Best low river	5.19	4.06	1.10	328.64	5.47	3.79	13.45	548.72	2014.93
Best blower Gr	5.69	4.20	0.97	326.88	5.44	3.86	9.80	531.29	1784.82
New best	5.69	4.20	0.97	326.76	5.43	3.86	9.80	531.15	1784.21
Average	5.47	4.03	1.04	328.84	5.51	3.90	10.95	533.14	1939.29
Reference	5.10	3.62	3.19	354.97	5.38	3.10	22.70	655.77	1968.77
% Improvement									
Best low river	1.66	12.38	65.49	7.42	1.74	22.39	40.75	16.32	-2.34
Best blower Gr	11.56	16.08	69.77	7.91	1.04	24.76	56.84	18.98	9.34
New best	11.53	16.08	69.77	7.95	1.02	24.76	56.84	19.00	9.37
Average	7.24	11.35	67.49	7.36	2.48	26.08	51.75	18.70	1.50

Overall, when dealing with a combination of scenarios, the average approximation leads to acceptable results. However, this should be further studied, as well as compared with other methods, like weighted average, case-base reasoning, fuzzy logic or neural networks. The method should be extended to provide solutions for any combination of scenarios as well as for new perturbations affecting the system.

8.6 Off-line decision support tool

In this thesis, the option of running the method on line as a parallel tool for real-time control is not considered. Running MC simulations for sensitivity analysis and exploring the space of possibilities is time consuming (between one day and one day and a half in an Intel® Core™ 2 Duo CPU. 2.79 GHz and 1.96 GB of RAM). Therefore, if the perturbation takes between a few hours and a few days, the solution obtained from this computing approach will be too late. However, the model itself can be run to evaluate the potential effects of new perturbations. Finally, the model can be used to train operators to confront new scenarios or combinations of scenarios. Modeling allows various design and operational scenarios and their impacts on the environment to be studied without having to physically alter the system or to set up physical laboratory-scale models. In that sense, it is feasible to use the model as an off-line tool for day-to-day management of UWSs. Finally, models can also be used to evaluate upgrading options for the WWTP or the SS.

8.7 Future research needs

Comparison with optimization methods

Several methods are widely applied for single and multiple objective optimization. The methodology proposed in this thesis could be improved by using an optimizer to find the best management strategies (e.g., Fu *et al.,* 2008; Muschalla, 2008). Future research will be focused on implementing these optimization algorithms and comparing the results of both approaches. The intensive computing required for both approaches will be solved by using a cluster.

Robustness analysis

Best management strategies have been implemented as a control algorithm in the same WEST simulation platform. The system identifies which problematic scenario it is facing and applies the proper operational strategies. Further studies will be focused on demonstrating that this strategy is more robust against several types of perturbations and against several sources of variability and uncertainty in the model inputs.

Model Uncertainty

Models themselves are built under uncertainties due to model input variables, model parameters and models structures. It is important to have a clear understanding of the types of uncertainty that the method addresses, to correctly interpret the model results (Cariboni *et al.,* 2007; Freni *et al.,* 2008; Sin *et al*., 2011). Recent studies have focused on integrated models' uncertainty, which appears to be very high due to the linkage of two or more models. Reducing the uncertainty will lead to better performances of the integrated model and avoid useless results (Freni *et al.,* 2009; Freni *et al*., 2001). Research will be conducted to handle uncertainty in the decision-making.

Full-scale validation

Although the method was developed in agreement with the "Consorci per la defensa de la conca del riu Besòs" experts, it was not possible to test the strategies found in the real case mainly because the system is not sufficiently automated. In addition, all the acquired knowledge has to be translated into rules connected to an online EDSS. This step is ongoing within the ENDERUS project (ENvironmental DEcision support system to select Robust operational strategies in Urban water Systems) where an EDSS is developed to integrate all the knowledge gained in this thesis.

CHAPTER 9

CONCLUSIONS

9. Conclusions

This thesis demonstrates that the integrated management of sewer systems (including storage tanks) and wastewater treatment plants is possible and represents big advantages for WFD implementation, where immission-based criteria become important. The proposed model-based approach is a valuable method to explore a wide range of possibilities to improve current management without performing resource and time-consuming measuring campaigns. Several conclusions can be drawn about the method.

- The method includes the following key steps: constructing a model, selecting problematic scenarios, choosing operational parameters, defining evaluation criteria and, finally, performing a set of simulations to conduct GSA and select the best operational strategies.

- This method has been applied in the Besòs River case study.

- For the case study, a model including all the elements of the UWS was successfully implemented in the WEST simulation platform, which includes, KOSIM for catchments and sewer system, ASM2d for WWTP and RWQM1 for river. The model facilitates the evaluation of different alternatives.

- The method was tested against nine problematic situations in the Congost River case study: dry weather (reference), storm, high load La Garriga, high load Granollers, increase of population, temperature, low river flow, blower failure in La Garriga, and blower failure in Granollers.

- The results of the sensitivity analysis detected the most sensitive operational parameters for each scenario and indicated how to modify them to improve the evaluation criteria.

- The results of the selection of operational strategies showed that:
  - Bypass and storage tanks in the UWS are extremely important because they allow reductions of ammonia peaks down to 50%.
  - Adjustment of the aeration capacity and sludge recirculation is also crucial to reduce operating costs and prepare the WWTP against a perturbation.
  - The method does not provide a single best alternative but rather a range of possibilities, from which the decision-maker can choose.

- The implementation of an on-line system that switches parameter values depending on the perturbation in the system would be very useful for improving river water quality. Detection rules and time-response options have been suggested to bring the strategy into practice.

CHAPTER 10

REFERENCES

10. References

Achleitner, S., Möderl, M. and Rauch, W. (2007). CITY DRAIN © - An open source approach for simulation of integrated urban drainage systems. *Environmental Modelling and Software*, 22(8), 1184-1195.

Aguiar, F.C., Feio, M.J. and Ferreira, M.T. (2011). Choosing the best method for stream bioassessment using macrophyte communities: Indices and predictive models. *Ecological Indicators*, 11(2), 379-388.

Ahnert, M., Tränckner, J., Gunther, N., Hoeft, S. and Krebs, P. (2009). Model-based comparision of two ways to enhance WWTP capacity under stormwater conditions. *Water Science and Technology,* 60(7), 1875-1883.

Andrés-Doménech, I., Múnera, J.C., Francés, F. and Marco, J.B. (2010). Coupling urban event-based and catchment continuous modelling for combined sewer overflow river impact assessment. *Hydrology and Earth System Sciences Discussions*, 7(3), 3281-3328.

Argent, R.M., Perraud, J.-M., Rahman, J.M.,Grayson, R.B., and Podger, G.M. (2009). A new approach to water quality modelling and environmental decision support system. *Environmentla Modelling and Software*, 24(7), 809-818.

Aulinas, M. (2009). Management of industrial wastewater discharges in river basins through agents' argumentation. PhD Thesis. Universitat de Girona, Spain.

Beck, M.B. (1976). Dynamic modelling and control applications in water quality maintenance. *Water Research,* 10(7), 575-595.

Benedetti L. (2006). Probabilistic design and upgrade of wastewater treatment plants in the EU Water Framework Directive Context. PhD Thesis. Universiteit Gent, Belgium.

Benedetti, L., Batstone, D.J., De Baets, B., Nopens, I. and Vanrolleghemt, P.A. (2008a). Global sensitivity analysis of biochemical, design and operational parameters of the Benchmark Simulation Model no. 2. *International Congress on Environmental Modelling and Software*, Barcelona, Spain, 7-10 July 2008.

Benedetti L., Dirckx, G., Bixio, D., Thoeye, C., and Vanrolleghem, P.A. (2008b). Environmental and economic performance assessment of the integrated urban wastewater system. *Journal of environmental Management* 88(4), 1262 - 1272.

Benedetti, L., Prat, P., Nopens, I., Poch, M., Turon, C., De Baets, B. and Comas, J. (2009). A new rule generation method to develop a decision support system for integrated management at river basin scale. *Water Science and Technology,* 60(8), 2035-2040.

Benedetti, L., De Baets, B., Nopens, I. and Vanrolleghem, P.A. (2010). Multi-criteria analysis of wastewater treatment plant design and control scenarios under uncertainty. *Environmental Modelling and Software,* 25(5), 616-621.

Bertrand-Krajewski, J.-. (1993). Solid transport modelling in combined sewer systems: the HYPOCRAS model. *Houille Blanche,* 48(4), 243-255.

Blind, M. and Gregersen, J.B. (2005). Towards an Open Modelling Interface (OpenMI) the HarmonIT project. *Advances in Geosciences,* 4, 69-74.

Butler, D. and Schütze, M. (2005). Integrating simulation models with a view to optimal control of urban wastewater systems. *Environmental Modelling and Software,* 20(4 SPEC. ISS.), 415-426.

Cariboni, J., Gatelli, D., Liska, R. and Saltelli, A. (2007). The role of sensitivity analysis in ecological modelling. *Ecological Modelling,* 203(1-2), 167-182.

Carstensen, J., Nielsen, M.K. and Strandbæk, H. (1998). Prediction of hydraulic load for urban storm control of a municipal WWT plant. *Water Science and Technology,* 37(12), 363-370.

CEC. 1991. Directive concerning urban wastewater treatment (91/271/EEC). *Official Journal of the European Community,* L135, 26-50.

CEC. 1996. Directive concerning integrated pollution prevention and control (96/61/EEC). *Official Journal of the European Community,* L 257, 1-73.

CEC. 2000. Directive 2000/60/EC establishing a framework for Community action in the field of water policy. *Official Journal of the European Community,* L327, 1-73.

CEC. 2001. Common implementation strategy for the Water Framework Directive (2000/60/EC). *Official Journal of the European Community,* Strategic Document.

CEDEC 2008. XXVI curso sobre tratamiento de aguas residuales y explotación de estaciones depuradoras. Tomo III. Tema 34.

Chapra, S., Pelletier, G. and Tao. H.(2006) QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality (Version 2.04) *Documentation Civil and Environmental Engineering Department*, Tufts University, Medford, MA. March 7

Chen, S.H., Jakeman, A.J. and Norton, J.P. (2008). Artificial Intelligence techniques: An introduction to their use for modelling environmental systems. *Mathematics and Computers in Simulation,* 78(2-3), 379-400.

China State Environmental Protection Administration (2002) *Environmental Quality Standards for Surface Water.* GB 3838-2002 (Beijing: China Environmental Science Press).

Claeys, F., Vanrolleghem, P.A. and Fritzson. P. (2006). Boosting the efficiency of compound virtual experiments through a priori exploration of the solver setting space. *European Modelling and Simulation Symposium* (EMSS), Barcelona, Spain October 4-6.

Claeys, F., Fritzon, P. and Vanrolleghen, P.A. (2007). Generating efficient executable models for complex virtual experimentation with the Tornado kernel. *Water Science and Technology,* 56(6), 65-73.

Clara, M., Strenn, B., Gans, O., Martinez, E., Kreuzinger, N. and Kroiss, H. (2005). Removal of selected pharmaceuticals, fragrances and endocrine disrupting compounds in a membrane bioreactor and conventional wastewater treatment plants. *Water research,* 39(19), 4797-4807.

Copp J.B. (2002). The COST Simulation Benchmark – Description and Simulator Manual. *Office for Official Publications of the European communities*, Luxemburg, ISBN 92-894-1658-0.

Crabtree, B., Earp, W. and Whalley, P. (1996). A demonstration of the benefits of integrated wastewater planning for controlling transient pollution. *Water Science and Technology,* 33(2), 209-218.

Crabtree, R.W., Ashley, R. and Gent, R. (1995). Mousetrap: Modelling of real sewer sediment characteristics and attached pollutants. *Water Science and Technology,* 31(7), 43-50.

Dalmau J. (2009). Knowledge-based modelling and simulation of operational problems of microbiological origin in wastewater treatment plants. PhD Thesis. Universitat de Girona, Spain.

De Gussem, K., Wambecq, T., Roels, J., Fenu, A., De Gueldre, G. and Van De Steene, B. (2011). Cost optimisation and minimisation of the environmental impact through life cycle analysis of the waste water treatment plant of Bree (Belgium). Water Science and Technology, 63(1), 164-170.

De Toffol, S., Engelhard, C. and Rauch, W. (2007). Combined sewer system versus separate system - A comparison of ecological and economical performance indicators. Water Science and Technology, 55(4), 255-264.

Devesa, F. (2005). Desenvolupament d'un Sistema de Suport a la Decisió Ambiental per a la Gestió de les Infrastructures Hidràuliques, amb l'Objectiu de Garantir la Qualitat de l'Aigua a la Conca del Besòs. PhD Thesis. Universitat de Girona.

Devesa, F., Comas, J., Turon, C., Freixó, A., Carrasco, F. and Poch, M. (2009). Scenario analysis for the role of sanitation infrastructures in integrated urban wastewater management. *Environmental Modelling and Software,* 24(3), 371-380.

Dodds, W.K. and Welch, E.B. (2000). Establishing nutrient criteria in streams. *Journal of the North American Benthological Society,* 19(1), 186-196.

Erbe, V., Risholt, L.P., Schilling, W. and Londong, J. (2002). Integrated modelling for analysis and optimisation of wastewater systems - The Odenthal case. *Urban Water,* 4(1), 63-71.

Erbe, V. and Schütze, M. (2005). An integrated modelling concept for immission-based management of sewer system, wastewater treatment plant and river. *Water Science and Technology,* 52(5), 95-103.

Faure, D., Payrastre, O. and Auchet, P. (2005). Radar-based alert system to operate a sewerage network: Relevance and operational effectiveness after several years of use. *Water Science and Technology,* 51(2), 203-211.

Flores-Alsina, X. (2008). Conceptual design of wastewater treatment plants using multiple objectives. PhD Thesis. Universitat de Girona, Spain.

Flores-Alsina, X., Rodríguez-Roda, I. Sin, G. and Gernaey, K.V. (2010) Multi-criteria evaluation of wastewater treatment plant control strategies under uncertainty. *Water Research,* 42(17), 4485-4497.

Fox, J. and Das, S. (2000). Safe and Sound. Artificial intelligence in hazardous applications. AAII Press / The MIT Press.

Freni, G., Mannina, G. and Viviani, G. (2009). Assessment of data availability influence on integrated urban drainage modelling uncertainty. *Environmental Modelling and Software,* 24(10), 1171-1181.

Freni, G., Mannina, G. and Viviani, G. (2010). Emission standards versus immission standards for assessing the impact of urban drainage on ephemeral receiving water bodies. *Water Science and Technology,* 61(6), 1617-1629.

Freni, G., Mannina, G. and Viviani, G. (2011). Assessment of the integrated urban water quality model complexity through identifiability analysis. *Water Research,* 45(1), 37-50.

Fronteau, C., Bauwens, W. and Vanrolleghem, P.A. (1997). Integrated modelling: Comparison of state variables, processes and parameters in sewer and wastewater treatment plant models. *Water Science and Technology,* 36(5), 373-380.

Fu, G., Butler, D. and Khu, S. (2008). Multiple objective optimal control of integrated urban wastewater systems. *Environmental Modelling and Software,* 23(2), 225-234.

Fu, G., Butler, D. and Khu, S. (2009a). The impact of new developments on river water quality form an integrated system modelling prespective. *Science of total Environment,* 407(4), 1257-1267.

Fu, G., Khu, S. and Butler, D. (2009b). Use of surrogate modelling for multiobjective optimisation of urban wastewater systems. *Water Science and Technology*, 60(6), 1641-1647.

Foundation for Water Research (1998). Urban pollution management manual: a planning guide for the management of urban wastewater discharges during wet weather. *Foundation for Water Research,* UK, ISBN 09-521-7124-4.

Gabriel, O. and Zessner, M. (2006). Discussion of an environment quality standard based assessment procedure for permitting discharge. *Water Science and Technology,* 54(11-12), 119-127.

Gernaey, K.V., Van Loosdrecht, M.C.M., Henze, M., Lind, M. and Jørgensen, S.B. (2004). Activated sludge wastewater treatment plant modelling and simulation: State of the art. *Environmental Modelling and Software,* 19(9), 763-783.

Giupponi, C. (2007). Decision Support Systems for implementing the European Water Framework Directive: The MULINO approach. *Environmental Modelling and Software,* 22(2), 248-258.

Guariso, G., Hitz, M. and Werthner, H. (1996). An integrated simulation and optimization modelling environment for decision support. *Decision Support Systems,* 16(2), 103-117.

Gutierrez, O., Park, D., Sharma, K.R. and Yuan, Z. (2010). Iron salts dosage for sulfide control in sewers induces chemical phosphorus removal during wastewater treatment. *Water research,* 44(11), 3467-3475.

Hair, J.F., Andersen, R.E., Tatham, R.L., Black, W.C., 1998. Multivariable Data Analysis, fifth ed. Prentice-Hall, London, UK.

Hamouda, M.A., Anderson, W.B. and Huck, P.M. (2009). Decision support systems in water and wastewater treatment process selection and design: A review. Water Science and Technology, 60(7), 1767-1770.

Hellawell, J.M. (1986). Biological indicators of freshwater pollution and environmental management. *Pollution monitoring series Londres.* Elsevier Applied Science Publishers.

Helton, J.C. and Davis, F.J. (2003). Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems. *Reliability Engineering and System Safety,* 81(1), 23-69.

Henze M., Gujer W., Mino T. and van Loosdrecht M.C.M. (2000). Activated Sludge Models ASM1, ASM2, ASM2d and ASM3. *IWA STR No 9.* IWA Publishing, London, UK.

Hering, D., Borja, A., Carstensen, J., Carvalho, L., Elliott, M., Feld, C.K., Heiskanen, A.-., Johnson, R.K., Moe, J., Pont, D., Solheim, A.L. and de Bund, W.V. (2010). The European Water Framework Directive at the age of 10: A critical review of the achievements with recommendations for the future. *Science of the Total Environment,* 408(19), 4007-4019.

Hoornbeek, J.A. (2004). Policy-making institutions and water policy outputs in the European Union and the United States: A comparative analysis. *Journal of European Public Policy,* 11(3), 461-496+567.

Hu, Z., Wentzel, M.C. and Ekama, G.A. (2007). A general kinetic model for biological nutrient removal activated sludge systems: Model development. *Biotechnology and bioengineering,* 98(6), 1242-1258.

Huber, W.C., (2001). New options for overland flow routing in SWMM. *Urban Dranaige Modelling*, pp. 22-29.

Hughes, D.A. and Louw, D. (2010). Integrating hydrology, hydraulics and ecological response into a flexible approach to the determination of environmental water requirements for rivers. *Environmental Modelling and Software,* 25(8), 910-918.

ITWH. 2000. KOSIM 6.2. Anwenderhandbuch. Institut für technisch-wissenschaftliche Hydrologie GmbH, Hannover, Germany.

Kallis, G. and Butler, D. (2001). The EU water framework directive: Measures and implications. *Water Policy,* 3(2), 125-142.

Kowalski, R., Reuber, J. and Köngeter, J. (1999). Investigations into and optimisation of the performance of sewage detention tanks during storm rainfall events. *Water Science and Technology,* 39(2), 43-52.

Kus, B., Kandasamy, J., Vigneswaran, S. and Shon, H.K. (2010). Analysis of first flush to improve the water quality in rainwater tanks. *Water Science and Technology,* 61(2), 421-428.

Lautenbach, S., Jürgen Berlekamp, Graf, N., Seppelt, R. and Matthies, M. (2009). Scenario analysis and management options for sustainable river basin management: Application of the Elbe DSS. *Environmental Modelling and Software,* 24(1), 26-43.

Lijklema, L., Tyson, J.M. and Lesouef, A. (1993). Interactions between sewers treatment plants and receiving waters in urban areas: A summary of the Interurba '92 workshop conclusions. *Water Science and Technology,* 27(12), 1-29.

Lim, S., Suh, S., Kim, J.-. and Park, H.S. (2010). Urban water infrastructure optimization to reduce environmental impacts and costs. *Journal of environmental management,* 91(3), 630-637.

Llorens, E., Thiery, F., Grieu, S. and Polit, M. (2008). Evaluation of WWTP discharges into a Mediterranean river using KSOM neural networks and mass balance modelling. *Chemical Engineering Journal,* 142(2), 135-146.

Makropoulos, C.K., Natsis, K., Liu, S., Mittas, K. and Butler, D. (2008). Decision support for sustainable option selection in integrated urban water management. *Environmental Modelling and Software,* 23(12), 1448-1460.

Malgrat Bregolat, P., Verdejo, J.M. and Vilalta Cambra, A. (2004). Storm water detention tanks in Barcelona. *Tecnologia del Agua,* 24(252), 36-40.

Mannina, G. and Viviani, G. (2010). An urban drainage stormwater quality model: Model development and uncertainty quantification. *Journal of Hydrology,* 381(3-4), 248-265.

Mannina, G. and Viviani, G. (2009). Separate and combined sewer systems: A long-term modelling approach. *Water Science and Technology,* 60(3), 555-565.

Mark, O., Hernebring, C. and Magnusson, P. (1998). Optimisation and control of the inflow to a wastewater treatment plant using integrated modelling tools. *Water Science and Technology,* 37(1), 347-354.

Marti, N., Ferrer, J., Seco, A. and Bouzas, A. (2008). Optimisation of sludge line management to enhance phosphorus recovery in WWTP. *Water research,* 42(18), 4609-4618.

Martinez, M., Rodríguez-Roda, I., Poch, M., Cortés, U. and Comas, J. (2006). Dynamic reasoning to solve complex problems in activated sludge processes: A step further in decision support systems. *Water Science and Technology,* 53(1), 191-198.

McMillin, W.E., Garner, G.R., Sigmund, T.W., Schultz, N.U. and Rowe, R.L. (2006). Guide to Managing Peak Wet Weather Flows in Municipal Wastewater Systems Guidance Practices. *Watern Environment Federation,* Alexandria, Virginia.

Meirlaen J. (2002). Immission based real-time control of the integrated urban wastewater system. PhD Thesis. Universiteit Gent, Belgium.

Metcalf and Eddy Inc. (2003). Wastewater engineering: Treatment and reuse. 3rd ed., *McGraw-Hill,* New York, USA, ISBN 978-0-07-041878-3

Morgan, M.G., Henrion, M. (1990) *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge University Press, Cambridge, UK

Morrison, D.F., Multivariate statistical methods, *Mc-Graw Hill,* Singapore, 1984.

Munné, A. and Prat, N. (2011). Effects of Mediterranean climate annual variability on stream biological quality assessment using macro invertebrate communities. *Ecological Indicators,* 11(2), 651-662.

Muschalla D., Reussner F., Schneider S. and Ostrowski M.W. (2006) Dokumentation des Schmutzfrachtmodells SMUSI Version 5.0, *Institut für Wasserbau und Wasserwirtschaft,* Technische Universität Darmstadt, Germany.

Muschalla, D. (2008). Optimization of integrated urban wastewater systems using multi-objective evolution strategies. *Urban Water Journal,* 5(1) 59-67.

Olsson, G., (2005). Instrumentation, control and automation in wastewater systems. IWA Publishing, London, UK, ISBN 19-002-2283-3.

Otterpohl, R. and Freund, M. (1992). Dynamic models for clarifiers of activated sludge plants with dry and wet weather flows. *Water Science and Technology,* 26(5-6), 1391-1400.

Paredes, J., Andreu, J. and Solera, A. (2010). A decision support system for water quality issues in the Manzanares River (Madrid, Spain). *Science of the Total Environment,* 408(12), 2576-2589.

Pfister, A., Stein, A., Schlegel, S. and Teichgräber, B. (1998). An integrated approach for improving the wastewater discharge and treatment systems. *Water Science and Technology,* 37(1), 341-346.

Pleau, M., Colas, H., Lavallée, P., Pelletier, G. and Bonin, R. (2005). Global optimal real-time control of the Quebec urban drainage system. *Environmental Modelling and Software,* 20(4 SPEC. ISS.), 401-413.

Poch, M., Comas, J., Rodríguez-Roda, I., Sànchez-Marrè, M. and Cortés, U. (2004). Designing and building real environmental decision support systems. *Environmental Modelling and Software,* 19(9), 857-873.

Prat, P., Aulinas, M., Turon, C., Comas, J. and Poch, M. (2009). Role playing games: A methodology to acquire knowledge for integrated wastewater infrastructures management in a river basin scale. *Water Science and Technology*, 59(9), 1809-1816.

Prat, P., Benedetti, L., Corominas, L., Comas, J. and Poch (2011). Model-based knowledge acquisition in Environmental Decision Support System for wastewater integrated management. *Accepted in press to Water Science and Technology.*

Rauch, W. and Harremoës, P. (1996). The importance of the treatment plant performance during rain to acute water pollution. *Water Science and Technology,* 34(3-4 -4 pt 2), 1-8.

Rauch, W., Aalderink, H., Krebs, P., Schilling, W. and Vanrolleghem, P. (1998). Requirements for integrated wastewater models - Driven by receiving water objectives. *Water Science and Technology,* 38(11), 97-104.

Rauch, W. and Harremoës, P. (1999). Genetic algorithms in real time control applied to minimize transient pollution from urban wastewater systems. *Water Research,* 33(5), 1265-1277.

Rauch, W., Bertrand-Krajewski, J.-., Krebs, P., Mark, O., Schilling, W., Schütze, M. and Vanrolleghem, P.A. (2002). Deterministic modelling of integrated urban drainage systems. *Water Science and Technology,* 45(3), 81-94.

Ravesteijn, W. and Kroesen, J.O. (2007). Tension in water management: Dutch tradition and European policy. *Water Science and Technology,* 56(4), 105-111.

Reichert, P. (1994). Aquasim - A tool for simulation and data analysis of aquatic systems. *Water Science and Technology,* 30(2 pt 2), 21-30.

Reichert, P., Borchardt, D., Henze, M., Rauch, W., Shanahan, P., Somlyódy, L. and Vanrolleghem, P. (2001). River Water Quality Model no. 1 (RWQM1): II. Biochemical process equations. *Water Science and Technology,* 43(5), 11-30.

Rousseau, D., Verdonck, F., Moerman, O., Carrette, R., Thoeye, C., Meirlaen, J. and Vanrolleghem, P.A. (2001). Development of a risk assessment based technique for design/retrofitting of WWTPs. *Water Science and Technology,* 43(7), 287-294.

Sànchez, M., R-Roda, I., Poch, M., Cortés, U. and Lafuente, J. (1994). Dai-depur architecture: Distributed agents for real-time wwtp supervision and control. *Annual Review in Automatic Programming*, 19(C), 147-152.

Schilling, W., Andersson, B., Nyberg, U., Aspegren, H., Rauch, W. and Harremoës, P. (1996). Real time control of wastewater systems. *Journal of Hydraulic Research*, 34(6), 785-797.

Schroeder, K. and Pawlowsky-Reusing, E. (2005). Current state and development of the real-time control of the Berlin sewage system. *Water Science and Technology,* 52(12), 181-187.

Schütze, M., Butler, D. and Beck, M.B. (1999a). Optimisation of control strategies for the urban wastewater system - An integrated approach. *Water Science and Technology,* 39(9), 209-216.

Schütze, M., Butler, D., Beck, M.B., (1999b). SYNOPSIS – A tool for the development and simulation of real-time control strategies for the urban wastewater system.

Eighth International Conference on Urban Storm Drainage; Sydney, Australia. 30 August – 3 September.

Schütze, M., Campisano, A., Colas, H., Schilling, W. and Vanrolleghem, P.A. (2004). Real time control of urban wastewater systems - Where do we stand today? *Journal of Hydrology*, 299(3-4), 335-348.

Sin, G., Gernaey, K.V., Neumann, M.B., Loosdrecht, M.C.M. and Gujer, W. (2011). Global sensitivity analysis in wastewater treatment plant model application: Prioritizing sources of uncertainty. *Water Research,* 45(2), 639-651.

Seggelke, K., Rosenwinkel, K., Vanrolleghem, P.A. and Krebs, P. (2005). Integrated operation of sewer system and WWTP by simulation-based control of the WWTP inflow. *Water Science and Technology,* 52(5), 195-203.

Sharma, K.R., Yuan, Z., de Haas, D., Hamilton, G., Corrie, S. and Keller, J. (2008). Dynamics and dynamic modelling of H2S production in sewer systems. *Water research,* 42(10-11), 2527-2538.

Solvi, A. M., Benedetti, L., Vandenberghe, V., Gillé, S., Schlosseler, P., Weidenhaupt, A. and Vanrolleghem, P.A., (2006). Implementation of an integrated model for optimised urban wastewater management in view of better river water quality: A case study. *IWA World Water Congress and Exhibition,* Beijing, China, 11 - 15 September.

Solvi A.M. (2007). Modelling the sewer-treatment-urban river system in view of the EU Water Framework Directive. PhD Thesis. Universiteit Gent, Belgium.

Takács, I., Patry, G.G. and Nolasco, D. (1991). A dynamic model of the clarification-thickening process. *Water research,* 25(10), 1263-1271.

Tilche, A. and Orhon, D. (2002). Appropriate basis of effluent standards for industrial wastewaters. *Water Science and Technology,* 45(12), 1-11.

Torno, H. (1975). A model for assessing impact of stormwater runoff and combined sewer overflows and evaluating pollution abatement alternatives. *Water research,* 9(9), 813-815.

Tränckner, J., Franz, T., Seggelke, K. and Krebs, P. (2007). Dynamic optimisation of WWTP inflow to reduce total emission. *Water Science and Technology,* 56(10), 11-18.

Turon, C., Freixó, A., Ripoll, F., Clara, P., Comas, J., Rodríguez-Roda, I and Poch, M. (2009). Sistema inteligente para la toma de decisiones en la gestión de una EDAR. *Ingeniería Química,* 466, 116-122.

Vanhooren, H., Meirlaen, J., Amerlinck, Y., Claeys, F., Vangheluwe, H. and Vanrolleghem, P.A. (2003). WEST: Modelling biological wastewater treatment. *Journal of Hydroinformatics,* 5(1), 27-50.

Vanrolleghem, P.A., Benedetti, L. and Meirlaen, J. (2005a). Modelling and real-time control of the integrated urban wastewater system. *Environmental Modelling and Software,* 20(4 SPEC. ISS.), 427-442.

Vanrolleghem, P.A., Rosen, C., Zaher, U., Copp, J., Benedetti, L., Ayesa, E. and Jeppsson, U. (2005b). Continuity-based interfacing of models for wastewater systems described by Petersen matrices. *Water Science and Technology,* 52(1-2), 493-500.

Vrecko D., Volcke E.I.P., Jeppsson U. and Gernaey K.V. (2007). Evaluation Criteria Description and Example for BSM2. *IWA BSM TG Technical Report* (available at www.benchmarkwwtp.org).

Wang, X., Yang, L., Sun, Y., Song, L., Zhang, M. and Cao, Y. (2008). Three-dimensional simulation on the water flow field and suspended solids concentration in the rectangular sedimentation tank. Journal of Environmental Engineering, 134(11), 902-911.

Weyrauch, P., Matzinger, A., Pawlowsky-Reusing, E., Plume, S., von Seggern, D., Heinzmann, B., Schroeder, K. and Rouault, P. (2010). Contribution of combined sewer overflows to trace contaminant loads in urban streams. Water research, 44(15), 4451-4462.

URL

http://aca-web.gencat.cat/aca/appmanager/aca/aca/

Agència Catalana de l'Aigua (Last checking: 17/10/2011).

http://www.idescat.cat/

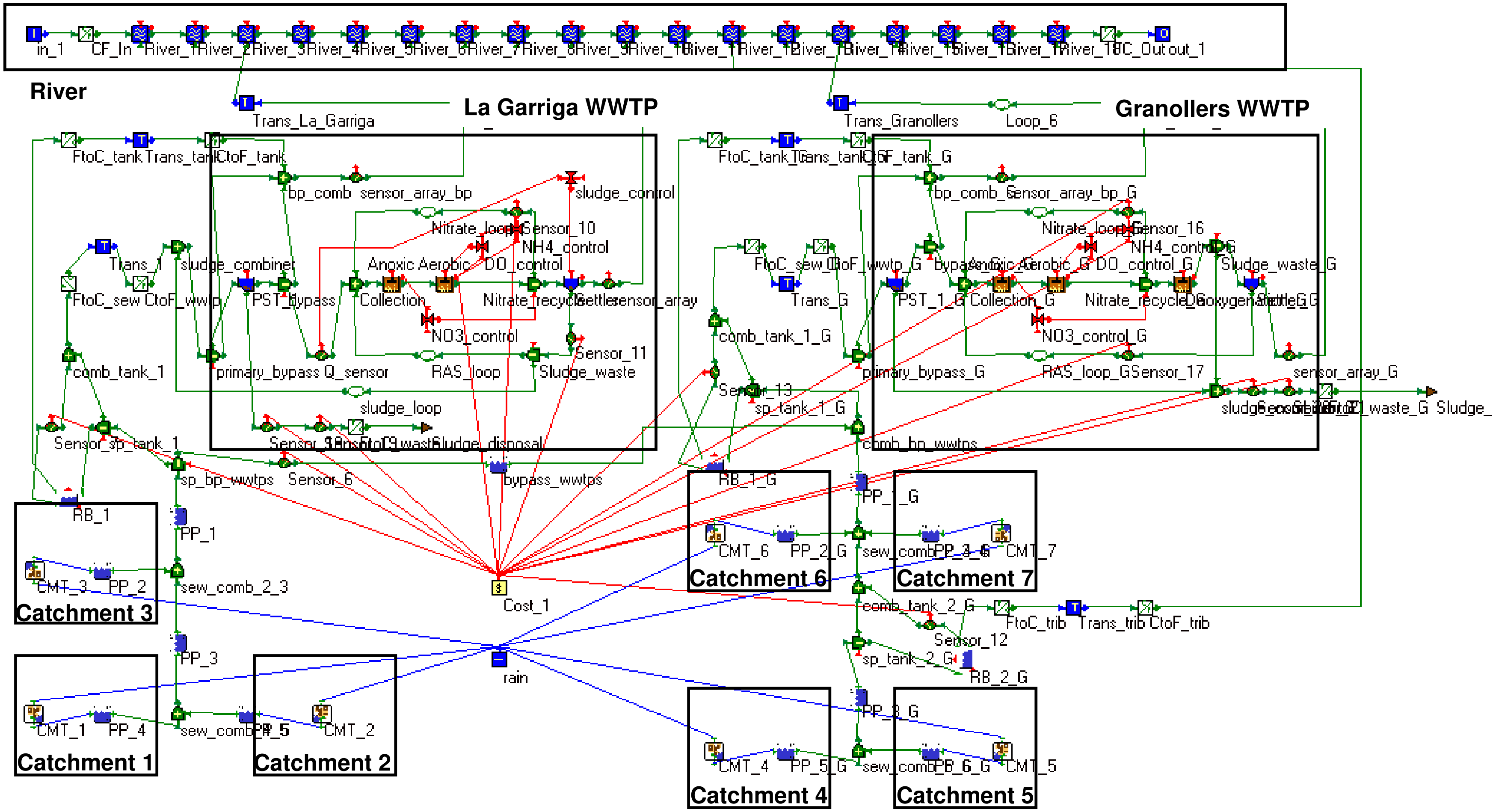
Web de l'estadística oficial de Catalunya (Last checking: 17/10/2011).

http://www.besos.cat/index_conca.htm

Consorci per la Defensa de la Conca del Besòs (Last checking: 17/10/2011).

ANNEXES

A1. WEST INTEGRATED MODEL



A2. RESULTS FROM GLOBAL SENSITIVITY ANALYSIS

Table A2.1. Sensitive parameters for dry weather scenario.

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	R^2=	0.60	R^2=	0.62	R^2=	0.55	R^2=	0.70	R^2=	0.70	R^2=	0.50	R^2=	0.61	R^2=	0.51	R^2=	0.72
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-12.96	2	-6.26	2	14.26	1	-0.92	11	-0.68	9	1.16	10	6.42	2	1.14	11	5.76	5
C_{Gr}, NH_4	-0.58	9	-0.06	18	-0.53	11	-7.43	2	-5.52	4	4.67	3	0.23	15	-1.43	8	0.19	14
C_{Ga}, NO_3	0.43	12	0.25	13	0.06	18	0.76	12	0.36	12	-1.08	11	-0.63	9	-1.21	9	4.37	7
C_{Gr}, NO_3	0.06	17	0.30	11	0.58	10	-0.02	18	0.87	8	-1.66	7	0.68	8	-6.54	3	8.32	2
$W_{Ga, P}$	0.66	8	0.16	15	0.33	13	-0.23	17	0.13	18	-0.18	17	-0.38	14	0.35	14	-0.12	16
$W_{Gr, P}$	0.53	10	0.53	7	-0.18	16	3.71	5	1.95	6	-1.51	8	-0.02	18	-2.56	4	1.33	9
R_{Gr}	0.22	14	0.48	8	-0.73	6	1.62	8	-0.21	15	-0.78	12	-0.48	11	-1.19	10	11.92	1
R_{Ga}	-0.17	15	-0.59	6	-0.09	17	-1.28	9	-0.48	10	1.46	9	-1.14	6	0.59	13	1.05	10
$W_{Gr,S}$	-0.30	13	-0.47	9	-0.36	12	7.16	3	6.27	3	4.20	4	-0.40	13	-2.13	6	7.18	4
$F_{Ga,S}$	-0.72	6	0.28	12	-3.17	4	0.25	15	0.15	17	0.48	14	-2.82	4	0.65	12	0.32	13
$F_{Gr,S}$	-0.82	5	-0.59	5	-0.33	14	2.23	6	-0.24	14	-6.80	2	-0.40	12	-9.83	2	4.69	6
$F_{Ga, P}$	-0.05	18	-0.10	16	0.20	15	-0.38	14	0.28	13	-0.19	16	0.59	10	0.03	18	-0.11	17
$F_{Gr,P}$	0.44	11	0.66	4	-0.65	9	-0.74	13	-0.45	11	0.19	15	-0.19	16	-0.17	16	0.05	18
C_{Ga},Sludge	-1.80	4	-0.42	10	-1.83	5	-0.25	16	-0.16	16	0.07	18	-1.93	5	-0.08	17	7.79	3
F_{Ga}	-13.14	1	-17.20	1	7.71	3	12.69	1	8.55	2	-1.94	6	17.32	1	-2.16	5	0.46	12
$F_{Ga, WWTP}$	3.69	3	-5.54	3	7.94	2	0.94	10	2.99	5	-0.75	13	3.19	3	0.35	15	-0.19	15
$F_{Gr, WWTP}$	-0.67	7	0.20	14	-0.72	7	5.40	4	-14.98	1	15.27	1	-0.11	17	12.53	1	2.06	8
F_{Gr}	-0.14	16	0.09	17	-0.68	8	1.72	7	-1.44	7	2.18	5	-0.69	7	1.81	7	-0.66	11

Table A2.2. Sensitive parameters for storm scenario

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	R^2=	0.72	R^2=	0.69	R^2=	0.74	R^2=	0.70	R^2=	0.21	R^2=	0.68	R^2=	0.69	R^2=	0.48	R^2=	0.60
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-3.36	3	-1.78	3	2.41	5	-4.18	4	0.91	14	0.92	10	3.77	4	1.23	11	3.30	6
C_{Gr}, NH_4	0.78	6	1.21	4	0.00	17	-7.96	2	-3.66	3	1.50	5	0.34	12	1.96	8	-0.60	14
C_{Ga}, NO_3	0.39	11	0.56	7	-0.43	8	0.51	17	-1.72	7	-0.55	13	-0.49	10	-0.15	18	2.98	8
C_{Gr}, NO_3	-0.04	18	0.14	11	0.29	9	-0.06	18	0.32	17	0.16	17	0.18	16	-1.64	9	8.38	2
$W_{Ga, P}$	0.81	5	0.69	6	-0.50	6	-0.57	15	-1.00	13	0.23	15	-0.68	7	0.38	15	-0.21	17
$W_{Gr, P}$	0.19	15	0.00	17	0.01	16	2.45	7	1.59	8	-0.91	11	-0.29	14	-1.97	6	1.73	9
R_{Gr}	0.49	8	0.27	9	0.00	18	-0.68	13	-1.72	6	-0.16	16	0.18	17	1.97	7	4.74	4
R_{Ga}	0.24	14	0.47	8	-0.17	13	-1.41	10	-1.15	11	0.54	14	0.65	8	1.17	13	-0.16	18
$W_{Gr,S}$	-0.19	16	0.05	15	0.44	7	4.20	3	1.03	12	1.06	9	0.55	9	-2.21	5	4.14	5
$F_{Ga,S}$	1.35	4	0.78	5	-8.05	2	2.76	6	1.44	9	-3.17	3	-10.64	2	-4.31	2	3.21	7
$F_{Gr,S}$	-0.35	12	-0.06	14	-0.14	14	14.64	1	3.20	4	-15.83	1	-0.23	15	-15.86	1	13.21	1
$F_{Ga, P}$	0.52	7	-0.02	16	-2.70	4	0.93	11	-0.31	18	-1.26	8	-3.76	5	-1.32	10	0.89	11
$F_{Gr,P}$	0.39	10	0.00	18	-0.17	12	0.55	16	0.65	15	-0.63	12	-0.15	18	-0.85	14	0.58	15
C_{Ga},Sludge	-0.44	9	0.07	13	-0.13	15	-0.60	14	-1.15	10	-0.11	18	-0.97	6	0.38	16	6.95	3
F_{Ga}	-19.33	1	-14.74	1	17.82	1	3.54	5	6.51	2	-1.44	7	15.45	1	-2.74	4	-0.68	12
$F_{Ga, WWTP}$	-3.62	2	-12.93	2	5.37	3	-2.34	8	-0.36	16	1.97	4	5.42	3	1.17	12	-0.45	16
$F_{Gr, WWTP}$	0.24	13	0.17	10	-0.22	10	-0.78	12	8.69	1	10.95	2	-0.48	11	4.07	3	-0.63	13
F_{Gr}	0.08	17	-0.14	12	0.20	11	2.25	9	-2.51	5	-1.45	6	-0.34	13	0.31	17	-1.54	10

Table A2.3. Sensitive parameters for high load La Garriga

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	R^2=	0.70	R^2=	0.64	R^2=	0.52	R^2=	0.70	R^2=	0.72	R^2=	0.57	R^2=	0.54	R^2=	0.51	R^2=	0.79
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-14.86	1	-8.61	2	12.10	1	0.02	17	-0.26	16	0.80	12	5.16	3	1.67	6	0.11	17
C_{Gr}, NH_4	-0.47	10	-0.26	10	-0.76	8	-8.13	3	-5.45	4	4.28	4	-0.36	13	-1.14	9	0.47	13
C_{Ga}, NO_3	0.56	7	0.02	18	-0.85	6	1.32	7	0.88	9	-1.26	9	-1.11	8	-1.39	8	3.36	6
C_{Gr}, NO_3	0.04	18	0.25	11	0.10	17	0.49	12	0.75	10	-1.57	7	-0.37	12	-5.58	3	8.89	2
$W_{Ga, P}$	0.67	5	0.45	6	-0.51	11	-0.11	16	0.24	17	-0.01	18	-1.14	7	0.21	14	-0.32	14
$W_{Gr, P}$	0.51	9	0.58	4	-0.01	18	3.34	4	2.00	6	-1.63	6	-0.09	18	-2.21	5	1.96	7
R_{Gr}	-0.07	16	-0.11	14	-0.34	14	1.56	5	0.29	14	-1.18	11	-0.39	10	-1.13	10	12.57	1
R_{Ga}	-0.09	14	-0.44	8	-0.81	7	-0.48	13	-0.05	18	1.31	8	-2.67	5	-0.01	18	1.20	10
$W_{Gr,S}$	-0.07	17	-0.09	15	-0.56	9	8.18	2	6.66	3	4.59	3	-1.02	9	-0.07	17	8.45	3
$F_{Ga,S}$	-0.56	8	0.03	17	-3.68	5	0.23	15	0.44	11	0.07	17	-2.00	6	0.35	12	0.17	16
$F_{Gr,S}$	-0.58	6	-0.57	5	-0.51	10	1.43	6	-0.31	13	-6.22	2	-0.37	11	-9.21	2	4.18	5
$F_{Ga, P}$	0.08	15	-0.04	16	0.38	13	0.01	18	0.28	15	-0.39	14	0.26	14	-0.10	15	0.22	15
$F_{Gr,P}$	0.27	12	0.42	9	-0.26	16	-0.40	14	-0.31	12	0.11	16	-0.15	16	-0.27	13	-0.01	18
C_{Ga},Sludge	-1.95	4	-0.44	7	-5.16	4	1.27	8	0.92	8	0.22	15	-8.24	2	-1.50	7	8.14	4
F_{Ga}	-12.79	2	-16.91	1	9.30	2	12.94	1	7.90	2	-1.19	10	14.67	1	0.10	16	1.68	8
$F_{Ga, WWTP}$	2.12	3	-3.46	3	7.29	3	1.23	9	2.43	5	-0.54	13	4.38	4	0.65	11	0.89	12
$F_{Gr, WWTP}$	-0.41	11	0.17	12	-0.28	15	0.94	11	-15.28	1	16.39	1	-0.16	15	13.65	1	1.55	9
F_{Gr}	-0.12	13	0.15	13	-0.50	12	1.15	10	-1.80	7	2.65	5	0.10	17	2.75	4	-0.97	11

Table A2.4. Sensitive parameters for High load Granollers

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	R^2=	0.66	R^2=	0.62	R^2=	0.53	R^2=	0.70	R^2=	0.72	R^2=	0.62	R^2=	0.61	R^2=	0.47	R^2=	0.75
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-14.32	1	-8.70	2	14.08	1	-0.12	16	0.13	17	0.63	12	6.12	2	0.35	14	5.60	5
C_{Gr}, NH_4	-0.67	8	-0.38	11	-0.82	7	-6.31	3	-4.99	4	3.04	4	0.12	17	0.73	10	0.13	13
C_{Ga}, NO_3	0.73	6	0.11	16	0.19	17	0.88	8	0.64	9	-1.04	10	-0.36	15	-1.40	8	4.08	7
C_{Gr}, NO_3	0.14	16	0.48	8	0.41	12	-0.29	13	-0.72	8	-0.51	14	0.40	12	-2.74	3	11.59	1
$W_{Ga, P}$	0.73	5	0.35	12	0.23	16	-0.10	18	0.28	14	0.04	18	-0.39	14	0.45	13	0.06	15
$W_{Gr, P}$	0.54	10	0.80	4	-0.39	14	3.92	4	1.94	6	-2.06	6	-0.45	9	-2.45	5	0.90	10
R_{Gr}	0.12	17	0.13	14	-0.41	13	1.16	6	0.34	12	-1.39	8	-0.25	16	-1.55	7	9.70	2
R_{Ga}	-0.19	15	-0.71	5	0.50	11	-0.63	11	-0.33	13	1.07	9	-0.48	6	0.90	9	1.06	9
$W_{Gr,S}$	-0.34	12	-0.41	9	-0.61	9	9.12	2	6.12	3	4.72	3	-0.41	10	0.11	17	7.98	3
$F_{Ga,S}$	-0.49	11	0.22	13	-3.75	4	0.12	17	0.07	18	0.41	15	-3.55	4	0.50	12	0.26	12
$F_{Gr,S}$	-0.71	7	-0.56	7	-0.31	15	0.98	7	0.25	15	-5.59	2	-0.47	8	-10.17	2	4.31	6
$F_{Ga, P}$	0.00	18	-0.03	18	0.01	18	-0.25	14	0.17	16	-0.04	17	0.41	11	0.14	16	0.05	16
$F_{Gr,P}$	0.28	13	0.40	10	-0.56	10	-0.73	10	-0.51	10	0.10	16	-0.10	18	0.10	18	-0.13	14
C_{Ga},Sludge	-1.72	4	-0.71	6	-1.75	5	-0.23	15	-0.35	11	0.52	13	-1.66	5	0.58	11	7.36	4
F_{Ga}	-12.83	2	-16.78	1	7.77	2	14.24	1	8.10	2	-1.79	7	17.19	1	-2.25	6	0.03	18
$F_{Ga, WWTP}$	2.26	3	-2.57	3	7.23	3	1.47	5	3.36	5	-0.64	11	4.25	3	-0.26	15	-0.03	17
$F_{Gr, WWTP}$	-0.64	9	0.12	15	-1.16	6	-0.59	12	-15.70	1	17.34	1	-0.47	7	13.30	1	2.14	8
F_{Gr}	-0.24	14	0.09	17	-0.62	8	0.79	9	-1.61	7	3.00	5	-0.39	13	2.64	4	-0.68	11

Table A2.5. Sensitive parameters for population.

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	R^2=	0.64	R^2=	0.68	R^2=	0.59	R^2=	0.70	R^2=	0.37	R^2=	0.23	R^2=	0.61	R^2=	0.28	R^2=	0.68
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-11.90	2	-6.24	2	14.36	1	-0.96	10	-0.40	15	0.68	16	4.85	2	0.93	8	6.07	6
C_{Gr}, NH_4	-0.73	5	-0.02	18	-0.89	6	-5.06	3	-3.88	3	3.58	4	-0.25	16	-0.22	15	-0.02	18
C_{Ga}, NO_3	0.46	10	0.23	10	-0.06	16	0.65	12	-0.66	12	0.89	12	-0.66	7	-0.21	16	4.30	8
C_{Gr}, NO_3	-0.17	17	0.09	15	0.61	8	0.05	18	0.69	11	-2.10	7	0.48	9	-4.97	3	8.14	2
$W_{Ga, P}$	0.45	11	0.20	11	0.32	11	-0.16	17	-0.22	16	0.37	17	-0.40	10	0.65	10	-0.53	12
$W_{Gr, P}$	0.65	7	0.54	5	-0.16	14	3.37	4	2.14	7	-2.01	8	-0.13	17	-2.52	5	1.63	11
R_{Gr}	0.32	13	0.28	7	-0.43	10	1.51	7	0.44	14	-1.21	9	-0.36	12	-1.31	7	9.87	1
R_{Ga}	-0.29	14	-0.71	4	-0.05	18	-0.81	11	0.04	18	0.86	13	-0.85	6	0.54	11	0.50	13
$W_{Gr,S}$	-0.22	15	-0.26	9	-0.31	12	6.75	2	3.70	4	5.38	2	-0.57	8	0.32	14	7.15	3
$F_{Ga,S}$	-0.48	9	0.13	13	-2.74	4	-0.21	16	0.70	10	-0.83	14	-3.23	4	0.08	17	0.38	14
$F_{Gr,S}$	-0.71	6	-0.50	6	-0.06	17	2.48	5	0.73	9	-5.64	1	-0.40	11	-11.54	1	6.47	5
$F_{Ga, P}$	-0.12	18	0.08	17	-0.14	15	-0.57	14	0.55	13	-0.79	15	0.31	13	-0.06	18	0.06	16
$F_{Gr,P}$	0.21	16	0.10	14	-0.55	9	-0.62	13	0.09	17	-0.30	18	0.07	18	-0.52	12	0.03	17
$C_{Ga,}$Sludge	-1.54	4	-0.08	16	-1.90	5	-0.31	15	0.84	8	-0.92	11	-2.83	5	-0.33	13	5.94	7
F_{Ga}	-14.58	1	-17.79	1	8.34	2	15.06	1	12.88	1	-4.86	3	17.73	1	-3.97	4	2.39	9
$F_{Ga, WWTP}$	3.83	3	-5.61	3	8.21	3	1.06	9	3.43	5	-1.11	10	3.41	3	-0.65	9	-0.16	15
$F_{Gr, WWTP}$	-0.52	8	-0.14	12	-0.65	7	1.39	8	-5.38	2	2.26	6	-0.27	15	5.37	2	6.75	4
F_{Gr}	-0.37	12	-0.26	8	-0.19	13	1.80	6	-2.94	6	3.26	5	-0.29	14	1.62	6	-1.69	10

Table A2.6. Sensitive parameters for temperature.

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	R^2=	0.59	R^2=	0.50	R^2=	0.63	R^2=	0.70	R^2=	0.74	R^2=	0.76	R^2=	0.53	R^2=	0.59	R^2=	0.74
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-16.88	1	-13.95	1	13.79	1	-2.02	5	-0.14	15	0.97	10	-2.54	4	-1.42	10	10.01	2
C_{Gr}, NH_4	-0.35	12	-0.46	11	-0.89	6	1.10	9	0.12	16	-0.07	18	-0.27	16	-0.53	13	0.75	13
C_{Ga}, NO_3	-0.07	18	0.16	16	-0.81	7	-0.35	16	1.14	7	-1.04	9	-2.02	5	-2.01	8	6.20	5
C_{Gr}, NO_3	-0.32	13	0.46	12	-0.08	15	1.27	7	2.00	6	-1.12	8	-0.01	18	-5.34	3	8.61	3
$W_{Ga, P}$	0.55	9	0.23	15	-0.35	10	-0.54	12	-0.23	13	0.16	16	-0.69	10	0.45	14	-0.59	15
$W_{Gr, P}$	0.80	7	0.27	14	0.07	16	6.27	3	2.01	4	-1.99	7	0.57	13	-2.80	6	1.38	11
R_{Gr}	-0.83	6	-0.48	10	-0.60	8	2.66	4	-0.79	10	-2.67	5	-0.77	9	-3.91	5	10.39	1
R_{Ga}	-0.28	15	-0.12	17	0.17	14	0.67	11	1.05	8	-0.17	14	-1.32	7	-0.36	15	0.92	12
$W_{Gr,S}$	-0.26	16	-0.07	18	0.02	17	8.82	2	7.51	2	9.98	2	-0.64	11	5.04	4	7.91	4
$F_{Ga,S}$	-0.36	11	-0.98	5	-2.23	4	0.41	15	0.27	12	0.45	12	-1.87	6	0.13	17	0.23	17
$F_{Gr,S}$	-0.54	10	-0.92	6	-0.55	9	1.36	6	0.34	11	-3.87	3	-0.61	12	-7.24	2	3.05	7
$F_{Ga, P}$	0.62	8	0.85	7	-0.22	12	0.08	18	-0.12	17	-0.37	13	0.81	8	-0.10	18	-0.03	18
$F_{Gr,P}$	-0.31	14	-0.29	13	0.20	13	-0.25	17	0.19	14	-0.13	17	-0.16	17	-0.34	16	0.32	16
C_{Ga},Sludge	-2.92	4	-1.54	4	-1.34	5	1.24	8	-0.11	18	0.17	15	-3.45	3	-0.65	12	4.08	6
F_{Ga}	-4.25	3	-10.30	2	9.15	3	16.94	1	7.02	3	-2.15	6	16.77	1	-1.02	11	-1.81	9
$F_{Ga, WWTP}$	6.53	2	-3.91	3	9.53	2	0.45	14	2.01	5	-0.50	11	5.34	2	1.45	9	-2.74	8
$F_{Gr, WWTP}$	-1.22	5	-0.69	9	-0.27	11	0.48	13	-16.39	1	16.93	1	-0.43	14	14.54	1	1.75	10
F_{Gr}	-0.26	17	-0.81	8	-0.02	18	0.71	10	-0.95	9	3.84	4	-0.39	15	2.70	7	-0.65	14

Table A2.7. Sensitive parameters for low river flow

	DO av Ga		**DO min Ga**		**NH$_4$ max Ga**		**DO av Gr**		**DO min Gr**		**NH$_4$ max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	R^2=	0.55	R^2=	0.55	R^2=	0.56	R^2=	0.70	R^2=	0.56	R^2=	0.54	R^2=	0.49	R^2=	0.53	R^2=	0.71
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH$_4$	-14.94	1	-7.20	2	14.49	1	0.37	15	-0.15	15	1.40	9	8.10	2	1.44	9	5.76	5
C_{Gr}, NH$_4$	-0.46	11	0.11	18	-0.40	11	-7.07	2	-8.26	3	4.42	3	0.07	16	-1.57	6	0.08	16
C_{Ga}, NO$_3$	0.51	10	0.16	15	-0.11	17	0.74	10	0.63	8	-1.00	12	-0.73	8	-1.15	10	4.46	7
C_{Gr}, NO$_3$	0.08	17	0.48	14	0.46	9	-0.24	18	0.62	9	-2.06	7	0.63	10	-7.09	3	8.43	2
$W_{Ga, P}$	0.63	9	0.48	13	-0.24	15	-0.39	14	0.07	17	-0.08	16	-0.55	13	0.49	13	-0.09	15
$W_{Gr, P}$	0.66	8	0.99	5	-0.28	13	2.74	5	1.29	6	-1.47	8	0.03	18	-1.45	8	1.43	9
R_{Gr}	0.31	14	0.53	8	-0.49	7	1.46	8	-0.27	14	-1.04	10	-0.48	14	-0.99	12	11.78	1
R_{Ga}	-0.43	12	-1.32	4	0.08	18	-0.91	9	-0.35	12	1.01	11	-1.06	6	0.30	15	0.90	10
$W_{Gr,S}$	-0.24	15	-0.52	9	-0.47	8	6.32	3	6.82	4	3.49	4	-0.60	11	-1.75	5	7.10	4
$F_{Ga,S}$	-0.78	6	0.48	12	-2.74	4	0.25	17	0.30	13	0.34	14	-3.16	4	0.14	17	0.37	12
$F_{Gr,S}$	-0.81	5	-0.54	7	-0.43	10	2.43	6	0.14	16	-6.03	2	-0.77	7	-9.43	2	4.73	6
$F_{Ga, P}$	0.03	18	0.13	17	0.25	14	-0.56	12	0.38	11	-0.01	18	0.59	12	0.13	18	-0.06	17
$F_{Gr,P}$	0.20	16	0.49	10	-0.13	16	-0.70	11	-0.44	10	0.06	17	0.04	17	-0.29	16	0.02	18
C_{Ga},Sludge	-2.23	4	-0.49	11	-2.27	5	-0.26	16	0.00	18	-0.18	15	-2.29	5	-0.47	14	7.74	3
F_{Ga}	-9.27	2	-15.28	1	7.32	3	13.23	1	9.48	2	-2.25	6	14.66	1	-1.49	7	0.20	14
$F_{Ga, WWTP}$	4.67	3	-7.16	3	8.15	2	0.46	13	3.55	5	-0.84	13	4.09	3	1.01	11	-0.33	13
$F_{Gr, WWTP}$	-0.74	7	0.56	6	-0.35	12	6.12	4	-10.69	1	16.09	1	-0.15	15	13.11	1	2.03	8
F_{Gr}	-0.37	13	-0.14	16	-0.55	6	2.11	7	-0.66	7	2.66	5	-0.65	9	2.14	4	-0.83	11

Table A2.8. Sensitive parameters for blower failure in La Garriga

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	$R^2=$ 0.81		$R^2=$ 0.51		$R^2=$ 0.73		$R^2=$ 0.70		$R^2=$ 0.70		$R^2=$ 0.38		$R^2=$ 0.80		$R^2=$ 0.51		$R^2=$ 0.77	
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-0.89	4	-0.37	11	1.32	3	0.86	12	0.41	12	0.33	15	1.10	3	0.17	17	2.23	8
C_{Gr}, NH_4	-0.48	8	-0.20	12	0.53	8	-8.76	2	-5.93	4	3.30	5	0.27	11	-0.81	11	0.51	13
C_{Ga}, NO_3	0.48	9	0.56	5	-0.70	5	1.15	9	0.87	8	-1.21	11	-0.89	4	-1.60	7	5.08	5
C_{Gr}, NO_3	-0.21	12	0.06	16	-0.02	17	0.31	14	0.68	10	-1.62	9	0.21	13	-4.85	4	8.61	3
$W_{Ga, P}$	0.94	3	0.79	3	-0.60	6	-0.27	15	0.13	18	0.12	18	-0.72	6	0.07	18	-0.37	15
$W_{Gr, P}$	-0.13	14	-0.42	10	-0.05	15	3.54	4	1.61	7	-0.38	13	0.13	15	-1.37	9	1.85	9
R_{Gr}	0.33	10	0.42	9	-0.20	11	1.33	7	0.40	14	-1.90	8	-0.48	8	-1.53	8	12.76	1
R_{Ga}	-0.57	7	-0.55	6	0.57	7	-0.92	11	-0.73	9	1.93	7	0.35	9	1.06	10	1.18	12
$W_{Gr,S}$	-0.80	5	-0.75	4	0.81	4	8.28	3	6.45	3	4.34	4	0.55	7	0.73	12	8.68	2
$F_{Ga,S}$	-0.13	15	0.49	7	0.09	12	0.20	16	0.41	13	0.51	12	-0.74	5	0.53	14	0.46	14
$F_{Gr,S}$	-0.15	13	-0.16	13	0.25	10	1.47	5	-0.33	15	-6.27	2	0.14	14	-8.12	2	4.27	7
$F_{Ga, P}$	0.10	16	0.15	14	-0.07	14	0.02	18	0.43	11	-0.28	17	0.12	16	-0.19	16	0.03	18
$F_{Gr,P}$	0.28	11	0.01	18	-0.31	9	-0.34	13	-0.15	17	-0.38	14	-0.25	12	-0.48	15	-0.04	17
C_{Ga},Sludge	-0.61	6	0.47	8	0.01	18	-0.15	17	-0.29	16	0.32	16	0.28	10	0.72	13	5.08	4
F_{Ga}	-20.67	1	-18.42	1	19.63	1	12.20	1	8.20	2	4.63	3	20.20	1	7.33	3	4.78	6
$F_{Ga, WWTP}$	-1.28	2	-7.94	2	4.34	2	1.46	6	2.72	5	1.53	10	4.00	2	1.87	6	-0.34	16
$F_{Gr, WWTP}$	0.04	18	0.10	15	-0.08	13	1.13	10	-14.98	1	12.84	1	0.02	18	12.86	1	1.41	10
F_{Gr}	0.04	17	-0.02	17	-0.05	16	1.25	8	-1.62	6	2.40	6	-0.11	17	2.58	5	-1.22	11

Table A2.9. Sensitive parameters for blower failure in Granollers

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	R^2=	0.65	R^2=	0.60	R^2=	0.52	R^2=	0.70	R^2=	0.87	R^2=	0.81	R^2=	0.60	R^2=	0.73	R^2=	0.76
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-14.36	1	-8.72	2	14.01	1	-1.01	8	-0.31	13	1.00	10	5.91	2	0.68	9	5.80	5
C_{Gr}, NH_4	-0.54	10	-0.36	11	-0.69	8	-1.55	5	-1.66	6	1.00	9	0.20	18	0.08	18	0.77	12
C_{Ga}, NO_3	0.75	6	0.19	15	0.00	18	0.06	18	0.12	18	-0.74	12	-0.61	9	-1.33	8	4.16	7
C_{Gr}, NO_3	-0.03	18	0.19	14	0.52	12	0.72	12	-0.70	8	-1.09	7	0.61	8	-3.50	4	7.95	3
$W_{Ga, P}$	0.83	5	0.40	9	0.32	16	-0.06	17	-0.18	16	-0.32	15	-0.36	17	0.25	13	-0.14	16
$W_{Gr, P}$	0.51	11	0.86	6	-0.33	15	5.02	3	2.31	5	-3.06	3	-0.42	12	-3.27	5	1.80	8
R_{Gr}	0.14	16	0.50	8	-0.45	13	0.79	10	0.60	9	1.00	8	-0.46	11	-0.21	16	12.35	1
R_{Ga}	-0.19	15	-0.91	4	0.57	11	0.16	15	-0.42	11	-0.15	17	-0.42	13	0.35	10	0.98	10
$W_{Gr,S}$	-0.37	13	-0.34	12	-0.63	10	10.63	2	3.56	3	-2.35	6	-0.46	10	-2.53	7	8.15	2
$F_{Ga,S}$	-0.72	7	-0.06	17	-3.37	4	0.30	13	0.20	15	0.29	16	-3.06	4	0.23	14	0.23	14
$F_{Gr,S}$	-0.68	8	-0.36	10	-0.41	14	-1.45	6	0.25	14	2.46	5	-0.68	6	-5.11	2	4.26	6
$F_{Ga, P}$	0.03	17	0.08	16	-0.01	17	-0.07	16	0.16	17	-0.70	13	0.36	16	-0.29	12	0.34	13
$F_{Gr,P}$	0.42	12	0.62	7	-0.69	9	-0.92	9	-0.52	10	0.45	14	-0.36	15	0.30	11	-0.05	18
C_{Ga},Sludge	-1.85	4	-0.87	5	-1.57	5	0.22	14	-0.33	12	-0.12	18	-1.43	5	0.21	15	7.65	4
F_{Ga}	-12.63	2	-16.53	1	7.61	2	16.33	1	8.68	2	-6.14	2	17.16	1	-4.26	3	0.16	15
$F_{Ga, WWTP}$	2.13	3	-2.72	3	7.47	3	1.20	7	3.45	4	-0.76	11	4.56	3	-0.19	17	-0.10	17
$F_{Gr, WWTP}$	-0.63	9	0.31	13	-0.97	6	-3.20	4	-18.17	1	18.62	1	-0.41	14	17.92	1	1.40	9
F_{Gr}	-0.30	14	-0.01	18	-0.92	7	0.73	11	-1.34	7	2.88	4	-0.64	7	2.61	6	-0.82	11

A3. COMPARISION BETWEEN REFERENCE AND BEST STRATEGY IN THE CASE OF STROM SCENARIO.

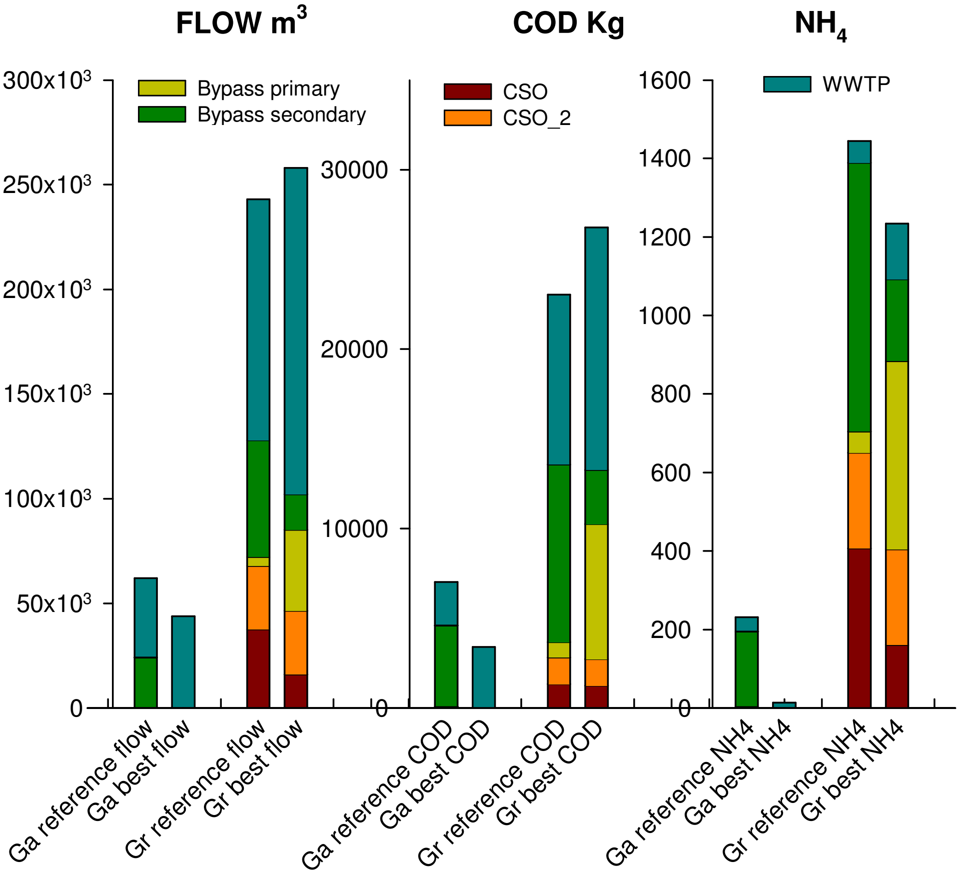


Figure A3.1. Comparision between reference and best strategy.

A4. RESULTS FROM GLOBAL SENSITIVITY ANALYSIS AND SCREENING FOR COMBINATION OF SCENARIOS

Table A4.1. Sensitive parameters for blower failure in La Garriga and storm.

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	R^2=	0.87	R^2=	0.79	R^2=	0.74	R^2=	0.70	R^2=	0.28	R^2=	0.79	R^2=	0.75	R^2=	0.83	R^2=	0.75
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
$C_{Ga,}$ NH_4	-0.92	3	-4.31	3	1.29	4	-1.74	8	0.98	10	0.54	12	2.79	4	0.99	8	0.88	13
$C_{Gr,}$ NH_4	0.11	15	0.44	9	-0.09	16	-7.92	2	-2.42	4	1.04	9	0.19	15	0.69	10	0.62	14
$C_{Ga,}$ NH_3	0.21	11	0.15	14	-0.74	5	-0.22	16	-0.97	11	-0.03	17	-0.49	12	0.01	18	3.35	7
$C_{Gr,}$ NH_3	-0.05	18	0.07	17	0.14	14	-0.49	15	-0.23	18	0.34	13	0.13	16	-0.33	15	7.75	2
$W_{Ga, P}$	0.15	14	0.10	16	-0.11	15	-0.04	18	-0.68	12	-0.29	14	-0.28	14	-0.25	17	-0.19	17
$W_{Gr, P}$	-0.05	17	-0.30	10	-0.38	11	1.74	9	1.37	7	-1.14	8	-0.58	11	-1.70	6	2.47	8
R_{Gr}	-0.29	8	-0.29	11	0.60	6	-0.62	14	0.34	17	-0.24	16	0.37	13	0.37	13	6.19	5
R_{Ga}	-0.42	5	0.25	12	0.53	7	-0.86	11	-0.57	14	0.01	18	1.27	6	0.36	14	1.09	10
$W_{Gr,S}$	-0.29	9	-0.13	15	0.45	10	2.94	5	1.29	8	1.53	7	0.65	9	-0.28	16	3.96	6
$F_{Ga,S}$	0.29	7	4.11	4	-3.20	3	1.61	10	2.26	5	-2.33	4	-5.81	2	-3.23	4	7.33	3
$F_{Gr,S}$	-0.22	10	0.07	18	-0.06	17	16.56	1	3.74	3	-16.68	1	-0.13	17	-19.72	1	13.17	1
$F_{Ga, P}$	-0.15	13	1.41	5	0.03	18	0.11	17	-0.36	16	-0.58	11	-1.46	5	-0.85	9	2.28	9
$F_{Gr,P}$	0.64	4	0.59	6	-0.50	8	0.65	13	0.57	13	-0.76	10	-0.77	8	-1.42	7	0.31	16
$C_{Ga,}$Sludge	-0.06	16	0.55	8	0.29	12	-0.78	12	-1.14	9	0.26	15	-0.81	7	0.59	12	6.85	4
F_{Ga}	-21.02	1	-16.33	1	19.08	1	1.75	7	7.45	2	-1.62	5	18.94	1	-3.46	3	0.03	18
$F_{Ga, WWTP}$	-2.19	2	-11.31	2	6.18	2	-3.17	4	-0.37	15	2.45	3	4.16	3	2.29	5	-1.03	12
$F_{Gr, WWTP}$	0.32	6	-0.23	13	-0.20	13	-3.77	3	10.98	1	11.36	2	-0.58	10	4.45	2	-0.39	15
F_{Gr}	-0.16	12	-0.57	7	0.45	9	2.89	6	-1.46	6	-1.56	6	0.12	18	-0.61	11	-1.04	11

Table A4.2. Sensitive parameters for blower failure in Granollers and storm.

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	$R^2=$	0.87	$R^2=$	0.79	$R^2=$	0.74	$R^2=$	0.70	$R^2=$	0.28	$R^2=$	0.79	$R^2=$	0.75	$R^2=$	0.83	$R^2=$	0.75
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-0.92	3	-4.31	3	1.29	4	-1.74	8	0.98	10	0.54	12	2.79	4	0.99	8	0.88	13
C_{Gr}, NH_4	0.11	15	0.44	9	-0.09	16	-7.92	2	-2.42	4	1.04	9	0.19	15	0.69	10	0.62	14
C_{Ga}, NH_3	0.21	11	0.15	14	-0.74	5	-0.22	16	-0.97	11	-0.03	17	-0.49	12	0.01	18	3.35	7
C_{Gr}, NH_3	-0.05	18	0.07	17	0.14	14	-0.49	15	-0.23	18	0.34	13	0.13	16	-0.33	15	7.75	2
$W_{Ga,\ P}$	0.15	14	0.10	16	-0.11	15	-0.04	18	-0.68	12	-0.29	14	-0.28	14	-0.25	17	-0.19	17
$W_{Gr,\ P}$	-0.05	17	-0.30	10	-0.38	11	1.74	9	1.37	7	-1.14	8	-0.58	11	-1.70	6	2.47	8
R_{Gr}	-0.29	8	-0.29	11	0.60	6	-0.62	14	0.34	17	-0.24	16	0.37	13	0.37	13	6.19	5
R_{Ga}	-0.42	5	0.25	12	0.53	7	-0.86	11	-0.57	14	0.01	18	1.27	6	0.36	14	1.09	10
$W_{Gr,S}$	-0.29	9	-0.13	15	0.45	10	2.94	5	1.29	8	1.53	7	0.65	9	-0.28	16	3.96	6
$F_{Ga,S}$	0.29	7	4.11	4	-3.20	3	1.61	10	2.26	5	-2.33	4	-5.81	2	-3.23	4	7.33	3
$F_{Gr,S}$	-0.22	10	0.07	18	-0.06	17	16.56	1	3.74	3	-16.68	1	-0.13	17	-19.72	1	13.17	1
$F_{Ga,\ P}$	-0.15	13	1.41	5	0.03	18	0.11	17	-0.36	16	-0.58	11	-1.46	5	-0.85	9	2.28	9
$F_{Gr,P}$	0.64	4	0.59	6	-0.50	8	0.65	13	0.57	13	-0.76	10	-0.77	8	-1.42	7	0.31	16
C_{Ga},Sludge	-0.06	16	0.55	8	0.29	12	-0.78	12	-1.14	9	0.26	15	-0.81	7	0.59	12	6.85	4
F_{Ga}	-21.02	1	-16.33	1	19.08	1	1.75	7	7.45	2	-1.62	5	18.94	1	-3.46	3	0.03	18
$F_{Ga,\ WWTP}$	-2.19	2	-11.31	2	6.18	2	-3.17	4	-0.37	15	2.45	3	4.16	3	2.29	5	-1.03	12
$F_{Gr,\ WWTP}$	0.32	6	-0.23	13	-0.20	13	-3.77	3	10.98	1	11.36	2	-0.58	10	4.45	2	-0.39	15
F_{Gr}	-0.16	12	-0.57	7	0.45	9	2.89	6	-1.46	6	-1.56	6	0.12	18	-0.61	11	-1.04	11

Table A4.3. Sensitive parameters for high load La Garriga and temperature.

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	R^2=	0.70	R^2=	0.64	R^2=	0.52	R^2=	0.70	R^2=	0.72	R^2=	0.57	R^2=	0.54	R^2=	0.51	R^2=	0.79
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-14.86	1	-8.61	2	12.10	1	0.02	17	-0.26	16	0.80	12	5.16	3	1.67	6	0.11	17
C_{Gr}, NH_4	-0.47	10	-0.26	10	-0.76	8	-8.13	3	-5.45	4	4.28	4	-0.36	13	-1.14	9	0.47	13
C_{Ga}, NH_3	0.56	7	0.02	18	-0.85	6	1.32	7	0.88	9	-1.26	9	-1.11	8	-1.39	8	3.36	6
C_{Gr}, NH_3	0.04	18	0.25	11	0.10	17	0.49	12	0.75	10	-1.57	7	-0.37	12	-5.58	3	8.89	2
$W_{Ga, P}$	0.67	5	0.45	6	-0.51	11	-0.11	16	0.24	17	-0.01	18	-1.14	7	0.21	14	-0.32	14
$W_{Gr, P}$	0.51	9	0.58	4	-0.01	18	3.34	4	2.00	6	-1.63	6	-0.09	18	-2.21	5	1.96	7
R_{Gr}	-0.07	16	-0.11	14	-0.34	14	1.56	5	0.29	14	-1.18	11	-0.39	10	-1.13	10	12.57	1
R_{Ga}	-0.09	14	-0.44	8	-0.81	7	-0.48	13	-0.05	18	1.31	8	-2.67	5	-0.01	18	1.20	10
$W_{Gr,S}$	-0.07	17	-0.09	15	-0.56	9	8.18	2	6.66	3	4.59	3	-1.02	9	-0.07	17	8.45	3
$F_{Ga,S}$	-0.56	8	0.03	17	-3.68	5	0.23	15	0.44	11	0.07	17	-2.00	6	0.35	12	0.17	16
$F_{Gr,S}$	-0.58	6	-0.57	5	-0.51	10	1.43	6	-0.31	13	-6.22	2	-0.37	11	-9.21	2	4.18	5
$F_{Ga, P}$	0.08	15	-0.04	16	0.38	13	0.01	18	0.28	15	-0.39	14	0.26	14	-0.10	15	0.22	15
$F_{Gr,P}$	0.27	12	0.42	9	-0.26	16	-0.40	14	-0.31	12	0.11	16	-0.15	16	-0.27	13	-0.01	18
C_{Ga},Sludge	-1.95	4	-0.44	7	-5.16	4	1.27	8	0.92	8	0.22	15	-8.24	2	-1.50	7	8.14	4
F_{Ga}	-12.79	2	-16.91	1	9.30	2	12.94	1	7.90	2	-1.19	10	14.67	1	0.10	16	1.68	8
$F_{Ga, WWTP}$	2.12	3	-3.46	3	7.29	3	1.23	9	2.43	5	-0.54	13	4.38	4	0.65	11	0.89	12
$F_{Gr, WWTP}$	-0.41	11	0.17	12	-0.28	15	0.94	11	-15.28	1	16.39	1	-0.16	15	13.65	1	1.55	9
F_{Gr}	-0.12	13	0.15	13	-0.50	12	1.15	10	-1.80	7	2.65	5	0.10	17	2.75	4	-0.97	11

Table A4.4. Sensitive parameters for high load Granollers and temperature.

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	$R^2=$	0.64	$R^2=$	0.62	$R^2=$	0.52	$R^2=$	0.70	$R^2=$	0.73	$R^2=$	0.61	$R^2=$	0.58	$R^2=$	0.45	$R^2=$	0.67
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-14.36	1	-8.81	2	13.94	1	-0.13	16	0.07	17	0.56	12	5.84	2	0.21	16	5.72	5
C_{Gr}, NH_4	-0.40	10	-0.22	12	-0.68	7	-6.30	3	-4.92	4	3.11	4	0.41	14	0.93	9	-0.28	13
C_{Ga}, NO_3	0.56	8	0.01	18	0.11	17	0.87	8	0.59	9	-1.09	9	-0.53	8	-1.51	7	4.21	6
C_{Gr}, NO_3	0.18	16	0.50	8	0.44	13	-0.29	13	-0.71	8	-0.49	14	0.44	9	-2.67	3	11.20	1
$W_{Ga, P}$	0.67	5	0.32	11	0.20	16	-0.10	18	0.27	14	0.02	18	-0.44	10	0.41	13	0.14	15
$W_{Gr, P}$	0.38	11	0.71	5	-0.47	11	3.91	4	1.89	6	-2.10	6	-0.61	6	-2.54	5	1.12	10
R_{Gr}	0.17	17	0.16	15	-0.37	14	1.16	6	0.36	11	-1.36	8	-0.18	17	-1.48	8	9.34	2
R_{Ga}	-0.27	13	-0.76	4	0.45	12	-0.64	11	-0.36	12	1.03	10	-0.56	7	0.83	10	1.16	9
$W_{Gr,S}$	-0.20	15	-0.32	10	-0.53	10	9.12	2	6.18	3	4.74	3	-0.26	16	0.21	15	7.54	3
$F_{Ga,S}$	-0.57	7	0.17	14	-3.78	4	0.12	17	0.05	18	0.38	15	-3.59	4	0.42	12	0.39	12
$F_{Gr,S}$	-0.66	6	-0.53	7	-0.28	15	0.98	7	0.27	15	-5.53	2	-0.42	11	-10.00	2	4.13	7
$F_{Ga, P}$	0.02	18	-0.02	17	0.02	18	-0.25	14	0.18	16	-0.04	17	0.42	12	0.15	17	0.03	17
$F_{Gr,P}$	0.29	12	0.41	9	-0.55	9	-0.72	10	-0.50	10	0.10	16	-0.08	18	0.12	18	-0.15	14
C_{Ga},Sludge	-1.60	4	-0.65	6	-1.68	5	-0.23	15	-0.31	13	0.55	13	-1.52	5	0.66	11	6.99	4
F_{Ga}	-12.62	2	-16.73	1	7.80	2	14.25	1	8.16	2	-1.74	7	17.04	1	-2.15	6	-0.11	16
$F_{Ga, WWTP}$	2.22	3	-2.58	3	7.20	3	1.46	5	3.37	5	-0.64	11	4.18	3	-0.26	14	-0.02	18
$F_{Gr, WWTP}$	-0.46	9	0.21	13	-1.07	6	-0.58	12	-15.70	1	17.26	1	-0.29	15	13.24	1	1.82	8
F_{Gr}	-0.27	14	0.07	16	-0.64	8	0.78	9	-1.63	7	2.97	5	-0.41	13	2.58	4	-0.62	11

Table A4.5. Sensitive parameters for low river flow and blower failure in La Garriga.

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	R^2= 0.81		R^2= 0.73		R^2= 0.70		R^2= 0.70		R^2= 0.58		R^2= 0.38		R^2= 0.77		R^2= 0.53		R^2= 0.75	
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-0.96	3	0.47	7	1.42	3	0.83	12	0.83	9	-0.36	17	1.17	3	-0.22	15	2.53	8
C_{Gr}, NH_4	-0.66	6	-0.44	9	0.69	6	-8.62	2	-8.36	3	3.51	4	0.41	10	-0.84	11	0.73	13
C_{Ga}, NH_3	0.40	9	0.53	6	-0.71	5	1.10	10	0.97	6	-0.87	12	-0.76	4	-1.34	7	4.93	5
C_{Gr}, NH_3	-0.47	7	-0.16	16	0.25	11	0.29	14	0.52	13	-0.56	13	0.41	11	-4.56	4	8.44	3
$W_{Ga, P}$	0.98	2	0.78	3	-0.51	7	-0.37	13	0.13	17	-0.37	16	-0.62	7	-0.07	18	-0.27	16
$W_{Gr, P}$	-0.43	8	-0.76	4	0.36	10	3.03	4	0.78	10	1.54	9	0.47	9	-0.17	17	1.66	9
R_{Gr}	0.02	18	-0.11	17	0.23	12	1.47	7	0.03	18	-1.04	10	-0.15	13	-1.11	8	12.69	1
R_{Ga}	-0.27	11	-0.17	15	0.17	14	-1.09	11	-0.88	8	1.61	8	0.01	17	0.67	13	1.09	12
$W_{Gr,S}$	-0.89	5	-0.67	5	0.85	4	7.58	3	6.80	4	3.41	5	0.65	5	1.02	9	8.84	2
$F_{Ga,S}$	-0.23	12	0.34	12	0.42	9	0.22	16	0.32	14	1.00	11	-0.62	6	0.69	12	0.35	15
$F_{Gr,S}$	-0.29	10	-0.46	8	0.47	8	1.74	6	-0.13	16	-5.44	3	0.30	12	-7.38	3	4.03	7
$F_{Ga, P}$	0.17	13	0.25	13	-0.15	15	-0.01	18	0.63	11	-0.46	15	0.01	18	-0.43	14	0.23	17
$F_{Gr,P}$	-0.02	17	-0.37	11	-0.02	18	-0.22	15	-0.27	15	-0.19	18	0.08	15	-0.17	16	-0.14	18
C_{Ga},Sludge	-0.92	4	0.38	10	0.18	13	-0.21	17	-0.56	12	0.55	14	0.54	8	0.90	10	4.96	4
F_{Ga}	-20.71	1	-19.10	1	19.54	1	12.58	1	8.81	2	9.81	2	19.92	1	8.56	2	4.79	6
$F_{Ga, WWTP}$	-0.10	14	-6.32	2	3.61	2	1.36	9	3.42	5	2.00	7	4.57	2	2.12	6	-0.50	14
$F_{Gr, WWTP}$	-0.10	15	-0.20	14	0.08	17	2.48	5	-11.54	1	10.27	1	0.14	14	13.00	1	1.15	11
F_{Gr}	0.03	16	0.04	18	-0.13	16	1.39	8	-0.93	7	2.30	6	-0.04	16	2.72	5	-1.39	10

Table A4.6. Sensitive parameters for low river flow and blower failure in Granollers.

	DO av Ga		**DO min Ga**		**NH_4 max Ga**		**DO av Gr**		**DO min Gr**		**NH_4 max Gr**		**RQI Ga**		**RQI Gr**		**TC**	
	$R^2=$	0.61	$R^2=$	0.56	$R^2=$	0.57	$R^2=$	0.70	$R^2=$	0.78	$R^2=$	0.80	$R^2=$	0.51	$R^2=$	0.74	$R^2=$	0.76
	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank	*t*PCC	rank
C_{Ga}, NH_4	-16.27	1	-7.25	2	14.84	1	-0.35	12	0.22	16	0.99	10	7.76	2	0.82	9	5.86	5
C_{Gr}, NH_4	-0.44	11	0.30	14	-0.76	7	-1.68	5	-2.41	5	0.97	11	-0.01	18	-0.15	15	0.80	11
C_{Ga}, NH_3	0.70	6	0.30	13	0.25	16	0.04	17	0.26	15	-0.76	13	-0.33	14	-1.31	8	4.20	7
C_{Gr}, NH_3	-0.04	18	0.47	8	0.51	13	0.68	11	-0.88	8	-1.00	9	0.66	8	-3.49	4	7.96	3
$W_{Ga, P}$	0.69	7	0.23	15	0.19	17	-0.12	15	-0.15	17	-0.40	14	-0.21	15	0.13	16	-0.10	16
$W_{Gr, P}$	0.52	10	0.80	5	-0.32	15	4.64	3	1.87	6	-2.80	4	-0.18	16	-2.54	6	1.67	8
R_{Gr}	0.24	13	0.22	16	-0.59	9	0.99	8	0.46	13	1.06	7	-0.59	10	-0.19	13	12.34	1
R_{Ga}	-0.05	17	-0.87	4	0.52	12	-0.04	16	-0.50	11	-0.27	17	-0.69	7	0.25	11	1.12	10
$W_{Gr,S}$	-0.23	15	-0.47	9	-0.53	11	10.22	2	3.93	4	-2.23	6	-0.57	11	-2.26	7	8.07	2
$F_{Ga,S}$	-0.59	9	0.41	11	-3.51	4	0.19	13	-0.02	18	0.36	16	-4.12	4	0.23	12	0.27	14
$F_{Gr,S}$	-0.85	5	-0.53	7	-0.40	14	-1.20	7	0.55	10	2.99	3	-0.78	6	-4.88	2	4.34	6
$F_{Ga, P}$	-0.08	16	0.11	18	-0.06	18	-0.02	18	0.29	14	-0.78	12	0.35	13	-0.45	10	0.31	13
$F_{Gr,P}$	0.24	14	0.62	6	-0.56	10	-0.77	10	-0.61	9	0.36	15	-0.05	17	0.17	14	-0.05	18
C_{Ga},Sludge	-1.98	4	-0.45	10	-1.58	5	0.13	14	-0.47	12	-0.16	18	-1.88	5	0.12	17	7.70	4
F_{Ga}	-8.82	2	-15.39	1	7.05	3	17.01	1	11.28	2	-6.37	2	14.83	1	-4.54	3	0.06	17
$F_{Ga, WWTP}$	3.53	3	-7.17	3	7.87	2	1.21	6	4.46	3	-1.01	8	4.78	3	0.00	18	-0.12	15
$F_{Gr, WWTP}$	-0.64	8	0.37	12	-1.02	6	-1.77	4	-15.58	1	18.45	1	-0.56	12	18.04	1	1.38	9
F_{Gr}	-0.27	12	0.18	17	-0.63	8	0.84	9	-1.18	7	2.75	5	-0.61	9	2.65	5	-0.68	12

Table A4.7. Screening results for blower failure in La Garriga and storm.

	LA GARRIGA				GRANOLLERS				TC
	DO av	**DO min**	**NH**	**RQI**	**DO av**	**DO min**	**NH**	**RQI**	
335	8.49	7.80	1.66	193.09	7.06	5.73	4.12	245.47	2014.33
400	8.60	7.49	1.65	191.15	7.00	5.78	4.52	251.96	2009.66
725	8.56	8.20	1.33	189.41	7.10	5.44	3.80	240.23	2005.38
794	8.48	7.78	1.70	193.52	7.00	5.15	4.40	253.57	1940.15
Reference	8.70	7.81	1.41	187.99	6.97	4.72	4.37	253.62	1997.86
% Improvement									
335	-2	0	-18	-3	1	21	6	3	-1
400	-1	-4	-17	-2	0	23	-3	1	-1
725	-2	5	5	-1	2	15	13	5	0
794	-3	0	-21	-3	0	9	-1	0	3

Table A4.8. Screening results for blower failure in Granollers and storm.

	LA GARRIGA				GRANOLLERS				TC
	DO av	**DO min**	**NH**	**RQI**	**DO av**	**DO min**	**NH**	**RQI**	
870	8.66	7.72	0.86	7.02	181.51	5.85	4.28	242.30	1923.33
Reference	8.68	7.81	1.40	187.68	6.93	4.71	4.38	253.10	1901.03
% Improvement									
870	-1	-1	38	2	4	24	2	4	-1

Table A4. 9. Screening results for high load La Garriga and temperature.

	LA GARRIGA				GRANOLLERS				TC
	DO av	DO min	NH	RQI	DO av	DO min	NH	RQI	
73	7.42	6.96	0.90	266.16	6.24	4.53	6.21	480.15	2043.98
86	6.96	5.91	0.95	276.63	6.28	4.63	6.39	481.83	2068.49
87	7.41	6.94	0.86	267.39	6.24	4.69	4.25	468.81	2072.98
148	6.77	5.86	0.96	275.70	6.38	5.00	3.57	465.07	2091.63
301	7.08	5.86	0.94	271.59	6.28	4.60	6.05	475.58	2091.91
307	7.45	7.01	0.82	264.45	6.24	4.78	3.52	464.83	2040.31
322	7.11	6.05	0.82	265.21	6.23	4.95	1.94	456.91	1951.65
338	6.88	6.07	0.90	277.52	6.33	4.83	3.38	466.89	2077.29
424	6.79	6.01	0.83	265.37	6.25	4.94	2.82	461.13	2058.87
460	6.67	6.04	1.21	268.17	6.26	4.99	2.18	455.93	2075.89
502	6.94	5.77	1.02	274.83	6.32	4.76	3.99	467.91	2082.43
540	6.90	6.34	0.75	276.22	6.32	4.70	4.29	473.78	2075.68
557	6.99	5.86	0.94	271.60	6.40	5.25	3.56	451.55	2054.27
589	6.91	6.25	0.83	256.30	6.30	5.16	3.38	445.85	2033.66
614	6.59	5.71	1.00	276.08	6.27	4.53	4.75	474.34	2092.09
661	7.15	6.19	0.96	266.36	6.26	4.89	4.06	473.81	1973.36
696	6.68	5.86	0.91	270.72	6.36	5.18	2.05	454.26	2031.40
721	6.96	5.95	0.88	272.90	6.35	4.98	5.91	478.06	2085.82
791	7.26	6.60	1.07	279.96	6.29	4.69	4.40	478.32	2072.69
837	6.91	5.92	0.91	276.14	6.29	4.47	5.95	477.03	2094.65
862	7.32	6.87	0.82	272.77	6.26	4.59	5.71	474.55	2023.91
867	6.81	5.92	0.90	269.16	6.25	4.78	3.70	458.61	2085.79
934	6.97	5.75	0.99	275.51	6.38	4.83	6.30	478.20	2097.32
972	6.77	5.88	0.89	272.44	6.31	4.66	6.16	473.85	2098.16
Reference	6.73	5.59	1.97	298.64	6.25	4.03	9.37	512.59	2448.26
				% Improvement					
73	10	25	55	11	0	12	34	6	17
86	3	6	52	7	1	15	32	6	16
87	10	24	57	10	0	16	55	9	15
148	1	5	51	8	2	24	62	9	15
301	5	5	53	9	1	14	35	7	15
307	11	26	59	11	0	18	62	9	17
322	6	8	59	11	0	23	79	11	20
338	2	9	55	7	1	20	64	9	15
424	1	8	58	11	0	22	70	10	16
460	-1	8	39	10	0	24	77	11	15
502	3	3	48	8	1	18	57	9	15
540	3	13	62	8	1	16	54	8	15
557	4	5	52	9	2	30	62	12	16
589	3	12	58	14	1	28	64	13	17
614	-2	2	50	8	0	12	49	7	15
661	6	11	51	11	0	21	57	8	19
696	-1	5	54	9	2	28	78	11	17
721	3	6	55	9	2	23	37	7	15
791	8	18	46	6	1	16	53	7	15
837	3	6	54	8	1	11	37	7	14
862	9	23	59	9	0	14	39	7	17
867	1	6	55	10	0	18	60	11	15
934	4	3	50	8	2	20	33	7	14
972	1	5	55	9	1	16	34	8	14

Table A4. 10. Screening results for high load Granollers and temperature.

	LA GARRIGA				GRANOLLERS				TC
	DO av	**DO min**	**NH**	**RQI**	**DO av**	**DO min**	**NH**	**RQI**	
29	6.68	5.88	0.90	242.62	6.24	4.99	2.53	427.23	2085.93
149	7.15	6.59	0.60	244.65	6.45	5.40	3.47	426.99	2024.84
182	6.65	5.76	0.99	246.82	6.27	4.94	3.74	428.70	2183.76
184	7.05	6.24	0.69	233.88	6.24	5.10	3.95	427.19	2100.13
218	6.66	5.96	1.17	242.99	6.20	4.94	4.05	437.46	2147.30
262	6.87	6.04	0.75	238.78	6.40	5.37	2.41	414.10	2094.70
295	6.90	5.81	1.09	250.84	6.19	4.83	3.65	433.12	2154.03
321	6.95	6.25	0.72	253.00	6.26	4.67	5.58	440.86	2183.83
376	7.00	5.97	0.90	246.10	6.23	5.03	2.20	426.49	2105.40
436	7.34	6.48	0.65	233.47	6.19	5.03	2.73	420.96	1999.95
548	6.97	6.44	0.64	251.11	6.33	4.92	5.04	448.25	2068.28
819	6.77	6.03	0.83	237.92	6.19	4.92	2.81	425.08	2146.61
884	6.96	6.26	0.72	250.87	6.15	4.62	4.87	443.17	2099.42
929	6.71	5.77	0.82	247.84	6.23	4.89	3.90	431.52	2165.50
982	6.81	5.96	0.78	241.04	6.25	5.10	2.12	421.48	2077.68
Reference	7.22	6.02	2.52	297.31	6.21	4.13	12.92	539.67	1856.35
% Improvement									
29	-7	-2	64	18	1	21	80	21	-12
149	-1	9	76	18	4	31	73	21	-9
182	-8	-4	61	17	1	19	71	21	-18
184	-2	4	73	21	1	23	69	21	-13
218	-8	-1	54	18	0	20	69	19	-16
262	-5	0	70	20	3	30	81	23	-13
295	-4	-4	57	16	0	17	72	20	-16
321	-4	4	71	15	1	13	57	18	-18
376	-3	-1	64	17	0	22	83	21	-13
436	2	8	74	21	0	22	79	22	-8
548	-4	7	75	16	2	19	61	17	-11
819	-6	0	67	20	0	19	78	21	-16
884	-4	4	72	16	-1	12	62	18	-13
929	-7	-4	67	17	0	18	70	20	-17
982	-6	-1	69	19	1	23	84	22	-12

Table A4. 11. Screening results for low river flow and blower failure in La Garriga.

	LA GARRIGA				GRANOLLERS				TC
	DO av	**DO min**	**NH**	**RQI**	**DO av**	**DO min**	**NH**	**RQI**	
73	5.55	3.72	20.50	531.60	5.62	4.03	8.93	606.65	1969.17
141	5.70	4.08	16.23	454.90	5.69	4.41	6.27	559.82	1934.04
161	5.67	3.85	19.32	506.04	5.60	4.14	7.98	590.36	1973.51
193	5.46	3.78	20.03	526.30	5.60	4.10	8.41	593.55	1950.05
668	5.60	3.77	20.06	521.89	5.60	4.17	8.36	590.69	1952.13
718	5.55	3.82	19.42	511.71	5.58	3.96	8.36	596.18	1956.01
727	5.75	3.93	18.53	490.10	5.64	4.35	7.33	576.20	1963.34
807	5.78	4.13	15.42	442.67	5.60	4.24	6.00	563.86	1925.75
848	6.20	4.36	12.33	401.60	5.72	4.62	4.59	537.08	1946.60
938	6.04	4.21	14.95	432.19	5.61	4.34	5.38	550.93	1972.60
Reference	5.16	2.80	25.07	646.38	5.63	3.34	12.17	675.38	1969.34
				% Improvement					
73	8	33	18	18	0	21	27	10	0
141	10	46	35	30	1	32	48	17	2
161	10	38	23	22	-1	24	34	13	0
193	6	35	20	19	-1	23	31	12	1
668	8	35	20	19	-1	25	31	13	1
718	7	36	23	21	-1	19	31	12	1
727	11	40	26	24	0	30	40	15	0
807	12	48	39	32	-1	27	51	17	2
848	20	56	51	38	2	38	62	20	1
938	17	50	40	33	0	30	56	18	0

Table A4. 12. Screening results for low river flow and blower failure in Granollers.

		LA GARRIGA				**GRANOLLERS**			**TC**
	DO av	**DO min**	**NH**	**RQI**	**DO av**	**DO min**	**NH**	**RQI**	
156	4.82	4.04	1.77	317.45	5.39	3.79	12.50	544.80	1995.12
322	4.95	4.16	0.95	322.87	5.39	3.43	17.72	591.10	2013.28
370	5.28	4.02	1.36	321.00	5.46	3.83	12.98	548.03	1966.28
436	4.83	3.97	1.08	331.61	5.75	4.18	9.98	524.54	1972.67
496	5.00	4.13	1.22	312.91	5.39	3.80	10.78	537.41	1949.60
576	4.96	4.22	1.32	310.31	5.66	4.01	9.97	523.28	1979.35
688	5.34	4.34	0.85	329.43	5.52	3.48	17.65	591.66	2006.93
691	4.79	4.11	1.05	320.30	5.75	4.08	10.24	526.37	2010.51
817	5.69	4.20	0.97	326.76	5.43	3.86	9.80	531.15	1784.21
853	5.14	4.73	1.92	314.61	5.49	3.73	11.51	533.96	1994.71
904	4.85	4.13	1.78	315.16	5.51	3.83	12.11	540.96	1995.94
922	4.89	3.97	1.55	318.83	5.53	3.99	9.97	525.24	1938.27
Reference	5.10	3.62	3.19	354.97	5.38	3.10	22.70	655.77	1968.77
				% Improvement					
156	-5	12	44	11	0	22	45	17	-1
322	-3	15	70	9	0	11	22	10	-2
370	3	11	57	10	1	24	43	16	0
436	-5	10	66	7	7	35	56	20	0
496	-2	14	62	12	0	23	53	18	1
576	-3	17	59	13	5	30	56	20	-1
688	5	20	73	7	3	12	22	10	-2
691	-6	14	67	10	7	32	55	20	-2
817	12	16	70	8	1	25	57	19	9
853	1	31	40	11	2	21	49	19	-1
904	-5	14	44	11	2	24	47	18	-1
922	-4	10	51	10	3	29	56	20	2

Table A4.13. Criteria values for the different options in case blower failure in Granollers (Gr) and storm.

		LA GARRIGA				**GRANOLLERS**			**TC**
	DO av	**DO min**	**NH_4 max**	**RQI**	**DO av**	**DO min**	**NH_4 max**	**RQI**	
Best storm	9.00	8.62	0.56	176.93	7.07	5.03	4.17	241.18	1941.19
Best Gr	9.13	8.85	0.54	174.77	6.83	4.60	5.17	300.05	1608.24
Best scenario	8.66	7.72	0.86	181.51	7.02	5.85	4.28	242.30	1923.33
Average	9.09	8.81	0.54	176.08	7.08	4.75	4.23	244.10	1800.7632
Reference	8.68	7.81	1.40	187.68	6.93	4.71	4.38	253.10	1901.03
				% Improvement					
Best storm	-4	-10	60	6	-2	-7	5	5	-2
Best Gr	-5	-13	62	7	1	2	-18	-19	15
Best scenario	0	1	38	3	-1	-24	2	4	-1
Average	-5	-13	61	6	-2	-1	3	4	5

Table A4.14. Criteria values for the different options in case of high load La Garriga (Ga) and temperature.

	LA GARRIGA				**GRANOLLERS**				**TC**
	DO av	**DO min**	**NH_4 max**	**RQI**	**DO av**	**DO min**	**NH_4 max**	**RQI**	
Best Temp.	6.54	5.73	0.87	277.74	6.42	5.32	2.17	449.92	2081.50
Best Ga	6.71	5.80	0.97	272.64	6.42	5.32	2.59	444.69	2078.95
Best	6.91	6.25	0.83	256.30	6.30	5.16	3.38	445.85	2033.66
Average	6.71	5.68	1.09	277.78	6.44	5.37	2.34	447.22	2094.03
Reference	6.73	5.59	1.97	298.64	6.25	4.03	9.37	512.59	2448.26
% Improvement									
Best Temp.	-3	2	56	7	3	32	77	12	15
Best Ga	0	4	51	9	3	32	72	13	15
Best	3	12	58	14	1	28	64	13	17
Average	0	2	45	7	3	33	75	13	14

Table A4.15. Criteria values for the different options in case of high load Granollers (Gr) and temperature.

	LA GARRIGA				**GRANOLLERS**				**TC**
	DO av	**DO min**	**NH_4 max**	**RQI**	**DO av**	**DO min**	**NH_4 max**	**RQI**	
Best Temp.	6.88	6.12	1.08	258.56	6.36	5.47	5.32	445.14	1910.00
Best Gr	7.46	7.13	0.77	264.80	6.49	5.74	8.08	480.20	1839.15
Best	7.34	6.48	0.65	233.47	6.19	5.03	2.73	420.96	1999.95
Average	7.37	6.96	0.89	273.85	6.43	5.61	6.53	463.20	1871.50
Reference	7.22	6.02	2.52	297.31	6.21	4.13	12.92	539.67	1856.35
%Improve									
Best Temp.	-5	2	57	13	3	32	59	18	-3
Best Gr	3	18	69	11	4	39	37	11	1
Best	2	8	74	21	0	22	79	22	-8
Average	2	15	65	8	4	36	49	14	-1

Table A4.16. Criteria values for the different options in case of low river flow and blower failure in La Garriga (Ga).

	LA GARRIGA				**GRANOLLERS**				**TC**
	DO av	**DO min**	**NH_4 max**	**RQI**	**DO av**	**DO min**	**NH_4 max**	**RQI**	
Best low river	5.41	3.69	20.82	543.73	5.69	4.36	8.88	583.12	2.007.22
Best Ga	6.20	4.36	12.33	401.69	5.72	4.62	4.59	537.25	1.947.16
Best	6.20	4.36	12.33	401.60	5.72	4.62	4.59	537.08	1.946.60
Average	5.70	3.88	19.01	499.73	5.69	4.50	7.34	562.85	1.998.99
Reference	5.16	2.80	25.07	646.38	5.63	3.34	12.17	675.38	1.969.34
% Improvement									
Best low river	5	32	17	16	1	31	27	14	-2
Best Ga	20	56	51	38	2	38	62	20	1
Best	20	56	51	38	2	38	62	20	1
Average	11	39	24	23	1	35	40	17	-2

Table A4.17. Criteria values for the different options in case of low river flow and blower failure in Granollers (Gr).

	LA GARRIGA				GRANOLLERS				TC
	DO av	**DO min**	**NH_4 max**	**RQI**	**DO av**	**DO min**	**NH_4 max**	**RQI**	
Best low river	5.19	4.06	1.10	328.64	5.47	3.79	13.45	548.72	2014.93
Best Gr	5.69	4.20	0.97	326.88	5.44	3.86	9.80	531.29	1784.82
Best	5.69	4.20	0.97	326.76	5.43	3.86	9.80	531.15	1784.21
Average	5.47	4.03	1.04	328.84	5.51	3.90	10.95	533.14	1939.29
Reference	5.10	3.62	3.19	354.97	5.38	3.10	22.70	655.77	1968.77
				% Improvement					
Best low river	2	12	65	7	2	22	41	16	-2
Best Gr	12	16	70	8	1	25	57	19	9
Best	12	16	70	8	1	25	57	19	9
Average	7	11	67	7	2	26	52	19	2

Table A4. 13. Selected management set points for average combination of scenarios.

	Reference	Blower failure La Garriga and storm	Blower failure Granollers and storm	High load La Garriga and temperature	High load Granollers and temperature	Low river flow and blower failure La Garriga	Low river flow and blower failure Granollers
C_{Ga}, NH_4	1	0.70	0.48	0.92	0.66	0.79	0.56
C_{Gr}, NH_4	1	0.69	0.69	1.26	0.83	0.61	0.61
C_{Ga}, NH_3	1	1	1	1.93	1.93	1	1
C_{Gr}, NH_3	1	0.90	0.90	1.65	0.95	1.63	1.63
$W_{Ga, P}$	50	50	50	50	50	50	50
$W_{Gr, P}$	600	600	1569.29	543.1435	615.61	600	1569.29
R_{Gr}	28800	38184.70	14669	32832.05	37328.05	27750.4	15992.55
R_{Ga}	200	200.00	200	200	200	200	200
$W_{Gr,S}$	500	954.73	598.35	839.1905	1039.28	1120.43	764.05
$F_{Ga,S}$	14500	25172.60	25172.60	24725.6	14500	14500	14500
$F_{Gr,S}$	46000	49035.90	54270.05	38258.8	45707.50	44973.5	50207.65
$F_{Ga, P}$	27648	27648	27648	27648	27648	27648	27648
$F_{Gr,P}$	76800	76800	76800	76800	76800	76800	76800
C_{Ga},Sludge	1.5	1.50	1.50	1.563204	2.16	1.5	1.5
F_{Ga}	27648	12749.50	13312.58	9988.51	9796.98	8784.65	9347.73
$F_{Ga, WWTP}$	27648	16445.25	15844.37	10898.965	6707.35	9551.63	8950.75
F_{Gr}	30000	30000	30000	30000	30000	11990.2	11990.2
$F_{Gr, WWTP}$	76800	67340.55	67866.70	26751	26243.20	28273.8	28799.95

ACRONYMS

AC	Aeration Cost
ASM	Activates Sludge Model
ASM1	Activated Sludge Model nº 1
ASM2	Activated Sludge Model nº 2
ASM2d	Activated Sludge Model nº2d
ASM3	Activated Sludge Model nº3
BOD	Biochemical Oxygen Demand
CDCB	Consorci per la Defensa de la Conca del riu Besòs
COD	Chemical Oxygen Demand
CSDT	Combined Sewer Detention Tanks
CSO	Combined Sewer Overflow
CWA	Clean Water Act
DO	Dissolve Oxygen
EDSS	Environmental Decision Support Systems
GSA	Global Sensitivity Analysis
GIS	Geographical Information Systems
GSI	Green Storm water Infrastructures
IRBM	Integrated River Basin Management
IWA	International Water Association
LHS	Latin Hypercube Sampling
MC	Monte Carlo
MSL	Model Specification Language
OCI	Operational Cost Index
PC	Pumping Cost
PCC	Partial Correlation Coefficient
PDF	Probability Density Function
RQI	River Quality Index
RTC	Real Time Control
RWB	Receiving Water Body
SA	Sensitive Analysis
SC	Sludge Cost
SS	Sewer System
SRC	Standardized Regression Coefficient
TC	Total Cost
TN	Total Nitrogen
TP	Total Phosphorus
UWS	Urban Wastewater Systems
WFD	Water Framework Directive
WWTP	WasteWater Treatment Plant