



Universitat de Girona

# COORDINATED MANAGEMENT OF URBAN WASTEWATER SYSTEM BY MEANS OF ADVANCED ENVIRONMENTAL DECISION SUPPORT SYSTEMS

**Damià MURLÀ TUYLS**

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Universitat de Girona

*PhD Thesis*

**Coordinated management of Urban Wastewater  
Systems by means of advanced Environmental Decision  
Support Systems**

**Damià Murlà Tuyls**

**2013**

Supervisors: Dr. Manel Poch Espallargas and Dr. Oriol Gutiérrez Garcia-Moreno

Tutor: Dr. Manel Poch Espallargas

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**Dr. MANEL POCH ESPALLARGAS**

Professor del Departament d'Enginyeria Química, Agrària i Tecnologia Agroalimentària de la Universitat de Girona i també de l'Institut de Medi Ambient.

**Dr. ORIOL GUTIÉRREZ GARCIA-MORENO**

Investigador Post-doc de l'Institut Català de Recerca de l'Aigua.

**Declaren**

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Que el llicenciat en 'Ciències Ambientals' per la Facultat de Ciències de la Universitat de Girona Damià Murlà Tuyls ha realitzat, sota la seva direcció, el treball que amb el títol "**Coordinated Management of Urban Wastewater Systems by means of advanced Environmental Decision Support Systems**", es presenta en aquesta memòria la qual constitueix la seva Tesi per optar al Grau de Doctor per la Universitat de Girona.

I perquè en prengueu coneixement i tingui els efectes que corresponguin, presentem davant la Universitat de Girona l'esmentada Tesi, signant aquesta declaració a

Girona, April 2013

Dr. Manel Poch Espallargas

Dr. Oriol Gutiérrez Garcia-Moreno



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A TOTS VOSALTRES, GRÀCIES



## **ABSTRACT**

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Wastewater treatment has become in the recent years an important issue to deal with in order to keep the quality of natural water resources as high as possible. In this line, the implementation of the Water Framework Directive (WFD (2000/60/EC)) provides to Urban Wastewater System (UWS) and Wastewater Treatment Plant (WWTP) managers a set of guidelines to choose the appropriate technology in order to reach a correct treatment level at river basin scale.

The main objective followed for this thesis is the development and test of a new Environmental Decision Support System (EDSS) based on mathematical modelling and artificial intelligence tools all fed by expert knowledge. The tool aims to present its benefits on the integrated management of the urban wastewater system and WWTP taking into account the water quality of the receiving body.

The methodology proposed for the EDSS development is based on five main steps: 1) problem statement, 2) data collection / knowledge acquisition, 3) relevant knowledge, 4) model selection and 5) model integration and implementation. The first step defines the main goal for which the tool is going to be built. The second stage uses several sources of information in order to give the tool different perspectives from different disciplines. As a result of this stage, the third phase of the EDSS development analyzes all this information and tries to get the best possible in order to identify useful knowledge. After this, a selection of the different types of available models is performed and only the ones that best meet the different needs of the tool are finally chosen. Finally, the selected models are implemented into the tool giving support to managers with the decision-making process.

Two virtual urban wastewater systems based on real ones have been taken into account (VilaConca and VilaPrat) with their respective sewerage systems, WWTPs and a single receiving body for both systems. By the execution of several model simulations of the virtual system, new expert knowledge of the integrated management of the system is obtained and further included into the knowledge based system as a set of if-then decision trees. Additionally, the EDSS tool has been tested with different rain scenarios and its results then compared with the standard situation, when no expert knowledge is applied, showing in each case the volume variation of the untreated wastewater discharged to the receiving body as well as for the released mass pollution.

Results of the use of the tool reveal an improvement of the whole wastewater system and have demonstrated the greater efficiency when an integrated management approach is applied. Future research can evolve to generate new knowledge which can be further used by EDSS tools in order to get a better efficient integrated river basin management and contributing thus, with the implementation of the WFD objectives.



## **RESUM**

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El tractament de les aigües residuals, és des de fa ja bastants anys una matèria important a resoldre per tal de mantenir de la millor manera possible la qualitat dels recursos hídrics disponibles. Això és d'especial importància en un país on, el risc de sequera permanent en un clima mediterrani com el nostre, es pot veure agreujada en la perspectiva del canvi climàtic. En aquest sentit, la implementació de la Directiva Marc de l'Aigua (WFD (2000/60/EC)) aporta als gestors de les Estacions Depuradores d'Aigües Residuals (EDAR) una sèrie de línees i guies a seguir per tal d'escollir la tecnologia més apropiada en cada cas. D'aquesta manera, el que s'aconsegueix és que l'aigua residual assoleixi un nivell de tractament apropiat a escala de conca.

El principal objectiu que cerca aquesta tesi és el desenvolupament i prova d'un nou Sistema de Suport a la Decisió Ambiental (EDSS) basat en eines de modelització matemàtica i d'intel·ligència artificial, a partir d'una base sòlida de coneixement expert. La nova eina pretén demostrar els beneficis que comporta realitzar una gestió integrada tant dels sistemes de drenatge urbà com de les EDARs tenint en compte la qualitat de les aigües del medi receptor.

La metodologia proposada per al desenvolupament de l'eina EDSS, basada en la proposta inicial desenvolupada per Poch et al. (2004), consta de cinc passos bàsics: 1) plantejament del problema, 2) recollida de dades / adquisició de coneixement, 3) coneixement rellevant, 4) selecció dels models i 5) integració i implementació dels models.

El primer pas defineix els principals objectius per als quals l'eina es desenvoluparà. En la segona fase, s'usen diverses fonts d'informació per tal de donar a l'eina diferents punts de vista des de diverses disciplines. En conseqüència, la tercera fase analitza tota la informació recollida i en tria la més útil i rellevant. Seguidament, es realitza la selecció dels diferents tipus de models disponibles i només els que millor reuneixen els requisits de l'eina són finalment seleccionats. Finalment, els models escollits s'implementen a l'eina, d'aquesta manera aporten als gestors una ajuda i un suport en el procés de decisió.

S'han escollit dos sistemes virtuals (VilaConca i VilaPrat) basats en sistemes reals amb les seves respectives xarxes de clavegueram, EDARs i un únic medi receptor. Mitjançant una sèrie de simulacions en el sistema virtual, s'ha assolit l'adquisició de nou coneixement pel que fa a la gestió integrada de conca, el qual ha estat posteriorment implementat al sistema basat en coneixement expert en forma d'arbres de decisió. L'eina EDSS ha estat provada amb diferents escenaris de pluja i els resultats han estat comparats amb els d'una gestió de conca estàndard (en la que no s'hi té en compte el coneixement expert). D'aquesta manera, s'aconsegueix il·lustrar quina és la variació de volum d'aigua residual sense tractar així com també de la quantitat de contaminant que finalment arriba al medi receptor.

Els resultats assenyalen que l'ús de l'eina EDSS produeix una millora del sistema i demostra que existeix una major eficiència i una millora en la qualitat del medi receptor quan es realitza una gestió integrada de la conca d'un riu. En un futur, la recerca pot anar enfocada a la generació de nou coneixement, que es pot integrar dins l'eina EDSS, per tal d'assolir una major eficiència en la gestió integrada de conca contribuint d'aquesta manera de forma activa en la implementació dels objectius marcats per la DMA.



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## Acronyms

<b>AI</b>	artificial intelligence
<b>ASM</b>	activated sludge model
<b>ASM 1</b>	activated sludge model n°1
<b>ASM 2</b>	activated sludge model n°2
<b>ASM 2d</b>	activated sludge model n°2d
<b>ASM 3</b>	activated sludge model 3
<b>COD</b>	chemical oxygen demand
<b>CSO</b>	combined sewer overflow
<b>CSV</b>	comma separated values
<b>DB</b>	data base
<b>DO</b>	dissolved oxygen
<b>DSS</b>	decision support system
<b>DWF</b>	dry weather flow
<b>EDSS</b>	environmental decision support system
<b>GIS</b>	geographical information systems
<b>GUI</b>	graphical user interface
<b>HYE</b>	hybrid edss
<b>HYS</b>	hybrid standard
<b>IRBM</b>	integrated river basin management
<b>IUWS</b>	integrated urban wastewater system
<b>IWA</b>	international water association
<b>IWS</b>	integrated wastewater system
<b>KA</b>	knowledge acquisition
<b>KB</b>	knowledge-base
<b>KBS</b>	knowledge-based system
<b>KOSIM</b>	kontinuierliches langzeit simulationsmodell
<b>LPA</b>	logic programming associates

<b>MOUSE</b>	model for urban sewers
<b>MSL</b>	model specification language
<b>ODE</b>	ordinary differential equations
<b>RTC</b>	real time control
<b>SCADA</b>	supervisory control and data acquisition
<b>SS</b>	sewer system
<b>TSS</b>	total suspended solids
<b>UWS</b>	urban wastewater system
<b>WEF</b>	water environment federation
<b>WEST</b>	world wide engine for simulation, training and automation
<b>WFD</b>	water framework directive
<b>WWF</b>	wet weather flow
<b>WWTP</b>	wastewater treatment plant

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***CHAPTER 1***  
***PREFACE***



## **1. Preface**

### **1.1 Hypotheses**

In the last decades there has been an increasing awareness of the importance to evaluate and optimise water resources supply and evacuation of the wastewater management. Despite that, it has been demonstrated that the wastewater treatment technologies as well as the sewer system management are a potential tool to increase wastewater management efficiency.

The main objective of this thesis is to demonstrate that the development of an environmental decision support system based on artificial intelligence and mathematical modeling tools produce an increased efficiency on the management of the wastewater system. This achievement is necessary in order to improve the quality of the receiving environment and to deal with the current policy in wastewater management.

### **1.2 Contributions**

The main contribution of this thesis is the development and test of an Environmental Decision Support System (EDSS) based on mathematical models and artificial intelligence tools all fed by expertise knowledge. The model is based on two real Urban Wastewater Systems (UWS) and has been developed using the WEST<sup>®</sup> modelling software (DHI (2011)) version 3.7.6 (2009). The latter, has been developed by means of a previously calibrated and validated model (developed with a different software) which has been used as the development basis. The expert knowledge is based on a rule based system all built by means of decision trees and then compiled with a specific software. The EDSS tool has been tested with different rain scenarios and its results are then compared with the standard situation, where expert knowledge is applied but an integrated management of the different UWS infrastructures is not taken into account. Results show in each case a decrease of the total volume of the untreated wastewater discharged to the receiving body as well as a decrease of the released mass pollution.

Results have led to an improving of the whole wastewater system and have demonstrated the greater efficiency of an integrated management. Future research can evolve to generate new knowledge which can be further used by EDSS tools in order to get a better efficient integrated river basin management.

### **1.3 Outline**

The work described in this document has been performed within the context of the Water Framework Directive (WFD) implementation. Via mathematical modelling simulations and expert decision trees, various rain scenarios of the Urban Wastewater System (UWS) (sewer network, WWTP and river) have been tested and compared. Such a tool has been developed to assess the impact of the integrated management of the UWS on the receiving rivers.

The structure of the present thesis is divided as follows:

In **Chapter 2** an introduction of the UWS is provided, describing the main elements and processes within this type of systems. A description of the legislative framework surrounding the WFD implementation is supplied too. Following that, a short summary is presented of the developed EDSSs for the management of single processes and structures and finally, for the integrated management of the UWS. In **Chapter 3** the objectives of this thesis are presented.

**Chapter 4** provides a complete description of the methodology used for the EDSS building. The first section introduces the specific problems surrounding the individual management of the different hydraulic infrastructures of the UWS. Following that, the data collection phase and the knowledge acquired within this phase is pointed out. The next section describes the model selection followed by the model integration and implementation. After that, there is a second knowledge acquisition loop encompassing the expertise knowledge of the different managers and the simulation results, which is all built up in form of decision trees. Finally, the last section devotes the EDSS integration as a prototype tool for the integrated management of the UWS.

Results of the EDSS operation are described in **Chapter 5** including a discussion of them and the tested rain scenarios. **Chapter 6** presents results and discussion of an heuristic knowledge approach of the EDSS performed with a water quality point of view. An additional economical impact evaluation is included in this chapter too. In **Chapter 7**, the general conclusions and future work of this thesis are pointed up. **Chapter 8** provides the references and finally the **Annex** presents an additional description of the selected model, a supplementary representation of the developed decision trees. Extra EDSS concepts and operational results are also presented. And finally the virtual system model layout developed with WEST<sup>®</sup>.

## 1.4 List of publications

### 1.4.1 Conference proceedings

Murlà, D., Monistrol, A., Comas, J., Poch, M. (2010). Development of a modular Environmental decision support system for the integrated management of the urban wastewater cycle on multiple river basin scales. Oral presentation in: International IWA Conference on sustainable solutions for small water and wastewater treatment systems. 19-22 April 2010. Girona. Spain.

Murlà, D., Monistrol, A., Poch, M., Sunyer, D. (2010). Development of a modular Environmental decision support System for the integrated management of the urban wastewater cycle at river basin scale. Oral presentation in: International Conference on Environmental Modelling and Software. 05-08 July 2010. Ottawa. Canada.

Murlà, D., Monistrol, A., Poch, M. (2010). Development of a modular Environmental decision support system for the integrated management of the urban wastewater cycle at river basin scale. Oral presentation in: 6th International conference on sewer processes and networks. 7-10 November 2010. Surfers paradise. Australia.

Martínez, M., Sunyer, D., Malgrat, P., Murlà, D., Gutierrez, O., Montero, C. (2012). Environmental Decision Support System for coordinated management of urban drainage systems and WWTPs. Oral presentation in: International IWA world water congress and exhibition. 16-21 September 2012. Busan. Korea.

### 1.4.2 Developed software

Murlà, D., Sunyer, D., Martínez, M., Benzal, A., Guasch, R., Poch, M., (2011). WENDCOM tool (Water ENvironmental Decision support system for COordinated Management).

### 1.4.3 Journal papers

Murlà, D., Sunyer, D., Martínez, M., Gutierrez, O., Benzal, A., Guasch, R., Poch, M., (2012). Environmental Decision Support System for coordinated management of urban drainage systems and WWTPs. Article in progress.

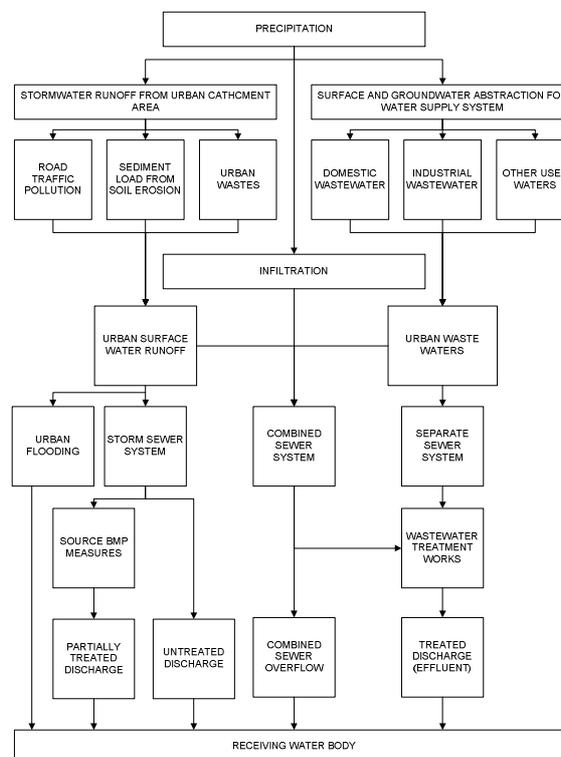
***CHAPTER 2***  
***INTRODUCTION***



## 2. Introduction

The general conservation of water resources has been of great interest during the last years due to the need to ensure its availability for future generations, which has always been directly related to human development. In this sense, water resources management becomes a complex problem since it involves multiple agents with a variety of interests acting at different scales and interacting with land use control (IAASTD (2009)).

The urban water cycle is the process by which water is captured from the natural cycle for its usage in a urban community until its returning to the natural cycle. First, water is collected and stored in reservoirs. Then it is transported to the potabilization facilities where water is prepared for consumption and distribution. After its utilisation wastewater is conveyed and processed into the WWTPs in order to obtain suitable water for its discharge in the receiving environment or for reuse purposes. During precipitation, rainfall water is introduced into the urban water cycle and it can either flow through storm water collection systems or through conventional WWTPs before being discharged into the receiving body. Figure 2.1 shows the movement of urban water.



**Figure 2.1.** Movement of water in urban environment. Originally from Andjelkovic (2001).

Considering the increasing magnitude of the different sanitation infrastructures of urban areas, the structure and function of UWS and associated changes in downstream processes have important ecosystem and public health implications. The traditional management aims to fulfill the legal emission limits but usually without bearing in mind the consequences on the receiving waters or on other wastewater facilities. This is usually due to the fact that the sewer system, the WWTP and the receiving water are generally managed by different companies or administrations (Devesa et al. (2009)).

## 2.1 Urban Wastewater System

Urban wastewater systems are the whole set of units in charge of transporting, treat and discharge wastewater to the receiving media. Most of these systems are mainly composed by a sewer system, which through a set of pipes are responsible to receive the wastewater produced in urban, industrial or agricultural areas and finally converge in the main collectors, where all wastewater flows to the WWTP. There, water is treated and finally discharged into the receiving body.

Sewer systems are the group of pipes and facilities used to transport the generated wastewater to the WWTP as quickly as possible (Marsalek et al. (1993)). These are used with the aim of avoiding a fall of the water quality in the receiving bodies. Collected wastewater can have several origins: black waters which have a domestic, industrial or agricultural source, or white waters, when rain water comes into the sewer system through runoff. If the wastewater flowing through the sewer system is higher than its hydraulic capacity, then the water leaves via emergency exits or Combined Sewer Overflows (CSOs).

Basically, two types of sewer systems can be distinguished: separated and combined. Separated systems have two types of pipes for transporting water out of the urban area. One is used for transporting rain water and another for wastewater. This type of sewer systems have the advantage that wastewater is not diluted during rain events and so, less amount of water has to be treated and in a more efficient way. On the other hand, combined systems have only one pipe for transporting both black and white waters. Its main advantage is that less construction costs are needed. But in this case, they lead to an increase of the amount of water to be treated during rain events which turns into a decrease of the WWTP efficiency and to higher hydraulic capacity needs (Butler and Davies (2004); De Toffol et al. (2007)).

Storage tanks and retention basins are the most commonly used facilities to prevent and reduce the number and volume of CSOs (Bode and Weyand (2002)). Equalization basins are structures designed to smooth wide variations in flow so that a constant or nearly constant flow rate can be achieved. They are normally used during dry weather flow to since they can provide an average flow or pollutant load to the WWTP. Additionally, these tanks can be also used to retain a certain wastewater volume before entering the WWTP, e.g. in case of an industrial discharge, where high pollutant concentrations are frequent, storm tanks are used to avoid critical episodes into the WWTP (Bolmstedt and Olsson (2005)).

Once the wastewater has flowed from its urban or industrial origin through the sewer system, it arrives to the WWTP. There are different processes to treat wastewater: (1) physical treatment (sedimentation or filtration), (2) chemical treatment (precipitation or flocculation) or (3) biological treatment (degradation of waste by bacteria) (Metcalf and Eddy (2003)). The latter, in combination with one or more physical or chemical treatment process are the most common plant layouts used to treat wastewater.

Nutrient removal technologies have been developed and introduced to the WWTP processes (Martínez (2006)). One of the most common practises for nitrogen removal is the nitrification-denitrification process with internal recirculation of wastewater. Part of the oxygen used to oxidise ammonia to nitrate is partially used for COD removal. On the other side, phosphorous can be removed in two ways, by chemical precipitation or biological precipitation.

Activated sludge systems, consisting in a series of tanks filled with bacteria and with specific conditions (anaerobic, anoxic and aerobic) are traditionally used for nutrient and organic carbon removal. Sludge produced by the bacterial growth is then separated from the effluent in a secondary settler since bacteria in the activated sludge tanks tend to aggregate and grow in flocs with its consequent greater density than water (Comas (2000)).

Rivers, lakes and seas are typical discharging points of WWTP effluents. Additionally, CSOs can also spill into creeks or streams. Rivers have other functions as are transport, drinking water source, irrigation or habitat for riparian ecosystems. In this sense, the right combination of water quantity and quality are essential for the maintenance of all these river functions.

River water quality is not only determined by the inputs of the urban system, but also several processes as are the physical, biological and chemical exchanges through the water column or the physical transport of water. The quantity of water flowing through the river can be also a determinant factor, especially in Mediterranean areas where water scarcity is common (Navarro-Ortega et al. (2012)). Thus, the role of WWTPs or the different management strategies adopted throughout the UWS become important as they can produce a considerable impact into the receiving water quality.

There are many parameters influencing each other and that 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 good, moderate or bad quality (Meirlaen (2002)).

## **2.2 The WFD implementation**

The WFD of the European Union (WFD (2000/60/EC)) is currently the most important water-related legislation in Europe. It encompasses the previous European directives on water management by considering the water cycle as a whole. The directive establishes a new idea in terms of water management considering the river basin as the working scale, and introduces the new concept of integrated river basin management (IRBM). This new point of view includes surface and ground waters. The main idea of the WFD is to reach a good quantity and quality status of water resources, which can be exploited as long as the ecological function of water is not affected significantly (Riegels et al. (2011)).

The main goals of the WFD are:

- Reach a ‘good’ ecological status of superficial, subterranean and coastal waters by 2015.
- Prevent deterioration and improve the aquatic ecosystems, including subterranean water.
- To reach the river basin management as work scale.
- Involve general public in water policy making.
- Control the emission limits and the quality objectives in a combined point of view.
- Promote the sustainable use of water and reduce water pollution.
- Contribute to the flood reduction and to water scarcity.

In a UWS context, additionally to the Wastewater Treatment Directive (CEC (1991)), and the Integrated Pollution Prevention and Control Directive (CEC (1996)), the WFD jumps from an emission-based approach to a combined approach controlling pollution at source through the setting of emission limit values and of environmental quality standards (Article 40, WFD). When considering the integrated management of the infrastructures of the UWS, an improvement of the quality of the water bodies and a reduction of its costs is then possible.

However, this is a laborious goal due to the system complexity and to the roles played by the managers and stakeholders. The development of water management tools to support decision making become thus, a necessary aspect to deal with the WFD objectives (Poch et al. (2004); Prat et al. (2012)).

Each authority has the responsibility to prepare and implement a River Basin Management Plan (RBMP) in order to achieve good environmental quality. According to the WFD, the RBMP should have been available from 22 December 2009 for all the river basin regions. Despite that, there have been strong delays in some of these districts. Spain has 25 river basin regions, out of which 6 are international sharing water courses with France (e.g. Cantabrian Eastern river basin) to the northeast and Portugal to the east (e.g. Duero or Tajo river basins). By the time of redacting this thesis, only Catalonia has adopted and published its RBMP (EC (2012)).

Despite there has been a turning point with water management and policy, the IRBM implementation has some aspects which are not effective enough and in consequence, the WFD is still a very important challenge to deal with for the European Union. For this reason, the IRBM is needed for the advance of society in order to improve the human health and hygienic conditions as well as to reduce the water resource dependency (Gourbesville (2008); Hering et al. (2010)).

### **2.3 Fundamentals of EDSS**

In the last decades, new strategies and tools have been developed since the traditional management of the individual components of the UWS do not always provide the best results onto the entire system (Rauch et al. (2002); Butler and Schütze (2005)). In this sense, the integrated management of the UWS infrastructures aims to improve the quality of the receiving ecosystem while they also reduce costs giving thus, greater efficiency to the global UWS management (Aulinas et al. (2010)). Nevertheless, to reach this objective it is necessary the support of various expert managers and stakeholders.

In this sense, the concept of Decision Support Systems (DSS) as technologies to support in the effort of developing technologies that inform environmental policy and management organizations trying to find solutions to complex problems has led to the development of the so called Environmental Decision Support Systems (EDSSs).

Various definitions of EDSSs are found in the literature, e.g. EDSSs are softwares fitted in the group of computer-based information systems developed for use in environmental domains integrating different modelling technologies, databases or other decision purposes in a way that decision makers can use (Rizzoli and Young (1997)). Cortés et al. (2000) define an EDSS as an intelligent information system able to enhance the time needed to produce a decision as well as its consistency and quality. Elmahdi and McFarlane (2009) define EDSSs as an intelligent analysis and information system able to produce in an easy way the different key aspects of a specific environmental-system problem.

EDSS are softwares fitted in the group of computer-based information systems able to link different modelling technologies as are numerical models or algorithms with knowledge-based systems, geographical information systems (GIS) or on-line data. They are used to tackle complex problems (Poch et al. (2004)) by recording, storing, processing and disseminating of information to support group or individual decision making (Díez and McIntosh (2009); Volk et al. (2010)).

Diverse alternatives of how to design and build an EDSS have been introduced as are Poch et al. (2004); Makropoulos et al. (2008); Lautenbach et al. (2009) and Van Delden et al. (2011). Although all the possible methodologies found in literature are valid for developing an EDSS, the final selection depends on the problem to be addressed, the available information or the type of system itself.

Adapted from McIntosh et al. (2011), Table 2.1 provides a set of recommendations for an improved developing process of EDSSs:

**Table 2.1.** Best practice recommendations for EDSS development. Adapted from McIntosh et al. (2011).

<b>EDSS development recommendations</b>	
Design for ease and use	Design user-friendly interfaces. Develop adaptable interfaces for different type of users.
Design for usefulness	Identify end-users/stakeholders and their roles, responsibilities and capabilities. Focus on the overall system. What problem is to be solved? Which are the EDSS end-users? Which us the added value? Select the base model on spatial and temporal scale and level of complexity required for problems.
Establishing trust and credibility	Be transparent about system weaknesses and needed improvement areas. Discuss development timelines with end-users. Collaborate with all parties in order to understand requirements and share expertise.
Promoting EDSS for acceptance	Find a way to promote the EDSS at different levels of organisation. Implement some strategy to ensure an easy and inexpensive use of the EDSS.
Plan for longevity	Ensure that required information and databases can be easily updated. Assure that the EDSS can be used to solve multiple environmental problems.
Starting simple and small	Avoid improper model complexity. Use a modular approach to modelling or environmental modelling frameworks.

In this case, some similarities with the one proposed by Poch et al. (2004) (Figure 2.2) can be found in the prototype tool developed in this thesis. The reasons leading to this building methodology are:

- Several previously developed EDSS following the same methodology allowed to address water related problems and as a consequence provided the consideration of multiple points of view and the achievement of different purposes.
- Additionally, the acquisition of new experiences is a very important task as well as the need to involve experts in problem solving processes.
- This methodology provides certain simplicity to acquire and integrate knowledge and data extracted from different sources and to represent it through different models (AI, statistical or numerical).

The methodology proposed by Poch et al. (2004) is based on the following steps: (1) *environmental problem analysis*, where the problem is defined. This first step is based on the characterization of the domain, the study of the background and the current state of the problem. (2) *Data collection and knowledge acquisition* phase starts, involving the analysis and acquisition of data and knowledge in order to arise with a set of problem solutions. (3) *Selecting the set of models* that best fit with the functionalities and with all kinds of knowledge required for the decision-making process (being not only applied to numerical, statistical but also AI methodologies). (4) *Model implementation* outlines the following step in the EDSS development. This consists on the codification of knowledge according to the model and software selected. The data and knowledge acquired can be represented by means of decision trees or mathematical equations. (5) *Integration* is the last step where all the developed modules are built up into a whole functional and structural tool, being thus the complete EDSS tool.

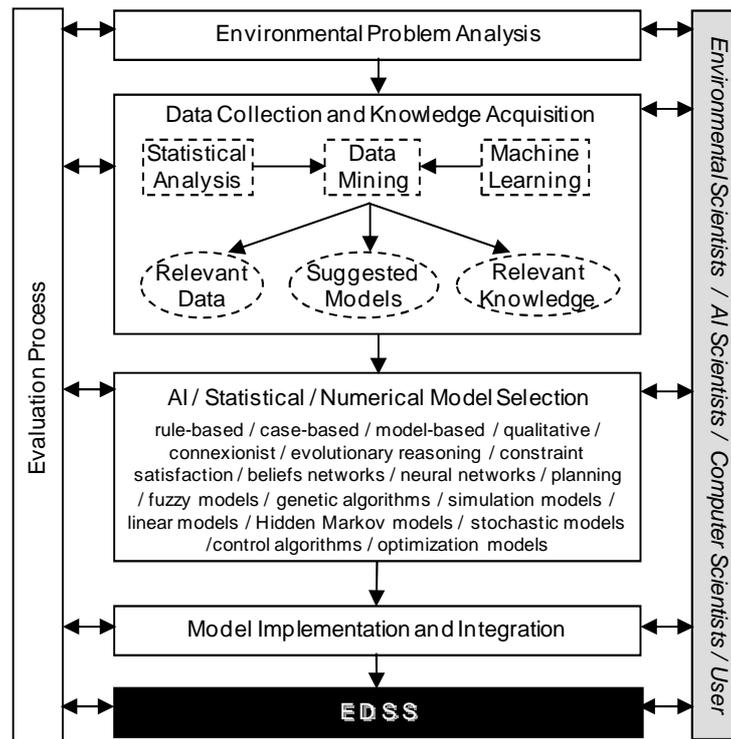


Figure 2.2. Development of an EDSS methodology proposed by Poch et al. (2004).

During the last decades, a variety of decision support tools for the UWS management have been developed with an increasing number of sophisticated computerized systems were used to integrate water resource processes at different temporal and spatial scales with simulation models and decision making approaches (Giupponi (2007)). Additionally, these systems have been developed for a large variety of purposes such as drought prevention, flood management and prevention or water pollution management. These tools try to make the existing knowledge available for water and wastewater managers so as to support them with the proposal and evaluation of alternative management and action plans (Kok et al. (2009)).

The next table illustrates some of the water related EDSSs developed during the last years:

**Table 2.2.** Review of the latest water related developed EDSS. Based on McIntosh et al. (2011).

<b>Tool name and reference</b>	<b>Main goal</b>	<b>End users and reported use</b>
mDSS (Mysiak et al. (2005))	User guidance through the identification of the main driving forces and pressures on water and help to evaluate possible solutions.	Presented after training stage but it has not had any continuity.
CLAM (Ticehurst et al. (2008))	Developed to encourage users to think critically about the trade-offs related to the coastal lake system management, evaluate the model results and questioning their validity.	Local government use and update the tool. No convincing evidence to be operational.
CAPER (Kelly and Merritt (2010))	Developed to explore the possible ecological alteration due to the changes in catchment exports of nutrients and suspended solids resulting from a different management in their lakes and catchments.	Tool used to negotiate and develop components of the great lakes water quality improvement plan as well as for the botany bay. Application in early development stage.
IBIS (Merritt et al. (2010))	Developed to explore the possible results of catchment water planning scenarios on the ecological characteristics of the inland wetlands systems in NSW Australia in order to plan and manage environmental flows at valley and wetland scales	Employed to explore possible impacts of climate change and water delivery scenarios defined in accordance with the proposed Murray Darling Basin Plan. Not yet operational.
Groundwater decision support system (GWDSS) (Pierce (2006))	The main aim is to face the complexities related with defining a reasonable groundwater policy.	Tool presented to a group of stakeholders to help define strategies for sustainable aquifer yield.
Gngangara decision support tool (GDST) (Elmahdi and McFarlane (2009))	DSS developed to provide quantitative assessments of land and water management options.	Used to set up scenarios in the DSS and analyse their impacts on Gngangara groundwater system and its values. No reported operability.
Elbe-DSS (Lautenbach et al. (2009))	This EDSS has been developed to demonstrate the capacity of the tool to support management duties related with water quality, flood risk and river ecological value of the riverscape.	Used to support basin management by the German hydrological institute for strategic planning.
Simplified modelling on Growing and Monitoring (SMOM) (Halide et al. (2009))	Developed in order to assist cage aquaculture managers. Gives support to site classification, site selection, holding capacity determination and economic evaluation of an aquaculture farm at a given location.	Users are aquaculture managers which aim to use it for design of new aquaculture facilities. No reported use.
Water resources aided by graphical interface-quality model (WARGI-QUAL) (Sulis et al. (2011))	Modelling of complex multi-reservoir and multi-use water systems based on Trophic State Index with additional consideration on algal composition in the reservoirs.	Updated and used by users from the Sardinian water authorities.

Specifically, examples of EDSS recently developed for integrated water resources management are Newham et al. (2004); Bazzani (2005); Hirschfeld et al. (2005); Volk et al. (2007); Giupponi (2007; Paar et al. (2008); Makropoulos et al. (2008); Lautenbach et al. (2009); Argent et al. (2009); Paredes et al. (2010).

Although during the last years improvements have been made in all important aspects of the EDSS development (use, science and IT), it is still a difficult to find decision support tools applied in real complex systems. As McIntosh et al. (2011) points out, the main challenges in developing EDSS can be summarized as

- Designing for ease of use.
- Designing for usefulness.
- Establishing trust and credibility.
- Promoting the EDSS for acceptance.
- Starting simple and small.

Additionally, the improvement of the communication between stakeholders as well as their increasingly involvement during the EDSS building is a necessary commitment and requires for further consideration (Volk et al. (2010)). On the other side, in order to increase the number of adopted EDSS in real complex systems, it is necessary to promote the EDSS so that the end user must be convinced of the effectiveness of the tool. Future EDSSs must be user friendly and useful tools in managing correctly and deal with water environmental problems and in consequence increase its utility and adaptability.

***CHAPTER 3***  
***OBJECTIVES***



### **3. Objectives**

The main objective of this thesis is to **develop** and **test** an **EDSS** based on **mathematical modelling** and **artificial intelligence** tools and show the benefits of using this tool for the integrated management of the urban wastewater system and wastewater treatment plant considering the quality of the receiving body.

The achievement of the main objective implies the following sub-objectives:

- ✓ Design of the application prototype and methodology used to build the environmental decision support tool;
- ✓ Gather data from the sewer system, wastewater treatment plant and receiving body and develop a virtual reality able to simulate the behaviour of a urban wastewater system, wastewater treatment plant and receiving water system;
- ✓ Acquire knowledge from different sources of information including theoretical and scientific literature and from management experts of the urban wastewater system, WWTP and river;
- ✓ Define several scenarios of some critical situations and daily management problems that can affect to water quality;
- ✓ Simulate the defined scenarios onto the virtual reality next to the knowledge acquisition of its results;
- ✓ Compile all the acquired knowledge in a set of rules built by means of Decision Trees;
- ✓ Apply and Test of the EDSS prototype;
- ✓ Apply an heuristic approach and economical impact evaluation of the discharges;



***CHAPTER 4***  
***EDSS BUILDING***



#### 4. EDSS building

How an EDSS is built varies depending on the type of environmental problem to be solved as well as on the type and amount of available information that can be acquired. Based on the EDSS development procedure purposed by Poch et al. (2004), five different levels have been used for this EDSS (See Figure 4.1): 1) Problem statement; 2) Data collection and Knowledge acquisition; 3) Relevant knowledge; 4) Model selection; 5) Model integration and implementation.. In addition, after the model integration and implementation phase, a new task is added: the second knowledge acquisition loop (KA II). The main objective of this new procedure is to use the developed model to acquire new knowledge, which can be further added to the Knowledge Base of the EDSS.

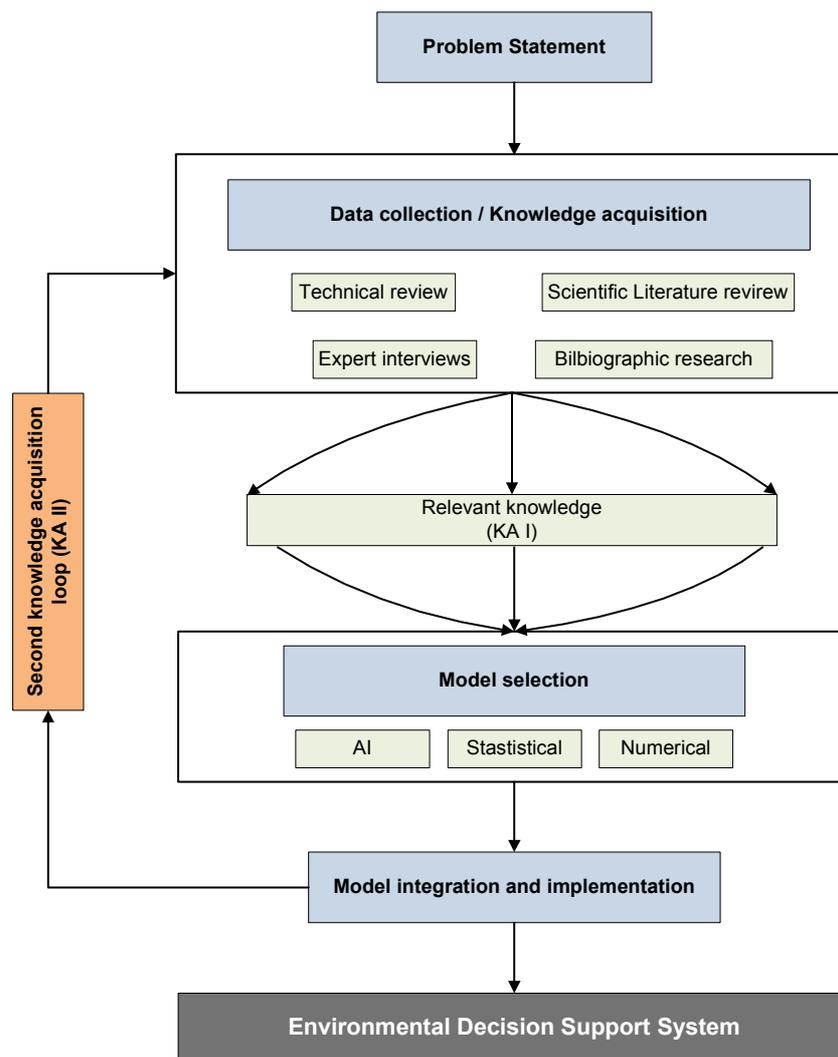


Figure 4.1. EDSS building methodology.

The first phase of the EDSS building, the *problem statement*, is a key element in the EDSS building process. It consists in identifying the main problem the tool aims to solve and identifies its potential causes. It also conveys the reason why the problem is important and to who or what is affecting to.

Once the problem has been already defined, the *data and knowledge acquisition* phase can get started. There are several available knowledge sources to be used which can be grouped in three main groups: existing literature of the topic under study; the data base sources that may be found on the system; and technical visits and expert interviews. The whole set allows to incorporate information as well as the integration of various points of view from different disciplines.

After the *data and knowledge gathering*, these have to be *analyzed* so as to extract all the available information. In the case of data, it will be necessary to classify and use data mining tools to identify different groups of data (clusters), compartments and interpret them in order to extract relevant information. In the case of knowledge, results of the interviews allow to identify specific knowledge acquired by the experts on a particular topic.

The *model selection* depends on the specialization level or its purpose, for this thesis four different types of models may be identified: The first group are the ones coming from the use of Geographical Information Systems (GIS). The second group are the numerical models which can be divided into deterministic models or empirical models. The first subgroup uses a set of equations describing a given knowledge of a determined process. The second subgroup is based on equations based on a determined system's behaviour. Furthermore, statistical models estimate the future probability of a particular event from its previous behaviour. Finally, artificial intelligence models are mostly based on rule based systems, case based systems or by agents.

The *model integration and implementation phase*, aims to group the selected models in a functional structure and to execute them either in parallel (to obtain a single result) or in series (the output of a model is the input for the next one). Finally, the implementation into a specific software is the last step in order obtain results which can help in the decision-making process.

Stated as one of the objectives to reach within this thesis, each of the steps described above constitute the EDSS design allowing development of the tool.

#### **4.1 Problem statement**

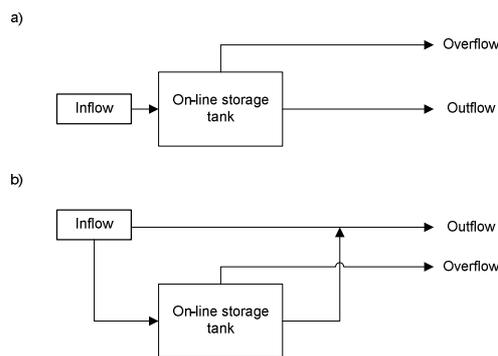
The ultimate goal of this work is to provide a tool that helps reduce the impact of urban water systems in the natural receiving media by discharging the wastewater at the best possible quality. In their path from its origin to the discharge point, the wastewater circulates through the different units of the UWS. Under dry weather conditions all the wastewater is collected in the sewers and conveyed to wastewater treatment plants before its return to nature. However during heavy rainfall, the storm water could exceed the treatment capacity of the WWTP resulting in uncontrolled discharges of sewage to the receiving waters in a series of events collectively called CSOs. Traditionally the different parts of the UWS have been, and still are, managed separately in a fragmented way due to the complexity of the system management. Therefore the objective of this work is to develop an EDSS for the combined management of the whole UWS, designed to improve the management in situations of wet weather conditions and to reduce the overflows of untreated wastewater.

For this purpose, a virtual system consisting on two virtual sub catchments of different sizes have been used. The reasons of this selection are the availability of operational data of sewer systems and WWTP, both under dry and wet weather conditions. It has to be mentioned that the final EDSS prototype will be setup to easily connect to any real UWS that has the data feed/inputs required to its operation.

The two virtual municipalities are nearly located and they both have its own sewer system and WWTP (one considered big and another one small / medium size) and connected between them by a sewer with a gate. The definition of the virtual system in an early step of the thesis, previous to the development of the EDSS prototype, avoids the temptation of adapting the “reality” to the EDSS needs instead of adapting the EDSS to the reality.

Municipality 1 called VilaConca whose catchments are inspired in the municipality of Mataró (a town located in the central coast of Catalonia). Municipality 2 called VilaPrat inspired in 2 catchments of Barcelona city. The wastewater treatment plant of VilaConca is inspired with the one of Mataró. This WWTP has been chosen since it has a series of available input data which is used for the WWTP development and for further phases of the EDSS building and because it surely has proportional measures in comparison with the wastewater production of VilaConca. In the case of VilaPrat, being the WWTP inspired with the one located in Barcelona-Prat, at the south-central coast of Catalonia which is already the ending point of the wastewater produced in the 2 catchments of Barcelona in which VilaPrat is inspired with.

Several types of water tank infrastructures can be found in both sewer systems in order to store water during rain events and prevent flooding or CSOs (Figure 4.2). For example, *off-line tanks* are in parallel to the sewer network and water is deviated and stored into these tanks when flow in the sewer network is increased and reaches a maximum level. *On-line tanks* are connected in series with the sewer network and both dry weather and wet weather flow passes through the tank.



**Figure 4.2.** a) On-line storage tank scheme and b) off-line storage tank scheme.

The combined sewer overflows and the wastewater treatments plants discharge their waters a river inspired on a real the Congost River. The chosen section of the river is the one flowing through the town of Granollers.

In Figure 4.3 there is a general scheme of the virtual system used to test the EDSS tool and the specific features of each subsystem are presented below.

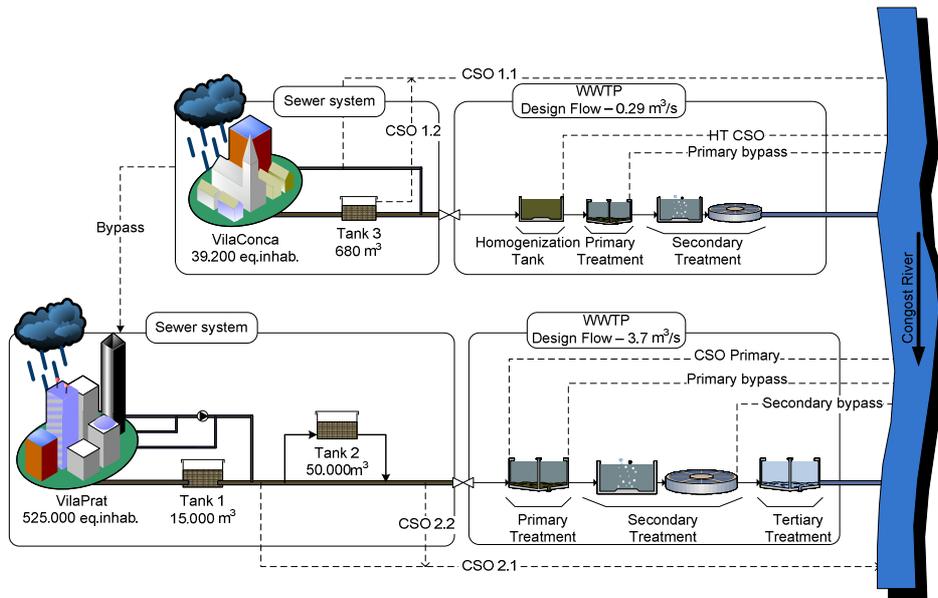


Figure 4.3. General scheme of the virtual system.

#### 4.1.1 VilaConca UWS

The developed virtual system uses two different catchments of the real sewer system of Mataró which are adapted in order to fit the wastewater flows and patterns of the WWT. As it has been already mentioned, the different elements of the WWT used in this virtual municipality are based from the WWT located in the Mataró municipality.

##### VilaConca sewer system

Information of a series of sub catchments from the sewer system of Mataró is used to build the new virtual model (see Figure 4.4). These have a total surface of 245 ha. and a population density of 16000 hab/km<sup>2</sup> which means the system is serving 39200 inhabitants, similar numbers as the sewer system of this urban community. The daily flow per person is high (550 l/hab/day) to take into account that the equivalent population of Mataró WWT is above 200000 eq. hab. so this way similar daily flows as the ones from this municipality can be obtained.

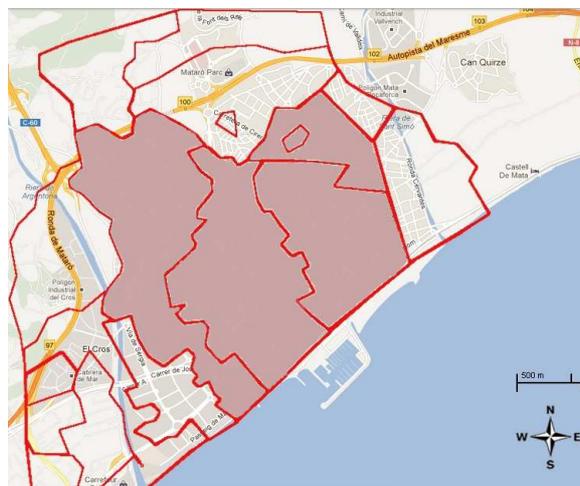


Figure 4.4. Mataró catchments used as the sewer system of the VilaConca municipality.

Additionally in one of the main sewer trunks of the system (see Figure 4.3) a small on-line anti CSO tank (Tank 3) with a volume of  $680 \text{ m}^3$  and with no existing real time control is added in order to show that these structures can also be modelled and included in the EDSS system. Finally, the sewer system has two main CSO points on the end of each of the main trunks after the interceptor, which takes the dry weather flow waters to the WWTP.

### VilaConca WWTP

The main characteristics of the WWTP of VilaConca are inspired in the Mataró WWTP (Figure 4.5). These are:

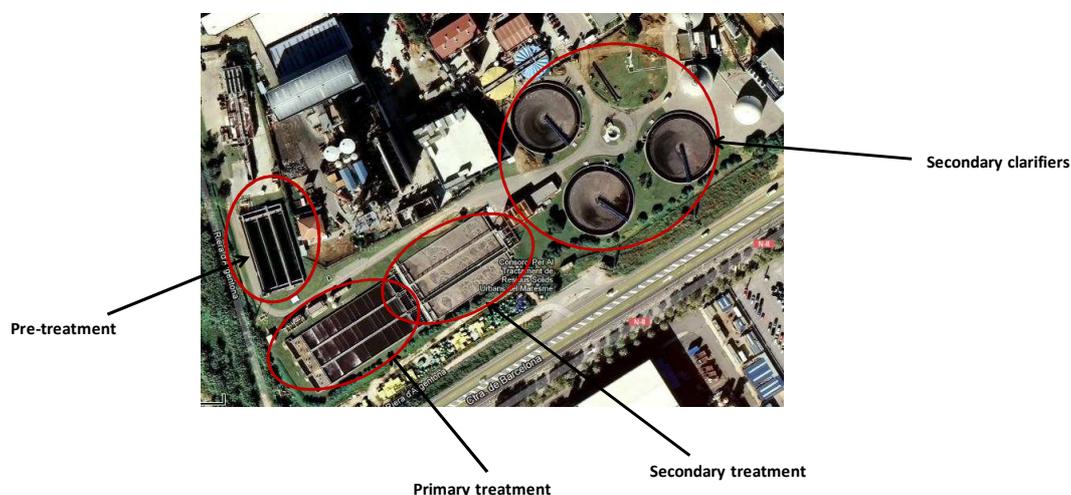
**Table 4.1.** Main features of the VilaConca WWTP.

Feature	Value	Units
Design flow (Qd)	25000 - 0.289	$\text{m}^3/\text{d} - \text{m}^3/\text{s}$
Equivalent population	204166	Eq. Inhabitants
Total population	40000	Habitants
Average dry weather daily flow (Qav)	0.13	$\text{m}^3/\text{s}$
Maximum dry weather daily flow (Qmax)	0.24	$\text{m}^3/\text{s}$

The water line in the WWTP starts with an equalization basin of  $8000 \text{ m}^3$  and a pre-treatment process. Then, primary treatment includes three primary settlers with a circular volume of  $1512 \text{ m}^3$  each.

The secondary treatment uses three oxidation reactors with a volume of  $8453 \text{ m}^3$  each consisting of approximately 50% of aerobic zone (aeration by diffusion) and 50% anoxic zone. Moreover, at the exit of the secondary treatment, ferric chloride is added to precipitate phosphorus, which is not removed biologically. The treated water goes through the circular settlers of  $3206 \text{ m}^3$  volume each. A CSO weir is included in the equalization tank as well as bypass gates before and after the primary treatment.

The capacity of the primary treatment is twice the design flow for the primary treatment ( $0.58 \text{ m}^3/\text{s}$ ) and once the design flow ( $0.29 \text{ m}^3/\text{s}$ ) for the secondary treatment. Despite this overdesign, a typical situation of WWTPs built a few years ago is that the inflows have increased significantly and right currently, the WWTP has not much more extra capacity to dilute waters in case of rain. This happens in this WWTP where the design flow ( $0.29 \text{ m}^3/\text{s}$ ) is not far away of the maximum daily weather flow ( $0.24 \text{ m}^3/\text{s}$ ).



**Figure 4.5.** Schematic view of the WWTP of Mataró.

VilaConca overflows

The sewer system has three different CSO points. On the one side, there is one CSO discharge point at each end of the main trunks (1.1 and 1.2) after the interceptor's dry weather flow leading to the WWTP (see Figure 4.3). Additionally the third CSO point is located at the entrance of the WWTP once the equalization basin is full and the water level at the tank reaches the CSO weir.

Two more discharging points exist in the WWTP. One is the usual discharge point of treated waters once they go through all the treatment process (primary and secondary) and the other one is located after the primary treatment and it is only used in emergency cases or in wet weather when more flow is treated in primary settlers than the one that can be accepted in the secondary treatment and the excess flow must be thrown to receiving waters.

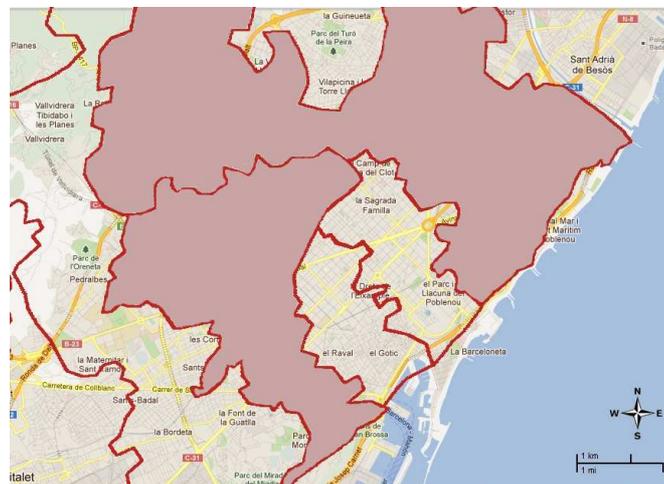
4.1.2 VilaPrat UWS

The sewer system of this municipality is inspired in a real system which is the sum of two catchments from Barcelona system. The WWTP has the same elements of the Barcelona WWTP called Prat del Llobregat, but the design flows of the settlers and different elements of the plant have been inspired according to the corresponding catchment flows.

VilaPrat sewer system

The sewer system in this virtual municipality corresponds to two catchments of Barcelona system with all the real features of the system in these areas including pipe network, cross sections, slopes, population density, actuators and tanks.

The modelled area has a surface of 19km<sup>2</sup> and a population of 525000inhabitants. In Figure 4.6 a representation of the Barcelona catchments used for the virtual system are represented.



**Figure 4.6.** Barcelona catchments used as the sewer system of the VilaPrat municipality.

The infrastructures found in this system are:

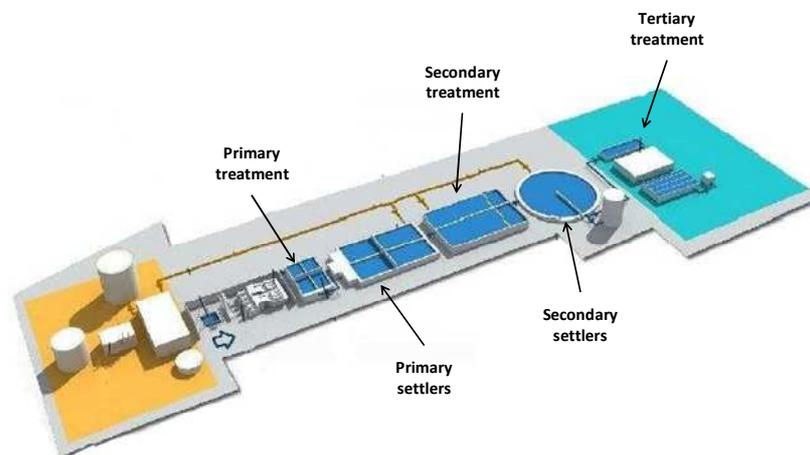
- Tank 1: Corresponding to Vilalba dels Arcs real tank, is an on-line tank, has an approximate volume of 15000 m<sup>3</sup> and its main purpose in the virtual reality is to avoid flooding and to reduce CSO. This tank is located online and emptied by gravity with a gate.
- Tank 2: Corresponding to Taulat real tank, it is an off-line tank, has an approximate volume of 50000 m<sup>3</sup> and its purpose is to reduce CSO events. The tank is filled through a gate at the entrance and emptied by pumps with a maximum capacity of 2 m<sup>3</sup>/s after storing wastewater during 36 h.
- A pumping station located at the interceptor is also found and has a maximum capacity of 4.1 m<sup>3</sup>/s.

### VilaPrat WWTP

The WWTP is inspired by the Barcelona Prat WWTP (Figure 4.7) with the flows and volumes of the treatment devices which are adapted in order to have some extra capacity to treat some rain flows:

**Table 4.2.** Main features and capacities of the VilaPrat WWTP.

Feature	Value	Units
Design flow (Qd)	320000 – 3.7	m <sup>3</sup> /d – m <sup>3</sup> /s
Equivalent design population	2000000	Eq. Inhabitants
Average dry weather daily flow (Qav)	0.87	m <sup>3</sup> /s
Maximum dry weather daily flow (Qmax)	1.56	m <sup>3</sup> /s
Primary treatment	7.4	m <sup>3</sup> /s
Secondary treatment	3.7	m <sup>3</sup> /s
Tertiary treatment	1.23	m <sup>3</sup> /s



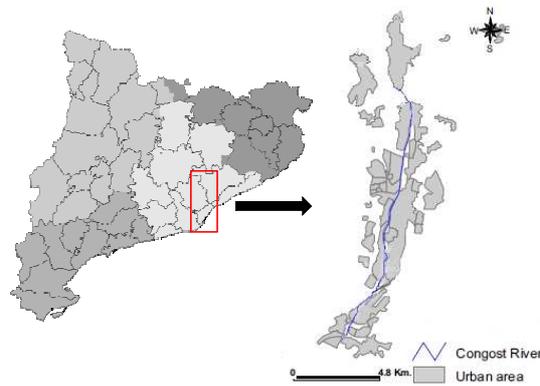
**Figure 4.7.** Schematic view of the WWTP of El Prat de Llobregat.

VilaPrat overflows

The sewer system has two main CSO points one at each end of the main trunks after the interceptor transfers the dry weather flows to the WWTPs (see Figure 4.3). Three more discharging points exist in the WWTP. One is the usual discharge point of treated waters once they have gone through all the treatment process (primary, secondary and tertiary treatment). The second one is located after the primary treatment and is used in wet weather flow when more flow is treated in primary settlers than the one that it can be accepted in the secondary treatment, so the excess flow must be thrown to receiving waters. The last one is located after the secondary treatment and it is used in rain events or in general when the water has not enough good quality to go through the tertiary treatment (for example when the suspended solids are higher than 500 mg/l).

4.1.3 Receiving water body

The receiving water of this system is a river which is inspired in the Congost river, located at Besòs River catchment, in Catalonia, NE of Spain. It has an average flow of 0.53m<sup>3</sup>/s, it is a typical Mediterranean river with sudden flash floods are frequent during wet weather periods. The studied river stretch has been performed between La Garriga and Granollers towns (see Figure 4.8).



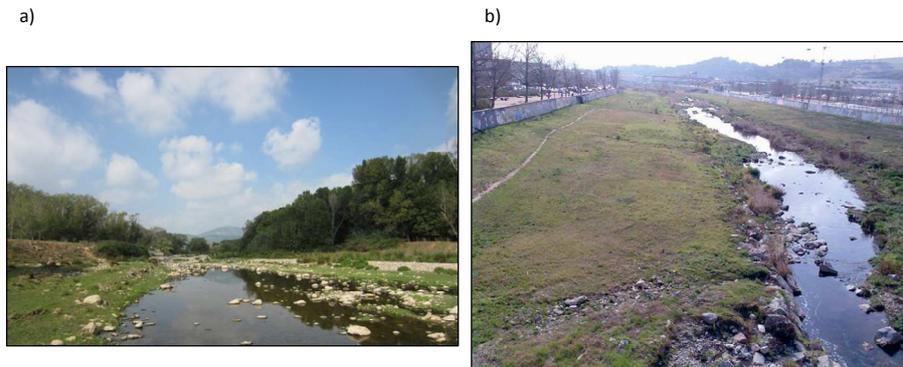
**Figure 4.8.** Congost River stretch used as receiving body for the virtual system.

As with the drainage system, the river has been chosen since a model of this river was already available with all the necessary data (cross sections, slopes, flows and quality parameters) which simplified the task of adapt it to the model. The stretch of the Congost River used has a length of 15 Km. In the upper part (Figure 4.9 a and b), the river goes through natural areas and tight cross sections.



**Figure 4.9.** a) and b) Upper part of the Congost River.

Slowly, the cross sections become wider and the presence of anthropogenic pressures becomes more evident (Figure 4.10 a and b). Finally, the last river stretch is channelled as it crosses over the municipality of Granollers.



**Figure 4.10.** a) and b) Congost River going through Granollers town.

So far, the problem statement corresponding to the first task of the EDSS development has been described in addition to all the necessary features and elements to be added into the virtual reality.

## 4.2 Data and knowledge acquisition

The second step on the EDSS build up is the data and knowledge acquisition. A variety of sources have been used for the development of the different knowledge bases (KB), including empirical, theoretical and historical information as are technical and scientific literature or the information and knowledge from various experts and managers or the referenced units of the UWS.

According to the results obtained from the data and knowledge acquisition, gathered information with the reviewed literature and the bibliographic research on integrated management of urban wastewater systems and WWTPs, it can be concluded that all the available elements, management actions and design strategies which can have an effect on the overall system are identified. This information has been classified in sewer network, WWTP or coordinated management knowledge.

### 4.2.1 Sewer network knowledge

The most common configuration found on these systems is combined sewer systems, meaning that they do not separate rain or storm water from wastewater. Therefore, CSO events can happen more frequently during wet weather. However, sewer systems have also some additional elements or actuators that have proven effectiveness in improving the performance of the sewer system in order to avoid floods or discharges.

These are:

- Valves used to restrict flows as are weirs or dynamic flow regulators.
- Storm and retention tanks.
- Gates which restrict the flow in a sewer or at the outlet of retention tanks.
- Pumping stations to empty retention tanks
- Interceptors or part of sewers used as retention tanks.
- Real time control (RTC).

Finally, the use of tools as flow meters, rain data (from rain gauges), quality stations, weather forecast and on-line rain information, SCADA alarms and graphs or the use of mathematical/hydraulic models provide useful data to support the enhancement of the sewer system management.

#### 4.2.2 WWTP knowledge

WWTP design are usually oversized in order to, at least, guarantee pre-treatment of part of the inflow during wet weather and have some extra capacity to avoid overflows. The use of retention tanks within the WWTPs with enough capacity to retain part of the wastewater during wet weather (and also toxics) can be also very useful.

Despite that, rain episodes can vary widely (as happens in Catalonia region) and produce CSOs events, discharging untreated wastewater to the receiving body. According to the data acquisition, changes in the WWTP configuration can improve its performance during wet weather.

These include:

- Re-routing flows within the WWTP to optimize overall treatment such as diverting screened and degrittied wastewater around primary clarifiers directly to the secondary treatment, or diverting primary effluent around secondary treatment and combining both streams immediately after the secondary clarifiers.
- Protecting activated sludge biomass from washout in secondary clarifiers in service during wet weather by: blending, in-plant splitting, step-feeding, high-rate treatment or flow equalization.
- Maximizing the number of secondary clarifiers in service.
- Creating an environment in the aeration basins encouraging formation of good settling biomass.
- Checking the correct functioning of all the machinery (pumps, screens, etc.).

#### 4.2.3 Coordinated management knowledge

Integrated design of the UWS should be considered in order to reduce the number of CSO discharges. Applying feasible coordinated management strategies (or global RTC) of the overall system, should include regular measurements of rainfall, sewage and storm water (flow/levels and quality) data and historical rainfall data.

All this information should be sent to a control centre in order to set up a group of integrated control strategies and thus support to:

- Reduce the risk of flooding by enhancing the overall storage capacity within and outside the sewer system.
- Minimize the operation costs by optimising pumping costs and providing the information necessary to allow effective maintenance procedures to be implemented.
- Enhance the WWTP performance, by balancing inflow loads and allowing the plant to operate closer to its design capacity thereby reducing the variability of the final effluent.
- Estimate spill frequencies and sizing of detention tanks.

### **4.3 Relevant knowledge (KA-I)**

The different sources of information used in the last section have given the necessary knowledge for the correct development of the EDSS in terms of UWS, WWTP and receiving water management as well as for its coordinated management as established the objectives found in **Chapter 3**.

The compiled information in the literature review, bibliographic research and information gathering (within the knowledge acquisition task) reveals that the use of coordinated strategies for design and operation of the system is not a very common scheme, even when the UWS and WWTP are managed by the same company

However, in some cases non-coordinated management practices as mathematical or hydraulic modelling of the UWS or WWTP, weather forecasting, RTC of the UWS or changes in the WWTP configuration have demonstrated to be efficient in improving the performance of the overall system and are also well considered for the development of a decision support tool. In most cases, the main objectives to reach include the prevention of flooding and following, the reduction of CSOs discharges or protection of the receiving waters.

In this sense, the existing configurations, elements and technologies of both the UWS and WWTP must be considered in an integrated way. This will allow the system to comprehend the effects that an action on the UWS or on the WWTP will have on the performance of the whole system and finally on the receiving ecosystem.

### **4.4 Model selection**

The fourth step in the EDSS building is the model selection. A set of tools can be selected after the analysis performed to the available information and knowledge. This does not only involve numerical models, but also Artificial Intelligence (AI) methodologies. The use of AI tools and models supplies direct access to expertise while their flexibility makes them capable for learning and decision making processes (Cortés et al. (2000)). Expert systems (ES) are the most commonly used and applied subcategory of AI tools. ES are based on expert knowledge translated into rules and following to understandable terms for computers.

Moreover, ES are normally used when the available expert knowledge is only general. Case-based systems (CBS) become more typically adopted when more specific knowledge is found. CBS recognise and reuse some results and experience from previous situations similar to the one affecting. Apart from these AI models, other models can be used as such as neural networks, lineal models, genetic algorithms, etc.

The current EDSS has been constructed using the combination of numerical models (mathematical equations) and ES tools. Both are interconnected supplying information, knowledge and data bidirectionally. The former represent the wastewater cycle from its generation in the several catchments of the virtual system under study to its discharge into the river after the WWTP treatment. The latter represent the expert knowledge in an easy and understandable way in order to support the decision making process.

#### 4.4.1 Catchment and sewer network models

Surface runoff in urban wastewater simulations is generally modelled using simplified hydrological principles. Nevertheless, specific data from pipes and structures may clearly define boundaries in water transport and make hydrodynamic modelling and simulation possible. Water transformations in the sewer system (physical and mathematical) can be described by the first order partial differential Saint-Venant equations (Yen (1973)) composed by a continuity equation for mass conservation and a momentum equation for energy conservation.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad \frac{1}{A} \frac{\partial Q}{\partial t} + \frac{1}{A} \frac{\partial}{\partial x} \left( \frac{Q^2}{A} \right) + g \frac{\partial y}{\partial x} - g(S_0 - S_f) = 0 \quad (4.1)$$

Where:

$A$	area of flow-cross section
$Q$	flow rate
$t$	time
$x$	distance
$S_0$	bed slope
$S_f$	friction slope

With an hydrological insight of the sewer system, pipes are modelled as a black box model using transfer function for transport and so without representing accurately the physical processes given into the configuration. The main idea is to consider the unsteady flow of the pipe as being steady in stretches of a certain length.

These assumptions allow modelling each of the subsections as linear reservoir and in consequence, replace the continuity equation (4.1) in a flow-volume relationship equation:

$$\frac{dV}{dt} = Q_{in}(t) - Q_{out}(t) \quad (4.2)$$

Where  $Q_{in}$  and  $Q_{out}$  are the inflow and outflows, and  $V$  is the water volume inside a tank. This way, a linear tank cascade (Figure 4.11) is given, and the parameters such as the number of tanks ( $n$ ) are determined from the physical properties of the pipe.

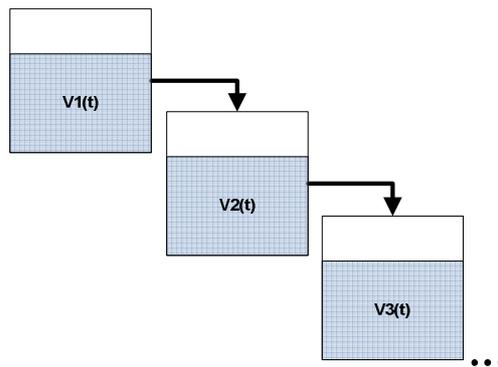


Figure 4.11. Linear tank cascade.

According to the integrated context of this thesis, hydrologic modelling of the urban wastewater system displays significant advantage compared to hydrodynamic modelling. Besides having lower calculations times, hydrologic models need fewer calibration data due to the reduced number of parameters. They provide a better overview of the model structure so it evolves to easier handling when running them. When trying to build an integrated model, it is considered to be appropriate in order to test the tool. However, if a detailed model of a system is available, it might be used to calibrate a simpler model with low calculation times (Meirlaen et al. (2001), Willems and Berlamont (1999), Solvi (2006)). Note that hydrological modelling will be also used for river flow simulations, which gives consistency to the whole integrated modelling approach.

### Pipes

As already explained, wastewater flow through the pipes is modelled as a linear tank cascade where each tank is supposed to be in steady state flow. The residence time ( $k$ ) in the tank and the number of tanks ( $n$ ) for a determined length ( $L$ ) of the pipe is calculated by a modification of the original Kalinin-Miljukov method for the application to partially filled pipes (Euler (1983)). The pipe length ( $L$ ) is divided into a number of tanks ( $n$ ) with a specific length

$$L_c = 0.4 \cdot \frac{d}{s} \quad (4.5)$$

Where the diameter of the circular pipe is ( $d$ ) and ( $s$ ) the slope.

### Storage Tanks

Water can flow out the tanks in by three different ways. The first one depends on the water level of the tank and a gate position at the outlet. The second possible path is fixed by a constant flow (normally given when water is pumped out) and finally, the last option is when  $Q_{out}$  depends by the relation  $Q-h$ .

For a given tank length ( $l_T$ ), width ( $w_T$ ), depth ( $d_T$ ), volume ( $V_T$ ) and a lateral overflow weir if the tank is full, the outflow of the tank depends on two main factors which are, the water level  $h(t)$  and the cross sectional area of the downstream pipe (with a fixed diameter ( $d$ )).

$$Q_{out}(t) \begin{cases} \sqrt{2gd_T} c_o c_P d^2 & \text{for } h > d_T \\ \sqrt{2gh(t)} c_o c_P d^2 & \text{for } d < h < d_T \\ \sqrt{2gh(t)} c_o c_P d h(t) & \text{for } h \leq d \end{cases} \quad (4.6)$$

Where  $c_P$  is the shape of the cross-section pipe ( $\pi/4$  for circular pipe) and  $c_o$  is a parameter (between 0 and 1) and is used to reduce the cross-sectional area depending on the gate opening of the tank.

### Pump stations

This kind of model is a modified version of the abovementioned tanks where the needs user to introduce a pumping flow rate which will start/stop depending on a defined volume ( $V_{start}$  and  $V_{stop}$ ).

### Rain and Evaporation

Rain data is introduced as an input in a simple time-rain format using the desired time interval for the model use. Despite that, this time step should be small enough in order to make sure to simulate peaks that activate combined sewer overflows (CSOs). The spatial distribution of the rain event is uniform for each catchment but can be different for each individual one. The amount of evaporation varies depending on the time of the year as well as it does on the time of the day

$$e(j) = \left[ \frac{7}{9} \sin \left( \frac{2\pi}{365} \cdot (j - 91) + 1 \right) \right] \cdot \frac{\bar{E}_y}{365} \quad (4.3)$$

Being  $e(j)$  the potential evaporation for a specific day ( $j$  the particular day of the year) and  $\bar{E}_y$  the mean annual evaporation

### Runoff

In the runoff module, the rain input is transformed into effective rain entering to the main collectors of the system. The total amount of rainwater entering the system depends on the area connected to the network and to the proportion of impervious and pervious area. Additionally, wetting losses and depression filling take also place for both surfaces, whereas infiltration into the soil happens only on pervious areas. During dry weather, this wetting, depression or infiltration capacities are able to regenerate due to the evaporation phenomena.

The effective rainfall  $R$  from impervious areas is:

$$R(t) = \psi_{max}[I(t) - D(t)] \quad (4.4)$$

Where  $\psi_{max}$  is the maximum runoff coefficient and stands between 0 and 1 and  $D$  is the maximum depression height. This equation states that as fallen rain water increases, storing capacity in depressions decreases. Additional runoff equations included into the model are presented in **Annexes**.

### Dry Weather Flow

An average daily wastewater flow is produced per population equivalent ( $\overline{Q_{PE}}$ ). Its amount and composition depends on the number of inhabitants living in the catchment, the time of the day and on the type of wastewater origin (urban, industrial, commercial, etc.). The model is also sensible to week-end variations and even to a tourism factor in several periods of the year.

### Remaining water

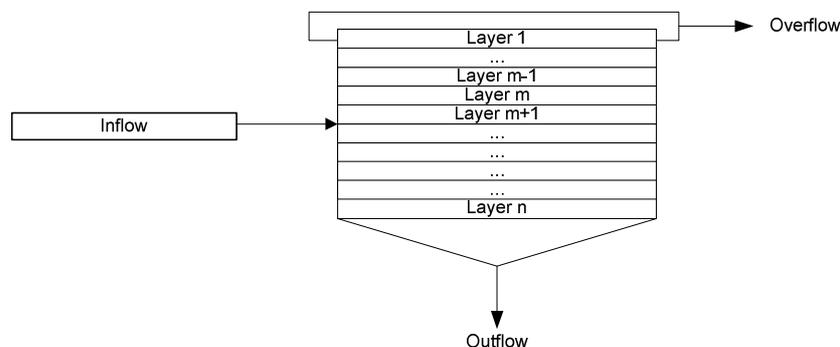
Finally, the amount of water entering into the sewer is particular for each sewer system. It is assumed the rain input as unpolluted water and is entered as a mean flow per total area of the connected catchment.

#### 4.4.2 The WWTP model (ASM2d)

This subsection presents the models used of the WWTPs for both catchments. The main elements to take into account with the configuration of a WWTP are the primary settler, biological reactor and secondary reactor which are necessary to simulate an activated sludge process. The IWA activated sludge models (Henze et al. (2000)) are the most commonly applied set of mathematical models for modelling activated sludge compartments of wastewater treatment plants. These models have been widely used and applied since they remain complex enough despite its simplicity and produce good results when predicting dynamic behaviour of WWTP. Concerning to this thesis, both WWTP of VilaConca and VilaPrat are modelled using the IWA standard model Activated Sludge Model n°2d (ASM2d) (Henze et al. (2000)). The ASM2d is an extension of the Activated Sludge Model 1 (ASM1), more complex and including a larger number of components and processes, majorly, in order to deal with biological phosphorous removal.

Although this model includes a complete description of the different biological and chemical processes occurring into the activated sludge processes of WWTP, the development of this EDSS prototype is focused on the enhancement of the receiving water body by the integrated management of the whole UWS. In this sense, only the hydraulic equations of the ASM2d model are taken into account. The list of variables and processes taking place into the activated sludge unit can be found in **Annexes**.

Additionally, settling processes are modelled with a multi-layer model using a double-exponential form of the flux model (Tákacs et al. (1991)). This type of model considers the clarifier as a number ( $n$ ) of horizontal slices with the feed into slice  $m$  (Figure 4.12). This kind of models are divided into slices (from 10 up to 100) having each division a volume of water and solids moving upwards or downwards. Moreover, solids settle in each slice from the slice above and settle out to the slice below. Finally, each slice is assumed to be well mixed. The mass balances taken into account are described in **Annexes**.



**Figure 4.12.** Multi-layer model used for primary and secondary settlers.

#### 4.4.3 The receiving body model (RWQM 1)

The River Water Quality Model n°1 RWQM1 (Reichert et al. (2001)) is the model used in this section in order to be compatible with the already existing Activated Sludge Models (ASM1, ASM2, ASM2d and ASM3, Henze et al. (2000)). Therefore, the state variables of the model are well suited for the ASM models, describing the organic matter, nutrients, oxygen, organic materials and organisms (bacteria, algae, and consumers). River hydraulics can be modelled using the Saint Venant equations (Yen (1973)) for energy and momentum conservation in order to describe the open-channel water movement. Concerning this thesis, the hydraulic routing is simplified to continuously stirred tanks in series.

Each tank in series receives the output from the previous tank and sends water to the subsequent tank. When integrating a quality sub model into the simplified hydrological model, concentrations (assuming perfect mixing) can be assured as:

$$\frac{d(V(t)c(t))}{dt} = Q_{in}(t)c_{in}(t) - Q_{out}(t)c(t) - V(t)r(c(t), p) \quad (4.7)$$

Where  $Q_{in}$  and  $Q_{out}$  are flow factors,  $V$  the volume,  $c_{in}$  and  $c$  are the concentration component vectors for the input to the tank for the one hand and referring to the concentration inside the considered tank on the other hand.  $r$  is the conversion rate vector (being function of the concentrations ( $c$ ) and model parameters ( $p$ )). Additionally, particulate matter is modelled likewise soluble material and sedimentation is not taken into account. The biochemical processes and the list of variables included into RWQM1 are not taken into account since efforts are put to perform an integrated management of the whole UWS. These can be found in **Annexes**.

#### 4.5 Model integration and implementation

The fifth step on the EDSS build up is the model integration and implementation. WEST<sup>®</sup> version 3.7.6 (2009) (DHI (2011)) has been the modelling software tool decided to use for the development of the virtual system reality used for this thesis. WEST<sup>®</sup> is a user friendly platform for the modelling and simulation that it allows to focus efforts on the development of the EDSS and to show its benefits through the integrated management (Figure 4.13).

WEST<sup>®</sup> tool allows the simulation of:

- Wastewater treatment.
- Water reuse.
- River.
- Sewer.
- Integrated Urban Water Systems.

The software includes hydraulics and quality modelling of several processes that can occur in the above systems. Some of its features are:

- Fast and easy setup of configurations.
- An extensive process library: next to the common activated sludge processes and settlers, it also includes SBR, MBR, TF, IFAS and MBBR models.
- Fast simulations.
- An open structure to implement models and methodology.
- Controller design.
- Coupling with on-line measurement data.
- Coupling with SCADA systems.

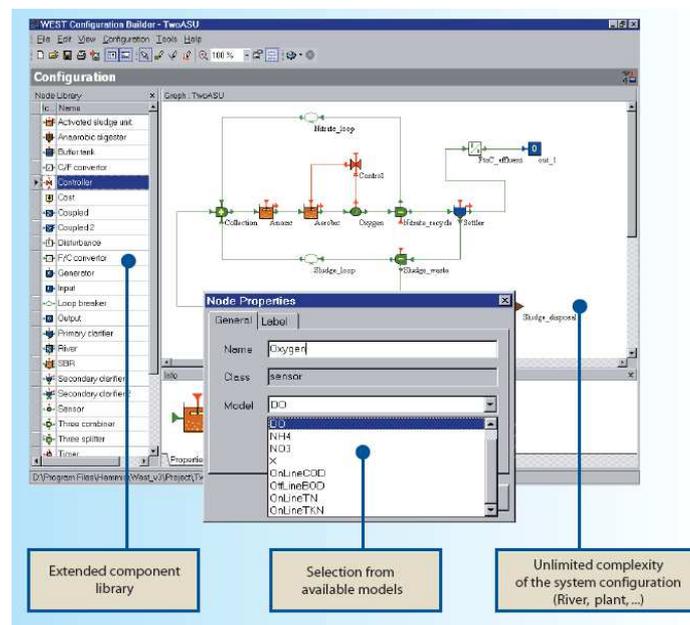
Other advantages of using this software are:

- Parallel simulations are possible so all the subsystems are computed at the same time step allowing considering the bidirectional influence of one system in the other making the simulation more realistic.
- Data transfer between models can be avoided so it is possible to further focus in the development of the EDSS tool instead of applying resources in this secondary work that would not be of any utility in the future when this prototype would be implemented in operational mode.

But of course, there are also some disadvantages of using WEST<sup>®</sup> compared to the traditional models, the most important is that some simplifications have to be applied to the algorithms to allow faster simulation times which implies a reduction of its robustness thus, higher calibration efforts need to be applied.

WEST<sup>®</sup> software has several modules. The ones that have been used in the thesis are:

- WEST<sup>®</sup> for Integrated Urban Water Systems (IUWS): It allows the configuration of the required elements to model the different systems (sewer, WWTP and river), includes information about the catchments, sewers, manholes, actuators (such as pumps, gates, etc.) primary and secondary treatment, and information about the river stretches, and many more.
- WEST<sup>®</sup> for Automation: With this module the user can apply several scenarios changing manually or automatically several parameters of the simulation through an API library. It also allows extracting results in .txt files. This module is the one that is continuously applied in the EDSS tool to launch periodically changing the input data (rain and actuators set points) and get the model results which are later used in the EDSS application as the virtual sensors data that define the behaviour of the virtual reality.



**Figure 4.13.** Example of WEST software screenshot.

In order to apply the EDSS in a virtual system it is needed to do integrated modelling for the whole IUWS. A problem found when creating an integral model is the fact that existing traditional models can simulate the behaviour of only one subsystem and they are quite complex and require sophisticated algorithms to solve the equations. So in order to create an integrated model it is required lots of data transfer to transform the outputs of one software as input for the other one.

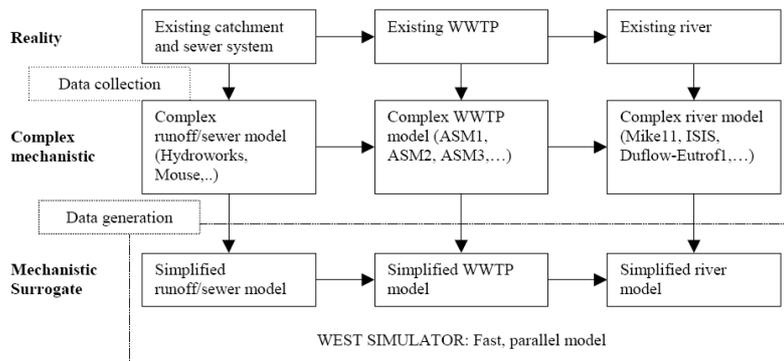
This approach has several disadvantages. The most important is the long calculation times required that make this approach impractical to use, specially within an application like the one developed in this thesis where every few minutes a new integral simulation is required in order to apply the new set points decided by the EDSS. WEST<sup>®</sup> software is a suitable option to avoid this problem.

WEST<sup>®</sup> is an open structure tool thought in a way that all the models implemented into the tool can be viewed and modified in the Model Editor environment and are described in the Model Specification Language (MSL). All models are developed in order to be available for the reuse of its existing knowledge which allows the user to modify any existing model or even add models to those already present, as are the IWA activated sludge models ASM1, ASM2, ASM2d or ASM3 Henze et al. (2000) or the River Water Quality Model n°1 RWQM1 Reichert et al. (2001).

The tool includes a configuration environment, where the user can build up (graphically) the system under study, in this case a whole integrated virtual system with two catchments, sewer systems, WWTPs and a single receiving body. Note that for each of the components of the system (e.g. pipes, storage tanks, activated sludge reactors, etc.) the user can choose from a set of available models included into the model base. Once the system is completely built up, the model is written in MSL and compiled into an executable file which can be further loaded using the experimentation environment of WEST<sup>®</sup>.

At this point, the user can perform a set of experiments and simulations of the model changing parameters of the system subcomponents. A specific module to interact with the model has been developed concerning to the objectives purposed for the EDSS prototype allowing these parameters to be changed automatically.

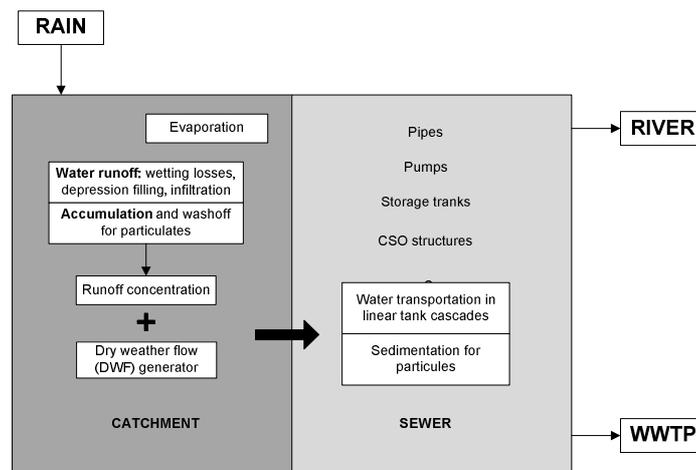
Several papers Meirlaen et al. (2001) Solvi A.-M. et al. (2005) reveal that WEST<sup>®</sup> can be correctly adjusted although it is true that these models need more calibration efforts than the traditional ones. This calibration can either be done collecting more data or comparing and adjusting the WEST<sup>®</sup> results with the traditional model results. In the figure below (Figure 4.14) it is explained this calibration process using complex mechanistic models.



**Figure 4.14.** Calibration process from reality to WEST<sup>®</sup> using complex models.

WEST<sup>®</sup> for IUWS integrates into its model base parts of the original KOSIM model (ITWH (2000)), a tool developed for long term simulation of dry weather flow generation, rainfall-surface runoff and transport in a sewer system and the model can represent six different pollutant loads. KOSIM model uses discrete time step equations which, in order to implement and make them suitable for WEST<sup>®</sup>, these have been transformed to fundamental differential equations (ODEs) since they can be now solved by the tool. This new model base approach implemented into the software is named KOSIM-WEST (Solvi (2006)).

Figure 4.15 illustrates the main processes and structures enclosed into WEST<sup>®</sup> which can be divided by the one hand, into the catchment system (surface runoff and DWF in local sewer networks) and the sewer system itself (main collectors).



**Figure 4.15.** Elements and processes within the KOSIM-WEST model Solvi (2006).

The model base is also applicable onto modelled pollutants. In this case, the variables have been specially chosen for an easy connectivity with the IWA standard Activated Sludge variables (ASM1, ASM2d and ASM3 Henze et al. (2000)) and also for RWQM1 Reichert et al. (2001).

Thus, components in the KOSIM-WEST model are water, soluble and particulate chemical oxygen demand (COD), total nitrogen (TN), total phosphorous (TP) and orthophosphates. WEST<sup>®</sup> uses four main elements in order to reproduce a complete urban wastewater system: catchment nodes, pipes, storage structures and finally combiners and splitter nodes.

#### 4.5.1 Sewer WEST<sup>®</sup> implementation

Catchment nodes represent the urban areas where wastewater is generated. Each of the catchments implemented into the model contain information about the number of inhabitants, surface area (pervious and impervious), wastewater generation per equivalent inhabitant, runoff, etc. All this information is used by the model to perform the calculations of wastewater and pollutants entering into the sewer system. In this particular case, VilaConca has been divided into 9 different sub catchments having each of them their own features converging all of them onto the WWTP entrance. On the other hand since VilaPrat is a bigger catchment, it is divided into 12 sub catchments having their own characteristics too and finally collecting all wastewater at the entrance of the WWTP of VilaPrat.

Moreover, each sub catchment node has an external input connection, which in this case is, the rainfall data. Table 4.5 summarizes the main features of both (a) VilaConca and (b) VilaPrat sub catchments respectively.

**Table 4.5a.** Sub catchment characteristics for VilaConca.

Sub catchment	Surface area (ha)	Inhabitants (IE)	Impervious area (%)	Pervious area (%)	Population density (IE/Km <sup>2</sup> )	Wastewater production (m <sup>3</sup> /d)
Mat 1	43.90	7029	54.46	45.54	15988.08	3865.95
Mat 2	30.57	4891	61.37	38.63	15998.30	2690.05
Mat 3	30.66	4905	62.54	37.46	15998.04	2697.75
Mat 4	32.03	5123	62.88	37.12	15994.38	2817.65
Mat 5	33.43	5344	63.68	36.32	15985.64	2939.20
Mat 6	13.46	2147	63.48	36.52	15947.41	1180.85
Mat 7	27.82	4454	62.02	37.98	16007.76	2449.70
Mat 8	21.59	3454	59.60	40.40	15998.15	1899.70
Mat 9	12.09	1937	60.44	39.56	16020.18	1065.35
<b>TOTAL</b>	<b>245.55</b>	<b>39284</b>	<b>550.47</b>	<b>349.53</b>	<b>143937.94</b>	<b>21606.20</b>

**Table 4.5b.** Sub catchment characteristics for VilaPrat.

Sub catchment	Surface area (ha)	Inhabitants (IE)	Impervious area (%)	Pervious area (%)	Population density (IE/Km <sup>2</sup> )	Wastewater production (m <sup>3</sup> /d)
Prat 1	80.00	10000	50.00	50.00	12500.00	1500.00
Prat 2	160.94	51542	63.30	36.70	32025.60	7731.30
Prat_industrial	572.25	161571	56.60	43.40	28234.30	24236.00
Prat 3	207.67	55836	72.00	28.00	26886.90	8375.40
Prat 4	189.79	53153	77.90	22.10	28006.20	7973.00
Prat 5	44.47	12772	87.50	12.50	28720.50	1915.80
Prat 6	304.94	86196	80.60	19.40	28266.50	12929.00
Prat 7	35.88	1542	75.00	25.00	4297.70	231.30
Prat 8	178.34	41226	46.40	53.60	23116.50	6183.90
Prat 9	23.48	3368	42.00	58.00	14344.10	505.20
Prat 10	79.30	16438	39.30	60.70	20728.90	2465.70
Prat 11	40.90	8507	44.10	55.90	20799.50	1276.10
<b>TOTAL</b>	<b>1917.96</b>	<b>502151</b>	<b>734.7</b>	<b>465.3</b>	<b>267926.7</b>	<b>75322.7</b>

Pipe nodes can be simulated depending on their shape, length, assigning different rugosity values depending on the material they are made off. For both catchment areas, each sub catchment has an associated pipe besides some additional pipes transporting wastewater through the sewer system. Table 4.6 sums up the information included for each of the pipes of the model, being (a) for VilaConca catchment and (b) for VilaPrat.

**Table 4.6a.** Pipe characteristics for VilaConca.

Pipe	Length (m)	Diameter (m)	Rugosity (n)	Slope (m/m)
MPipe 1	389.10	2.85	0.015	0.057
MPipe 2	788.64	3.50	0.015	0.025
MPipe 3	713.92	2.75	0.015	0.045
MPipe 4	669.68	3.80	0.015	0.029
MPipe 5	414.95	4.45	0.015	0.014
MPipe 6	441.98	3.80	0.015	0.020
MPipe 7	228.81	2.90	0.015	0.020
MPipe 8	256.64	2.00	0.015	0.040
MPipe 9	374.89	2.80	0.015	0.001
MPipe 10	359.01	3.85	0.015	0.020
MPipe 11	167.58	2.90	0.015	0.022
MPipe 13	308.15	1.00	0.015	0.002
MPipe 14	379.59	2.00	0.015	0.002
MPipe 15	250.00	1.00	0.015	0.003

**Table 4.6b.** Pipe characteristics for VilaPrat.

Pipe	Length (m)	Diameter (m)	Rugosity (n)	Slope (m/m)
Pipe 1	117.57	1.80	0.015	0.075
Pipe 2	829.00	3.13	0.015	0.004
Pipe 3	1913.25	3.70	0.015	0.016
Pipe 4	1365.62	5.72	0.015	0.003
Pipe 6	1134.06	3.55	0.015	0.002
Pipe 7	3312.01	2.00	0.015	0.002
Pipe 8	955.84	1.20	0.015	0.008
Pipe 10	815.09	7.55	0.015	0.0002
Pipe 11	680.95	4.58	0.015	0.003
Pipe 12	819.98	1.93	0.015	0.010
Pipe 13	2102.27	3.99	0.015	0.001
Pipe 14	1510.34	4.54	0.015	0.001
Pipe 15	583.81	1.72	0.015	0.003
Pipe 16	2476.29	2.00	0.015	0.001
Pipe 17	388.26	2.00	0.015	0.005

The main purpose of storage nodes is to retain temporally, the first wastewater peak during a rain event which, through runoff process enters into the system. It is during this peak flow period when wastewater contains a higher amount of pollutants because of the washing process on urban surfaces, dragging most of the solids accumulated through the time. VilaPrat has two storage tanks (Table 4.7), one on-line and another off-line, both used for the same objective. Another function of storage nodes is the lamination of WWTP inflows during dry weather periods. Daily flow variations due to urban consumption habits may vary such a lot making storage nodes useful during peak hours discharging wastewater when inflow has descended. VilaConca catchment has only a CSO Tank and a homogenization tank used for this purpose. Finally, storage nodes can be also helpful during punctual pollution episodes, following the same flow lamination principle.

**Table 4.7.** Storage tank characteristics for VilaPrat and VilaConca.

Tank	Location	Position	Volume (m <sup>3</sup> )	Outflow	
				Configuration	Values
Tank1	VilaPrat	On-line	15000	Gate opening	0/0.89/1 (m)
Tank 2	VilaPrat	Off-line	50000	Flow pumping	0.33/0.66/0.99/2 (m <sup>3</sup> /s)
Tank 3	VilaConca	On-line	680	Overflow	-
Homog.Tank	VilaConca	On-line	8000	Overflow	-

Regarding to the rain data, it is introduced as an input to WEST<sup>®</sup> in a simple time-rain format using the desired time interval for the model use. Despite that, the time step should be small enough in order to make sure to simulate peaks that activate combined sewer overflows (CSOs). The spatial distribution of the rain event is uniform for each catchment but can be different for each individual one. The amount of evaporation varies depending on the time of the year as well as it does on the time of the day

Pump nodes are modelled in WEST<sup>®</sup> like storage tanks and, depending on their volume activate/deactivate the predefined pump flow. The off-line storage tank of VilaPrat, is modelled as specific storage tank node which allows introducing a pumping set point by the user too. In some cases, if different pumping set points are needed, the use of splitters and sensors together with pump nodes allow separating fluxes to different pump nodes depending on its value having each pump node a predefined pumping set point. In this thesis, VilaPrat is the only catchment having pumping nodes, which in this case are separated in 3 different nodes and pumping set points.

Table 4.8 illustrates the different pumping set points and volumes for each pump/tank node.

**Table 4.8.** Pump characteristics of the different pump/tank nodes of the system.

	<b>Pump 1</b>	<b>Pump 2</b>	<b>Pump 3</b>	<b>Tank 2 pump</b>
Volume start	70.69m <sup>3</sup>	157.08 m <sup>3</sup>	196.35 m <sup>3</sup>	-
Volume stop	7.85 m <sup>3</sup>	39.27 m <sup>3</sup>	75.54 m <sup>3</sup>	-
Pump flow	0.2m <sup>3</sup> /s	0.2m <sup>3</sup> /s	3.6m <sup>3</sup> /s	2 m <sup>3</sup> /s

Moreover, WEST<sup>®</sup> includes a set of elements named combiners and splitters. *Combiners* are nodes able to add different flows and pollutant fluxes from separate origins into one unique flux ( $Q_1 + Q_2 \rightarrow Q_3$ ). *Splitter* nodes have the opposite purpose. They separate one flux into two or three independent ones. Indeed, CSOs modelled with WEST<sup>®</sup> are splitters activated by exceeding a critical value. A layout representation of the different pipes, tanks and pumps included into the virtual system can be found in **Annexes**.

#### 4.5.2 WWTP WEST<sup>®</sup> implementation

Both wastewater treatment plants included into the virtual system VilaConca and VilaPrat are developed using WEST<sup>®</sup> with a set of models for activated sludge units, buffer tanks, settlers, clarifiers, sensors and controllers.

Regarding to VilaConca WWTP, the first phase in the model construction is the build up of the configuration nodes of the WWTP. The main elements of the plant are the homogenization tank (HT), primary settler (D1\_C), two activated sludge units, one anoxic tank for denitrification, and one aerobic for nitrification processes (Anx\_C and Aer\_C for anoxic and aerobic units respectively) and finally a secondary settler (D2\_C) with its interrelationships between each other (input/output or recirculation flows). From the given information of the system characteristics, physical data was detailed in the model including dimensioning of each unit, pumping capacities, recirculation flows, purge flows or aeration (and controls if necessary). Figure 4.16 illustrates a scheme (adapted to WEST<sup>®</sup>) of the wastewater treatment plant water line model of VilaConca. Additionally, sludge and nitrate recirculation have been defined separately with a set of combiners and splitters while a DO control is also installed. Transformation nodes (T) are introduced as they convert variables from one model to the other. In this case, the first Transformer node is used to convert KOSIM-WEST to ASM2d while the second one is used for ASM2d to RWQM transformation. Finally, flux converters (F/C or C/F) are also introduced into the model converting from Flux to Concentration or vice verse depending on each situation.

As an example of the water course at the WWTP, during dry weather, the plant operates in normal conditions and wastewater follows the normal paths through the plant. It first enters into the WWTP system through the Homogenization Tank (HT), which has a constant outflow rate in order to laminate flow. Afterwards, water flows through the transformer node (transforming from KOSIM-WEST to ASM2d water parameters) passing through the flux converters too (first from flux to concentration and then from concentration back to flux). In dry weather conditions, wastewater passes through the primary treatment (D1\_C) and its subsequent purge flow. It then enters the secondary treatment. The first tank (Anx\_C, Anoxic) is in charge of the denitrification process and the second tank (Aer\_C, Aerobic) is in charge of the nitrification process. Attached to the Aerobic tank, a DO control (DO\_ctrl) is also implemented into the model, maintaining the DO concentration constant into the tank. After the Aerobic tank, Nitrate\_recycle splitter separates wastewater flow into two different streams allowing the denitrification process into the Anoxic tank.

After the aeration basins, water flows to the secondary clarifiers, where sludge is separated from treated wastewater and redirected or to the entrance of the secondary treatment (Co\_C3 and Sludge loop) or flows out of the system as waste. Treated wastewater flows to Co\_C4 and to the final transformer node (from ASM2d to RWQM1). After that, treated water enters to the river system.

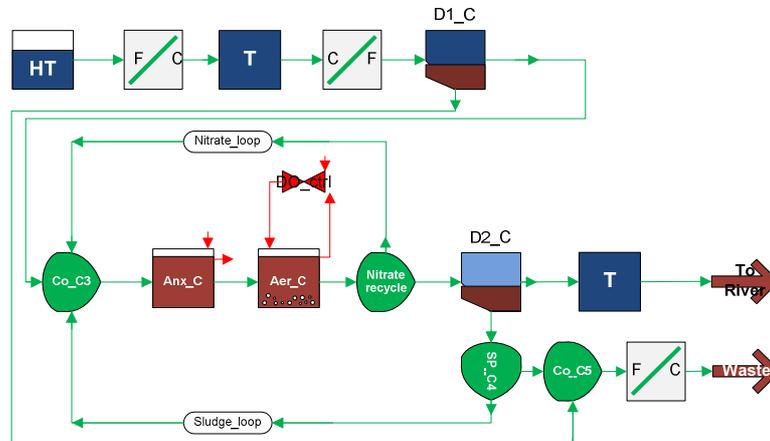


Figure 4.16. WWTP of VilaConca scheme in WEST®.

In the case of the WWTP of VilaPrat, the model construction and node configuration has been carried similar to VilaConca. In this case, as described in section 4.1.2, the WWTP has a primary settler, two activated sludge units (anoxic/aerobic) and secondary settler nodes and the WWTP includes a tertiary treatment unit (see Figure 4.17). A set of recirculation loops, DO control combiners/splitters for flow redirections transformation nodes are also implemented following the virtual system characteristics.

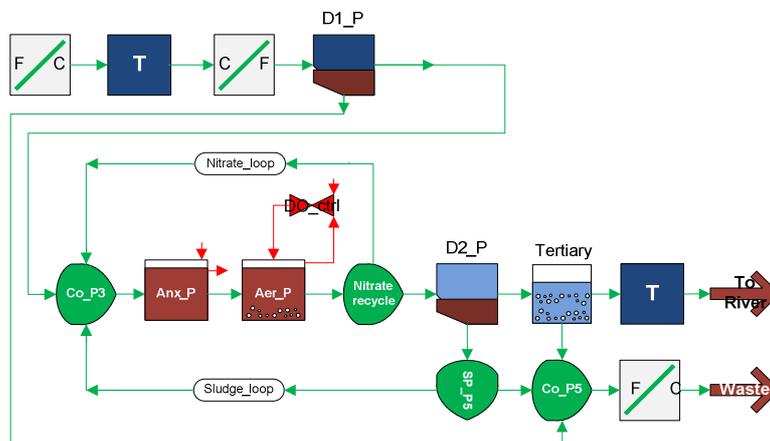


Figure 4.17. WWTP of VilaPrat scheme in WEST®.

4.5.3 River WEST<sup>®</sup> implementation

A reduced version of the RWQM1 has been included into WEST<sup>®</sup>. The river model has been divided into 18 sectors connected to each other (see Table 4.9 and Figure 4.18). Additionally, the river has 8 possible inputs, i.e. the first one is the water supply coming from upstream, input number four ( $I_4$ ) and number eight ( $I_8$ ) are treated wastewater discharge from both WWTPs while the remaining inputs are CSO discharges of untreated wastewater of VilaConca and VilaPrat catchments.

Table 4.9. River main features.

Node	Length (m)	Node	Length (m)
River 1	207	River 10	727
River 2	684	River 11	884
River 3	411	River 12	454
River 4	243	River 13	500
River 5	281	River 14	691
River 6	467	River 15	500
River 7	1185	River 16	907
River 8	431	River 17	5000
River 9	421	River 18	1412
<b>TOTAL</b>		<b>15405</b>	

There are two flux converter nodes, the first one (C/F) converts concentration units into flux since it is a model (RWQM 51) requirement. Once water has flown through the river nodes, it can be transformed again into concentration values and finally providing the final output values of the river model.

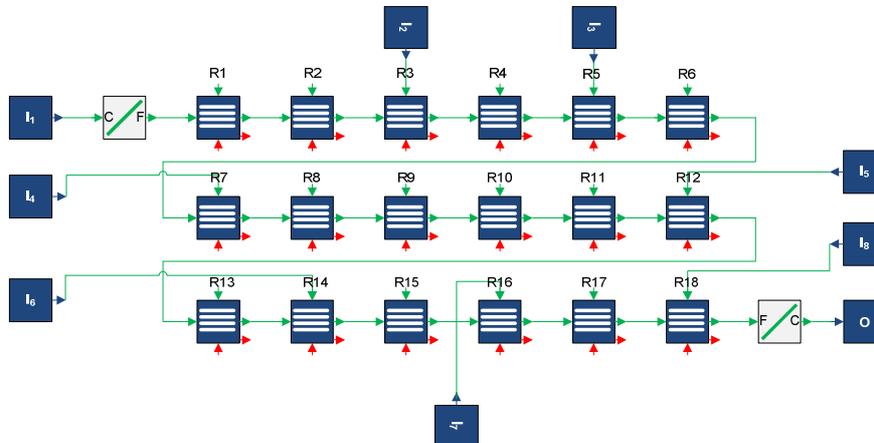


Figure 4.18. River Congost stretch scheme in WEST<sup>®</sup>.

#### 4.5.4 WEST<sup>®</sup> calibration

Model calibrations often require the use of measurement campaigns, which in consequence increase the global costs of the study. Although the level of calibration of each model depends on the objectives of the study, it is usually necessary the use of cost minimization techniques (simplified models, optimal design of measurement campaigns, etc.)(Devesa (2006)). The main purpose of this section is to calibrate the UWS of the virtual system during both dry weather and wet weather conditions.

In this sense, the private partner in collaboration with this thesis has provided a previously calibrated and validated model of the sewer system of Barcelona which has been developed with the Model for Urban Sewer (MOUSE<sup>®</sup>, DHI (1996)), which is a software used for modelling collection systems for urban wastewater or storm water. VilaPrat sewer system (inspired in part of Barcelona sewer network) has been used to calibrate WEST<sup>®</sup> model with the available data from MOUSE<sup>®</sup> model. The calibration of the sewer system of VilaPrat illustrates to the overall model an acceptable robustness regarding to this thesis purpose. Consequently, calibration has not been performed to VilaConca sewer system, WWTPs of VilaConca and VilaPrat neither to the receiving body.

The calibration criteria has been established according to the WAPUG (Wastewater Planning Users Group of CIWEM) modelling guides (WaPUG (2009)) and has been used to compare MOUSE<sup>®</sup> and WEST<sup>®</sup> results. The calibration criteria are described below:

Dry weather flow:

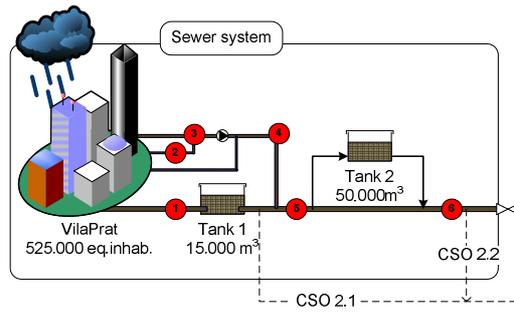
- Times between peaks and valleys don't vary in more than an hour.
- Peak flows should be within a  $\pm 10\%$  range.
- Volumes should be within a  $\pm 10\%$  range.
- Rain events:
  - Times between peaks are similar and should be between  $\pm 25\%$  range.
  - Flows and water levels should be between  $+30\%$  and  $-15\%$  range.
  - Volumes should be between  $+20\%$  and  $-10\%$ .

#### Dry weather flow calibration

For the dry weather flow calibration process, the daily flow pattern of the MOUSE<sup>®</sup> model was modified and adapted so that the dry weather flow pattern of this model would fit to the one chosen with the WEST<sup>®</sup> virtual model.

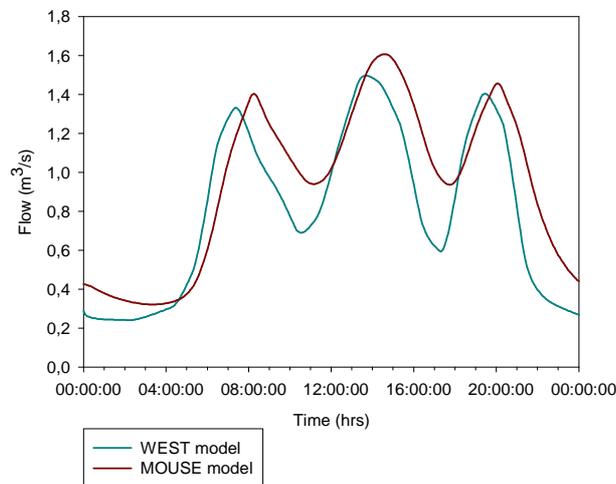
Six points of the sewer system of VilaPrat were selected for this dry weather calibration (see Figure 4.19) being the first one located before Tank1, point number two is positioned after a few sub catchments, and point number three is located after a diversion.

The fourth point is in the interceptor after the pumping station, the fifth one is in the main trunk of the sewer system and finally the sixth one is before the WWTP of VilaPrat. All simulations have been performed with a total length of 24h both for WEST<sup>®</sup> than for MOUSE<sup>®</sup> models.



**Figure 4.19.** Calibration points for DWF sewer system of VilaPrat.

As an example, Figure 4.20 illustrates the calibration results during dry weather flow of the entrance of the WWTP of VilaPrat (corresponding to point 6). There are three different peaks (08:42; 15:01; 20:38) corresponding to the daily water consuming variations. Additionally, two valleys can be also identified (11:49; 18:29) throughout the graphical representation.



**Figure 4.20.** Dry weather flow calibration results of point 6 for VilaPrat system.

Results of the whole set of calibration points of VilaPrat system are shown in the next set of tables (see Tables 10a,b,c,d,e,f) displaying for MOUSE<sup>®</sup> and WEST<sup>®</sup> models flow values and their time occurring peaks and valleys for each of the calibration points. Finally, flow and temporal errors are also represented into these tables.

**Table 10a.** Calibration results of Point 1 of VilaPrat system during DWF.

	MOUSE		WEST		Flow error (%)	Time error (%)	
	Flow	Time	Flow	Time			
	(m <sup>3</sup> /s)	(hh:mm)	(m <sup>3</sup> /s)	(hh:mm)			
Point 1	Peak 1	0.027	7:31	0.030	7:00	10.0	-7.1
	Peak 2	0.032	13:30	0.032	13:00	-0.3	-3.8
	Peak 3	0.029	19:30	0.031	19:00	5.2	-2.6
	Minimum 1	0.015	10:30	0.015	9:58	-2.0	-5.4
	Minimum 2	0.015	16:33	0.014	16:56	-4.3	2.3
	<b>Total (m<sup>3</sup>)</b>	<b>1500</b>	-----	<b>1498</b>	-----	<b>-0.1</b>	-----

**Table 10b.** Calibration results of Point 2 of VilaPrat system during DWF.

		MOUSE		WEST		<i>Flow error</i>	<i>Time error</i>
		<b>Flow</b>	<b>Time</b>	<b>Flow</b>	<b>Time</b>		
		(m <sup>3</sup> /s)	(hh:mm)	(m <sup>3</sup> /s)	(hh:mm)		
<b>Point 2</b>	Peak 1	0.719	7:44	0.741	7:05	3.0	-9.2
	Peak 2	0.842	13:50	0.834	13:26	-0.9	-3.0
	Peak 3	0.769	19:44	0.782	19:12	1.7	-2.8
	Minimum 1	0.419	10:46	0.383	10:19	-9.3	-4.4
	Minimum 2	0.402	17:00	0.345	17:05	-16.5	0.5
	<b>Total (m<sup>3</sup>)</b>	<b>39992</b>	-----	<b>38615</b>	-----	<b>-3.6</b>	-----

**Table 10c.** Calibration results of Point 3 of VilaPrat system during DWF.

		MOUSE		WEST		<i>Flow error</i>	<i>Time error</i>
		<b>Flow</b>	<b>Time</b>	<b>Flow</b>	<b>Time</b>		
		(m <sup>3</sup> /s)	(hh:mm)	(m <sup>3</sup> /s)	(hh:mm)		
<b>Point 3</b>	Peak 1	0.166	7:35	0.184	7:04	9.8	-7.3
	Peak 2	0.194	13:40	0.209	13:14	7.2	-3.3
	Peak 3	0.178	19:36	0.196	19:04	9.2	-2.8
	Minimum 1	0.095	10:38	0.100	10:09	5.0	-4.8
	Minimum 2	0.091	16:45	0.089	16:58	-2.2	1.3
	<b>Total (m<sup>3</sup>)</b>	<b>9227</b>	-----	<b>9877</b>	-----	<b>6.6</b>	-----

**Table 10d.** Calibration results of Point 4 of VilaPrat system during DWF.

		MOUSE		WEST		<i>Flow error</i>	<i>Time error</i>
		<b>Flow</b>	<b>Time</b>	<b>Flow</b>	<b>Time</b>		
		(m <sup>3</sup> /s)	(hh:mm)	(m <sup>3</sup> /s)	(hh:mm)		
<b>Point 4</b>	Peak 1	0.250	-----	0.250	-----	0.0	-----
	Peak 2	0.500	-----	0.500	-----	0.0	-----
	Peak 3	-----	-----	-----	-----	-----	-----
	Minimum 1	-----	-----	-----	-----	-----	-----
	Minimum 2	-----	-----	-----	-----	-----	-----
	<b>Total (m<sup>3</sup>)</b>	<b>24237</b>	-----	<b>22869</b>	-----	<b>-6.0</b>	-----

**Table 10e.** Calibration results of Point 5 of VilaPrat system during DWF.

		MOUSE		WEST		<i>Flow error</i>	<i>Time error</i>
		<b>Flow</b>	<b>Time</b>	<b>Flow</b>	<b>Time</b>		
		(m <sup>3</sup> /s)	(hh:mm)	(m <sup>3</sup> /s)	(hh:mm)		
<b>Point 5</b>	Peak 1	0.906	7:58	0.916	7:05	1.1	-12.5
	Peak 2	1.060	14:09	1.045	13:33	-1.4	-4.4
	Peak 3	0.964	19:59	0.975	19:14	1.1	-3.9
	Minimum 1	0.54	11:05	0.507	10:20	-6.5	-7.3
	Minimum 2	0.521	17:33	0.449	17:06	-16.0	-2.6
	<b>Total (m<sup>3</sup>)</b>	<b>50707</b>	-----	<b>49440</b>	-----	<b>-2.6</b>	-----

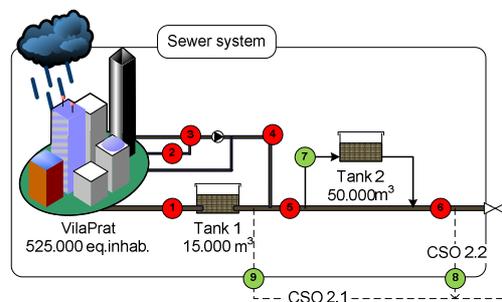
**Table 10f.** Calibration results of Point 6 of VilaPrat system during DWF.

	MOUSE		WEST		Flow error (%)	Time error (%)	
	Flow	Time	Flow	Time			
	(m <sup>3</sup> /s)	(hh:mm)	(m <sup>3</sup> /s)	(hh:mm)			
Point 6	Peak 1	1.430	8:42	1.315	8:23	-8.7	-3.8
	Peak 2	1.601	15:01	1.531	14:37	-4.6	-2.7
	Peak 3	1.480	20:38	1.407	20:06	-5.2	-2.7
	Minimum 1	0.870	11:49	0.791	11:29	-10.0	-2.9
	Minimum 2	0.870	18:29	0.750	18:04	-16.0	-2.3
	<b>Total (m<sup>3</sup>)</b>	<b>79515</b>	-----	<b>73731</b>	-----	<b>-7.8</b>	-----

According to the calibration criteria it can be seen that each of the three daily peaks of the six different points do not differ by more than  $\pm 10\%$  respect one another model. Regarding to the minimums, there are some points where this difference is slightly higher (Points 2, 5 and 6). This is probably due to small design variations and little errors in the simplification of the sewer model. Furthermore it can be considered of no major consequence as the peak flows are the real bottlenecks that can cause problems into the UWS. Finally, results from point number 4 do not differ from the MOUSE<sup>®</sup> model as it is located just after the pumping station, and its design is equal for both models. With regard to the timing differences, all points vary in less than an hour so they were considered valid.

#### Wet weather flow calibration

The points used in the wet weather calibration process are the same as the ones used in dry weather plus three more points (Tank 2 inflow, CSO 2.1 and CSO 2.2). These calibration points are shown in the next figure (see Figure 4.21).

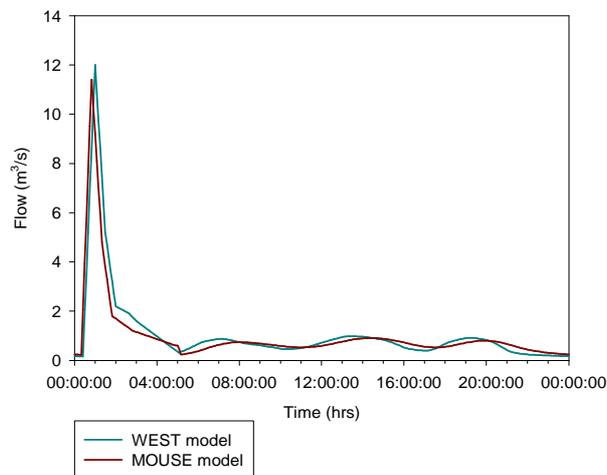
**Figure 4.21.** Calibration points for WWF sewer system of VilaPrat.

Two rain events with different characteristics each one, were used for the calibration and then a third rain event was used for validation. All three rain episodes are based on real data and its main features are:

**Table 4.11.** Rain episodes used for calibration and validation of VilaPrat sewer system.

	Rain event 1	Rain event 2	Rain event 3
Date (dd/mm/yyyy)	17/09/2009	19/02/2010	20/09/2009
Type	Calibration	Calibration	Validation
Duration (h)	1.00	3.00	1.41
Total precipitation (mm)	8.70	26.70	35.60
Average intensity (mm/h)	8.70	8.90	25.12
20 min. maximum intensity (I20) (mm/h)	23.70	41.40	75.90
Return period (months)	2.16	3.60	1.50

Figure 4.22 illustrates the calibration results of point number 2 for the rain event 1 at the system of VilaPrat. The highest peak corresponds to the rain, which occurs at the beginning of the simulation (01:00). As happens in DWF, the daily flow variations can be also appreciated although in a smaller degree (09:16, 13:21, 19:08).



**Figure 4.22.** Wet weather flow calibration results of point 2 for VilaPrat system.

Similarly as in the dry weather flow calibration, results are shown below in a group of tables for each of the studied rain events (see Tables 12a, b and c). In this case, the total volume and the time of the rain peak for each calibration point is represented. It can be seen that in some particular cases, the difference in percentage between models is over the established criteria. Although in most of these points this difference is minimal, there are several points where it is greater.

Major reasons are, as in DWF calibration, due to the differences on the sewer system design which during rain events becomes higher. Another possible reason is the difference on the wastewater transport equations implemented to each of the models along the urban wastewater network, which during wet weather events, make these differences higher too.

Concerning to the rain event 1, points 1, 6, 8 and 9 are the ones varying the most with the established calibration criteria. Point 1 is located at the beginning of the system and thus, generated wastewater volumes are small which may mean significant percentage changes due to difference between models. Point 6 does not differ much from the calibration criteria (-10%) and its differences are probably caused by the major reasons exposed above. The error found at point number 8 was probably due to the error accumulation throughout the system. Finally, error of point 9 (CSO 2.1) is due to the fact that MOUSE<sup>®</sup> model presents very low CSO values (close to 0 m<sup>3</sup>) while WEST<sup>®</sup> model results are small CSO (but not 0) which in consequence produce high error values. As in point 8, this error is probably caused by the error accumulation downstream VilaPrat sewer system.

**Table 12a.** Calibration results rain event 1(17<sup>th</sup> September).

		MOUSE		WEST		<i>Volume error</i> (%)	<i>Time error</i> (%)
		<b>Volume</b>	<b>Time</b>	<b>Volume</b>	<b>Time</b>		
		(m <sup>3</sup> )	(hh:mm)	(m <sup>3</sup> )	(hh:mm)		
<b>17<sup>th</sup> September</b>	Point 1	5718	00:38	4951	00:35	<i>-15.5</i>	<i>-8.6</i>
	Point 2	82856	01:00	79441	01:05	<i>-4.3</i>	<i>4.7</i>
	Point 3	25201	00:46	27195	00:50	<i>7.3</i>	<i>8.0</i>
	Point 4	52434	01:13	51498	01:07	<i>-1.8</i>	<i>-8.9</i>
	Point 5	112420	01:16	104144	01:11	<i>-7.9</i>	<i>-7.0</i>
	Point 6	141200	01:52	127036	01:45	<i>-11.1</i>	<i>-6.7</i>
	Point 7	30777	01:40	32724	01:47	<i>5.9</i>	<i>6.5</i>
	Point 8	14058	01:14	11822	01:22	<i>-18.9</i>	<i>9.8</i>
	Point 9	3.67	00:00	12152	01:44	<i>100.0</i>	<i>100.0</i>

For the rain event 2, calibration points number 5, 6, 8 and 9 are presenting the highest errors. Error at point number 5 can be considered near to the calibration criteria and differences may be caused by variations in the sewer system design or to the implemented model equations. Error at point 6 is a bit higher but does not differ much from the calibration criteria. Differences in model equations and error accumulation effect may be the major reasons for this point. The last two calibration points (8 and 9) present the highest differences respect with the MOUSE<sup>®</sup> model. Number 8 may be caused by an increasing error accumulation and to differences between the equation models and to the model simplification. Errors at point 9 may be due to the ones mentioned for the other points added to the possible ones caused by the equation variations found in the two model equations at Tank 1.

**Table 12b.** Calibration results rain event 2 (19<sup>th</sup> February).

		MOUSE		WEST		<i>Volume error</i> (%)	<i>Time error</i> (%)
		<b>Volume</b>	<b>Time</b>	<b>Volume</b>	<b>Time</b>		
		(m <sup>3</sup> )	(hh:mm)	(m <sup>3</sup> )	(hh:mm)		
<b>19<sup>th</sup> February</b>	Point 1	13715	00:37	12897	00:34	<i>-6.3</i>	<i>-8.8</i>
	Point 2	179850	00:49	169950	00:54	<i>-5.8</i>	<i>9.3</i>
	Point 3	62968	01:04	72200	01:10	<i>12.8</i>	<i>-5.7</i>
	Point 4	73450	00:57	89753	01:12	<i>18.2</i>	<i>6.9</i>
	Point 5	244247	01:12	218187	01:09	<i>-11.9</i>	<i>-4.3</i>
	Point 6	193305	01:39	168140	01:33	<i>-15.0</i>	<i>-6.5</i>
	Point 7	47630	01:21	48804	01:19	<i>2.4</i>	<i>-2.5</i>
	Point 8	84470	01:09	66692	01:03	<i>-26.7</i>	<i>-8.2</i>
	Point 9	92953	01:38	118989	01:47	<i>21.9</i>	<i>8.4</i>

The third rain event used for validation presents three points where the error is higher. These are points 1, 5 and 8. The first one, as it has been explained in the first rain scenario may be due to the situation of this point at the beginning of the sewer system, where volumes are still small and little differences between them can evolve to higher percentage changes. Point number 5, has an error not far from the calibration criteria limit (-10%). In this case, a small error accumulation and differences between the model simplification and the model equations may be the main reasons found for this point. Finally, error at point number 8, even being small, it may be probably caused by the same reasons as for the other two rain scenarios.

Nevertheless, this rain scenario is the biggest one (in terms of total precipitation) and therefore, is more likely to reach the sewer system limit, produce CSO episodes and thus reduce the volume difference between the compared models.

**Table 12c.** Validation results rain event 3 (20<sup>th</sup> September).

	MOUSE		WEST		Volume error (%)	Time error (%)	
	Volume	Time	Volume	Time			
	(m <sup>3</sup> )	(hh:mm)	(m <sup>3</sup> )	(hh:mm)			
20 <sup>th</sup> September	Point 1	25021	00:50	19905	00:46	-25.7	-8.7
	Point 2	273514	01:00	249532	00:57	-9.6	-5.3
	Point 3	113710	00:49	121069	00:53	6.1	7.5
	Point 4	61477	00:58	75577	01:03	18.7	7.9
	Point 5	344953	01:13	296942	01:07	-16.2	-9.0
	Point 6	182636	01:16	170609	01:10	-7.0	-8.6
	Point 7	48454	01:15	48816	01:17	0.7	2.6
	Point 8	187512	01:02	163552	00:58	-14.6	-6.9
	Point 9	199920	00:59	184477	00:55	-8.4	-7.3

After the calibration process of the developed model it can be stated that during dry weather, most of the studied points are found within the established criteria for both flow and time values being the latest all of them within the range. Flow errors are located at minimum positions and thus do not evolve to further consequence since peak flows are the ones who can cause problems in the UWS. Concerning to the wet weather calibration process, it can be considered that most of the studied points are within the established range criteria too (for both parameters volume and time) and being all time results correct. Most of the error percentages found have a negative value meaning that the WEST<sup>®</sup> model produces less volume of wastewater in comparison with MOUSE<sup>®</sup>. Thus, it can be considered that the calibration results are reasonable to represent reality according to the EDSS requirements.

#### 4.6 Second knowledge acquisition loop (KA II)

The sixth step in the build up of the EDSS presented in this thesis is the second knowledge acquisition loop. In subchapter 4.2, a first knowledge acquisition loop (KA-I) has been performed by applying cognitive analysis, data analysis and an extended bibliographic research on coordinated management and finally introduced into the EDSS data base. Besides, the virtual system and the model selection have been defined and implemented into a specific software WEST<sup>®</sup>.

The objective of the second knowledge-acquisition loop is to benefit from the calibrated models to generate more useful knowledge that can be included in the data base of the EDSS to create.

The KA-II loop is carried out following the next steps:

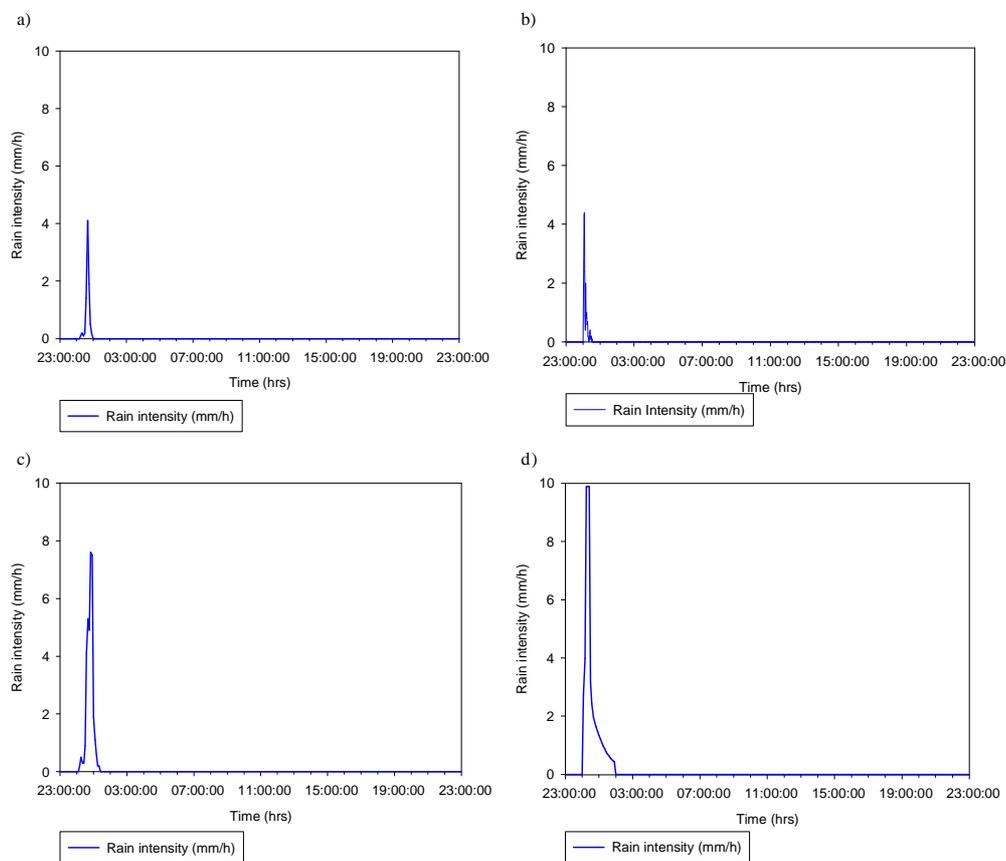
- Scenario definition.
- Standard operation results analysis.

### 4.6.1 Scenario definition

Four rain events have been selected for this second knowledge acquisition loop task (Figure 4.23). The chosen rain events are the same as the ones used in the calibration plus an additional heavy storm event. They are chosen as representative of different types of rain and they are all based in real data provided by CLABSA, the sewer management company of Barcelona area. Table 4.13 summarizes the list of the selected testing scenarios.

**Table 4.13.** List and brief description of the scenarios evaluated.

Scenario n°	Precipitation (mm/h)	Duration (h)	Return Period (months)
1	8.7	1	2.16
2	26.7	3	3.6
3	35.6	1.41	18
4	58.53	1.91	60



**Figure 4.23.** Rain events used for the testing scenarios for the EDSS results comparison.

#### 4.6.2 Standard Operation results

The rain scenarios described above have been tested into the virtual system model (Figure 4.24) and the main profiles of the standard operational results of the different elements of the system are shown below. It must be pointed out that most of the efforts of these scenario tests have been put onto the hydraulic management of the overall system and therefore, results display the wastewater behavior of a 24 h simulation through the system during the tested rain events. The standard management of the system is derived from the most common ways to manage the system which are found both in literature or from the expert system managers.

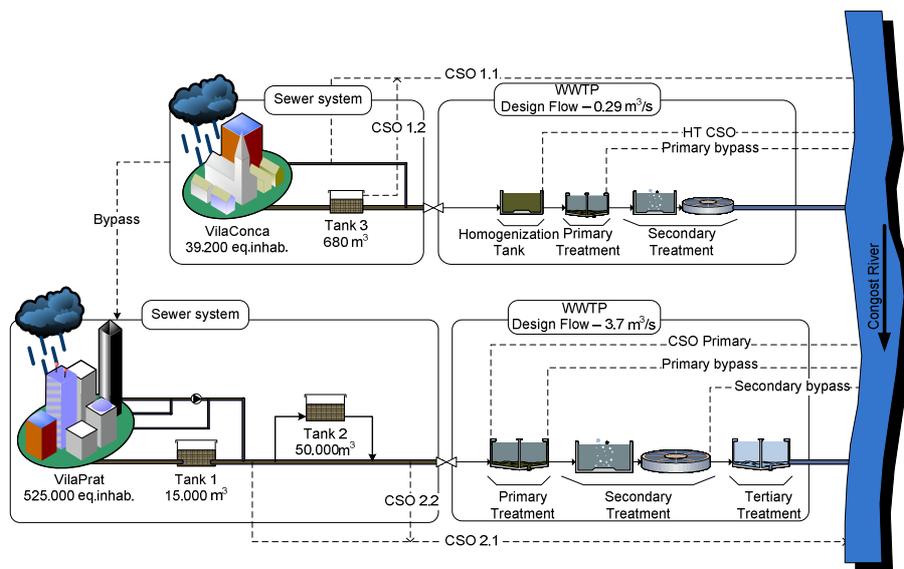


Figure 4.24. General scheme of the virtual system.

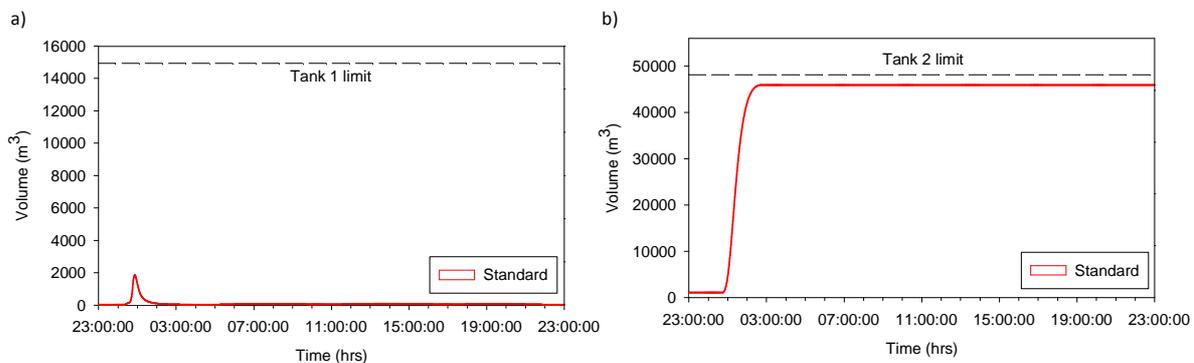
In this standard operation approach, each system is operated independently. This means that the by-pass gate between VilaPrat and VilaConca subsystems is not operational during a rain event. a) The Homogenization Tank (HT) of VilaConca during dry weather flow operates in order to avoid inflow variations of the WWTP, so it stores wastewater and sends a constant average daily flow to the WWTP. Only during rain events, when the volume in the tank exceeds  $5000 \text{ m}^3$ , the flow sent to the WWTP is the maximum capacity of the primary treatment. During a rain event the WWTP operates at its maximum capacity but on a traditional way, meaning that the primary treatment works at its maximum flow capacity and then part of its waters are sent to the secondary and tertiary treatment, while the extra treated flows that cannot be treated in the secondary are directly discharged to the receiving waters. b) On the other hand, in VilaPrat catchment, Tank 1 operates only with the goal of avoiding flooding at its critical point. Tank 2 is an off-line tank operated to avoid or reduce CSO events. This means that there is no water entry during dry weather flow, and when rain starts all water enters to the tank until it is full. From that point, there is no more inflow incoming the tank. Additionally, the WWTP is operated exactly as in VilaConca, at its maximum primary treatment capacity, and sending exceeding overflow directly to the river.

Rain scenario 1

The first plots refer to the stored volume of (a) Tank 1 (on-line) and (b) Tank 2 (off-line) in VilaPrat during scenario 1. As explained, the objective of the storage tanks in the standard operation mode is to avoid floods caused by rain episodes. Figure 4.25, illustrates the stored volume variation over time during this scenario, which increases up to 1800 m<sup>3</sup> and then decreases as the rainfall. Once the rain event is over, the tank empties the stored volume and it recovers its normal volume. In this case, the amount of rainfall is not high enough to cause any flood.

Tank 2 standard operation results show the volume variation of the second tank through time. Tank 2 operates remaining empty until the rain event starts. From that point, all the upstream wastewater is redirected to the off-line Tank 2 where it is stored. When the rainfall has finished, the produced wastewater flows again through its normal path to the WWTP of VilaPrat. In this case, the rainfall is not high enough to produce any CSO discharge so that stored wastewater does not exceed the maximum capacity of the tank.

It must be remarked that there is no emptying of Tank 2 within the 24h simulation since the standard operation mode stores wastewater during 36 h before emptying the tank.

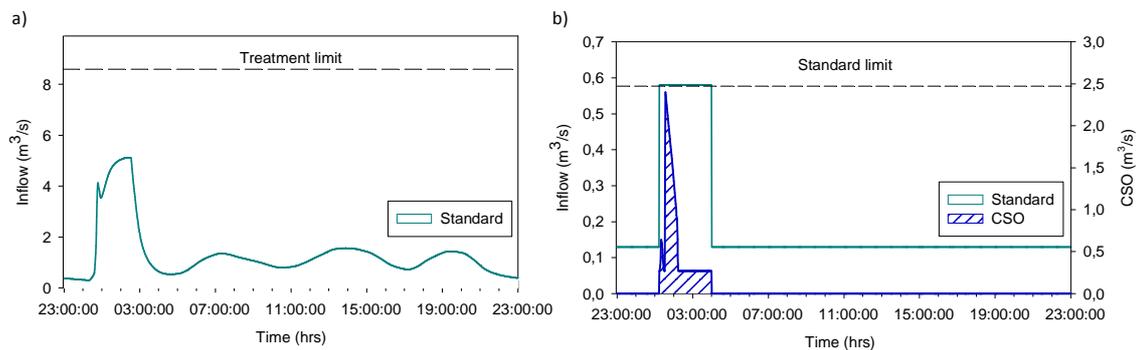


**Figure 4.25.** VilaPrat Tank 1 and Tank 2 standard management for scenario 1.

Regarding to the WWTP of VilaPrat, Figure 4.26a shows the wastewater flow of the plant during the simulation of scenario 1. As stated, the WWTP has a primary treatment capacity of twice the design flow (7.4 m<sup>3</sup>/s), the secondary treatment capacity is of 3.7 m<sup>3</sup>/s and the tertiary treatment capacity is of 1.23 m<sup>3</sup>/s. During the rainfall, the inflow increases up to approximately 5 m<sup>3</sup>/s. Consequently, all wastewater is treated by the primary treatment while only 3.7 m<sup>3</sup>/s flow through the secondary line. Thus, the remaining flow (1.3 m<sup>3</sup>/s) receives only primary treatment and is then discharged into the receiving body. When the rain event is over, the WWTP recovers its normal DWF activity.

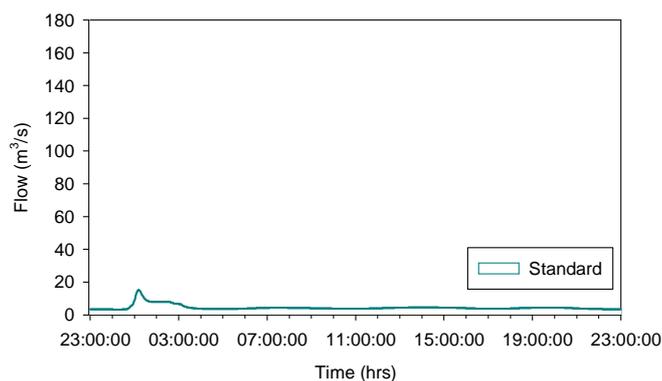
It is important to regard that the WWTP of VilaConca receives an average flow during dry weather of 0.13 m<sup>3</sup>/s (after the Homogenization Tank). The primary treatment is able to treat up to 0.58 m<sup>3</sup>/s (twice the design flow) and the secondary treatment capacity is of 0.29 m<sup>3</sup>/s. The management of the wastewater entering the WWTP of VilaConca (Figure 4.26b) shows that during DWF conditions, the WWTP operates at average inflow conditions (0.13 m<sup>3</sup>/s). On the other hand, when the rainfall starts, the inflow increases up to 0.58 m<sup>3</sup>/s. This means that all the incoming water is treated by the primary treatment and only 0.29 m<sup>3</sup>/s are treated by the secondary line (design flow).

The excess flow, either from CSO 1.1 CSO 1.2 or from the partially treated wastewater from the primary treatment is discharged into the receiving body (corresponding to 5905 m<sup>3</sup>).



**Figure 4.26.** Inflow of WWTP of (a) VilaPrat and (b) VilaConca during scenario 1.

Considering the river flow after the WWTP of VilaPrat (Figure 4.27), it can be seen that during dry weather, the flow is always near 3 m<sup>3</sup>/s and has the typical daily flow pattern. In contrast, during the rain event, the flow increases up to 15 m<sup>3</sup>/s due to the rainfall supply. Moreover, after the rain peak, this flow decreases to 8 m<sup>3</sup>/s approximately, which corresponds to the WWTP of VilaPrat treated wastewater input.



**Figure 4.27.** River water flow after the WWTP of VilaPrat for scenario 1.

Table 4.14 shows the discharges into the receiving body for this first scenario. The amount of rainfall introduced into the system is not high enough to produce high discharge volumes. The only spilling element is the WWTP of VilaConca (5905 m<sup>3</sup>) which is a small system and consequently reaches easier to its maximum capacity.

**Table 4.14.** Discharge results of Scenario 1.

<b>Rain scenario 1</b>	
<b>Component</b>	<b>Discharged volume (m<sup>3</sup>)</b>
Tank 1	0
Tank 2	0
WWTP VilaPrat	0
WWTP VilaConca	5905
<b>TOTAL</b>	<b>5905</b>
<b>Total volume river</b>	<b>379647</b>

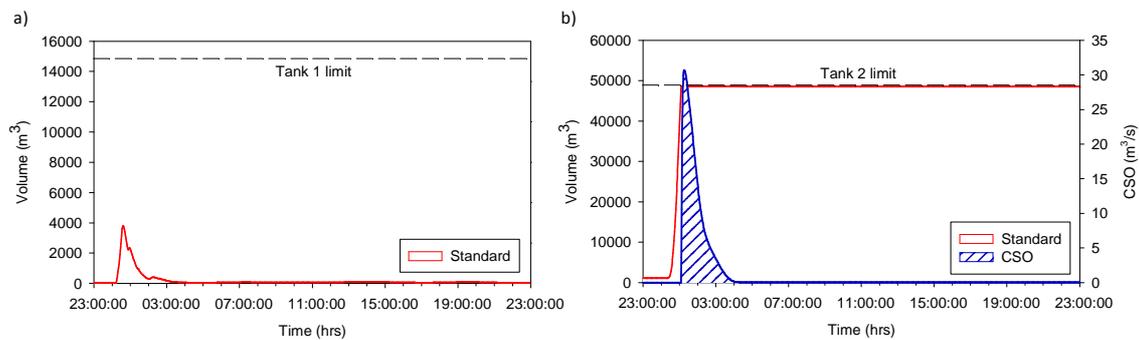
In conclusion, the two UWSs under study are able to treat the majority of water during rainfall events similar to Scenario 1 and therefore do not compromise the quality of the receiving body.

Rain scenario 2

Results of the standard operation mode of the virtual system for rain scenario number 2 are shown. Figure 4.28a illustrates the stored water volume in Tank 1 during the 24h simulation. As it can be seen, the storage volume increases as the rain event overpasses, i.e. before the rain starts, the volume of the tank is very low since the wastewater flow is too low to produce accumulation into the storage tank. Once the rainfall begins, the volume into the tank starts to increase in the same manner as does the intensity of rain. The maximum volume reached is near 4000 m<sup>3</sup> and thus, this rain episode does not produce any CSO discharge (Tank 1 maximum volume = 15000 m<sup>3</sup>). Once the rain event is over, the stored volume decreases up to its initial values.

Regarding to Tank 2 standard operation results (Figure 4.28b), since it is an off line tank, no wastewater enters into the tank until the rain event starts. From that point, all wastewater from upstream is redirected to the tank.

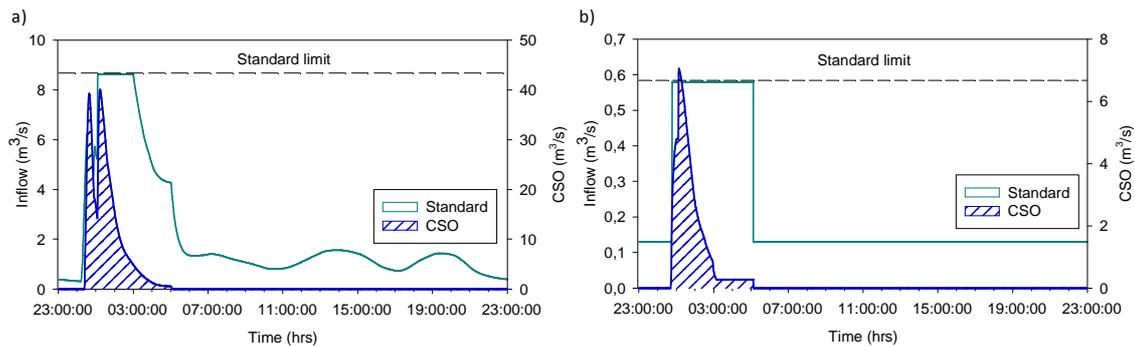
The volume into the tank reaches its maximum capacity during the rainfall at 01:00 and in consequence, produces a CSO discharge (corresponding approximately to 1784 m<sup>3</sup>). After the rain event, water remains stored into the tank as for these testing scenarios, no pumping set point has been introduced.



**Figure 4.28.** Standard operation volumes of (a) Tank 1 and (b) Tank 2 during scenario 2.

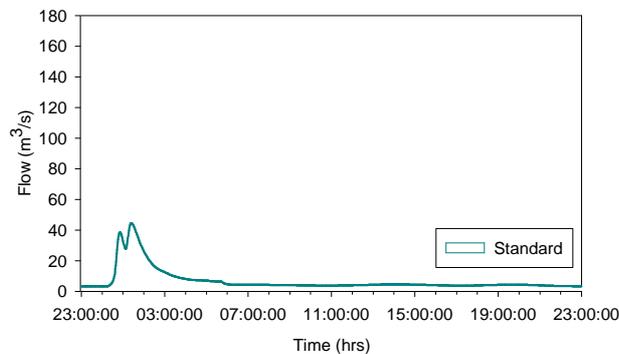
The standard operational results for the inflow of WWTP of VilaPrat (Figure 4.29a), show that while there is no rainfall (23:00 to 00:15 approximately and after the rain event 05:30) the inflow into the plant is the DWF and thus, wastewater flows through the complete treatment process (primary and secondary treatment). During the rain episode, this flow increases significantly up to its treatment limit (8.63 m<sup>3</sup>/s) being 7.4 m<sup>3</sup>/s treated by the primary treatment, 3,7 m<sup>3</sup>/s of them also by the secondary treatment and 1.23 m<sup>3</sup>/s by the tertiary treatment. The remaining waste flow is spilled partially treated or untreated into the receiving body by CSO discharges (191486 m<sup>3</sup>). Two different peaks can be distinguished being the first one corresponding to the first CSO (2.1) at the beginning of the system, after Tank 1. The second peak is a combination of the second CSO (2.2) and the partially treated wastewater discharged after primary treatment.

Figure 4.29b shows how in VilaConca WWTP, for this second scenario, the inflow while there is no rainfall (23:00 to 00:45) is 0.13 m<sup>3</sup>/s, which is the average daily dry weather flow. When the rainfall starts, this inflow reaches 0.58 m<sup>3</sup>/s (twice the design flow). In this case, the duration of time in which the inflow into the WWTP is at its maximum capacity is higher than for the previous scenario since the rainfall input into the system is higher. The excess of water is discharged into the river corresponding to 28441 m<sup>3</sup>. In this situation three main CSO sources are distinguished: CSO 1.1, CSO 1.2 and CSO after primary treatment. The first two discharge wastewater totally untreated into the river while the latest discharges partially treated wastewater.



**Figure 4.29.** Inflow of WWTP of (a) VilaPrat and (b) VilaConca during scenario 2.

Figure 4.30 shows results of the river flow after WWTP of VilaPrat contribution. It must be remarked that while the rain event is taking place, the water flow of the river is increased by the different CSO discharges produced by the rainfall input. After the CSOs, the flow slowly decreases until its normal DWF conditions, when the WWTP VilaPrat reaches its normal conditions too.



**Figure 4.30.** River water flow after the WWTP of VilaPrat for scenario 2.

Table 4.15 illustrates discharges into the receiving body during scenario 2. Since the rainfall for this second rain event is higher, the system is not able to accept all the amount of produced wastewater and in consequence generates a higher volume of CSOs. Tank 1 does not spill, Tank 2 spills 1784 m<sup>3</sup>, WWTP VilaPrat 191486 m<sup>3</sup> and WWTP VilaConca 28441 m<sup>3</sup>. The total amount of CSO discharged into the receiving body during the second scenario is of 221711 m<sup>3</sup>.

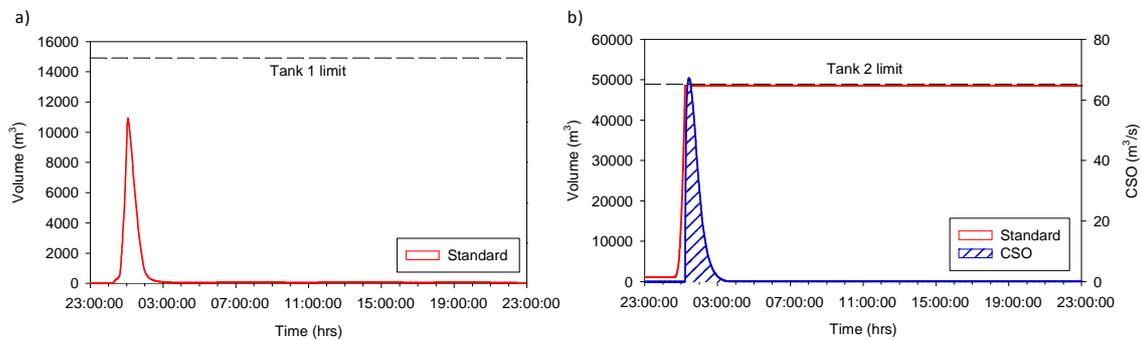
**Table 4.15.** Discharge results of Scenario 2.

<b>Rain scenario 2</b>	
<b>Component</b>	<b>Discharged volume (m<sup>3</sup>)</b>
Tank 1	0
Tank 2	1784
WWTP VilaPrat	191486
WWTP VilaConca	28441
<b>TOTAL</b>	<b>221711</b>
<b>Total volume river</b>	<b>589175</b>

The rainfall of the second scenario produces CSOs in most of the studied elements for this standard operation mode. Despite this rainfall has a return period of 3.6 months, the chance of CSO and flood events in the UWS may be high.

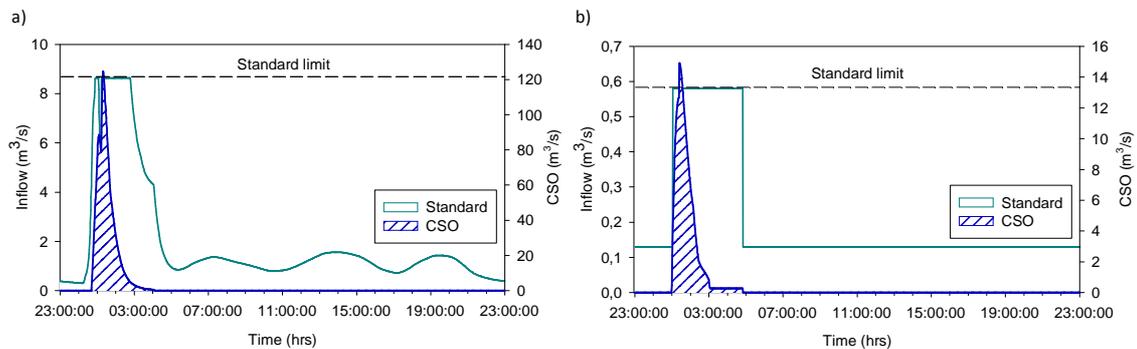
Rain scenario 3

The standard operational simulation results for the rain scenario number 3 are shown below. In this case, the rain event has a higher intensity than the previous rain events (see Figure 4.23c) and the water input is also higher. Figure 4.31a shows the water volume stored into Tank 1 during scenario 3. The stored volume remains low while there is no rain input. However, when the rain starts (00:15), the stored volume increases and decreases in the same way it does the rainfall episode. This is due to the fact that it is an on line tank and while the inflow of the tank is lower than the maximum outflow, the tank does not increase its storing volume. The peak volume reached during the simulation is approximately 10800 m<sup>3</sup> which is much closer to its maximum (15000 m<sup>3</sup>) than for scenarios 1 and 2. Once the rain is over, the stored volume descends quickly to its normal DWF conditions. Figure 4.31b shows simulation results of Tank 2 during scenario 3. The wastewater is only deviated into the tank when the rain event starts. In this case, the tank reaches its maximum storage capacity and produces a CSO discharge of untreated wastewater into the river (3115 m<sup>3</sup>). After the rain event, water remains stored into the tank as happens in the previous testing scenarios.



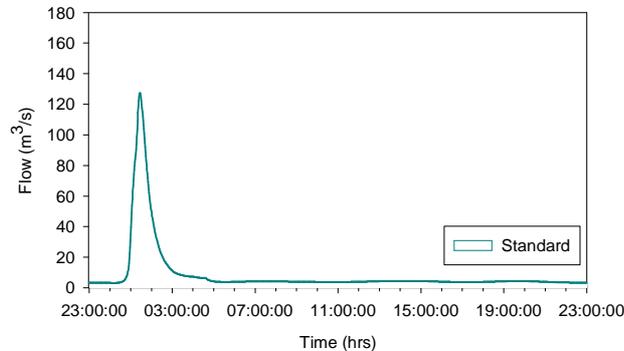
**Figure 4.31.** Standard operation volumes of (a) Tank 1 and (b) Tank 2 during scenario 3.

Figure 4.32a shows results of the WWTP input of VilaPrat. The plant remains in DWF conditions while there is no rain. During the rainfall, the plant reaches its maximum capacity (8.63 m<sup>3</sup>/s) at time 00:50 approximately. At that point, the wastewater is diverted in the following way: 7.4 m<sup>3</sup>/s treated by the primary treatment and 3.7 m<sup>3</sup>/s of them by the secondary treatment too, and the rest (1.23 m<sup>3</sup>/s) only receive a tertiary treatment. The rest is discharged into the river by CSO spills (370167 m<sup>3</sup>). Figure 4.32b shows results of the WWTP of VilaConca. As a direct consequence of the homogenization tank position, the flow entering the WWTP is always regular. During DWF conditions, this is of 0.13 m<sup>3</sup>/s while during the rainfall increases up to 0.58 m<sup>3</sup>/s (twice the design flow). The wastewater excess from the different CSO points of the system, from the HT tank and after the primary treatment (partially treated wastewater) is directly discharged into the river (48595 m<sup>3</sup>). After the rainfall, the water input descends again to its average 0.13 m<sup>3</sup>/s.



**Figure 4.32.** Inflow of WWTP of (a) VilaPrat and (b) VilaConca during scenario 3.

The last plot of this scenario shows results of the river flow after the discharge of WWTP of VilaPrat (Figure 4.33). The maximum peak reached by this scenario is a consequence of the different CSO discharges produced during the rain event (mostly from VilaPrat catchment). In consequence, the contribution of treated water from the WWTP can be hardly appreciated as it is hidden within the area under the CSO peak.



**Figure 4.33.** River water flow after the WWTP of VilaPrat for scenario 3.

Table 4.16 shows discharges into the receiving body during scenario 3. In this case, the rainfall intensity is higher and consequently the volume of CSOs is higher too. Despite that, stored wastewater into Tank 1 does not reach the maximum tank capacity. Tank 2 discharges 3115 m<sup>3</sup>, WWTP VilaPrat 370167 m<sup>3</sup> and WWTP VilaConca 48595 m<sup>3</sup>.

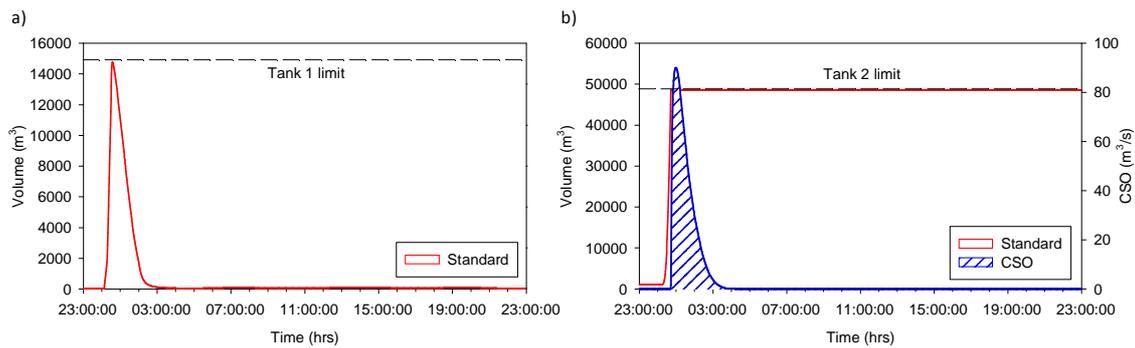
**Table 4.16.** Discharge results of Scenario 3.

<b>Rain scenario 3</b>	
<b>Component</b>	<b>Discharged volume (m<sup>3</sup>)</b>
Tank 1	0
Tank 2	3115
WWTP VilaPrat	370167
WWTP VilaConca	48595
<b>TOTAL</b>	<b>421877</b>
<b>Total volume river</b>	<b>750383</b>

As expected higher CSO discharges into the receiving body occur for this scenario in comparison with the previous ones since the rainfall is also higher (421877 m<sup>3</sup>). This is due to the fact that the system cannot accept much more volume of water. Stronger rain events will produce higher released volumes into the UWS.

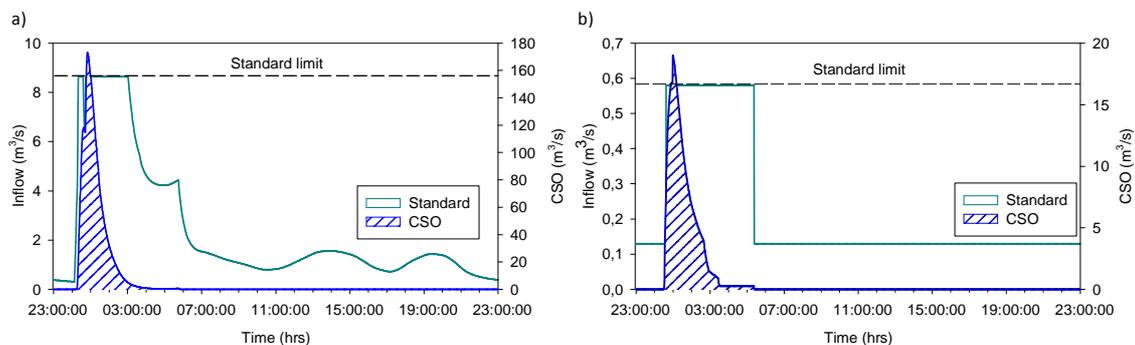
Rain scenario 4

This last rain event has the higher water input and intensity into the system and can thus, produce higher impacts into the system and in consequence into the receiving body. Figure 4.34a illustrates the stored wastewater volume during the rain event in Tank 1, VilaPrat. The reached peak during the rain event (00:33) is close to the maximum storage capacity of the tank ( $15000 \text{ m}^3$ ). Once the rain has finished, the on-line tank empties quickly sending its stored wastewater downstream the sewer system. With regard to the simulation results of Tank 2 (VilaPrat), Figure 4.34b shows how the stored volume increases once the rain event starts. In this case, as the rain input is very high, the tank quickly reaches its maximum capacity producing CSO and discharging untreated wastewater directly to the river ( $5771 \text{ m}^3$ ). Once the rain event is over, the tank is still not emptied and remains full for the next 36 h.



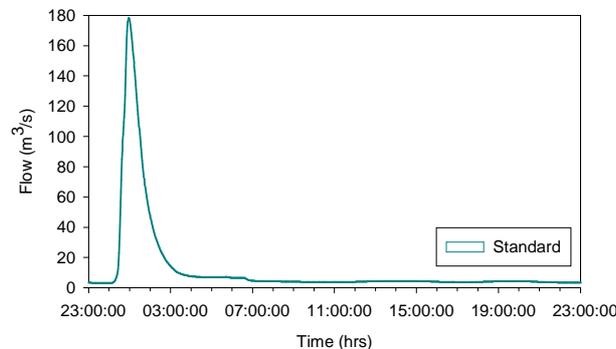
**Figure 4.34.** Standard operation volumes of (a) Tank 1 and (b) Tank 2 during scenario 4.

Simulation results of the WWTP of VilaPrat during scenario 4 (Figure 4.35a) show that before the rain begins, the plant operates at DWF conditions. Once the rain starts, the plant reaches soon its maximum treatment capacity ( $8.63 \text{ m}^3/\text{s}$ ). There, wastewater is redirected in to following way,  $7.4 \text{ m}^3/\text{s}$  are treated through the primary treatment and  $3.7 \text{ m}^3/\text{s}$  of them by secondary treatment too. The rest ( $1.23 \text{ m}^3/\text{s}$ ) receive only tertiary treatment. Remaining wastewater is discharged to the river ( $649971 \text{ m}^3$ ). Additionally, once the rain event is over, the plant takes a little longer to decrease its inflow and operate on DWF conditions. This is due to the greater volume of stored water of Tank 1. The water input of the WWTP of VilaConca during the last testing scenario (Figure 4.35b) remains in DWF conditions while there is no rain event ( $0.13 \text{ m}^3/\text{s}$ ). However, during the rain event it increases up to its maximum treatment capacity, which is twice the design flow ( $0.58 \text{ m}^3/\text{s}$ ). As this rain event is stronger, the time in which the plan operates at maximum capacity is higher (from 00:40 to 05:20). The remaining volume of water is spilled to the river ( $83775 \text{ m}^3$ ) from the different CSO points of the system, from the HT or after the primary treatment (partially treated wastewater). Finally, once the rain has stopped, the WWTP descends the inflow and operates in normal DWF conditions.



**Figure 4.35.** Inflow of WWTP of (a) VilaPrat and (b) VilaConca during scenario 4.

Finally, Figure 4.36 shows results of the river flow after the WWTP of VilaPrat. Since the rain intensity and water input levels are high, the maximum reached for this scenario is near  $180 \text{ m}^3/\text{s}$ . However, after the rainfall event, the river flow descends and returns to the DWF conditions ( $3 \text{ m}^3/\text{s}$  approximately).



**Figure 4.36.** River water flow after the WWTP of VilaPrat for scenario 4.

Table 4.17 shows the amount of discharged wastewater into the receiving body. Although Tank1 does not divert water, Tank 2, the WWTP of VilaPrat and WWTP of VilaConca spill  $5771 \text{ m}^3$ ,  $649971 \text{ m}^3$  and  $83775 \text{ m}^3$  respectively.

**Table 4.17.** Discharge results of Scenario 4.

<b>Rain scenario 4</b>	
<b>Component</b>	<b>Discharged volume (<math>\text{m}^3</math>)</b>
Tank 1	0
Tank 2	5771
WWTP VilaPrat	649971
WWTP VilaConca	83775
<b>TOTAL</b>	<b>739517</b>
<b>Total volume river</b>	<b>1057327</b>

As happens with the other scenarios, as the rainfall intensity increases, so it does the discharged volume into the river. In this case, it is a strong rainfall event since the return period is 5 years. As a result, the standard operation of the UWS produces a total amount of  $739517 \text{ m}^3$  within the 24h simulation.

After the simulation results for the four rain scenarios tested in standard conditions it can be concluded that VilaConca, with the considered infrastructures, has a limited storage capacity within the UWS and its WWTP already operates at maximum treatment capacity. In consequence, for all the tested rain scenarios, the system produces CSO spills either from the sewer system (CSO 1.1; 1.2) the HT or after the primary treatment. The total amount of wastewater discharged into the river for VilaConca system for all scenarios is of  $166716 \text{ m}^3$ . On the other hand, VilaPrat is a bigger system, has a larger storage capacity and the plant does not operate so stressed as VilaConca. However, CSO spills are present in all the tested rain scenarios in exception of scenario number one, who does not produce any CSO. These can be produced by the different CSO points located throughout the system (CSO 2.1; 2.2), Tank 2 weirs and after the primary treatment. The total amount of wastewater discharged into the river by VilaPrat system is of  $1222294 \text{ m}^3$ . It is clear that VilaPrat produces the largest CSO volumes and thus, efforts have to be made in this direction for a more efficient management of this sub catchment.

The above simulated scenarios are carried out within an information research framework for the identification of possible consequences that some critical situations (e.g. rain or storm episodes, industrial spills, sensible receiving body or other operational problems) could have on the receiving body.

By analyzing the simulation results the second knowledge acquisition loop is made in order to perform a diagnosis of the UWS and determine the best solutions. Combining the new knowledge acquired in this second loop with the one obtained in the first loop (section 4.2.4), a set of decision trees are developed in order to manage different hydraulic infrastructures available in the system.

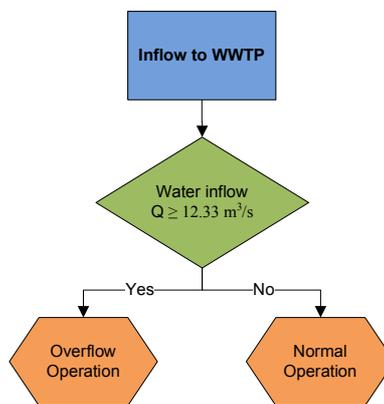
#### 4.7. Build up of Decision Trees

The seventh task in the EDSS development is the built up the decision trees. Decision trees are an easy and understandable way to represent knowledge in a hierarchical chain of nodes and arcs used for problem solving. Each node corresponds to a question related to a particular set of information, whereas each arc between nodes corresponds to a possible value for that information, finishing in decision nodes which summarize the conclusions or actions to carry out. This organized structure of interactions among the nodes of the decision tree allows the direct interpretation of diagnostic reasoning. The knowledge of each arc of a decision tree is translated into a rule in the <IF-THEN> form.

Figure 4.37 illustrates a simple example of an if-then decision tree where the objective is to determine which is the best operation mode according to the inflow of a given WWTP. The tree sequence is as follows:

<IF>  $Q \geq 12.33 \text{ m}^3/\text{s}$  <THEN> *Overflow Operation*

<IF>  $Q < 12.33 \text{ m}^3/\text{s}$  <THEN> *Normal Operation*



**Figure 4.37.** Simple if-then decision tree example.

The developed decision trees have been divided into 3 different levels. The first level is the *meta tree* and is in charge to activate hierarchically second level trees. The second level trees examine the system conditions and perform a complete *diagnosis*. As a result of this diagnosis, second level trees switch hierarchically third level trees. The latest level is in charge to transmit *solutions* (set points, gate positions, flow redirections, etc.) to the model. Besides, second and third level trees can also give additional information as messages or alerts to the user without interacting with the model.

### 4.7.1 First Level Tree

The first level tree has only one single decision tree named *diagnosis meta-tree* (Figure 4.38), it calls the different trees that will operate the systems depending on the rain gauges measurements and the rain forecast level. This general tree is periodically launched. The variables contained into this tree are: rain gauges 1 and 2 (from catchments of VilaConca and VilaPrat), and rain forecast level.

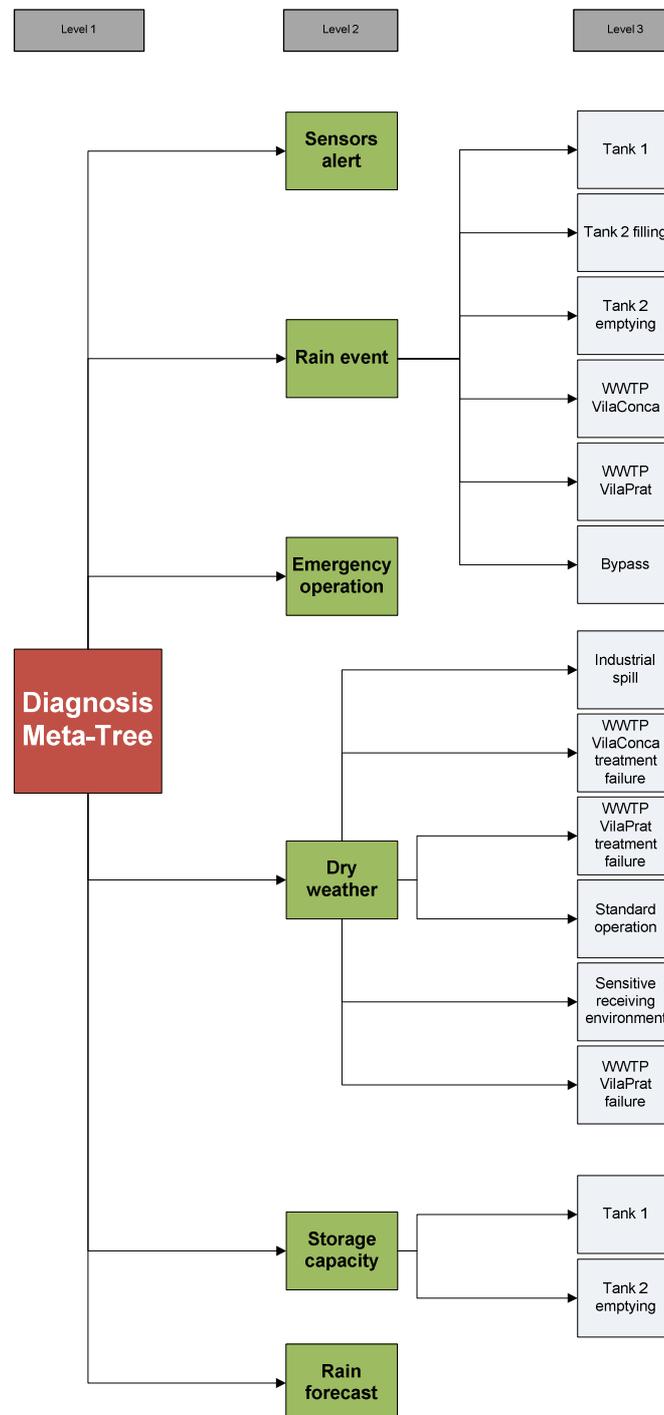


Figure 4.38. Diagnosis meta-tree.

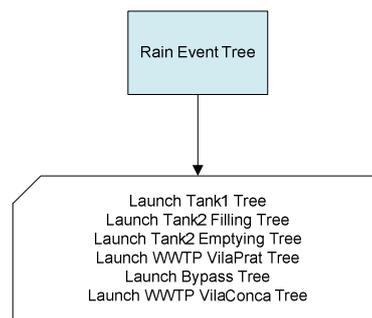
### 4.7.2 Second Level Trees

The second level trees are positioned between the first and third level trees and operate as a consequence of this first level tree. Depending on the rain gauges and rain forecast values, some of the second level trees are activated. Regardless of which are activated or not during a simulation, the second level decision trees are:

- *Sensors alert tree* controls that all sensor measurements have logical values.
- *Rain event tree* controls all actions to be done in case of rain.
- *Emergency operation tree* gives an example of protocol tree informing the operator of different actions to be done in case of rain event.
- *Dry weather tree* orders the actions to be applied in dry weather.
- *Storage capacity tree* empties all storage tanks up to normal levels whenever possible.
- *Rain forecast tree* defines the actions to be performed in case of rain forecast.

In this section, the only trees that are displayed are those that are directly related to the different testing scenarios performed within this thesis described in section 4.5.1. These are the *rain event tree*, *storage capacity tree* and *dry weather tree*. The rest of the trees can be found in the **Annexes**.

The *rain event tree* is the general tree applied when there is a rain event. Its function is to launch several trees related to rain episodes which are *Tank 1 tree*, *Tank 2 filling tree*, *Tank 2 emptying tree*, *WWTP VilaConca tree*, *WWTP VilaPrat tree* and finally *Bypass tree*. Figure 4.39 illustrates the launch function of this particular tree.



**Figure 4.39.** Rain event tree.

Next to it, the *storage capacity tree* (Figure 4.40) is in charge of analysing if any tank's volume is above its normal level and if so it calls the corresponding trees (*Tank 1* and *Tank 2*) with the objective of emptying them, except for Tank 2, where it will be previously checked if the tank is retaining water due to an industrial episode or a VilaPrat WWTP's failure event. The variables checked for this tree are the Tank 1 and Tank 2 volumes and the Industrial and WWTP VilaPrat episodes (being 1 active, 0 inactive).

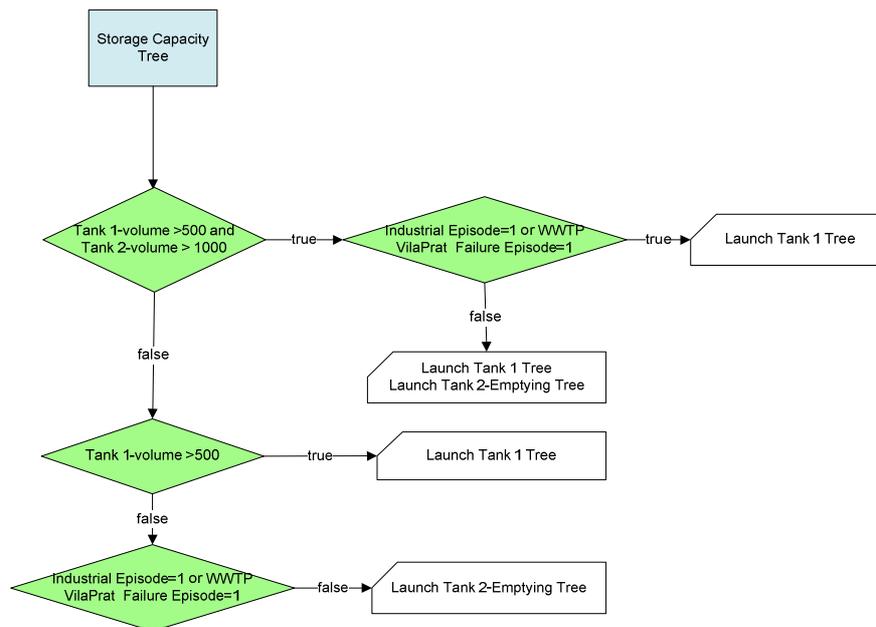


Figure 4.40. Storage capacity tree.

The *dry weather tree* is the general tree applied when the system is in normal conditions. This tree launches a set of third level trees to check the system operates correctly. These trees are the *industrial spill tree*, the *WWTP VilaConca and VilaPrat treatment failure trees* (two independent trees) the *WWTP VilaPrat failure tree* the *sensitive receiving environment tree* and the *standard operation tree*. Figure 4.41 shows the general scheme of the dry weather tree.

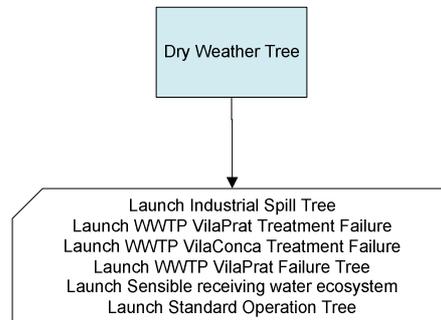


Figure 4.41. Dry weather tree scheme.

### 4.7.3 Third Level Trees

On the third level, diagnosis of the system has already been carried out and thus, third level trees provide the user possible solutions with set points of the different variables of the system and supplying several operational suggestions so as to solve the detected problems. According to the general scheme of the *Diagnosis meta-tree*, third level trees can proceed from three different second level trees. First, the *rain event tree* launches the *Tank 1 tree*, *Tank 2 filling tree*, *Tank 2 emptying tree*, *WWTP VilaConca tree*, *WWTP VilaPrat tree* and finally, *Bypass tree*.

As happens with the second level trees, only the most relevant trees are displayed, which are in one hand the ones related with the storage tanks and WWTP management during rain events. On the other hand, during dry weather, the most significant tree is the standard operation tree. The rest of the developed trees can be found in the **Annex**. For a better comprehension of the third level trees, Figure 4.42 illustrates the UWS layout.

*Tank 1 tree* is designed to control the outflow gate movement of Tank 1. It is divided in two main parts: an anti-flood management branch and an anti-CSO management branch, (see Figure 4.43) which are activated depending on three different variables: when rain forecast is high risk, Tank 2 outflow is above  $6 \text{ m}^3/\text{s}$  (meaning we are close to have flooding problems in the critical point) or when the volume in the Tank is above  $5600 \text{ m}^3$  or  $4200 \text{ m}^3$  which is the maximum volume that in normal circumstances would be applied for CSO purposes, letting the rest of the volume always free for avoiding floodings. There are two maximum values ( $5600$  and  $4200 \text{ m}^3$ ) to avoid hysteresis problems: if there was only one value here, the gate in some circumstances would keep opening and closing every time step when volume would be around that unique value. This is a similar solution to the normal operation of pumps in pumping stations.

The anti-flooding branch tries to keep volume as low as possible letting out as much water as possible without causing flooding problems. For this purpose, it checks if tank volume is above  $7800 \text{ m}^3$  or outflow is above  $5 \text{ m}^3/\text{s}$ . In any of both cases, the gate, which has an opening range between 0 (closed) and 1 m (fully opened) is positioned at a partially opened position of 0.89 m which does not cause flooding. In any other case the gate can be fully open without causing problems.

The anti-CSO part checks if Tank 2 (which purpose is 100% to avoid CSO) is being emptied and if there are more than  $1000 \text{ m}^3$  of free space in that tank. If this is the case, gate is opened and water is sent to Tank 2, and in any other case, gate is closed so the Tank 1 retains water to contribute reducing CSO.

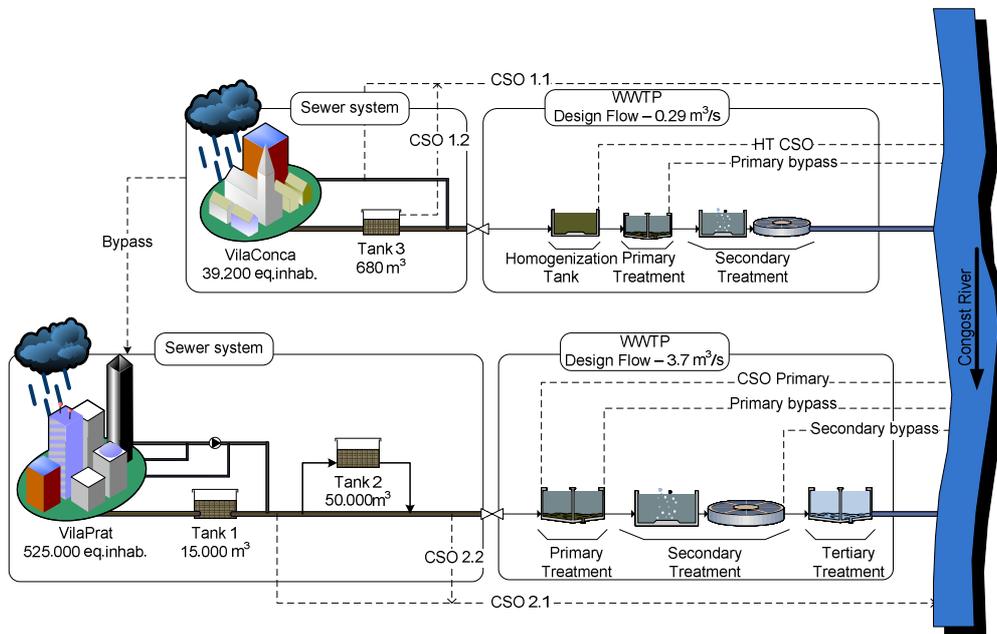


Figure 4.42. Virtual UWS layout.

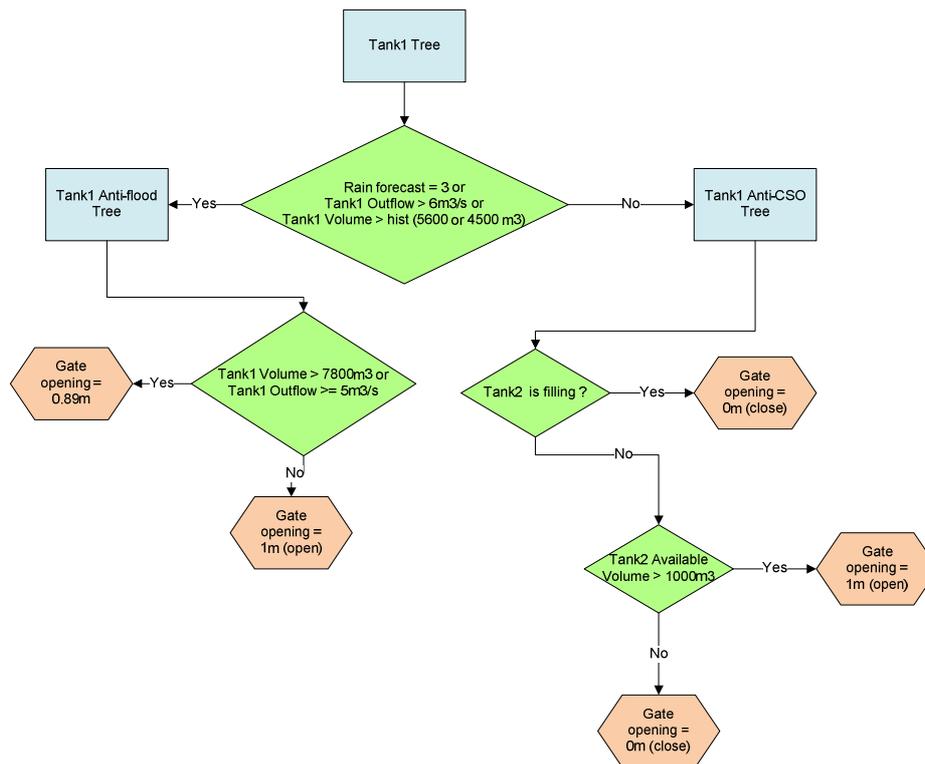


Figure 4.43. Tank 1 management tree.

There are two different trees for Tank 2 management. The first one is the *Tank 2 filling tree* which controls the dry weather flow by pass gate for this tank (Figure 4.44). This tree is responsible for checking the inflow to the WWTP. If this value is above the maximum primary treatment capacity of VilaPrat ( $7.4 \text{ m}^3/\text{s}$ ), the gate closes so that no wastewater is by passed and all gets into the tank. In case of a lower inflow to the WWTP (DWF) up to a maximum of  $2 \text{ m}^3/\text{s}$  by pass the Tank 2 and flow directly to the treatment plant.

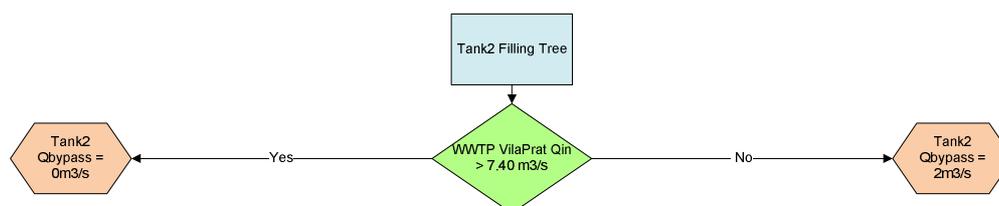
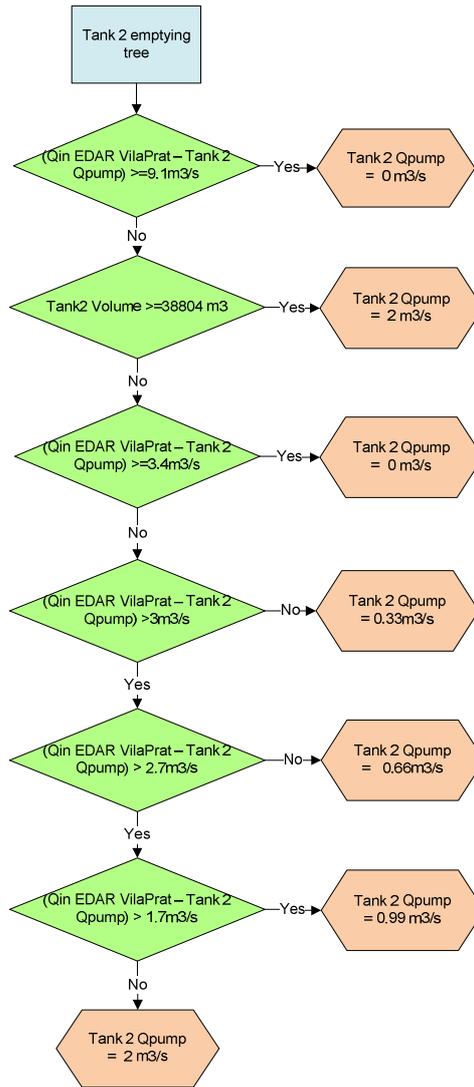


Figure 4.44. Tank 2 filling tree.

The second management tree for this tank is the *Tank 2 emptying tree* (see Figure 4.45). This tree activates the available pumps installed into the tank. Three of them are able to pump  $0.33 \text{ m}^3/\text{s}$  and a fourth one of  $1 \text{ m}^3/\text{s}$  and are activated trying to send a maximum flow of  $3.7 \text{ m}^3/\text{s}$  to the WWTP which means that all the flow will be completely treated with primary secondary and tertiary treatment. Only when Tank 2 volume is above 90% ( $38800 \text{ m}^3$ ) pumps are activated and work at full capacity trying to send as much water as possible to the WWTP although this water does not receive full treatment, but at least partial treatment.



**Figure 4.45.** Tank 2 emptying tree.

The next tree in of the set of third level trees from the *rain event tree* is the *WWTP VilaConca tree*. The main function of this decision tree is to control the pump operation in the Homogenization Tank and the valves governing the water path inside the WWTP trying to treat as much water as possible through the full treatment (primary and secondary). If the volume of the Homogenization Tank is full, the tree provides a warning message to the system informing of this situation. Figure 4.46 illustrates this management tree.

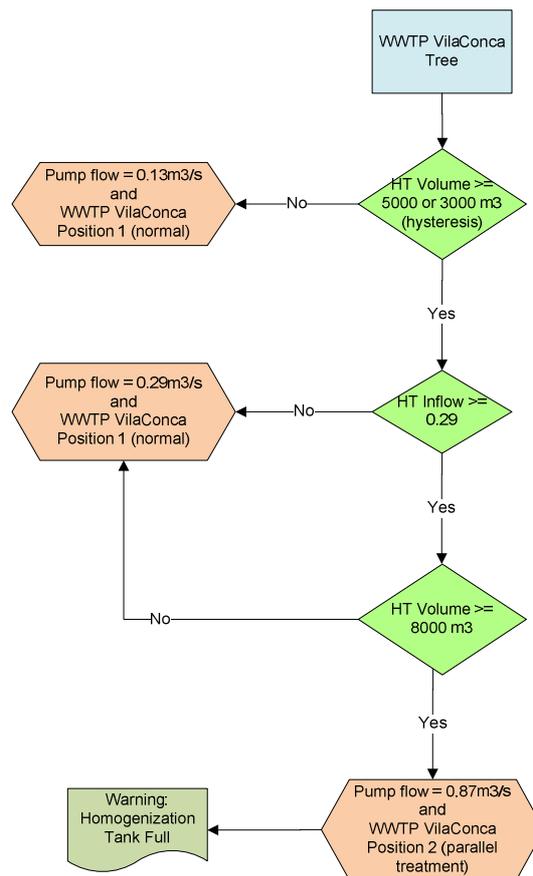


Figure 4.46. WWTP VilaConca management tree.

*WWTP VilaPrat tree (Annex)* works equally as VilaConca. The tree is responsible of activating the different available operational positions of the WWTP.

Third level trees coming from the *dry weather tree* try to control and manage the system during dry weather flow. The set of trees are composed by the *industrial spill tree*, the *WWTP VilaConca treatment failure tree*, *WWTP VilaPrat treatment failure tree*, *standard operation tree*, *sensible receiving environment tree* and *WWTP VilaPrat failure tree*.

The most significant tree is the *standard operation tree* which is described below (Figure 4.47). This tree is responsible to check positions of all actuators (gates, pumps, and WWTP valves) and in case anything is in a different position than the normal dry weather set point, the tree provides a warning to the operator and then its position is modified to the standard set point, except in case there is an industrial spill episode or WWTP failure episode activated.

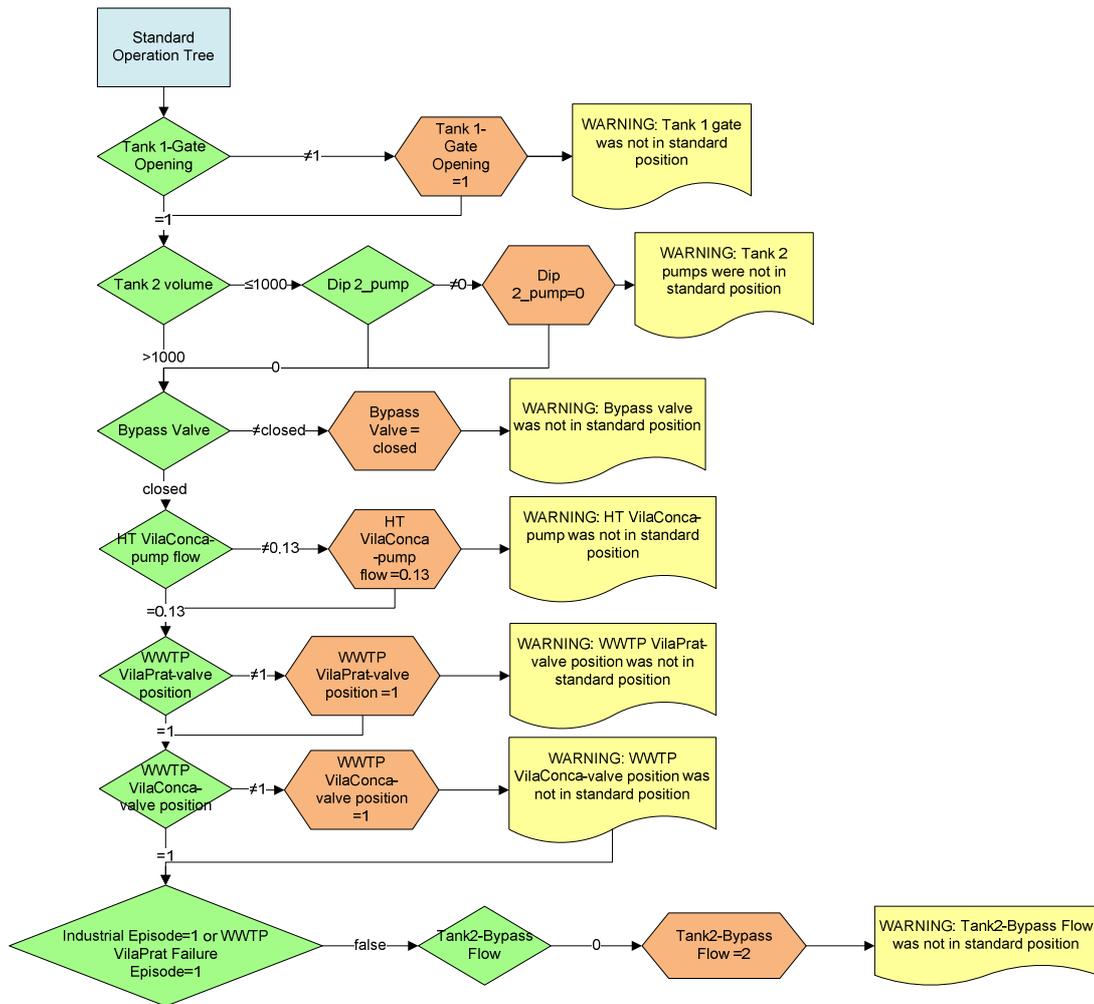


Figure 4.47. Standard operation tree.

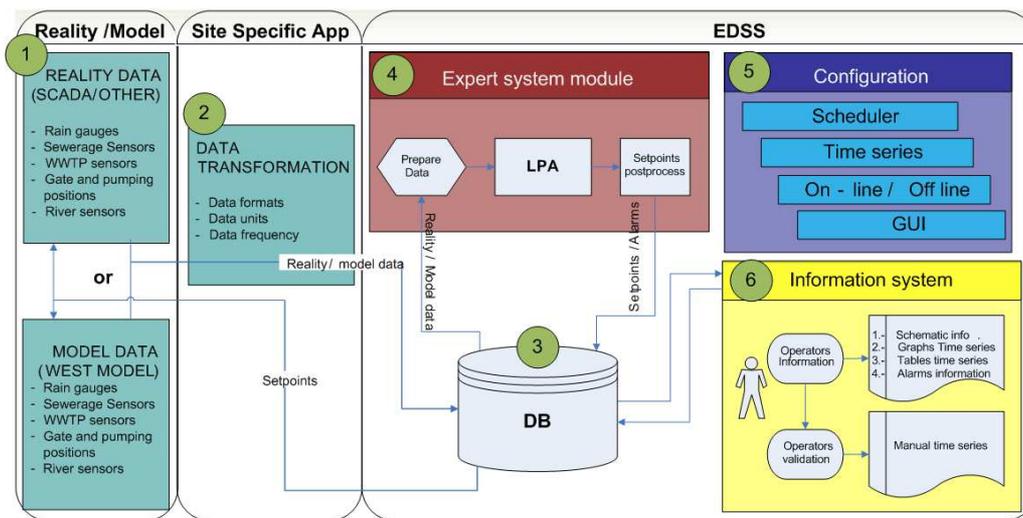
As it has been stated, one of the objectives of this thesis is the compilation of the acquired knowledge in a set of rules built by means of decision trees. A first knowledge acquisition phase has been performed including bibliographic research, study of empirical, historical and theoretical KBs and knowledge from experts and managers. Additionally, the virtual reality has been developed and calibrated in order to test several rain scenarios on it and extract knowledge from its results. Finally, all this knowledge and information has been gathered and integrated in a set of decision trees able to make a system diagnosis, detect the various problems that can occur in the virtual system and give orders (set points, gate positions, flow redirections and pumping flows) in order to improve the system management and optimize the overall system.

## 4.8 EDSS integration

The integration is the final step of the EDSS building. Integration is defined as the process by which the different models used are made into a whole functional and structural EDSS. It can be conducted in parallel when two or more models work simultaneously to obtain a result or in series when the output of one model is the input of the following one.

### 4.8.1 Main modules of the EDSS integration

The developed EDSS prototype is divided in five main modules. Each module has a specific function into the overall decision support system and is described below (see Figure 4.48):



**Figure 4.48.** EDSS prototype tool Architecture.

(1) The reality/model module: from which real-time data is continuously gathered. External data can be imported as time series and exported as time series or set-point values. In the current, real time data from reality has its origin in the WEST<sup>®</sup> model results.

(2) The data transformation unit module: where the format, units and frequency of the data are standardized according to the requirements of the system. Specifically, this site specific module (called WEST Exchange) was developed with the aim to connect the real data with the EDSS tool. In order to apply this connection between the EDSS tool and the virtual system, this module is in charge of the next functions:

- Launch periodically the virtual model developed with WEST<sup>®</sup> and execute simulations.
- Extract time series from the simulation results (such as water levels, tank volumes, CSO discharges, etc.) and import them into the EDSS prototype which are further considered as input data for the decision trees.

At the same time the module 2 is responsible of extracting actuator set points fixed from the EDSS tool (such as gate or valve positions or flows, pumping flows) and introduce them into the model in order to simulate the new system state (flows, water levels, quality data) due to the new set points.

(3) The data base module: where both the gathered data and the decisions made by the tool are stored as well as the configuration data for the system.

(4) The Expert System module: has the main responsibility of making the expert decisions by means of decision trees.

All the decision trees described in subchapter 4.6 were transformed into a specific programming language understandable by the EDSS tool. The LPA- Winprolog<sup>®</sup> (LPA (1980)) tool has been used for this codification purpose. The first step is to transform and adapt the conceptual trees into readable trees by the LPA- Winprolog<sup>®</sup> system.

LPA-Winprolog<sup>®</sup> 4900 is a PROLOG software compiler system with a graphical tool (VISIRULE) for developing and delivering rule systems and components simply by drawing the decision logic. It transforms the codification from drawing decision logic into the PROLOG programming language. PROLOG was one of the first logic programming languages associated with artificial intelligence and it remains among the most popular today with many free and commercial implementations available. The developed tool integrates this software because it allows developing decision trees using a simple graphical user interface (GUI), and once it is created, the software automatically does all the codification to the PROLOG programming language. This means that the user does not need programming skills to prepare decision trees and easily implement them into the EDSS.

The expert system module is part of the main EDSS tool and is in charge of the next features:

- Import the set of rules that will be periodically launched. These rules must be created previously using the Visirule GUI (part of the LPA Winprolog<sup>®</sup> package).
- The rule system will be launched periodically in a way that values will be read and some consequences/actions will be taken. These actions range from writing messages or providing new set points that will be used in the next simulations.

(5) The configuration module: where the key elements of the tool such as the functioning mode (on-line/off-line), the scheduler (timing to start actions on data acquisition and expert module) or the time series can be configured. As an example, the scheduler is responsible of sending petitions of executions to the Site Specific and Expert System modules. The user can configure when to send these petitions by going to the component configuration menu of the GUI.

(6) The information system module: including the graphical user interface, showing the results or decisions to the final user. In the developed prototype, results can be shown in different formats: graphics (showing time series or set-points in a temporal range); tables showing temporal results on time series or set-points and synoptic (this is a more visual way to show values/set-points represented in a background image of the system. Figure 4.49a/b/c shows an example of result's representation of the EDSS tool.

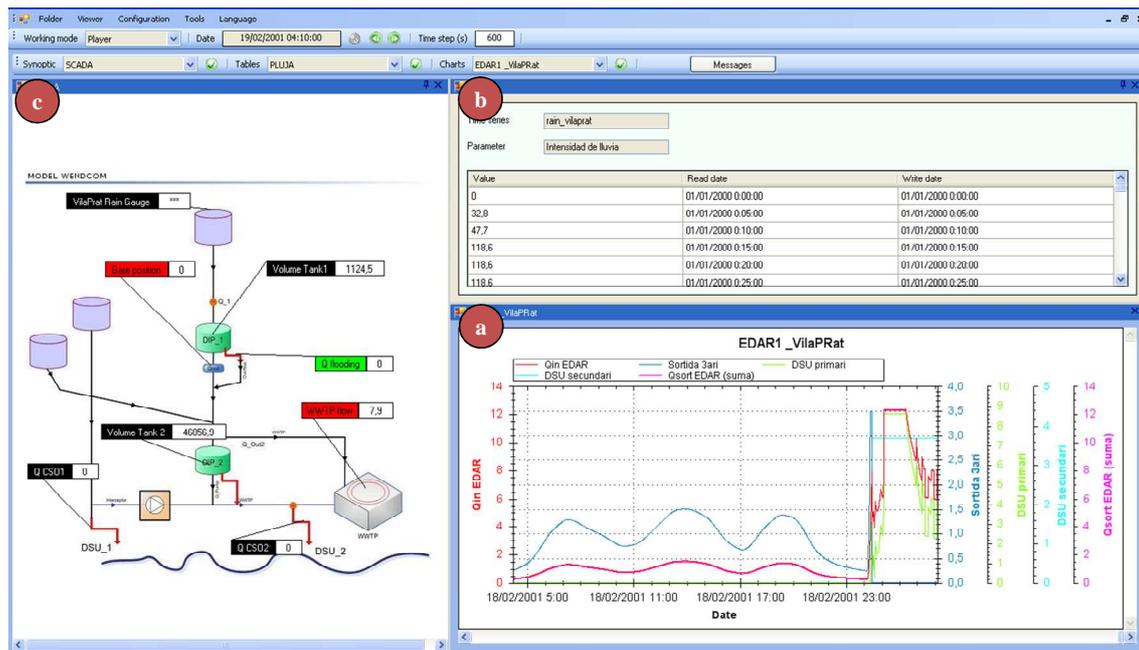


Figure 4.49. a) Graphical, b) Table and c) Synoptic representation of the EDSS results.

#### 4.8.2 Basic concepts of the EDSS prototype

The next section presents the basic concepts introduced into the EDSS prototype which are needed to understand the operation of the decision support tool.

##### Parameters

Parameters are properties that are measured or measurable. In the case of this prototype, parameters are measured using the developed virtual system. New parameters can be added into the EDSS system configuration. For each new parameter the user must give a name adapted to the end user needs, the units of the parameter and a conversion factor to be used when converting values from the decision support system to WEST<sup>®</sup> and vice versa. The need of a conversion factor is due to the WEST<sup>®</sup> model, which can require of values in a different unit than the ones found in the EDSS prototype.

Table 4.17. Parameter names and units defined by default in the tool.

Name	Units	Conversion Factor for WEST <sup>®</sup>
Rain Intensity	mm/h	0.0833
Volume	m <sup>3</sup>	1
Flow	m <sup>3</sup> /s	86400
Gate Position	m	1
Quality Mass Flow	g/d	1

The user can add, edit or delete parameters with the only exception of the Rain Intensity parameter, which cannot be deleted.

System time and virtual time

The system time is the time of the computer in which the application is running. The system time must always use the same time reference along the entire year. The system time must be equal to UTC + a factor. The external data sources must have the same referential time as the system time. On the other hand, the virtual time is imposed by the user, which can change the date and hour of the application. In this case the user can arbitrarily define the referential time.

Time series

Time series are the time evolution of a previously measured or modelled parameter along a period of time. They can be represented in a table (two columns). In the case of the EDSS prototype, one time series is only associated with one parameter. All time series values are stored into the DB of the system.

This EDSS system distinguishes between three different types of time series which are described below:

- *Normal time series* are the most common ones. They contain measured or modelled values. They can also store set points that will be applied to reality or to the virtual system (in case of off line mode).
- *Grouped time series* are used to group time series. The only time series which are allowed to be grouped are the normal or grouped time series. They use the same time interval frequency as their base time series.
- In *manual time series* the user is the one who creates and adds values in it. When configuring a manual time series the user has to introduce some information regarding to the name of the time series, the frequency in which the values are stored, a default value in case of no found value and the different options that the end user will be able to choose for uploading values.

WEST Exchange concepts

A *run period* is the time interval simulated by the model in a single run. The run period is created using the scheduler current time and the hindcast and forecast times configured in that component:

$$\text{Start date} = \text{Scheduler Current time} - \text{Hindcast Time}$$

$$\text{End date} = \text{Scheduler Current time} + \text{Forecast Time}$$

*WEST*<sup>®</sup> *model variables* correspond to the ones that the expert user must link with the EDSS time series in order to use them. Three types of model variables are found:

- *Input* model variables: they need to use some linked time series which will use their values to create the input data file, necessary to run the simulation.
- *Set point* model variables: this type of variables use several linked time series, which will use their values / set points to change parameters during a simulation. Typical set points can be gate positions, pumping flows, valves, etc.
- *Output* model variables: when a simulation is finished WEST Exchange uploads values for all the Output Model Variables linked to several EDSS time series.

Expert System concepts

*Rules* are the way of how the decision support system can check different variables, which depending on their values, the EDSS does different actions. Those actions include writing new set points, messages or jumping to another rule.

*Rule variables* are the ones which the user will have to link to the EDSS time series in order to allow the rule run correctly. Two different types of rule variables are found:

*Starting rule* is the one used by the Expert System every time a component has to be executed.

Site specific application / WEST Exchange

The WEST Exchange module works as a site specific application in a way that it can be installed in another computer different than where the EDSS is. The only requirement is that WEST Exchange must be installed in the same computer where the WEST<sup>®</sup> software is installed.



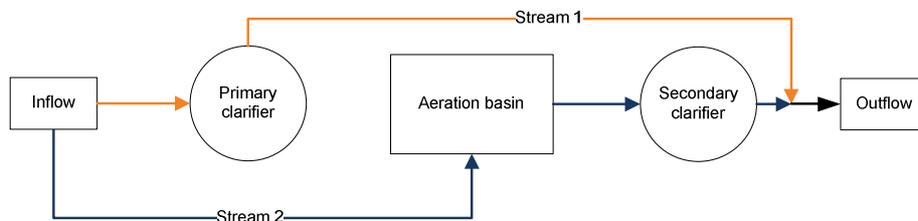
***CHAPTER 5***  
***EDSS OPERATION***



## 5. EDSS Operation

In this chapter, the scenarios described in section 4.6.1 have been tested comparing the differences of managing the virtual system using the Standard operation mode or using the EDSS operation mode (taking into account the decision trees described in subchapter 4.8). Efforts on the management strategies have been focused in the hydraulic enhancement of the integrated UWS, i.e. management strategies give priority to the reduction of the number and amount of CSO episodes. The main variations found in the overall system operation of the EDSS mode are a result of the first and second knowledge acquisition loops which are integrated into the set of developed decision trees. These imply some modifications on the UWS operation in order to execute the decision tree rules. Operational changes are described below:

When inflow to VilaConca WWTP is higher than the maximum capacity of the primary treatment, the plant separates flow in two independent streams. One stream flows through the primary treatment and after that is directly sent to the receiving body. The other stream is redirected to the secondary treatment without passing through the primary settler. Figure 5.1 shows how the plant is divided into two independent streams:



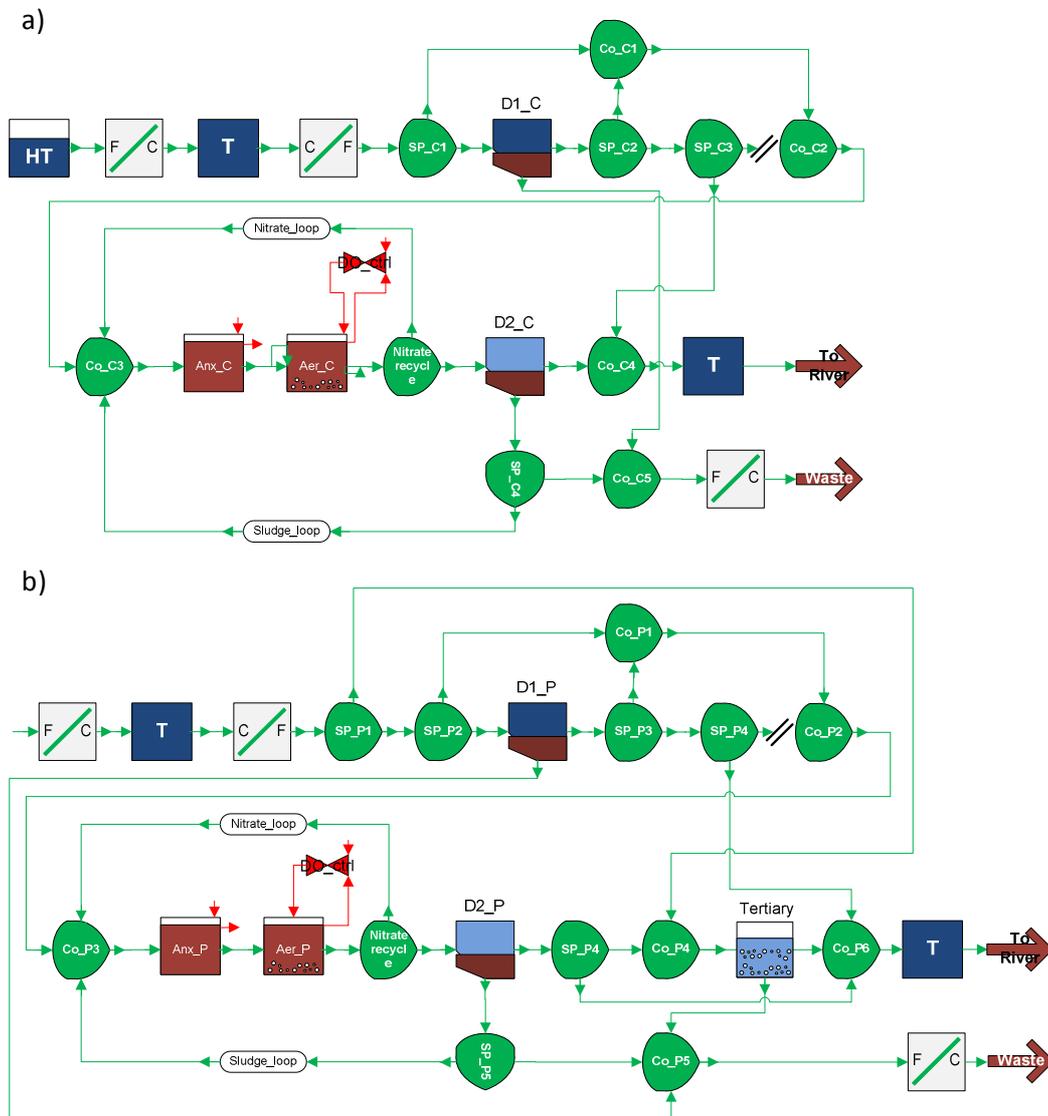
**Figure 5.1.** WWTP of VilaConca operation during wet weather flow. Adapted from WEF (2006).

In case of rain prediction, the HT of VilaConca is emptied in order to increase its storage volume. Once a rain event is over, the tank empties its stored wastewater never exceeding the design capacity of the WWTP, so all waters can be completely treated.

Regarding to VilaPrat system, while there is no flood risk, Tank 1 employs 40% of its volume to reduce CSOs, sending gradually wastewater to the WWTP. During rain events, Tank 2 of VilaPrat is operated as an on-line CSO tank and all combined waters are conveyed to the tank. If the tank is full, it acts like a decantation tank (reducing the pollution load). The WWTP of VilaPrat is operated exactly as in VilaConca, redirecting flows through primary and secondary treatment during wet weather events (when inflow is higher than the maximum capacity of the primary treatment). In some specific cases, depending on the inflow quality, some wastewater treated by the secondary flux can also be sent and treated onto the tertiary treatment

Finally, VilaConca and VilaPrat can be interconnected. The by-pass gate between them is operational and wastewater can be transferred from VilaConca to VilaPrat as long as it does not produce CSO in the latest.

For a correct application of the developed decision trees, it is first necessary to expand the models of WWTP of VilaConca and VilaPrat developed with WEST<sup>®</sup> (Figure 5.2). Both WWTP models have been modified adding a set of combiners and splitters in order to give the WWTPs the possibility to treat wastewater in the different positions described in the decision trees.



**Figure 5.2.** Modified configuration of the WWTPs of (a) VilaConca and (b) VilaPrat after the decision tree development.

In order to carry out the comparison, there are some important elements of the EDSS too that need to be pre-configured:

- Import rain data into the EDSS DB.
- Import the model (virtual system) into the tool.
- Import the developed decision trees into the tool.
- Link time series with model and rule variables.
- Configure the schedule for the EDSS components.

The four rain scenarios considered in section 4.6.1 are introduced into the DB. They are the same as the ones used for the standard operation mode. In a similar way, the imported virtual system model is also the same as for the standard operation mode but includes the mentioned modifications. Imported decision trees are described in subchapter 4.6. Time series are linked with its corresponding model and rule variables. E.g. Tank 1 inflow time series (named *Tank1\_Qin*) is linked with the model variable (named *modTank1\_Qin*) as well as with the rule variable (named *ruleTank1\_Qin*). The scheduler for the virtual system and for the expert system is also defined to correctly configure the run period of the EDSS.

Each simulation is configured to be launched every 10 minutes at minutes 00 (00, 10, 20, 30, 40 and 50) of each hour. Every time it is launched it simulates 18 hours backwards (hindcast time) and 8 minutes forward (forecast time). On the other hand, the expert system (decision tree execution) is configured to be launched every 10 minutes at minutes 08 (08, 18, 28, 38, 48 and 58) of each hour.

### 5.1 EDSS rain Scenario 1

This scenario is based on real data with a duration of 1 hour, a total precipitation of 8.7 mm and a return period of 2.16 months. Figure 5.3 illustrates this rain episode

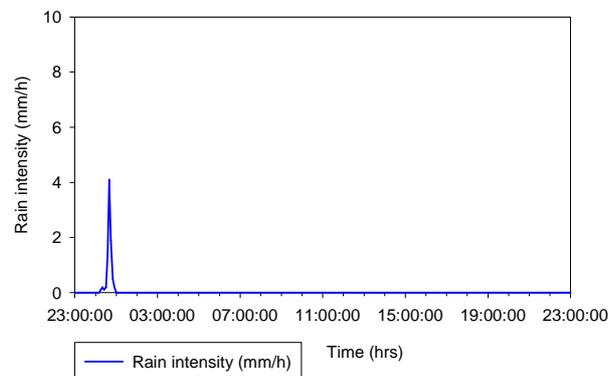


Figure 5.3. Rain intensity plot of the testing scenario 1.

Figure 5.4 presents the relevant points of VilaConca and VilaPrat UWSs where the impact of the EDSS used can be remarked.

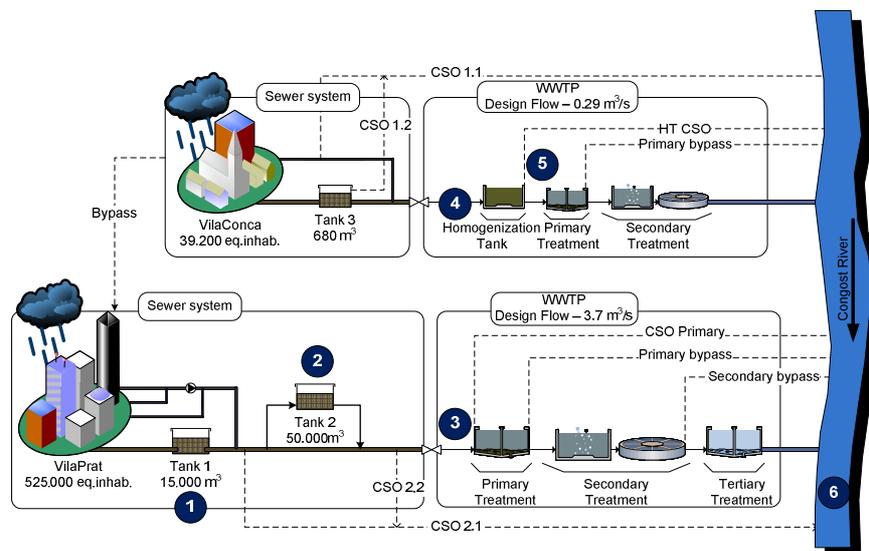
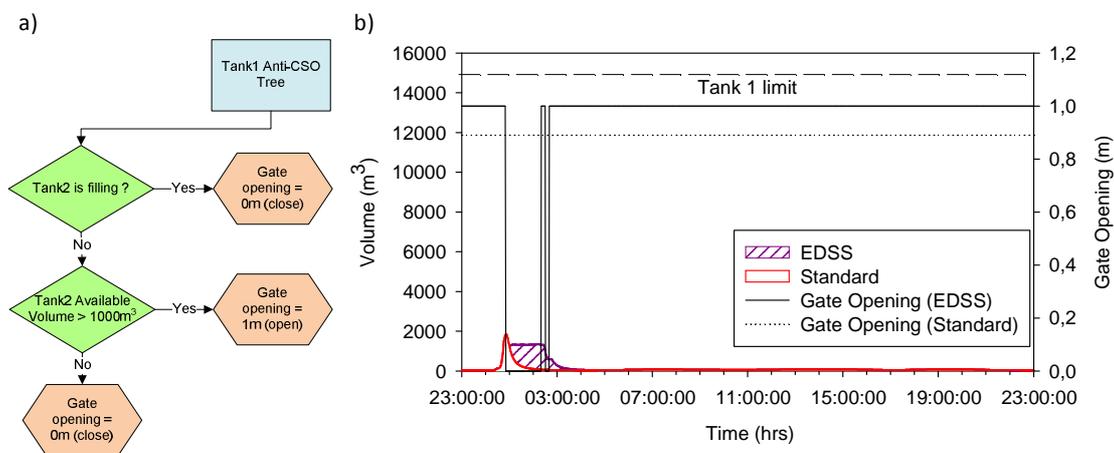


Figure 5.4. VilaConca and VilaPrat system scheme for scenario 1.

VilaPrat Tank 1 (1)

According to the decision tree at Tank 1, before the rain starts (DWF), the outflow gate position of Tank 1 is fully opened (1 m). When the rain event begins, the gate closes because Tank 2 (VilaPrat) starts to fill. The rainfall volume for this scenario is quite small and consequently Tank 2 has enough storage space ( $\geq 1000 \text{ m}^3$ ) so according to Tank 1 decision tree (Figure 5.5a), the gate remains closed until the rain has finished and Tank 2 stops filling. Later on (02:30), Tank 1 starts to empty the stored wastewater so Tank 2 fills again and in consequence the gate closes once more. Finally, when Tank 2 is emptying (and has more than  $1000 \text{ m}^3$  of free storage space) gate of Tank 1 opens and empties the stored wastewater recovering DWF conditions.

Figure 5.5b illustrates how use of the EDSS operation mode has benefits on the amount of wastewater that Tank 1 is able to store. Thus, all this wastewater is available for its further treatment. For this scenario the total volume of wastewater added into the system and in consequence avoided to produce CSO is of  $107767 \text{ m}^3$ .



**Figure 5.5.** (a) Detailed portion of Tank 1 management tree and (b) Tank 1 management for scenario 1.

VilaPrat Tank 2 (2)

Tank 2 storage management of VilaPrat depends on the one hand, on the input to the WWTP of VilaPrat and on the free volume of the tank itself. Figure 5.6b illustrates how, before the rain starts the flow entering the WWTP of VilaPrat is very low (DWF conditions) and no wastewater needs to be stored into the tank (A). When the rainfall begins (00:50) Tank 2 starts to fill and, according to Tank 2 emptying decision tree (Figure 5.6a) during a small time frame the WWTP inflow is lower than  $3 \text{ m}^3/\text{s}$  and thus the tank pumps  $0.33 \text{ m}^3/\text{s}$  (B) trying to avoid possible CSOs.

During the rainfall, inflow to the WWTP exceeds  $3.4 \text{ m}^3/\text{s}$  and all wastewater is stored into Tank 2 (no pump activity, execution C). Once the rain is over, the inflow to the WWTP goes below  $3 \text{ m}^3/\text{s}$  so pumps start emptying gradually the tank, first at  $0.33 \text{ m}^3/\text{s}$  (D). In the next time step (02:50), inflow into the WWTP is lower than  $2.7 \text{ m}^3/\text{s}$  and pumps send  $0.66 \text{ m}^3/\text{s}$  (E). Finally, pumps work at its maximum flow potential at  $2 \text{ m}^3/\text{s}$  (F) never exceeding the maximum capacity of the WWTP. Figures 5.6a illustrates the different commands given by the EDSS to Tank 2.

For this scenario, the EDSS operation mode causes very different results for Tank 2 in comparison with the standard operation mode. The main reason is that the standard operation does not consider any pumping set points within the 24h simulation and thus, there are significant stored volume differences between them. The use of expert knowledge to manage the tank is better in order to minimize the stored volume into the tank and maximize the treated wastewater into the WWTP of VilaPrat avoiding CSO discharges.

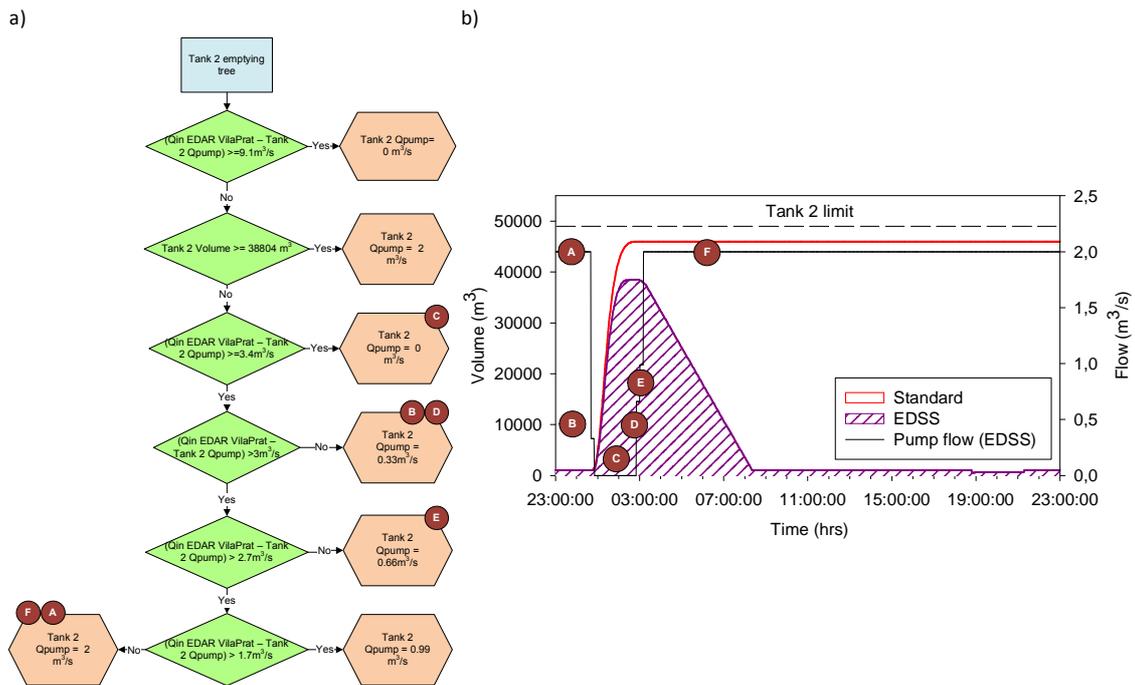


Figure 5.6. (a) Tank 2 emptying tree execution time line, (b) Volume and pump flow during scenario 1.

WWTP VilaPrat (3)

Figure 5.7 illustrates the simulation results during Scenario 1 and for the WWTP inflow of VilaPrat.

As explained in Tank 2 management, before rain begins, the WWTP operates in DWF conditions. During the rainfall, the plant has a first peak flow of 5.4 m³/s. Once the rain is over the inflow starts to descend. Later on, the plant receives a second peak of 6 m³/s and operates at position 2 regarding the decision tree of WWTP VilaPrat (the inflow is between 3.7 m³/s and 8.63 m³/s and TSS concentration over 500 gr/m³). After that, the inflow approximately descends to 3 m³/s due to the influence of Tank 2. Finally, flow decreases to DWF conditions and all wastewater is fully treated.

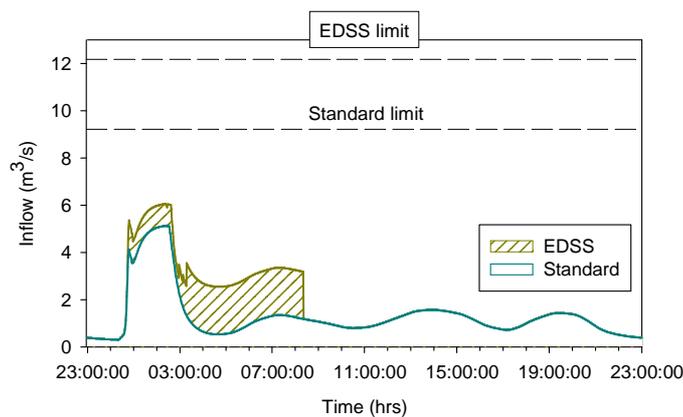


Figure 5.7. WWTP of VilaPrat inflow during scenario 1.

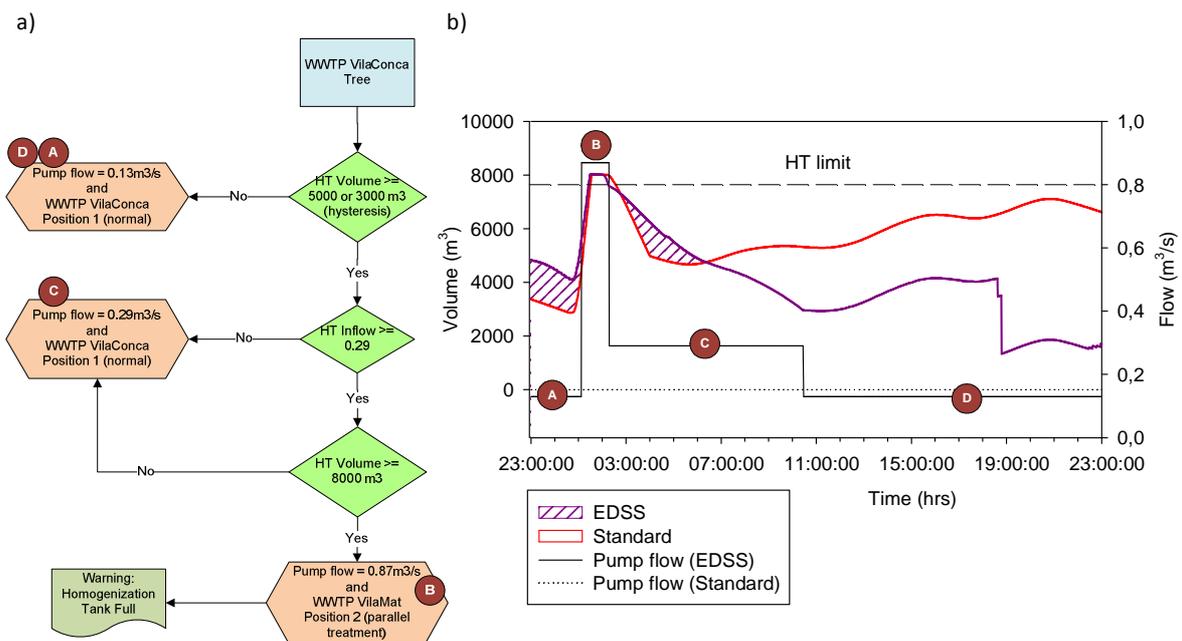
The total volume of treated wastewater by the WWTP with the EDSS operation mode is considerably higher in comparison with the Standard operation mode, especially when the rain is over and the WWTP receives more inflow due to the effect of the stored wastewater by Tanks 1 and 2. The EDSS operation mode presents a variation of 45820 m<sup>3</sup> of the water input in comparison with the Standard mode.

VilaConca Homogenization Tank (4)

It must be remarked that VilaConca catchment has a very small CSO tank (Tank 3) with a volume of 680 m<sup>3</sup>. There is no decision tree and therefore for Tank 3 it has not been taken into account.

Figure 5.8b shows the HT management results during scenario 1 for both the EDSS and the Standard operation modes. It is important to note that the HT for the EDSS mode is managed by the WWTP of VilaConca tree. According to this, before the rainfall begins, the tank is operated as dry weather flow since the stored volume is below 5000 m<sup>3</sup>/s and thus, the pumping set point is 0.13 m<sup>3</sup>/s (A) (Figure 5.8a).

Once the rain starts, the plant inflow is above 0.29 m<sup>3</sup>/s, the tank reaches 8000 m<sup>3</sup> and the pumping set point rises to 0.87 m<sup>3</sup>/s (B). During a certain period of time, the tank volume is above 5000 m<sup>3</sup> but in contrast inflow decreases below 0.29 m<sup>3</sup>/s then the pumping set point decreases to 0.29 m<sup>3</sup>/s (C). Finally, the tank volume is below 3000 m<sup>3</sup> (taking into account the hysteresis) and the tank recovers the dry weather position pumping at 0.13 m<sup>3</sup>/s (D).

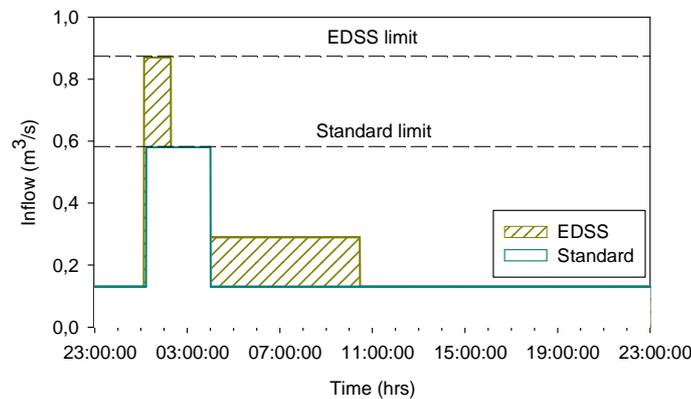


**Figure 5.8.** (a) WWTP VilaConca decision tree execution time line and (b) HT volume and pump flow during scenario 1.

The stored volume with the EDSS operation is higher than the Standard mode because the latter has a constant pump flow and once the rain is over, the tank empties its stored wastewater. In contrast, the EDSS mode takes into account the WWTP VilaConca conditions trying to avoid CSO spills at the plant.

WWTP VilaConca (5)

For rain scenario number 1, WWTP of VilaConca EDSS operation results (Figure 5.9) show how before the rain starts, the WWTP receives the average daily flow ( $0.13 \text{ m}^3/\text{s}$ ) from the HT. When the rain starts (01:05), inflow to the WWTP turns into  $0.87 \text{ m}^3/\text{s}$  (divided into  $0.58 \text{ m}^3/\text{s}$  only flowing through primary treatment and  $0.29 \text{ m}^3/\text{s}$  through secondary treatment). When the inflow decreases to  $0.29 \text{ m}^3/\text{s}$  wastewater is fully treated. Finally the flow descends back to dry weather flow conditions ( $0.13 \text{ m}^3/\text{s}$ ).



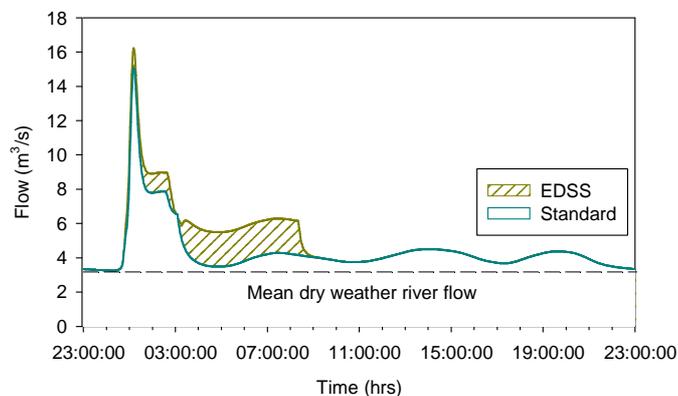
**Figure 5.9.** WWTP of VilaConca inflow during scenario 1.

VilaConca WWTP for the EDSS mode during scenario 1 has two main differences respect with the Standard mode. It has a higher treatment limit ( $0.87 \text{ m}^3/\text{s}$ ). Additionally, the plant can treat up to its design flow ( $0.29 \text{ m}^3/\text{s}$ ) increasing this way the volume of treated wastewater. Both measures suppose a reduction of the volume of CSOs spilled into the receiving body ( $3207 \text{ m}^3$ ).

Receiving body (6)

Figure 5.10 shows simulation results of the river flow after WWTP of VilaPrat during scenario 1. Taking into account that the first scenario can be considered a small rain event, CSO episodes are avoided both for VilaConca and VilaPrat catchments. Despite that, the EDSS operation mode allows the system to treat a higher wastewater volume ( $45719 \text{ m}^3$ ). The river flow during DWF conditions is around  $3 \text{ m}^3/\text{s}$ . The total discharged volume to the river for both operation modes is the same.

However, the river flow for the EDSS operation is higher than the Standard mode. This is due to the stored wastewater into Tank 2 in the Standard mode, which is not discharged within the 24h simulation (and consequently does not appear in the river flow).



**Figure 5.10.** River water flow after the WWTP of VilaPrat for scenario 1.

A summary of the general improvement between the Standard operation mode and the EDSS operation mode for the first rain scenario is shown in Table 5.1. Results of the volume of stored wastewater in Tank 1 present an enhancement of 45.1% respect the Standard mode. The expert management of the tank by the EDSS allows storing a higher volume of wastewater and thus to reduce the probability to cause CSO discharges.

**Table 5.1.** Summary table of stored water (Tanks) and treated water (WWTPs) during scenario 1.

	<b>Standard (m<sup>3</sup>)</b>	<b>EDSS (m<sup>3</sup>)</b>	<b>Variation percentage (%)</b>
Tank 1	131041	238809	45.1
Tank 2	-	-	-
VilaPrat WWTP	113400	159160	28.8
HT	-	-	-
VilaConca WWTP	15741	19044	17.3

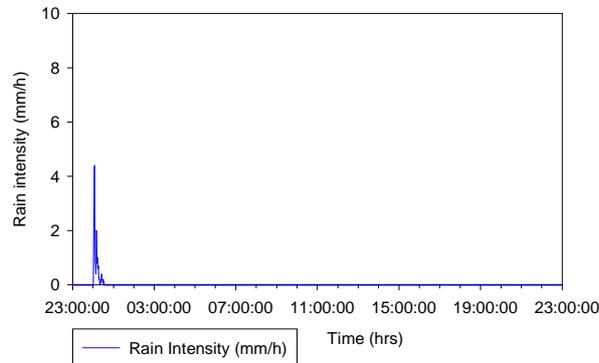
Improvement of Tank 2 cannot be calculated since water in the Standard mode remains stored into the tank within the 24h simulation while in the EDSS mode not.

The latter uses the expert knowledge in order to store or empty the tank depending on the UWS conditions. WWTP VilaPrat presents an enhancement of 28.8% of volume of treated wastewater. The plant has higher treatment capacity and receives the stored wastewater of Tank 1 and Tank 2 of VilaPrat catchment.

The HT enhancement is not applicable since in the Standard mode, the tank has a constant pumping set point and in consequence there is more stored wastewater which does not represent a better management. In the EDSS mode, the tank is able to store most of the receiving waters but is also ready to empty the tank as quickly as possible without casing CSOs to the WWTP of VilaConca.

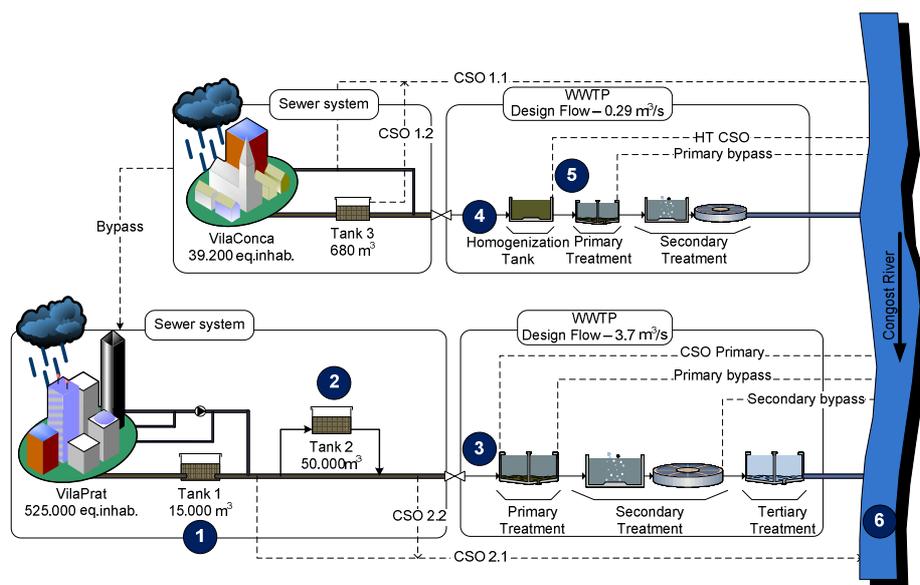
## 5.2 EDSS rain Scenario 2

Figure 5.11 illustrates the rainfall of the second scenario, based on real data similar to the first rain scenario. It has a duration of 3 h, a total precipitation of 26.7 mm, corresponding to 1602 m<sup>3</sup> and a return period of 3.6 months.



**Figure 5.11.** Rain intensity plot of the testing scenario 2.

Figure 5.12 presents the relevant points of VilaConca and VilaPrat UWSs where the impact of the EDSS used can be remarked.



**Figure 5.12.** VilaConca and VilaPrat system scheme for scenario 2.

### VilaPrat Tank 1 (1)

Figure 5.13b shows the Tank 1 management for the EDSS mode in comparison with the Standard mode during scenario 2. Before the rain starts, the gate is at its normal DWF position 1 m (A). Once the rain begins, according to Tank 1 management tree (see Figure 5.13a), the gate closes to position 0 m (B) because Tank 2 starts to fill. When stored volume is between 5600 m<sup>3</sup> and 7800 m<sup>3</sup> the gate position opens to 1 m (C) in order to empty the tank as soon as possible and avoid possible flooding. When the volume of the tank is below 4500 m<sup>3</sup> the gate closes again to 0 m (D) to retain volume against CSO since Tank 2 is still filling.

Note that the gate opens when volume is 5600 m<sup>3</sup>, but does not close until it reaches 4500 m<sup>3</sup>. This is done to avoid the gate opening and closing repeatedly around the same volume.

Once the rain is over the gate remains closed and the wastewater slowly fills the tank until Tank 2 available volume is over 1000 m<sup>3</sup>. At this point, gate position turns to 1 m (fully open) (E) to empty the tank but as a direct effect of that Tank 2 increases the stored volume (coming from Tank 1 emptying) and the gate closes once more (F). After a short time frame, the gate opens again to position 1 m (G) as Tank 2 is emptying again and has more than 1000 m<sup>3</sup> of available volume. During the whole rain event water flowing out of the tank is controlled, never exceeding the 6 m<sup>3</sup>/s which would cause flooding.

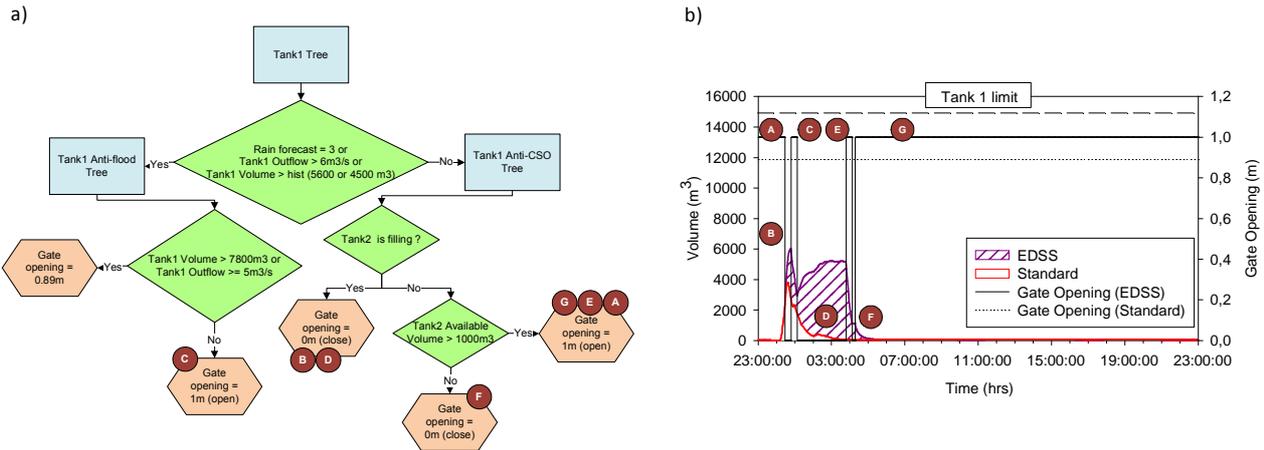


Figure 5.13. (a) Tank 1 decision tree, execution time line, (b) Volume and gate position during scenario 2.

The management of the tank has very different results in comparison with the Standard operation mode. For the one side, the peak reached during the rain event is higher (never exceeding the storage limit) and thus wastewater can be released without producing CSOs. Additionally, once the rain event is over, the tank stores wastewater taking into account the conditions of the other infrastructures of the UWS. It is clear how the amount of stored wastewater during the rain event changes between the EDSS and Standard modes (844854 m<sup>3</sup>). The use of expert knowledge allows the system to store a higher volume of wastewater which in consequence can be further treated.

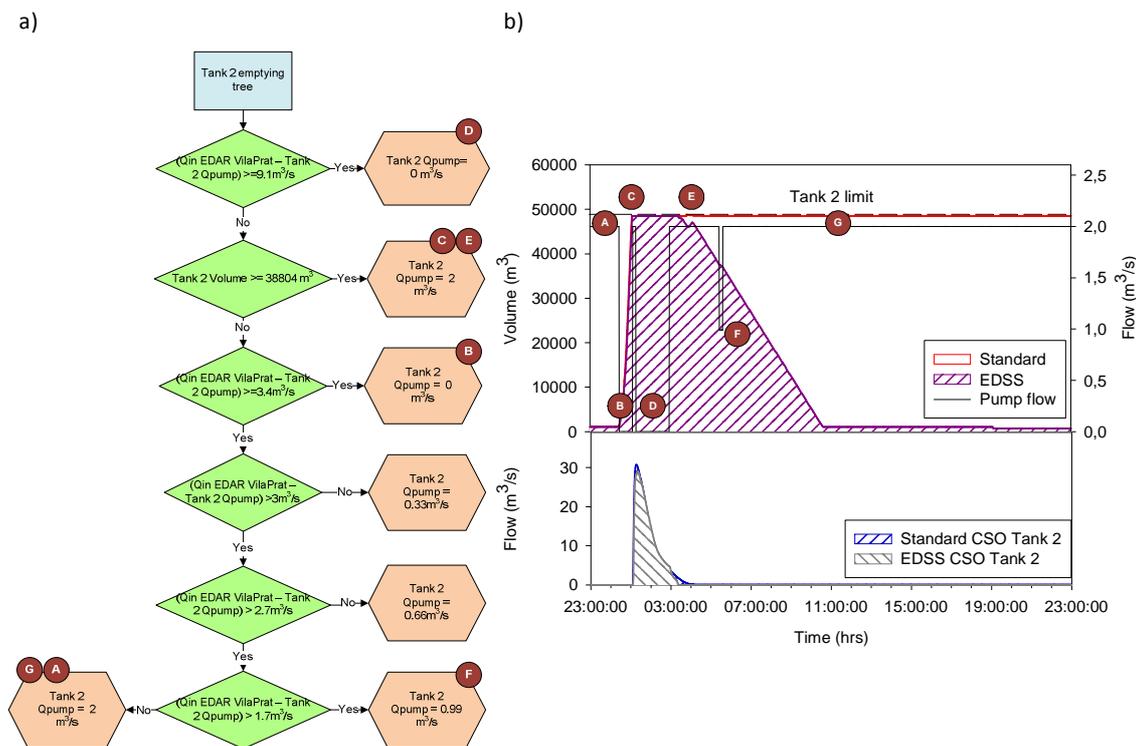
### VilaPrat Tank 2 (2)

Figure 5.14b illustrates the simulation results of Tank 2 management during scenario 2 for the EDSS mode in comparison with the Standard mode. The tank management depends mainly on the inflow to WWTP VilaPrat and the free volume of the tank itself.

Following the execution time line of Tank 2 (Figure 5.14a), before the beginning of the rain the flow entering the WWTP is very low (DWF) and the pumping set point is set to 2 m<sup>3</sup>/s (A). When the rain event begins, Tank 2 starts to fill until the inflow of the WWTP is above 3.4 m<sup>3</sup>/s. A new pumping set point is 0 m<sup>3</sup>/s and water is stored into the tank (B). As wastewater keeps entering to the tank, the volume quickly reaches 38804 m<sup>3</sup> and according to the Tank 2 emptying decision tree, pumps start to operate trying to empty as fast as possible at 2 m<sup>3</sup>/s (C). After that, although the tank is full pumps stop (0 m<sup>3</sup>/s) (D) because the WWTP is operating at its maximum treatment capacity (12.33 m<sup>3</sup>/s) so incoming wastewater is directly discharged to the river (CSO). Once the rain event is over, the tank volume is still above 38804 m<sup>3</sup> but the WWTP has capacity to accept more flow so all pumps are then activated to 2 m<sup>3</sup>/s (E). After a while, the tank volume decreases.

If the inflow to the WWTP of VilaPrat is not below  $1.7 \text{ m}^3/\text{s}$  the wastewater is pumped at  $0.99 \text{ m}^3/\text{s}$  (F). Finally, the pumping set points are set again to  $2 \text{ m}^3/\text{s}$  (G), never exceeding the upper capacity of the WWTP and restoring the storage capacity of the tank.

Regarding to the CSO produced during this rain event, Figure 5.14b shows that there is not much difference in volume of spilled water between the Standard mode ( $107055 \text{ m}^3$ ) and the EDSS mode ( $103278 \text{ m}^3$ ). Despite that, once the rain is over the Standard operation mode stores all wastewater into the tank while it is gradually emptied in the EDSS mode.



**Figure 5.14.** (a) Tank 2 decision tree and execution time line and (b) Tank 2 management (volume and pump flow) and CSO discharge during scenario 2.

The simulation results for Tank 2 management between Standard and EDSS modes are quite different. The EDSS mode stores wastewater during the rainfall and once it has finished, the tank is emptied as long as the WWTP of VilaPrat can accept the flow. The Standard mode has no given pumping set points, in consequence all wastewater is stored into the tank and is thus susceptible to cause flooding or CSO spills.

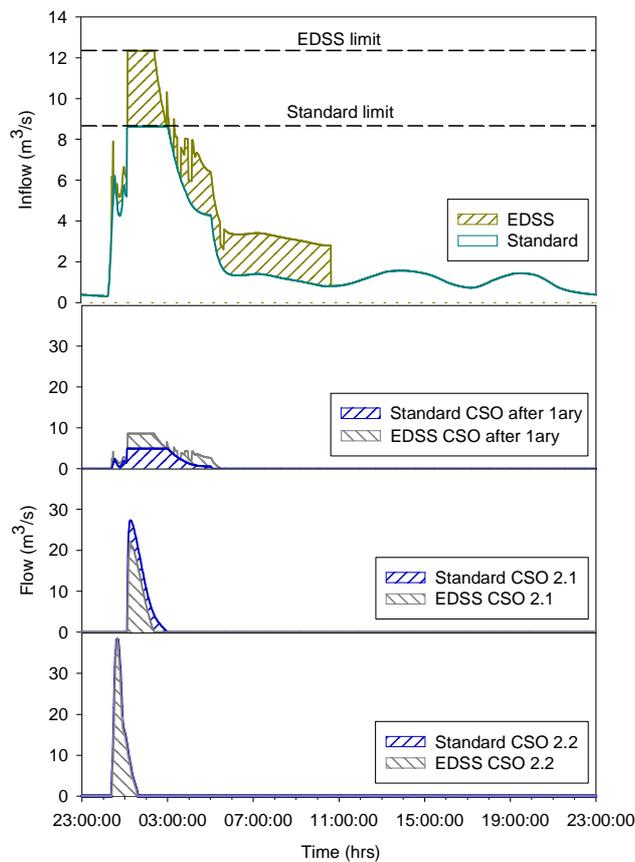
### WWTP VilaPrat (3)

Figure 5.15 shows the simulation results for WWTP of VilaPrat during scenario 2. At the beginning of the rain scenario, the inflow is below  $3.7 \text{ m}^3/\text{s}$  and wastewater is treated through the different process stages of the plant avoiding any overflows after the primary treatment. When the rain intensity increases, the inflow is between  $3.7 \text{ m}^3/\text{s}$  and  $12.33 \text{ m}^3/\text{s}$ . Consequently the WWTP of VilaPrat operates at position 2 separating the flow in two independent streams.  $7.4 \text{ m}^3/\text{s}$  are treated by the primary treatment and spilled to the river and  $3.7 \text{ m}^3/\text{s}$  are treated by the secondary treatment and spilled to the receiving body. The excess is directly discharged into the river before entering the plant in the different CSO points located at VilaPrat sub catchment.

Once the rain finishes, inflow to the WWTP descends but can be fluctuant due to Tank 1 and Tank 2 emptying cycle. Finally, the WWTP recovers the DWF conditions and treats wastewater through the complete process.

Furthermore Figure 5.15 illustrates three different CSO spills produced in this scenario. CSO after primary treatment has a higher value in the EDSS mode (85447 m<sup>3</sup>) than in the Standard one (49906 m<sup>3</sup>). This is due to the greater amount of wastewater treated by the plant. Despite that, it is better to discharge partially treated than completely untreated wastewater to the receiving body.

CSO 2.1 is only shown during the rain event and presents smaller values for the EDSS mode (52073 m<sup>3</sup>) than for the Standard one (78502 m<sup>3</sup>) so the effect on the river is smaller with the use of the expert knowledge. CSO 2.2 is only displayed during the rain event and has very similar values for both modes being its difference of only 37 m<sup>3</sup>. Finally, the stored wastewater into Tank 2 during the Standard mode (50000 m<sup>3</sup> approximately) can also produce CSOs.



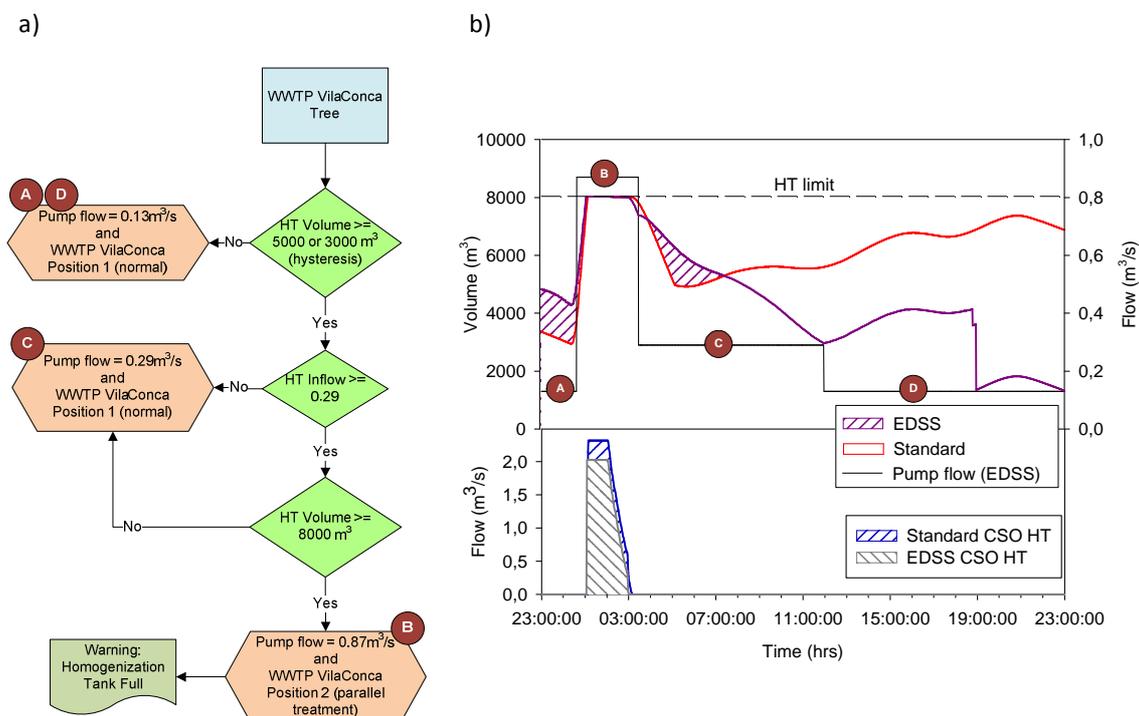
**Figure 5.15.** WWTP of VilaPrat simulation results and CSOs during scenario 2.

Simulation results of the WWTP of VilaPrat for this scenario show how the treatment limit in the EDSS mode is increased from 8.63 m<sup>3</sup>/s to 12.33 m<sup>3</sup>/s. This gives the plant a greater treatment potential during wet weather and decrease the impact on the river. Although the total amount of spilled wastewater into the river is approximately the same for both modes, the discharge of partially untreated wastewater after the primary treatment avoids a greater spill at any other CSO point of the system.

### VilaConca Homogenization Tank (4)

Figure 5.16b illustrates the progress of stored wastewater into the HT during scenario 2. It is important to note that the tank is managed by VilaConca WWTP tree since the main objective of the tank is to give a constant flow and avoid CSOs, flooding or washoff events into the WWTP (see Figure 5.16a). Before the rain starts the stored volume is below 5000 m<sup>3</sup> and thus the tank operates in DWF conditions pumping 0.13 m<sup>3</sup>/s (A). Once the rain has started, the tank volume reaches 5000 m<sup>3</sup> and its inflow is above 0.29 m<sup>3</sup>/s so the pumped flow turns into 0.87 m<sup>3</sup>/s (B).

After that, the tank volume remains above 5000 m<sup>3</sup> but the rain is over, the tank inflow decreases below 0.29 m<sup>3</sup>/s and thus the pumping set point is of 0.29 m<sup>3</sup>/s (C). When, the volume of the tank decreases under 3000 m<sup>3</sup> the tank can operate in DWF conditions again, pumping 0.13 m<sup>3</sup>/s (D) to the WWTP of VilaConca.



**Figure 5.16.** (a) WWTP VilaConca decision tree and execution time line and (b) HT management and CSO results during scenario 2.

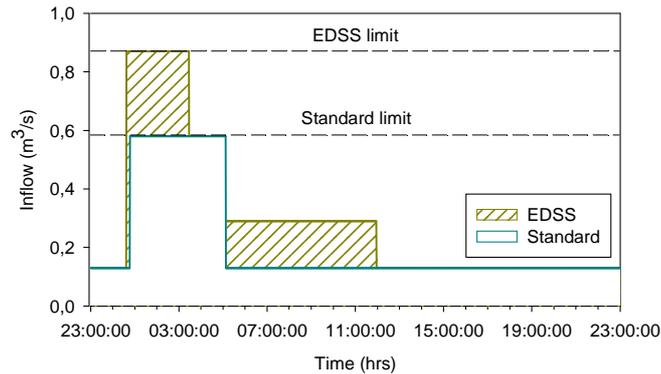
CSOs produced by the HT during this rain event are very similar for both the EDSS and Standard modes. This is due to the limited management options found upstream of VilaConca system and to the small capacity of the HT which gives little margin to the overall catchment. The amount of CSO saved by the EDSS mode is of 1682 m<sup>3</sup>.

Results of the HT management during this second scenario for the EDSS mode allow the system to reduce the volume of untreated wastewater discharged into the receiving body. Additionally, the way the tank is emptied after the rain event differs from the Standard mode. The Standard needs more time as it has a constant pumping flow set point. This gives the tank more probability to produce CSOs in case of another rain event. On the other hand, the EDSS mode empties the tank as soon as the WWTP of VilaConca can accept the wastewater.

WWTP VilaConca (5)

Figure 5.17 shows results of the WWTP of VilaConca management for the EDSS mode in comparison with the Standard mode during rain scenario 2. Since the WWTP inflow depends directly of the HT management the inflow remains always constant. Before the rain begins, the inflow of the plant is the average daily flow ( $0.13 \text{ m}^3/\text{s}$ ).

At the beginning of the rain, the inflow increases to  $0.87 \text{ m}^3/\text{s}$  which, according to the WWTP VilaConca decision tree,  $0.58 \text{ m}^3/\text{s}$  are treated by the primary treatment and  $0.29 \text{ m}^3/\text{s}$  by the secondary treatment. Once the rain is over, the inflow decreases to  $0.29 \text{ m}^3/\text{s}$  and all wastewater can be completely treated. After a while, flow descends again to DWF conditions ( $0.13 \text{ m}^3/\text{s}$ ).



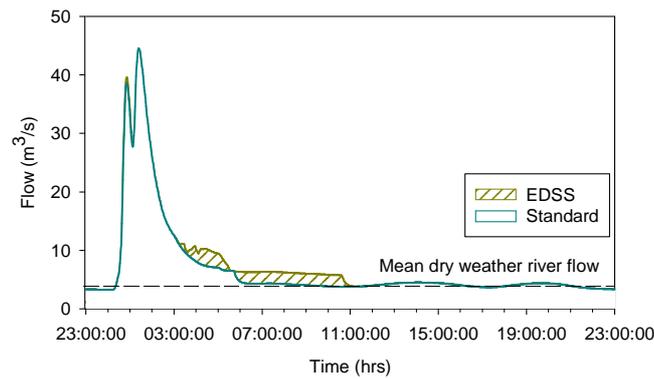
**Figure 5.17.** Inflow to the WWTP VilaConca simulation results for scenario 2.

The use of the EDSS mode for the management of WWTP VilaConca during this scenario presents for the one hand a higher treatment capacity of the plant ( $0.87 \text{ m}^3/\text{s}$ ), which supposes a reduction on the number and probability to produce CSO spills. On the other hand, the WWTP presents another innovation with respect to the Standard mode. The plant is optimized by treating wastewater at its maximum design flow capacity ( $0.29 \text{ m}^3/\text{s}$ ). The improvement reached by the EDSS mode represents an increasing of  $5397 \text{ m}^3$  of the treated wastewater.

Receiving body (6)

Figure 5.18 illustrates the simulation results of the river flow after the WWTP of VilaPrat during scenario 2 for the EDSS mode in comparison with the Standard one. Two different peaks can be observed ( $40 \text{ m}^3/\text{s}$  and  $45 \text{ m}^3/\text{s}$  approximately) corresponding both of them to CSO discharges during the rain period. After that, the river flow decreases gradually showing on one hand Tank 1 emptying phase and then for Tank 2. Despite that, the EDSS operation mode treats a higher volume of wastewater ( $48853 \text{ m}^3$ ) in comparison with the Standard operation mode.

However, the total discharged volume of water to the river must be the same using both operation modes. The differences found in the simulation results respond to two main reasons. On one hand to Tank 2 stored wastewater, which during the EDSS mode is slowly discharged while in the Standard mode all wastewater remains stored. On the other hand, differences can also be a consequence of some modelling instabilities and differences in volume inside the systems between the beginning and the end of the simulation.



**Figure 5.18.** River water flow after the WWTP of VilaPrat for scenario 2.

Table 5.2 shows the general improvement of this second scenario between the EDSS and the Standard modes. The application of the expert knowledge for Tank 1 means an improvement of  $844855 \text{ m}^3$  (76.1%) in stored volume with respect to the Standard mode.

In this sense, Tank 1 is able to store a higher volume of water during wet weather and reduces the number and volume of CSOs. Improvement of Tank 2 cannot be calculated since the Standard mode does not consider any pumping set points and all wastewater remains stored into the tank after the rain event. Nevertheless, the application of the expert knowledge allows the tank to be emptied as soon as the WWTP of VilaPrat can accept the stored wastewater.

**Table 5.2.** Summary table of stored water (Tanks) and treated water (WWTPs) during scenario 2.

	Standard ( $\text{m}^3$ )	EDSS ( $\text{m}^3$ )	Variation percentage (%)
Tank 1	265199	1110054	76.1
Tank 2	-	-	-
VilaPrat WWTP	189306	262987	28.0
HT	-	-	-
VilaConca WWTP	18279	23676	22.8

VilaPrat WWTP management is improved in 28% due to a higher treatment capacity of the plant increased from  $8.63 \text{ m}^3/\text{s}$  to  $12.33 \text{ m}^3/\text{s}$ . This allows the WWTP to treat more wastewater during wet weather. Despite that, CSO spills are very similar for both modes since in the Standard mode, stored wastewater into Tank 2 is not taken into account and the rain event is high enough to produce CSO discharges even when the expert knowledge is applied to the overall system management. HT results cannot be applied because in the Standard mode the tank is still not emptied within the 24h simulation. In any case, the volume of CSO discharged into the river is smaller for the EDSS mode than for the Standard mode demonstrating the effectiveness of the expert knowledge on the tank management. Finally, VilaConca WWTP presents a general improvement of 22.8% respect the Standard mode. The higher treatment capacity of the plant ( $0.87 \text{ m}^3/\text{s}$ ) and the possibility to fully treat wastewater at its maximum design flow ( $0.29 \text{ m}^3/\text{s}$ ) optimize the overall performance of the WWTP.

Summary results of the first scenario show how the UWS is managed by the use of the expert decision trees. The system is optimized without causing CSO discharges and protecting the river quality. In contrast, scenario 2 is higher and the system cannot receive and treat the whole amount of water (rainfall water and produced wastewater) so that several CSO discharges are produce. Rain scenarios 3 and 4 present higher intensities and water inputs when compared with scenarios 1 and 2. Therefore, the UWS is not able to treat all water input and CSOs are generated too.

The main difference between results of scenario 2 and the ones of scenarios 3 and 4 is the discharge duration and the CSO volume spilled to the receiving body. For this reason, the outline tables of scenarios 3 and 4 are presented below while the simulation results and execution time lines can be found in **Annex**

### 5.3 EDSS rain Scenario 3

A summary of the general improvement reached by the EDSS mode in comparison with the Standard mode during rain scenario 3 is shown in Table 5.3. Tank 1 enhancement is of 32.7% with regard to the Standard mode. The tank stores a higher volume of wastewater during the rain event and in consequence reduces the number and volume of CSO discharges. Tank 2 progress cannot be calculated since the Standard mode does not take into account the possibility to empty the tank after the rainfall and thus all wastewater remains stored into the tank. However, the use of the EDSS mode allows the tank to store wastewater during the rain episode in order to protect the WWTP of VilaPrat inflow and avoid possible CSO spills as far as possible.

**Table 5.3.** Summary table of stored water (Tanks) and treated water (WWTPs) during scenario 3.

	Standard (m <sup>3</sup> )	EDSS (m <sup>3</sup> )	Variation percentage (%)
Tank 1	532307	790672	32.7
Tank 2	-	-	-
VilaPrat WWTP	168362	238431	29.4
HT	-	-	-
VilaConca WWTP	17361	22152	21.6

The management of VilaPrat WWTP during the rain event is improved in 29.4% respect the Standard mode. The higher treatment capacity of the plant and the possibility to partially treat wastewater avoiding the discharge of completely untreated water into the river, are the main reasons of WWTP enhancement. HT results comparison cannot be applied since the Standard mode has a constant pumping flow. This means that after the rain event, this mode needs more time to empty the tank. However, the EDSS mode applies the expert knowledge changing the pumping set points along the simulation, protecting the WWTP of VilaConca from CSOs and emptying the tank as fast as possible. Finally, the WWTP of VilaConca for the EDSS mode has an improvement of 21.6% respect the Standard one. This enhancement is mainly due to the higher treatment capacity of the plant (0.87 m<sup>3</sup>/s) and the possibility to fully treat wastewater up to the design flow (0.29 m<sup>3</sup>/s) contributing both measures to the CSO minimization.

### 5.4 EDSS rain Scenario 4

The global enhancement achieved by the EDSS mode in comparison with the Standard one, is shown in Table 5.4 Tank 1 presents an enhancement of 26.3% respect the Standard mode. The tank is able to store a higher wastewater volume during the rain event and reduces CSO discharges. The improvement of the stored volume of Tank 2 cannot be calculated since in the Standard mode, the wastewater remains stored into the tank after the rain event.

However, the EDSS mode stores wastewater during the rain in order to protect the WWTP of VilaPrat inflow but, once the rainfall is over, the decision tree gives orders to the tank in order to quickly empty the stored volume as far as the WWTP of VilaPrat can accept wastewater.

**Table 5.4.** Summary table of Scenario 4.

	Standard (m <sup>3</sup> )	EDSS (m <sup>3</sup> )	Variation percentage (%)
Tank 1	957599	1298996	26.3
Tank 2	-	-	-
VilaPrat WWTP	207822	290211	28.4
HT	-	-	-
VilaConca WWTP	18927	24792	23.7

The WWTP of VilaPrat presents an improvement of 28.4% for the use of the EDSS mode in comparison with the Standard mode. The main reasons of this enhancement are the higher treatment capacity of the plant and the possibility to partially treat wastewater avoiding higher CSO spills of totally untreated wastewater. Besides, the correct management of Tank 1 and Tank 2 during the rain event, allow the plant to receive water input more gradually and in consequence optimize its treatment. Results of the HT cannot be compared between the two management modes since in the Standard mode, the pumping set point is constant and after the rainfall, wastewater needs more time to be emptied. However, the expert knowledge applied in the EDSS mode allows the tank to change pumping set points during the rain event and send wastewater gradually in order to protect the inflow of VilaConca WWTP from CSOs.

The management of WWTP of VilaConca for the EDSS mode presents an improvement of 23.7% respect the Standard mode. This enhancement is possible thanks to the higher capacity of the plant allowing thus a higher inflow into the plant, the possibility to partially treat wastewater (avoiding totally untreated CSOs) and finally to the capacity of the WWTP to fully treat wastewater up to its design capacity, which is not applicable in the Standard mode.

## 5.5. Discussion

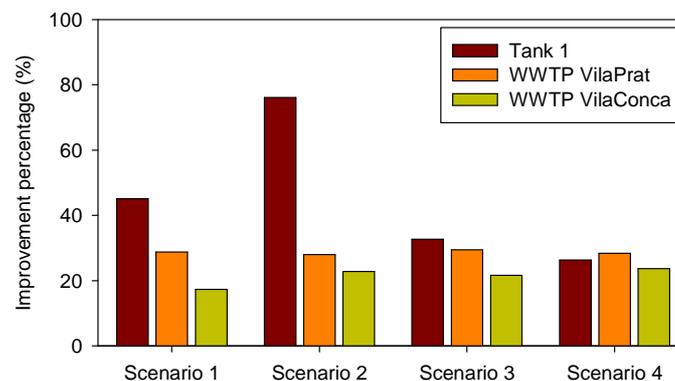
Four different rain scenarios have been tested with the EDSS mode and then compared with the Standard mode. Table 5.5 and Figure 5.19 summarize the reduction percentage of the studied points of the system (*Tank 1, Tank 2, WWTP VilaPrat, HT and WWTP VilaConca*) for each rain scenario.

**Table 5.5.** Enhancement percentage in terms of stored wastewater (Tank 1) and volume of treated wastewater (WWTPs of VilaPrat and VilaConca).

	Scenario 1 (%)	Scenario 2 (%)	Scenario 3 (%)	Scenario 4 (%)
Tank 1	45.1	76.1	32.7	26.3
Tank 2 (CSO)	-	-	-	-
VilaPrat WWTP	28.8	28	29.4	28.4
HT (CSO)	-	-	-	-
VilaConca WWTP	17.3	22.8	21.6	23.7

Regarding to Tank 1, the highest achievement is reached in scenario number two (76.1%). The main reasons of this enhancement are the catchment characteristics (VilaPrat) combined with the rain input for this scenario which allow the tank to operate with a higher management efficiency.

The first scenario presents an improvement percentage of 45.1% for Tank 1 but in this case, the rain input is probably not high enough so the Standard operation mode is able to manage accurately this rain event too. Scenarios 3 and 4 are stronger rain events and both of them present similar percentage values (32.7% and 26.73% respectively). Nevertheless for all the tested scenarios, the EDSS mode has better results in comparison with the Standard mode. Tank 2 improvement percentage cannot be applied for the tested scenarios since the Standard mode does not consider any pumping set point and in consequence, all wastewater remains stored into the tank during the 24 h rain event.



**Figure 5.19.** Improvement percentage of the tested scenarios on the UWS.

The management of the WWTP of VilaPrat presents similar results for all the tested scenarios (around 28%). Although the rain input changes, the amount of treated wastewater of the EDSS mode in comparison with the Standard one is in all cases similar, and thus presents a better performance when applying the expert knowledge. In the case of the HT, the comparison of the stored volume cannot be applied since in the Standard mode, the pumping set point is constant and in consequence after each rain event, the tank takes a longer time to empty. This does not represent a better performance as the objective of the HT is to store wastewater and then send it gradually to the WWTP of VilaConca as long as the plant can admit it. WWTP of VilaConca results present a similar behaviour for all the rain scenarios. The improvement percentage is around 21% which means that the EDSS mode has a better operation when compared to the Standard mode.

When results are compared in a wider viewpoint, it is shown that the compilation of the acquired knowledge (decision trees) and its incorporation into the EDSS prototype (DB) result in a better performance of the overall UWS management. The tested rain scenarios illustrate how in the upper points of the system (Tank 1) improvement percentages are better as rain accumulation is lower. Focusing in the downstream points of the system (WWTPs of VilaPrat and VilaConca) the improvement percentages do not differ much between each other (28% and 21%) respectively neither amongst the different rain scenarios. Thus, in all situations the UWS under study is enhanced by the application of the EDSS prototype in comparison with the Standard mode. Considering the possibility to apply different rain scenarios, intermediate to those who have been studied, the system would be able to execute the corresponding set of rules. Depending on the UWS diagnosis, the executed decision trees would be comparable to the most similar rain scenario. In other cases, different decision trees would be executed but always preserving the expert reasoning for the overall UWS enhancement.

So far, the amount of water spilled into the river is only considered in a hydraulic viewpoint. In the next chapter, the water quality parameters are taken into account.

***CHAPTER 6***  
***HEURISTIC KNOWLEDGE APPROACH***



## 6. Heuristic knowledge approach.

Since the use of the EDSS, developed by the combination of models and expert systems has been exemplified, this chapter aims to evaluate the effectiveness of the EDSS mode when more influence is given to the expert knowledge. In this sense, efforts are focused to analyze the tool in a quality point of view. Two quality parameters are chosen, the Chemical Oxygen Demand (COD) and Ammonia ( $\text{NH}_4^+$ ) as they provide information of the amount of organic compounds and nutrients found in wastewater. In order to carry out this analysis, a combination of the hydraulic data (from models) and quality data (from experts) is used as a new operational mode named *Hybrid* (Figure 6.1). As a result, the comparison is performed between the Hybrid Standard Mode (HYS) and the Hybrid EDSS mode (HYE).

It is important to remark that all data and information used as heuristic knowledge about water quality evolution in the different elements of the UWS is provided by the experts and managers inquired during the first knowledge acquisition loop (KA-I) performed within the development of the EDSS tool in section 4.2.4.

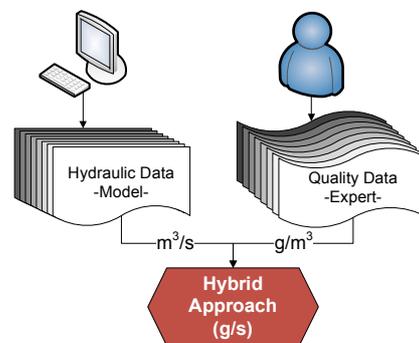


Figure 6.1. Data combination procedure for the Hybrid operational mode.

The first step of the Hybrid operation mode is to define the input quality values to the WWTPs of VilaConca and VilaPrat (Table 6.1 and Figure 6.2). These values are equal for both the HYS and the HYE modes. Differences between the catchment characteristics between VilaConca and VilaPrat, the presence of any storage tanks or the WWTP scale are not taken into account at this point.

In order to distinguish between dry weather and wet weather conditions, values over the maximum dry weather daily flow for VilaPrat ( $1.6 \text{ m}^3/\text{s}$ ) and VilaConca ( $0.29 \text{ m}^3/\text{s}$ ) are considered as wet weather.

Table 6.1. WWTP input from the expert knowledge approach and maximum daily flow for VilaPrat and VilaConca.

	VilaConca WWTP input		VilaPrat WWTP input	
	COD ( $\text{g}/\text{m}^3$ )	$\text{NH}_4^+$ ( $\text{g}/\text{m}^3$ )	COD ( $\text{g}/\text{m}^3$ )	$\text{NH}_4^+$ ( $\text{g}/\text{m}^3$ )
Dry weather conditions	600	20	600	20
Wet weather conditions	900	20	900	20
Maximum Daily Flow	$0.29 \text{ m}^3/\text{s}$		$1.6 \text{ m}^3/\text{s}$	

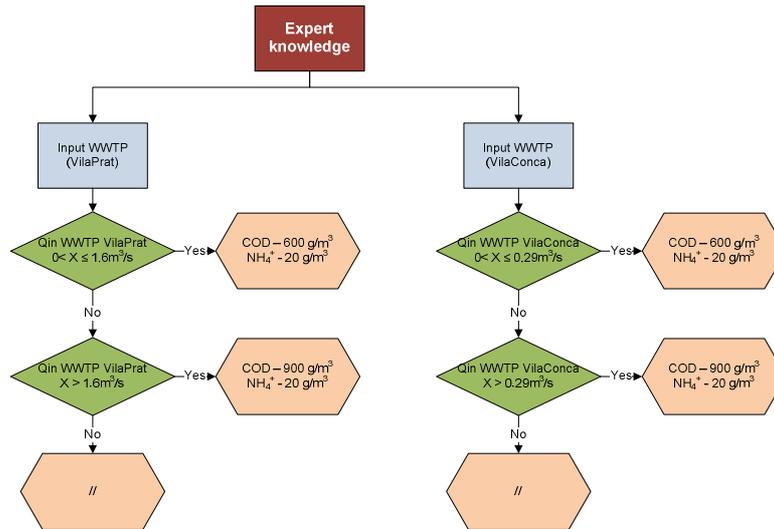


Figure 6.2. WWTP input decision tree of the Hybrid operation mode.

Both VilaConca and VilaPrat catchments include several hydraulic infrastructures installed upstream each of the WWTPs in order to protect and manage the system. Removal efficiencies for the HT (VilaConca), Tank 1 and Tank 2 (VilaPrat) are considered (Table 6.2). The amount of COD removed from these tanks is a consequence of the settling process which takes places during storage. HT and Tank 1 have smaller removal efficiencies as they are smaller tanks (20%) while for Tank 2 this value is higher (50%). Additionally,  $\text{NH}_4^+$  is removed biologically only in the WWTPs so the removal efficiency in the storage tanks is 0%.

Table 6.2. Removal efficiencies of the retention basin infrastructures for the Hybrid approach.

Retention basin removal efficiency (%)		
	COD	$\text{NH}_4^+$
HT	20	0
Tank 1	20	0
Tank 2	50	0

Table 6.3 summarizes the removal efficiencies of COD and  $\text{NH}_4^+$  concentrations of each for the possible treatment streams where the wastewater can flow through the WWTP for both the Hybrid Standard and EDSS modes.

The complete treatment of VilaConca WWTP, includes primary and secondary treatment, so under normal conditions removal efficiencies are of 80% for both COD and  $\text{NH}_4^+$  concentrations. In case of flow redirections during wet weather (only for HYE mode) the single primary treatment has a 30% removal for COD and 0% for  $\text{NH}_4^+$  while the secondary treatment has 50% removal for COD and 75% removal for  $\text{NH}_4^+$ .

VilaPrat WWTP has an additional tertiary treatment and in consequence has more stream redirection possibilities that must be taken into account. When wastewater flows through the complete process, including tertiary treatment the removal efficiencies are of 90% for COD and 85% for  $\text{NH}_4^+$ .

During wet weather (only for HYE mode) the single tertiary treatment removes 40% of COD and 10% of  $\text{NH}_4^+$ . The remaining treatment possibilities have the same removal efficiencies as VilaConca.

**Table 6.3.** Removal efficiency of the WWTPs for the Hybrid mode.

<b>WWTP removal efficiency (%)</b>		
	COD	$\text{NH}_4^+$
1ary Tr.	30	0
1ary and 2ary Tr.	80	80
1ary, 2ary and 3ary Tr.	90	85
2ary Tr.	50	75
3ary Tr.	40	10

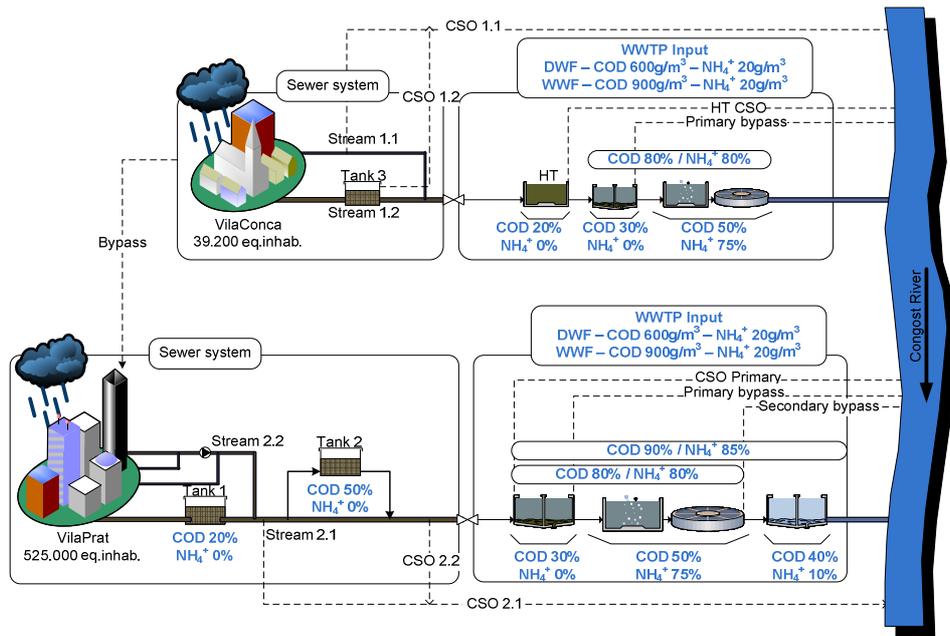
The combination of the WWTP input concentrations (Table 6.1) with the set of removal efficiencies of the retention basins and WWTP (Tables 6.2 and 6.3) for each of the catchments (VilaConca and VilaPrat), provides the output concentration values for COD and  $\text{NH}_4^+$ . They are represented in a set of if-then decision trees for both the HYS and HYE modes.

It is important to remark that under wet weather conditions wastewater can flow through different streams within VilaConca and VilaPrat sewer networks. VilaConca has two different streams. The first one (1.1) represents the 60% of the wastewater production of this catchment and has no retention basin on its way to the WWTP. The other stream (1.2) represents 40% of the wastewater flow and includes a small retention basin (Tank 3). On the other hand VilaPrat has two different streams too. The first one (2.1) represents 80% of the wastewater production and includes retention basins (Tank 1 and Tank 2) while the other stream (2.2) represents only 20% of the flow and does not include any installed retention basin. In consequence, removal efficiencies described in Table 6.3 are only applied for those wastewater ways with an installed retention infrastructure. Table 6.4 describes the different distribution percentages of the virtual system.

**Table 6.4.** VilaConca and VilaPrat flow distribution and presence of retention basins.

<b>Catchment</b>	<b>Stream n°</b>	<b>Flow percentage (%)</b>	<b>Retention basin?</b>
VilaConca	1.1	60	No
	1.2	40	Yes
VilaPrat	2.1	80	Yes
	2.2	20	No

Figure 6.3 summarizes the main features of the Hybrid mode illustrating the WWTP input concentrations for both plants, removal efficiencies of the different retention basins found in the UWS and for each of the treatment possibilities. The available streams of the virtual system are also shown in the figure.



**Figure 6.3.** Purposed removal efficiencies (COD and  $\text{NH}_4^+$ ) for the Hybrid mode of the virtual system.

It must be noted that all removal efficiencies are based in concentration values ( $\text{g}/\text{m}^3$ ). In this sense, pollutant quantities (e.g.  $\text{gr}/\text{s}$  of COD) directly depend of water volumes flowing through the UWS.

### 6.1 Hybrid Standard operation mode (HYS)

The HYS mode manages the system as in the standard operation mode. The HT provides a constant flow to the WWTP of VilaConca (during DWF) and sending up to  $0.87 \text{ m}^3/\text{s}$  (during wet weather). Tank 1 operates only with anti flooding purposes and Tank 2 is an off line tank operating to avoid CSO spills. During wet weather, both WWTPs operate in a way that the primary treatment works at its maximum flow capacity and sends part of this water to the secondary (and tertiary for VilaPrat) treatment while the excess is directly discharged into the receiving body. There is no bypass connection between the two systems.

#### VilaConca HYS operation

Figure 6.4 illustrates the decision tree for the full treatment option of the HYS mode for COD and  $\text{NH}_4^+$  output concentrations of the WWTP of VilaConca. The WWTP performance has different removal efficiencies depending on the plant inflow. For values under  $0.13 \text{ m}^3/\text{s}$  (DWF) the plant operates treating wastewater through all the possible streams (primary and secondary) with removal efficiencies of 80% for both COD and  $\text{NH}_4^+$ . The HT provides an additional COD removal of 20% so, given the incoming pollutant concentration during DWF ( $600 \text{ g}/\text{m}^3$  - COD;  $20 \text{ g}/\text{m}^3$  -  $\text{NH}_4^+$ ), outputs are of  $96 \text{ g}/\text{m}^3$  for COD and  $4 \text{ g}/\text{m}^3$  for  $\text{NH}_4^+$ .

When flow increases up to the maximum capacity of the secondary treatment ( $0.29 \text{ m}^3/\text{s}$ ), removal efficiencies descend to  $144 \text{ g}/\text{m}^3$  for COD and  $4 \text{ g}/\text{m}^3$  for  $\text{NH}_4^+$ .  $\text{NH}_4^+$  does not vary its concentration over the mentioned flows due to the fact that its removal efficiency depends on the biological treatment which has its limit at  $0.58 \text{ m}^3/\text{s}$  and therefore its efficiency is not affected.

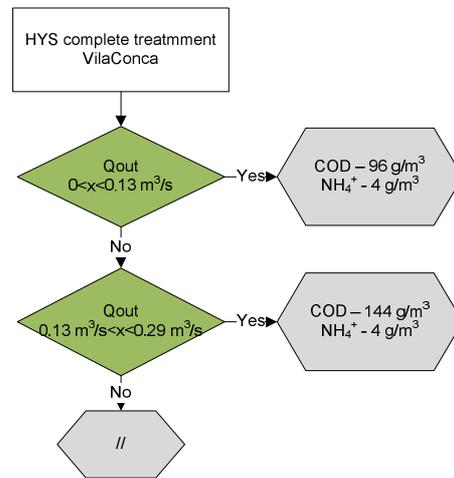


Figure 6.4. HYS complete treatment tree for VilaConca.

When inflow is between  $0.29 \text{ m}^3/\text{s}$  and  $0.58 \text{ m}^3/\text{s}$ ,  $0.29 \text{ m}^3/\text{s}$  flow through primary and secondary treatment (HYS complete treatment tree) and the excess flow flows only by the primary treatment. Figure 6.5 illustrates the HYS primary treatment tree. In this case there is only COD removal and, taking into account the wet weather inflow concentrations and HT removal efficiencies, its outflow values are of  $504 \text{ g}/\text{m}^3$  for COD and  $20 \text{ g}/\text{m}^3$  for  $\text{NH}_4^+$ .

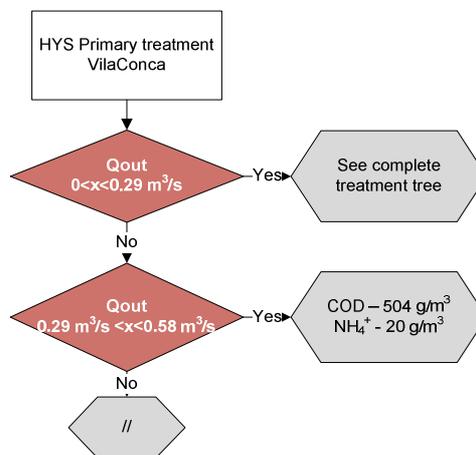
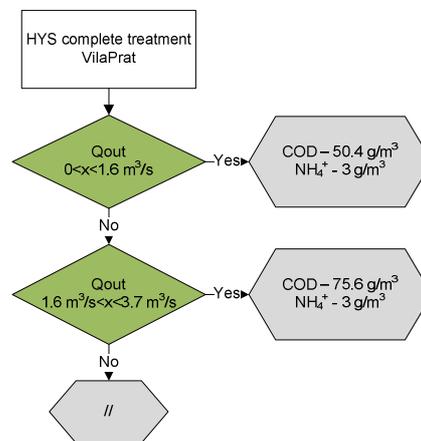


Figure 6.5. HYS primary treatment tree for VilaConca.

VilaPrat HYS operation

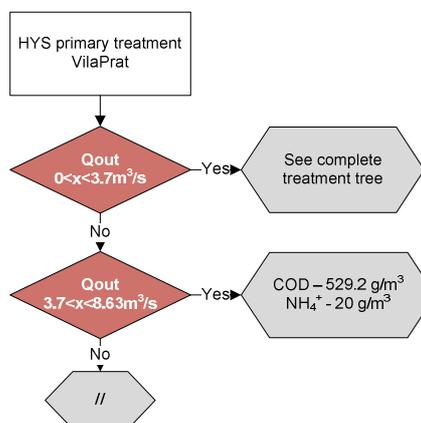
Figure 6.6 illustrates the decision tree for the complete treatment of VilaPrat WWTP by the HYS mode regarding to COD and  $\text{NH}_4^+$  output concentrations. During DWF, the inflow is lower than  $1.6 \text{ m}^3/\text{s}$  and quality values are  $600 \text{ g}/\text{m}^3$  (COD) and  $20 \text{ g}/\text{m}^3$  ( $\text{NH}_4^+$ ). Wastewater flows through primary, secondary and tertiary treatment so removal efficiencies are of 90% for COD and 85% for  $\text{NH}_4^+$ .

Tank 1 provides an additional COD removal of 20% due to the settling process while Tank 2 has no influence because flow is not high enough to send wastewater to the off line tank. Taking into account all these elements, the output concentrations of the WWTP are  $50.4 \text{ g}/\text{m}^3$  for COD and  $3 \text{ g}/\text{m}^3$  for  $\text{NH}_4^+$ . When the rain starts, the plant is able to fully treat wastewater while inflow does not exceed  $3.7 \text{ m}^3/\text{s}$  so removal efficiencies of the WWTP remain 90% for COD and 85% for  $\text{NH}_4^+$ . Tank 1 provides 20% of COD removal and 0% for  $\text{NH}_4^+$  and Tank 2 removes 50% of COD but is not taken into account since the tank has no pumping set points and thus, the tank is not emptied. Taking into account these elements, the outflow concentrations for COD and  $\text{NH}_4^+$  during wet weather are of  $75.6 \text{ g}/\text{m}^3$  and  $3 \text{ g}/\text{m}^3$  respectively.



**Figure 6.6.** HYS complete treatment tree for VilaPrat.

As explained during wet weather the plant is able to accept up to  $8.63 \text{ m}^3/\text{s}$ .  $3.7 \text{ m}^3/\text{s}$  flow through all the processes (primary, secondary and tertiary treatment) and the excess only by the primary treatment. Figure 6.7 shows the quality output concentrations after the HYS primary treatment of VilaPrat WWTP. Tank 1 contribution is also taken into account (20% COD) and the primary settler removes 30% of COD and 0% of  $\text{NH}_4^+$ , which is removed biologically.



**Figure 6.7.** HYS primary treatment for VilaPrat.

To summarize the HYS operation mode, it can be seen that during dry weather VilaPrat WWTP has lower discharge COD and  $\text{NH}_4^+$  concentrations than VilaConca WWTP. This is due to the decantation process occurring at Tank 1 and Tank 2 (only for COD) at VilaPrat sub catchment and to the tertiary treatment.

During wet weather (but still with complete treatment) output concentrations are for both WWTPs higher due to the higher amount of pollutants entering the UWS. Despite that, VilaPrat sub catchment presents lower discharge values in comparison with VilaConca WWTP due to the same reasons as during dry weather (decantation in tanks and tertiary treatment). When wastewater flows only by the primary treatment, output concentration values are higher for both WWTPs. This is because water is only partially treated and consequently the effluent is more polluted.

## **6.2 Hybrid EDSS operation mode (HYE)**

The HYE operation mode consists of the management of the virtual system from a quality point of view and takes into account the knowledge applied by means of decision trees in the EDSS mode. The main features of this management strategy are that the HT empties the stored volume in case of rain prediction in order to increase the free volume. Tank 1, uses 40% of its volume to reduce CSOs while there is no flood risk and Tank 2 is operated as an on-line CSO tank so that all combined waters are sent to the tank (during rain events). Regarding to the WWTPs, they are both able to separate flow into two independent streams (when inflow exceeds the maximum primary treatment capacity). The first stream flows only through primary treatment and is then discharged into the river while the second stream flows only through the secondary treatment and is then spilled into the receiving body. Only in the case of VilaPrat WWTP, when the TSS concentration does not exceed  $500 \text{ g/m}^3$  some wastewater can also be sent to the tertiary treatment. Finally, the bypass gate between VilaConca and VilaPrat is operational and both sub catchments are interconnected.

### VilaConca HYE operation

Figure 6.8 shows the complete treatment decision tree of VilaConca WWTP for the HYE mode. The plant is able to fully treat wastewater up to  $0.29 \text{ m}^3/\text{s}$ , which is the design flow of the WWTP. During DWF (under  $0.13 \text{ m}^3/\text{s}$ ) removal efficiencies are 80% for both COD and  $\text{NH}_4^+$ . Additionally, the HT provides an extra COD removal of 20% due to the settling process taking place into the tank. Thus given the wastewater quality input of  $600 \text{ g/m}^3$  for COD and  $20 \text{ g/m}^3$  for  $\text{NH}_4^+$ , the output qualities for both parameters are  $96 \text{ g/m}^3$  and  $4 \text{ g/m}^3$  respectively.

During wet weather, while the plant does not exceed the design flow ( $0.29 \text{ g/m}^3$ ) all wastewater is treated through the complete process (primary and secondary treatment) and HT COD removal contribution is also present. The only difference is in the inflow quality, which increases to  $900 \text{ g/m}^3$  for COD and stays equal to  $20 \text{ g/m}^3$  for  $\text{NH}_4^+$ . In consequence, discharged values at wet weather are of  $144 \text{ g/m}^3$  (COD) and  $4 \text{ g/m}^3$  ( $\text{NH}_4^+$ ).

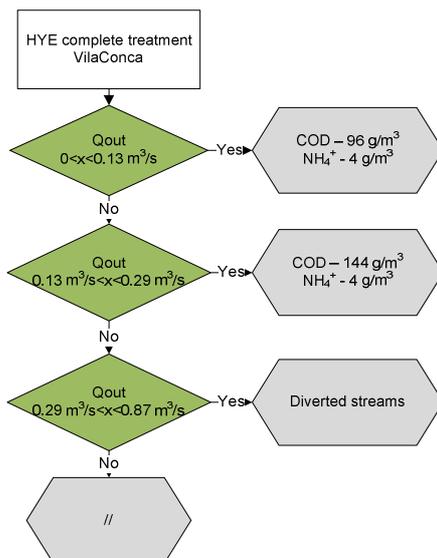


Figure 6.8. HYE complete treatment for VilaConca.

When the influent into the WWTP is over  $0.29 \text{ m}^3/\text{s}$ , the plant divides flow in two independent streams. The first one corresponds to the single secondary treatment. Figure 6.9 illustrates the management of this stream, named HYE secondary treatment tree. In this case, the HT eliminates 20% of the COD concentration while the secondary treatment removes 50% of COD and 75% of  $\text{NH}_4^+$ . Thus, the outflow concentrations for COD and  $\text{NH}_4^+$  are of  $360 \text{ g/m}^3$  and  $5 \text{ g/m}^3$  respectively.

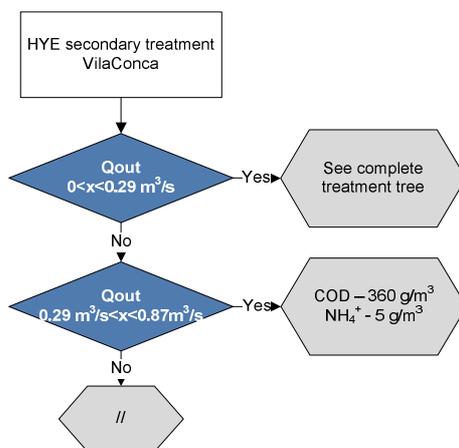


Figure 6.9. HYE secondary treatment for VilaConca.

The remaining flow is treated only by the primary treatment stream. Figure 6.10 shows how this stream is managed for the WWTP of VilaConca. While the inflow into the plant does not exceed  $0.29 \text{ m}^3/\text{s}$  wastewater is fully treated. Once the inflow is higher,  $0.29 \text{ m}^3/\text{s}$  are treated by the secondary treatment stream and the rest by the primary treatment one. HT contributes in 20% of COD elimination and for this particular process, the pollutant removal efficiencies are of 30% (COD) and 0% ( $\text{NH}_4^+$ ).

The calculated output quality values are  $504 \text{ g/m}^3$  for COD concentration and  $20 \text{ g/m}^3$  for  $\text{NH}_4^+$  concentration.

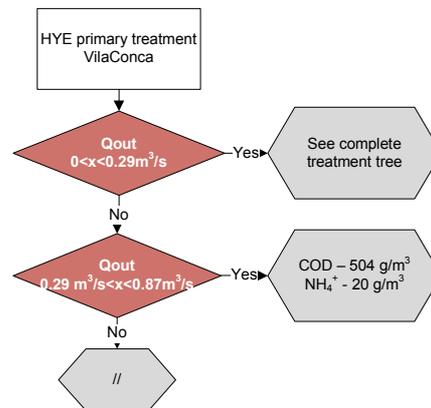


Figure 6.10. HYE primary treatment for VilaConca.

VilaPrat HYE operation

Figure 6.11 illustrates the complete treatment decision tree of VilaPrat WWTP for the HYE operation mode. While the plant inflow is below  $1.6 \text{ m}^3/\text{s}$  (maximum dry weather daily flow), the pollutant load is of  $600 \text{ g/m}^3$  for COD and  $20 \text{ g/m}^3$  for  $\text{NH}_4^+$  and wastewater is treated through all the WWTP processes (primary, secondary and tertiary treatment). Tank 1 also contributes in 20% of COD elimination while Tank 2 is not taken into account since it is not raining (DWF). With all these elements, the effluent concentration of COD and  $\text{NH}_4^+$  variables during DWF are  $50.4 \text{ g/m}^3$  and  $3 \text{ g/m}^3$  respectively. When it starts to rain and the plant inflow increases but does not exceed its design flow ( $3.7 \text{ m}^3/\text{s}$ ), wastewater is treated through all the processes of the plant and Tank 1 (20%) and Tank 2 (50%) contribute in the COD removal too. Because of the rain concentration, the pollutant production increases to  $900 \text{ g/m}^3$  for COD and  $20 \text{ g/m}^3$  for  $\text{NH}_4^+$ . Taking into account all these elements, the output values for COD and  $\text{NH}_4^+$  are of  $37.8 \text{ g/m}^3$  and  $3 \text{ g/m}^3$  respectively. COD concentration is lower for a higher flow because of Tank 2 contribution during wet weather, which is not taken into account during DWF as it is an off-line tank. For higher flows, the WWTP is divided in individual streams and in consequence, does not treat wastewater through the whole plant processes.

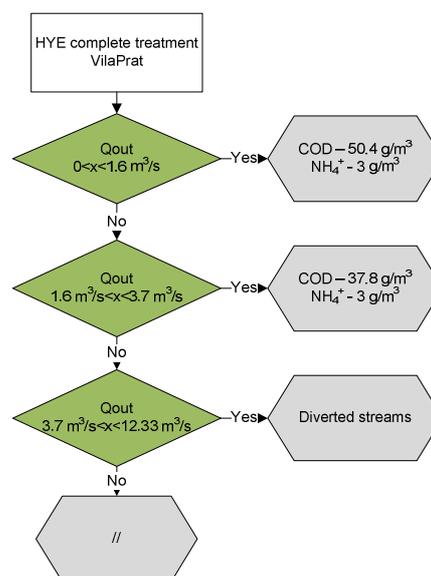


Figure 6.11. HYE complete treatment for VilaPrat.

During wet weather, the WWTP flow of VilaPrat is divided in different streams. Figure 6.12 shows the secondary treatment decision tree for the HYE mode of VilaPrat WWTP. While flow of the plant is lower than  $3.7 \text{ m}^3/\text{s}$  all wastewater is fully treated through all processes. When the flow is increased up to  $12.33 \text{ m}^3/\text{s}$ ,  $3.7 \text{ m}^3/\text{s}$  of the total are only treated by the secondary treatment (50% COD and 75%  $\text{NH}_4^+$ ) and the rest is treated by the primary treatment only (30% COD and 0%  $\text{NH}_4^+$ ). Additionally, Tank 1 (20%) and Tank 2 (50%) contribute on the COD removal. Taking into account these elements and that the pollutant production corresponds to wet weather ( $900 \text{ g}/\text{m}^3$  COD and  $20 \text{ g}/\text{m}^3$   $\text{NH}_4^+$ ), the output concentrations of the WWTP are  $189 \text{ g}/\text{m}^3$  corresponding to COD and  $5 \text{ g}/\text{m}^3$  to  $\text{NH}_4^+$ .

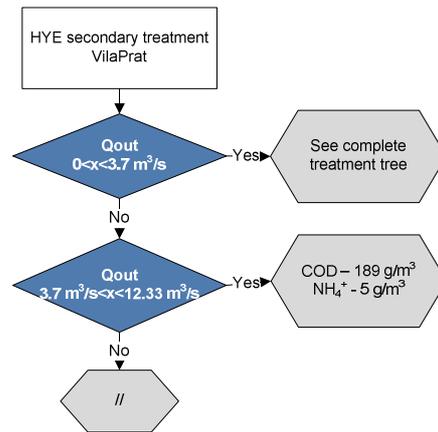


Figure 6.12. HYE secondary treatment for VilaPrat.

The second stream observed during wet weather in the WWTP of VilaPrat for the HYE mode is the single primary treatment and Figure 6.13 illustrates its management. Removal efficiencies for this stream are of 30% for COD and 0% for  $\text{NH}_4^+$  (removed biologically). Besides, Tank 1 and Tank 2 contribute in a 20% and 50% respectively in the COD elimination and the pollutant production corresponds to wet weather ( $900 \text{ g}/\text{m}^3$  COD and  $20 \text{ g}/\text{m}^3$   $\text{NH}_4^+$ ). Taking into account all these features, the output load for COD and  $\text{NH}_4^+$  on the total secondary stream is of  $264.6 \text{ g}/\text{m}^3$  and  $20 \text{ g}/\text{m}^3$  respectively.

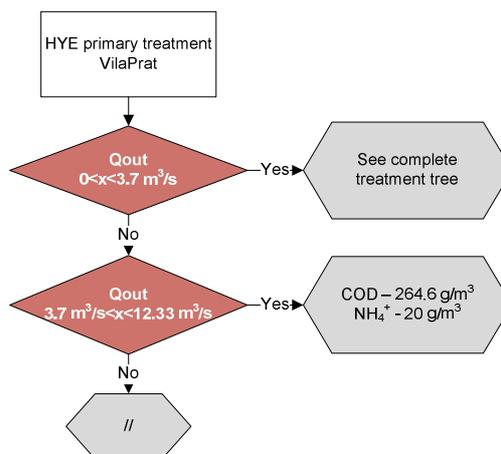


Figure 6.13. HYE primary treatment for VilaPrat.

In some particular cases, when TSS concentration does not exceed  $500 \text{ g}/\text{m}^3$ , there is a third stream that can be redirected directly to the tertiary treatment, which is only able to remove 40% of COD and 10% of  $\text{NH}_4^+$ .

Figure 6.14 shows the decision tree of this third stream for the HYE mode in VilaPrat WWTP. In this case, the pollutant load concentrations in the output is of 226.8 g/m<sup>3</sup> (COD) and 18 g/m<sup>3</sup> (NH<sub>4</sub><sup>+</sup>).

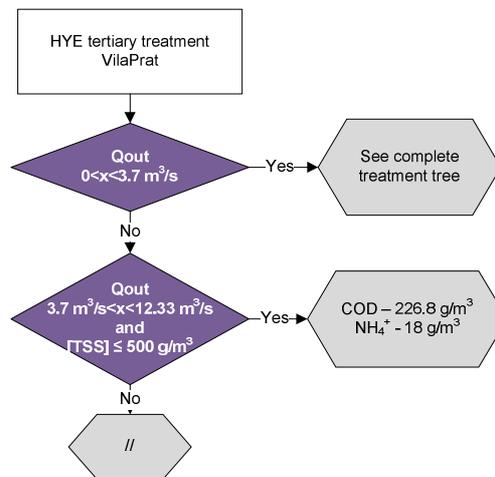


Figure 6.14. HYE tertiary treatment for VilaPrat.

In summary, the use of HYE mode during DWF presents higher COD concentration values in VilaConca than in VilaPrat. This is due to the presence of Tank 1 and the tertiary treatment in VilaPrat sub catchment which give additional COD removal efficiency. When comparing NH<sub>4</sub><sup>+</sup> concentrations, the effluent values for both sub catchments are similar (4 gr/m<sup>3</sup> in VilaConca and 3 gr/m<sup>3</sup> in VilaPrat).

Only the tertiary treatment of VilaPrat provides an extra 5% of NH<sub>4</sub><sup>+</sup> removal. Regarding to the single primary or the single secondary treatments, differences between VilaConca and VilaPrat are also found. The reason is the effect of Tank 1 and Tank 2 in COD elimination.

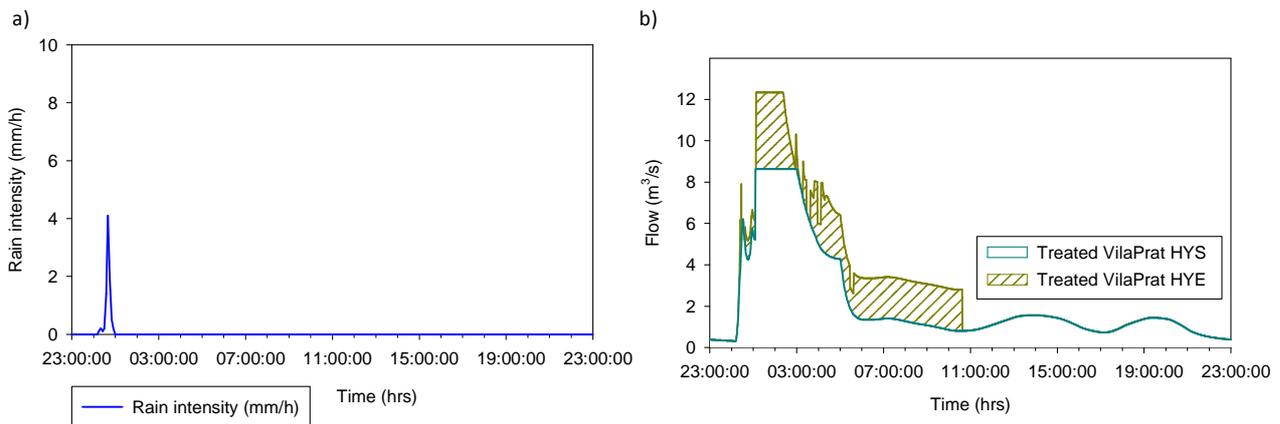
The HYE operation mode presents both for VilaConca and VilaPrat systems, better quality results during DWF. This is due to the fact that a complete treatment through all the WWTP processes is always better than a partial treatment. Nevertheless, a partial treatment is always a better option than an untreated spill into the river.

### 6.3. HYS and HYE comparison

A comparison between the HYS mode and the HYE mode has been carried out for the 4 rain scenarios detailed in section 4.6.2. Although this evaluation is done for all scenarios and catchments, the input vs the output of VilaPrat WWTP during Scenario 2 has been selected for the graphical representation of this comparison. The rain event has been chosen given its medium intensity and water input. The rest of scenarios are presented in the **Annex**. A summary of the whole results including the 4 rain scenarios is presented at the end of this subchapter. Figure 6.15 show the water effluent of the WWTP of VilaPrat using the (a) HYS mode and (b) HYE mode during scenario 2.

Regarding to the HYS mode, before the rain starts, the flow of the plant is low (DWF) and thus, all wastewater is treated through the complete processes of the plant. Once the rainfall begins, the flow rises up to its limit ( $8.63 \text{ m}^3/\text{s}$ ).  $3.7 \text{ m}^3/\text{s}$  are fully treated and the rest only by the primary treatment. Once the rain is over, flow starts to decrease gradually until reaching DWF conditions.

Concerning to the HYE mode, before the rainfall begins, the flow of the plant is low and all wastewater is fully treated through primary, secondary and tertiary treatment. Once the rain starts, the flow increases (up to  $12.33 \text{ m}^3/\text{s}$ , limit of HYE mode) and is separated in different streams (single primary, single secondary and when possible single tertiary treatment). Once the rain is over, the flow starts to decrease gradually to recover DWF conditions. Tank 1 and Tank 2 emptying contribution is also observed.



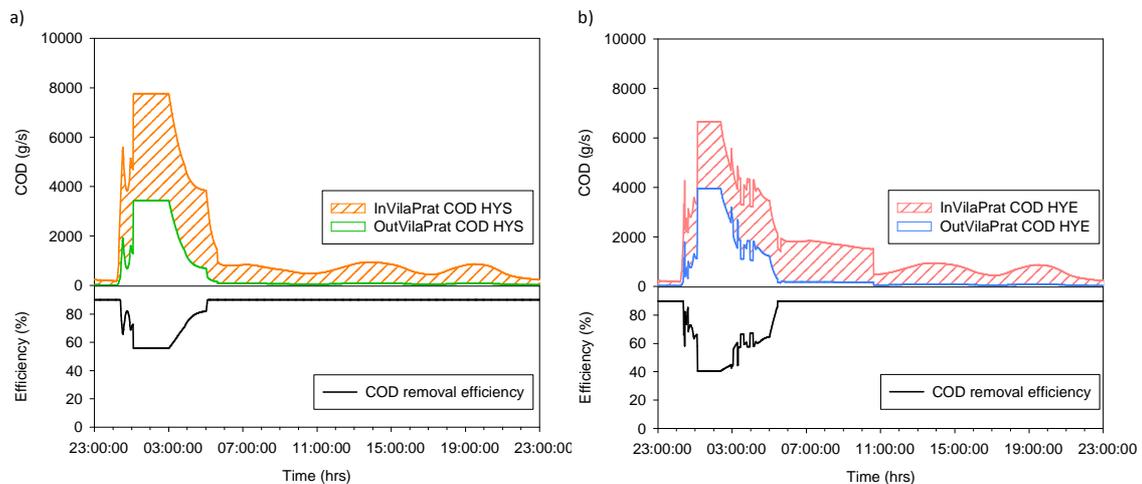
**Figure 6.15.** (a) Rain intensity of rain scenario 2, (b) Treated wastewater of VilaPrat WWTP for HYS and HYE operation modes during scenario 2.

Figure 6.16 illustrates the input and output of COD mass flow (g/s) of VilaPrat WWTP during scenario 2 for both the (a) HYS and (b) HYE operation modes.

The HYS operation mode results (Figure 6.16a) illustrate that in the first hour, before the rain starts, the amount of removed pollutant is high (90%) since the WWTP is operating in DWF conditions and all wastewater is fully treated. Once the rain starts, the removal efficiency descends up to 60%. This is due to two reasons. The first one is that during rainfall the amount of COD produced by VilaPrat catchment is higher. The second reason is that the plant is able to treat only  $3.7 \text{ m}^3/\text{s}$  through the complete process while the rest is only treated by the primary treatment and in consequence efficiency descends. Once the rain is over, the COD input descends and consequently effluent values are lower too recovering the DWF conditions.

When paying attention to the COD mass flow of VilaPrat for HYE during scenario 2 (Figure 6.16b) it can be observed that before the rain starts, COD removal efficiency is 90% because the WWTP is operating in DWF conditions and all wastewater is treated through all the plan processes. Once the rainfall starts, the elimination efficiency descends until the minimum of about 40%. This is due to the flow diverting in independent streams in VilaPrat WWTP in order to avoid CSO spills.

Once the rainfall stops, removal efficiency increases gradually but the effect of Tank 1 and Tank 2 emptying is also appreciated. Finally, COD removal efficiency recovers normal DWF values (90%).



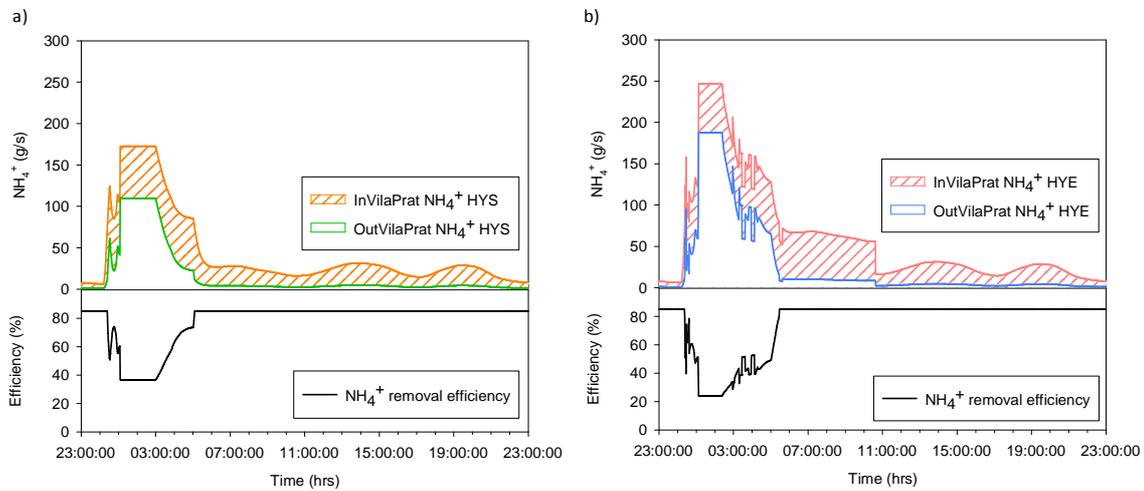
**Figure 6.16.** COD mass flow and removal efficiency of VilaPrat WWTP for (a) HYS and (b) HYE operation modes during scenario 2.

Comparing results between HYS and HYE operation modes, it can be seen that the removal efficiency has lower values for HYE than for HYS modes. Despite that, the duration of this minimum is shorter for the HYE operation mode (1 h). The output maximum reached by the HYE operation mode is also higher than for the HYS mode. However, this is shorter in time too. Although the maximum COD output values are higher for the HYE mode, HYS operation does not consider flow redirection so may produce a greater amount of untreated CSO spills. Finally, the total amount of COD discharged into the river by VilaPrat WWTP during scenario 2 for both operation modes is of 239.6 t (for HYS) and 129.8 t (for HYE). It must be pointed out that, the amount of stored wastewater in Tank 2 for the standard mode has also been taken into account. Figure 6.17 shows the input and output of  $\text{NH}_4^+$  mass flow (g/s) of VilaPrat WWTP for both the (a) HYS and (b) HYE operation modes during scenario 2.

Regarding to the HYS operation mode, Figure 6.17a illustrates that before the rain starts, the WWTP of VilaPrat treats wastewater through all processes so  $\text{NH}_4^+$  removal efficiency is 85%. Once the rain begins (00:10) the removal percentage starts to descend as the plant inflow increases. The minimum removal percentage (40%) is reached at 01:05 corresponding with the maximum  $\text{NH}_4^+$  input into the WWTP. After the rainfall, efficiency values increase gradually to DWF conditions (85%).

Concerning to HYE operation (Figure 6.17b), results show that before the rain begins, the WWTP operates at DWF conditions and wastewater is fully treated. Consequently,  $\text{NH}_4^+$  removal efficiency is of 85%. At the beginning of the rainfall, the inflow increases and flow is separated in different streams.

Therefore, elimination efficiency of  $\text{NH}_4^+$  decreases, reaching its minimum (24%) at 01:10 approximately. About 1 hour later, flow decreases and the plant starts to recover its normal flow although the Tank 1 and Tank 2 emptying stages is also perceived. The plant finally recovers DWF conditions and  $\text{NH}_4^+$  removal efficiency is of 85%.



**Figure 6.17.**  $\text{NH}_4^+$  mass flow and removal efficiency of VilaPrat WWTP for (a) HYS and (b) HYE operation modes during scenario 2.

Differences found between HYS and HYE operation modes in  $\text{NH}_4^+$  removal efficiencies show that the minimum reached by the HYE mode is lower than for the HYS mode but is shorter in time than the HYS operation (40 min.). The  $\text{NH}_4^+$  input and output values of the VilaPrat WWTP are higher for the HYE operation mode. This is due to the higher amount of water input since the plant has a higher treatment capacity. Although the  $\text{NH}_4^+$  output maximum is higher for the HYE operation, the HYS does not consider any flow diverting and consequently may produce more untreated CSO spills (0.5 t). Finally, the total amount of  $\text{NH}_4^+$  discharged into the river by VilaPrat WWTP during scenario 2 is 5.8 t for the HYS mode (which takes into account the amount of stored wastewater into Tank 2) and 4.7 t for HYE.

Table 6.5 shows the summary results for all the studied scenarios comparing the HYS and the HYE operation modes. The table includes the volume of treated wastewater, the amount of COD and  $\text{NH}_4^+$  discharged into the river for all the studied scenarios and for both sub catchments, VilaConca and VilaPrat.

**Table 6.5.** Summary table of the total discharges of (a) COD, (b) NH<sub>4</sub><sup>+</sup> and (c) Treated wastewater to the river by HYS and HYE operation modes for all scenarios and catchments.

a)

			Units	Scenario 1	Scenario 2	Scenario 3	Scenario 4
HYS operation mode	VilaConca	COD	Kg	7854.2	26953.1	42248.6	70344.9
	VilaPrat		Kg	63412.4	239555.0	394479.6	659030.5
	<b>Total HYS</b>	<b>Total COD</b>	<b>Kg</b>	<b>71266.6</b>	<b>266508.1</b>	<b>436728.2</b>	<b>729375.4</b>
HYE operation mode	VilaConca	COD	Kg	4971.7	22847.8	38598.4	65752.6
	VilaPrat		Kg	24091.1	129763.0	250516.2	430323.0
	<b>Total HYE</b>	<b>Total COD</b>	<b>Kg</b>	<b>29062.8</b>	<b>152610.8</b>	<b>289114.6</b>	<b>496075.7</b>

b)

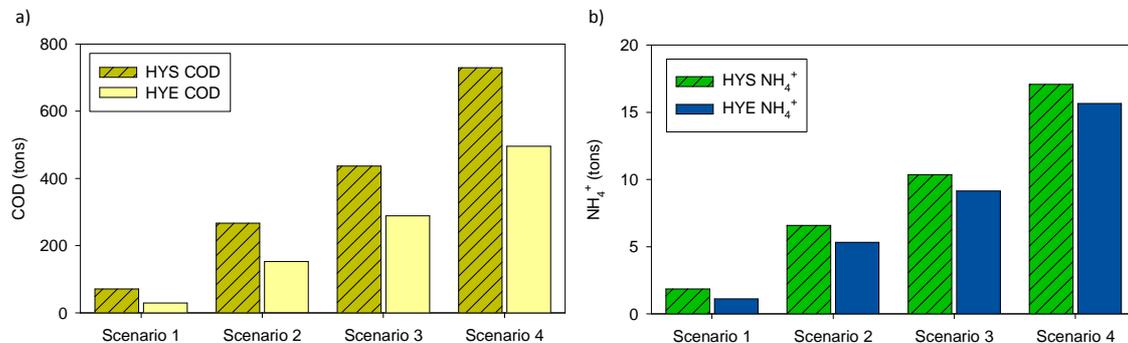
			Units	Scenario 1	Scenario 2	Scenario 3	Scenario 4
HYS operation mode	VilaConca	NH <sub>4</sub> <sup>+</sup>	Kg	242.0	764.1	1147.1	1886.5
	VilaPrat		Kg	1605.4	5812.1	9201.3	15196.1
	<b>Total HYS</b>	<b>Total NH<sub>4</sub><sup>+</sup></b>	<b>Kg</b>	<b>1847.4</b>	<b>6576.2</b>	<b>10348.4</b>	<b>17082.6</b>
HYE operation mode	VilaConca	NH <sub>4</sub> <sup>+</sup>	Kg	165.9	668.8	1061.3	1778.3
	VilaPrat		Kg	945.0	4661.3	8075.8	13884.6
	<b>Total HYE</b>	<b>Total NH<sub>4</sub><sup>+</sup></b>	<b>Kg</b>	<b>1110.9</b>	<b>5330.0</b>	<b>9137.2</b>	<b>15662.9</b>

c)

			Units	Scenario 1	Scenario 2	Scenario 3	Scenario 4
HYS operation mode	VilaConca	Treated wastewater	m <sup>3</sup>	15741.0	18279.0	17361.0	18927.0
	VilaPrat		m <sup>3</sup>	113400.1	189305.8	168362.3	207822.3
	<b>Total HYS</b>	<b>Total wastewater</b>	<b>m<sup>3</sup></b>	<b>129141.1</b>	<b>207584.8</b>	<b>185723.3</b>	<b>226749.3</b>
HYE operation mode	VilaConca	Treated wastewater	m <sup>3</sup>	18948.0	23676.0	22152.0	24792.0
	VilaPrat		m <sup>3</sup>	159160.4	262986.7	238430.5	290211.1
	<b>Total HYE</b>	<b>Total wastewater</b>	<b>m<sup>3</sup></b>	<b>178108.4</b>	<b>286662.7</b>	<b>260582.5</b>	<b>315003.1</b>

## 6.4. Discussion

In VilaConca sub catchment in the HYS mode, the amount of COD discharged into the river increases in every scenario due to the higher rain intensity of each scenario. The same happens with the amount of  $\text{NH}_4^+$  discharged into the river. Treated wastewater shows the same pattern except for scenario number 3, which is a little smaller in comparison with scenario 2. VilaPrat HYS operation mode also shows how COD discharge increases its values in each scenario. The amount of discharged  $\text{NH}_4^+$  into the receiving body by VilaPrat sub catchment and for HYS operation mode is increased in each scenario (Figure 6.18). The volume of treated follows the same pattern except for scenario 2. When focusing on HYE results combined both for VilaConca or VilaPrat subsystems, results show how the amounts of discharged pollutant (COD and  $\text{NH}_4^+$ ) increase in each scenario but the volume of treated wastewater discharged into the river for both catchments is bit lower in scenario 3 in comparison with the second one. This variation may be caused by the smaller difference in the rainfall input into the UWS between scenario 2 and scenario 3 ( $21805 \text{ m}^3$ ) which is higher amongst the other rain scenarios. Another reason may be system performance, allowing treating a greater amount of wastewater.



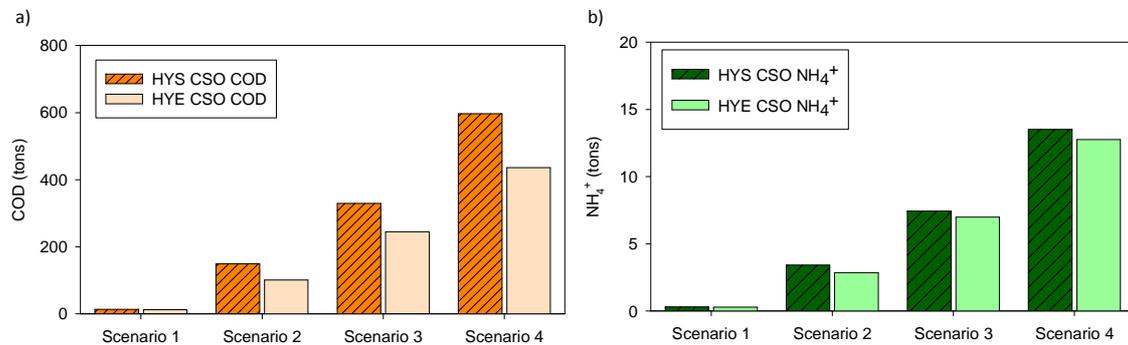
**Figure 6.18.** Total pollutant discharge (COD and  $\text{NH}_4^+$ ) by HYS and HYE operation modes of the tested scenarios on the UWS.

Analyzing results of the HYS and HYE operation modes it can be observed that in VilaConca catchment, pollutant loads (both COD and  $\text{NH}_4^+$ ) present higher values for HYS mode in comparison with HYE mode. This means that the expert management of the system discharges a smaller amount of pollutant into the receiving body. The volume of treated wastewater discharged to the river is higher using HYE mode than HYS mode meaning that more wastewater is treated by the expert mode. Focusing on the comparison between HYS and HYE in VilaPrat catchment, results show that the amount of pollutants (both COD and  $\text{NH}_4^+$ ) discharged into the river is higher for the HYS mode while the volume of treated wastewater is higher for the HYE mode. This means that the use to the expert mode causes a pollutant load reduction and that the WWTP of VilaPrat is able to treat a higher amount of wastewater.

Table 6.6 illustrates the amount of COD and  $\text{NH}_4^+$  discharged into the river by CSOs for HYS and HYE operation modes for all scenarios and sub catchments. Results include the additional CSO spill of untreated wastewater produced by HYS operation mode in comparison with the HYE mode for all rain scenarios.

The HYS operation mode shows how the amount of pollutants COD and  $\text{NH}_4^+$  discharged by CSOs increased in each scenario. As the system receives a greater volume of rain water, the storage and treatment capacity of the UWS decreases and consequently the CSO load is increased. The same pattern is found with the HYE operation mode (Figure 6.19).

Comparing HYS and HYE operation mode each other, it can be observed that discharged loads for the HYE mode are smaller than the HYS mode for all scenarios. The reason is because in the HYE operation mode, the UWS has a greater treatment capacity and in consequence COD and  $\text{NH}_4^+$  pollutants are removed in a larger quantity.



**Figure 6.19.** CSO pollutant discharge (COD and  $\text{NH}_4^+$ ) by HYS and HYE operation modes of the tested scenarios on the UWS.

Evaluating the total (Figure 6.18) and the CSO (Figure 6.19) pollutant discharges it can be seen that during smaller rain scenarios (1 and 2) the difference between them is more significant for both HYS and HYE modes. E.g. the amount of total COD in comparison with the untreated CSO for HYS operation mode during scenario 1 is 81.6% higher. Thus, most of water is treated before river disposal during the first two scenarios. In contrast, this percentage is reduced in scenarios 3 and 4 and results are more similar for both figures (the percentage for the same example is reduced to 18.1%) So the amount of pollutant discharged into the river derived from treated water is decreased.

**Table 6.6.** Summary table of untreated CSO (a) COD, (b) NH<sub>4</sub><sup>+</sup> and (c) spilled wastewater discharges to the river by HYS and HYE operation modes for all scenarios and catchments.

a)

			Units	Scenario 1	Scenario 2	Scenario 3	Scenario 4
HYS operation mode	VilaConca	COD	Kg	2282.4	18505.6	34673.7	61245.2
	VilaPrat	COD	Kg	10860.9	131122.4	295029.6	535816.8
	<b>Total HYS</b>	<b>Total COD</b>	<b>Kg</b>	<b>13143.3</b>	<b>149628.0</b>	<b>329703.3</b>	<b>597062.0</b>
HYE operation mode	VilaConca	COD	Kg	1665.8	17380.3	33796.5	59964.6
	VilaPrat	COD	Kg	10819.9	83870.0	210329.6	375621.8
	<b>Total HYE</b>	<b>Total COD</b>	<b>Kg</b>	<b>12485.7</b>	<b>101250.3</b>	<b>244126.1</b>	<b>435586.4</b>

b)

			Units	Scenario 1	Scenario 2	Scenario 3	Scenario 4
HYS operation mode	VilaConca	NH <sub>4</sub> <sup>+</sup>	Kg	68.4	510.4	918.6	1614.1
	VilaPrat	NH <sub>4</sub> <sup>+</sup>	Kg	241.4	2913.8	6556.2	11907.0
	<b>Total HYS</b>	<b>Total NH<sub>4</sub><sup>+</sup></b>	<b>Kg</b>	<b>309.8</b>	<b>3424.2</b>	<b>7424.8</b>	<b>13521.1</b>
HYE operation mode	VilaConca	NH <sub>4</sub> <sup>+</sup>	Kg	49.9	476.4	892.3	1575.8
	VilaPrat	NH <sub>4</sub> <sup>+</sup>	Kg	240.4	2384.5	6094.0	11192.9
	<b>Total HYE</b>	<b>Total NH<sub>4</sub><sup>+</sup></b>	<b>Kg</b>	<b>290.3</b>	<b>2860.9</b>	<b>6986.3</b>	<b>12768.7</b>

c)

			Units	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Added CSO spills	VilaConca	CSO	m <sup>3</sup>	3303	5397	4791	5865
	VilaPrat	CSO	m <sup>3</sup>	45760	73681	70069	82389
	<b>Total</b>	<b>Total CSO</b>	<b>m<sup>3</sup></b>	<b>49063</b>	<b>79078</b>	<b>74860</b>	<b>88254</b>

### 6.5. Economical impact evaluation of the discharged load

An economic evaluation has also been carried out according to the methodology proposed by Hernández-Sancho et al. (2010). Considering the water treatment as a productive process where a desirable output (treated water) is obtained together with a set of undesirable outputs (water pollutants) then a shadow price can be calculated for these undesirable components. A shadow price of these water pollutants can be understood as the equivalent of the environmental damage avoided. If pollution levels are assumed optimal, then shadow prices of water pollutants can be interpreted as an approximation of the environmental benefits gained from the wastewater treatment process.

The shadow price is calculated using the estimation of the distance function concept (Fare et al. (1993)). Conceptually, a distance function measures the distance between the produced outputs of the process under study and the outputs of a more efficient process. It is first necessary to assign a reference price for the desirable output (treated water) which depends on its destination and potential users. In this case, the reference prices are based on average values that the Spanish authorities have paid in the fields of reuse. These are found in Table 6.7.

According to Reig-Martinez et al. (2001) and Hernández-Sancho et al. (2010), shadow prices for undesirable outputs are considered negative. This is due to the fact that, in a viable viewpoint, they cannot generate an economic income. However, in an environmental point of view these prices can be interpreted as positive as they represent an avoided cost.

Table 6.7 shows the obtained shadow price for the two water pollutants taken into account in subchapter 6.3 (COD and N). The environmental damage avoided (or environmental benefit) depends on the pollutant and its destination. It can be observed that nitrogen (and consequently  $\text{NH}_4^+$ ) presents the main environmental benefits. This nutrient (together with phosphorous) is present in all organisms, but an excess causes eutrophication problems and can significantly reduce biodiversity. Elimination of COD is performed by microorganisms in the receiving environment and demands a high volume of oxygen. An excess of COD (and BOD) may produce low levels of oxygen in organisms (hypoxia) or dissolved in water (asphyxia).

**Table 6.7.** Reference price of water (€/m<sup>3</sup>) and shadow prices for water pollutants (€/Kg). Adapted from Hernández-Sancho et al. (2010).

Destination	Reference price water €/m <sup>3</sup>	Shadow prices for undesirable outputs (€/Kg)	
		N	COD
River	0.7	-15.353	-0.0098
Sea	0.1	-4.612	-0.010
Wetlands	0.9	-65.209	-0.122
Reuse	1.5	-26.182	-0.140

Using this idea, a comparison is made between the two operation modes (HYS and HYE) revealing which is the environmental benefit produced by the use of the HYE mode. For this evaluation, the treatment costs per m<sup>3</sup> of wastewater (with nutrient removal) have been also taken into account (Molinos-Senante et al. (2010)).

These values are of 0.2149 €/m<sup>3</sup>. This means that the higher treatment capacities of the WWTPs with the HYE operation mode represent higher treatment costs too. The economical evaluation results between HYS and HYE operation modes are found in Table 6.8.

Focusing on COD, results show that the economic benefit increases in each rain scenario. The highest savings are found in scenario 4 which in economic terms represent 22863 €.  $\text{NH}_4^+$  results present the same pattern where the environmental benefit is higher for each rain scenario and the highest value is found in scenario 4 too (18057 €).

Comparing the saved amount of pollutant (Kg) it can be seen that COD values are much higher in comparison with  $\text{NH}_4^+$ . This is because the various storage tanks (Tank 1, Tank2 and HT) of the UWS provide an additional COD removal apart from the one found in the different WWTP units. However,  $\text{NH}_4^+$  presents a higher shadow price of in comparison with COD and consequently, pollutant savings in economical terms (€) are higher for  $\text{NH}_4^+$  than for COD.

**Table 6.8.** Results of the economic evaluation and environmental benefit.

	Units		Scenario 1	Scenario 2	Scenario 3	Scenario 4
COD	Not spilled	Kg	42203.8	113897.4	147613.6	233299.8
	Saved	€	4136.0	11161.9	14466.1	22863.4
$\text{NH}_4^+$	Not spilled	Kg	736.5	1246.2	1211.3	1419.7
	Saved	€	9367.4	15849.9	15406.4	18057.2
Additional treatment cost	Treated cost	$\text{m}^3$	48967.3	79077.9	74859.3	88253.8
		€	10523.1	16993.8	16087.3	18965.8
<b>Total environmental benefit</b>		€	<b>2980.3</b>	<b>10018.0</b>	<b>13785.3</b>	<b>21954.8</b>

The balance between the environmental benefit generated by COD and  $\text{NH}_4^+$  and the additional treatment cost reflect positive values for all scenarios. The additional treatment cost that the HYE operation mode represents in comparison with the HYS operation mode shows the highest value in scenario 4 (18965.8 €). Scenario 2 is the following highest value and is very similar to scenario 3. So the use of the HYE operation mode provides an environmental benefit (or environmental damage avoided) for all the rain scenarios studied in this approach. The economical impact evaluation of COD and  $\text{NH}_4^+$  discharges show how the application of the expert rules present better results in comparison with the standard operation of the UWS. However, the application of the EDSS should be considered in a wider viewpoint. The cost of the EDSS implementation onto the overall system should be considered too in order carry out a cost-benefit evaluation for the correct economical validation.

***CHAPTER 7***  
***CONCLUSIONS***



## **7. Conclusions**

After the development and testing of the EDSS prototype it can be concluded that:

- ✓ A virtual reality has been developed (VilaConca and VilaPrat) and is able to simulate the real behaviour of a UWS with WEST<sup>®</sup> as the simulation platform.
- ✓ Different sources of knowledge have been used as are empirical, theoretical or historical information, scientific and technical literature as well as information from various experts and managers. All this information is classified according to the EDSS requirements into sewer network, WWTP and coordinated management knowledge and finally all the expertise is acquired and introduced into the EDSS for its correct development.
- ✓ Four different rain events have been tested. They are all based in real data and have varied characteristics. Their duration moves from 1h. to 3h. Rainfall intensity ranges from 8.7 mm/h to 58.53 mm/h and finally their return periods reach from 2.16 months to 5 years.
- ✓ The 4 rains scenarios are tested on the standard operation of the virtual system. The main conclusions are that VilaConca is a small system and has a limited storage capacity while its WWTP already operates at the maximum treatment capacity so in consequence, CSO spills are frequent. On the other hand, VilaPrat is a bigger system and has a higher storage capacity. However, CSO spills were also present in VilaPrat so efforts must be focused for the UWS optimization.
- ✓ Analyses of testing results were used to develop a set of rules by means of decision trees which were also introduced into the EDSS tool.
- ✓ The EDSS has been compiled in a unique tool linking together the virtual system, the rule system, the data base, the configuration system and the information system. The rain scenarios are tested using the decision support tool and results are compared and analyzed with the standard operation mode demonstrating that the use of the EDSS for the coordinated management presents a better performance in comparison with the standard operation mode of the virtual system.
- ✓ An heuristic and economical approach evaluation of the system focused in quality parameters was also performed. Results have shown how the use of the EDSS can avoid environmental damage and thus produce economical savings.

Additionally, the future research needs are considered and described as follows:

### *Model uncertainty*

All types of models, simpler or more complex have uncertainties. These are caused by different aspects as model variables and parameters, input data or even the model architecture. The different types of uncertainties present in the models must be correctly understood as they provide a better interpretation of the obtained results (Freni et al. (2009); Sin et al. (2011)). Integrated models may carry higher uncertainties due to the different model linkages. So better results can be reached if efforts are put to reduce these type of uncertainties (Freni et al. (2009)).

*Expert system enhancement*

The expert system approach employed in this thesis is developed in a set of rules implemented by means of decision trees. Future studies will add a case based system into the tool. Efforts will be put to define a set of cases and its decisions both for dry weather and wet weather conditions. A constant review of the different knowledge sources (literature, experts, simulations) used to feed the DB will be performed too. The implementation of two complementary types of expert systems will provide robustness to the final decisions produced by the EDSS.

*Pilot scale and full scale implementation*

The EDSS is ready to be implemented in an on-line real system. However, there are several steps that will be carried out before the final implementation. First, the tool will be tested in a pilot scale system. Results will be then analyzed to apply changes and improve the overall performance of the EDSS. Once the analysis will be completed, the EDSS will be implemented in a full scale system. Several tests will be conducted during different situations and scenarios. Dry weather and wet weather results will be carefully analyzed and changes will be applied to enable the full EDSS implementation into a real scale system. Besides, a full scale implementation protocol will be written for further uses into different systems and scenarios.

***CHAPTER 8***  
***REFERENCES***



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***ANNEX***



## ADDITIONAL DESCRIPTION OF THE SELECTED MODELS

### Rain and evaporation

In order to take into account the daily evaporation, ( $e(j)$ ) is multiplied by an hourly factor  $f(h)$  to provide the potential evaporation for a certain hour,

$$e(j, h) = f(h) \cdot e(j)$$

### Runoff

In order to take into account the first flush concentrations, the conceptual models used to simulate accumulation and wash-off of particulate matter on impervious surfaces is described by the following differential equation:

$$\frac{dW}{dt} = i(t) \text{ when } W(t) \leq W_{max}$$

Where  $i$  is the rain intensity and  $W(t = t_w) = W_{max}$ .  $W_{max}$  is the maximum storage volume available for wetting. Surface depressions store rain water when  $t > t_w$  and  $W(t) = W_{max}$ . The filling state  $D$  is modelled using the next equation:

$$D(t) = D_{max} \cdot (1 - e^{-c \cdot I(t)}) \text{ being } I(t) = \int i(t) dt$$

Where,  $c$  is the rate of storage loss and  $I$  the height of rain fallen down after wetting.

Furthermore, for pervious wetting, rain does not only wet pervious surfaces but is also absorbed by vegetation. The combination of these two wetting-absorption losses is understood using the same mathematical expressions but the parameters differ.

Infiltration process reduces the total amount of runoff water. This infiltration capacity ( $f$ ) depends on the nature of the soil, which concerning to this thesis, the model is based on the time dependent Horton equations given by:

$$f(t) = f_{\infty} + (f_o - f_{\infty})e^{-k-t} \text{ for } i(t) > f(t)$$

Where  $f_o$  is the maximum or initial value,  $f_{\infty}$  is the minimum infiltration capacity and  $k$  is the regression constant. On the other hand, the regeneration process equations of the infiltration capacity with absence of rain are given by:

$$f(t) = f_o - (f_o - f_{\infty})e^{-k_+t} \text{ for } i(t) = 0$$

Being  $k_+$  the regeneration rate.

After the water losses, the remaining water has to flow through the surface and the local sewer network in order to arrive finally to the main collectors.

Pipes

Additionally to the pipe length equation, the expression used in order to find the linear reservoir constant (k) of one tank is:

$$k = 0.064 \cdot L^* \cdot \frac{d^2}{Q_{max}}$$

Where  $Q_{max}$  is the maximum discharge flow of an individual pipe.

Storage tanks

The model includes information of how the overflow is calculated with the rectangular weir equation (Butler and Davies (2004)),

$$Q_{over}(t) = \alpha [H(t)]^{3/2} \quad \text{being} \quad \alpha = \frac{2}{3} c_d w_w \sqrt{2g}$$

Where  $H(t)$  is the height of water surface above the weir crest,  $w_w$  is the weir width and finally  $c_d$  is the discharge coefficient of the weir depending on its geometry (values between 0.6 and 0.7).

WWTP model base (ASM2d)

The different equations describing the behaviour of substrate (S) and biomass (X) into the reactor are the following:

Biomass growth:

$$\mu = \mu_{max} \frac{S}{K_s + S}$$

Where  $\mu$  is specific growth velocity ( $d^{-1}$ ),  $X$  is the biomass concentration ( $g/m^3$ ),  $S$  is the substrate concentration ( $g/m^3$ ),  $\mu_{max}$  is the maximum growth velocity ( $d^{-1}$ ) and  $K_s$  is the saturation coefficient ( $g/m^3$ ).

Endogenous metabolism:

$$v_{decay} = K_d X$$

Being  $v_{decay}$  the endogenous decay rate ( $g/m^3 \cdot d$ ),  $K_d$  ( $d^{-1}$ ) the endogenous decay coefficient and  $X$  is the biomass concentration ( $g/m^3$ ).

Substrate consumption:

$$v_{s \text{ consumption}} = -\frac{1}{Y} \mu X$$

Where:

$V_{s\ consumption}$  is the substrate decay rate ( $\text{g}/\text{m}^3 \cdot \text{d}$ ).

$Y$  is the efficiency ( $\text{g}_{\text{biomass}}/\text{g}_{\text{consumed substrate}}$ ).

$\mu$  is specific growth velocity ( $\text{d}^{-1}$ ).

$X$  is the biomass concentration ( $\text{g}/\text{m}^3$ ).

Additionally, the different factors of the balance for the biomass into reactor are

Outputs:

Effluent ( $Q_e X_e$ ) and purge ( $Q_w X_w$ )

Inputs:

Influent ( $Q_i X_i$ )

Accumulation:

$$V \frac{dX}{dt}$$

Generation:

$$V[v_{\text{growth}} - v_{\text{decay}}] = V \left[ \frac{\mu_{\text{max}} S}{K_s + S} X - K_d X \right]$$

While for substrate,

Outputs:

Effluent ( $Q_e X_e$ ) and purge ( $Q_w X_w$ )

Inputs:

Influent ( $Q_i X_i$ )

Accumulation

$$V \frac{dS}{dt}$$

Generation:

$$V v_{S\ consumption} = V \left[ -\frac{1}{Y} \mu X \right] = V \left[ -\frac{1}{Y} \frac{\mu_{\text{max}} S}{K_s + S} X \right]$$

Where for each of the stated equations:

$Q_i$ ,  $Q_w$ ,  $Q_e$  are the influent, purge and effluent flows respectively. The inflow makes reference to the outflow of the primary settler.

$S_i$ ,  $S_w$ ,  $S_e$  are the substrate concentrations at the influent, purge and effluent respectively

$V$  is the Volume of the biological reactor

$v_i$  is the reaction velocity of the process  $i$

From the mass balance equation (Input + Generation = Output + Accumulation + Consumption) for each of the state variables a balance is obtained. For the biomass balance, the differential equation is the following:

$$[Q_e X_e + Q_w X_w] - Q_i X_i + V \frac{dX}{dt} = V \left[ \frac{\mu_{max} S}{K_s + S} X - K_d X \right]$$

On the other side, for substrate, the balance equation is the following:

$$[Q_e S_e + Q_w S_w] - Q_i S_i + V \frac{dS}{dt} = V \left[ -\frac{1}{Y} \frac{\mu_{max} S}{K_s + S} X \right]$$

Where for each of the stated equations:

$Q_i$ ,  $Q_w$ ,  $Q_e$  are the influent, purge and effluent flows respectively. The inflow makes reference to the outflow of the primary settler.

$S_i$ ,  $S_w$ ,  $S_e$  are the substrate concentrations at the influent, purge and effluent respectively

$V$  is the Volume of the biological reactor

$v_i$  is the reaction velocity of the process  $i$

With the objective to simplify the representation of the employed differential equations, the Petersen matrix is used, which is a way to represent a model in an easy and intuitive form (representing only the generation term of the mass balance since influent, effluent and accumulation can be deduced more easily). Table A.1 represents the Petersen matrix for a simplified model. Growth and decay process are constituted in rows while state variables in columns. The last row illustrates the reaction rates for each of the considered processes.

**Table A.1.** Petersen matrix scheme for a simplified model or a biological reactor.

State variables / Processes	X	S	Reaction rate
Growth	+1	$-\frac{1}{Y}$	$\frac{\mu_{max} S}{K_s + S} X$
Decay	-1	-	$K_d X$
<b>Stoichiometric coefficients</b>	Biomass	Substrate	<b>Kinetic parameters</b>
Y, efficiency			$\mu_{max}, K_s, K_d$

The settling process mass balances equations depend on the settler position. For slices  $i$  ( $i = 1, \dots, m-1$ ) the solids mass balance is the given,

$$h_i A_i \frac{dx_i}{dt} = q_o (x_{i+1} - x_i) + A_i (f_{i-1} - f_i)$$

For slices  $j$  ( $j = m+1, \dots, n$ ) the solids mass balance is the given,

$$h_j A_j \frac{dx_j}{dt} = q_u (x_{j-1} - x_j) + A_j (f_{j-1} - f_j)$$

Finally, the feed slice  $m$  solids mass balance looks like,

$$h_m A_m \frac{dx_m}{dt} = q_f x_f - (q_o - q_u) x_m + A_m (f_{m-1} - f_m)$$

Where  $h$  is the height of the slice,  $A$  is the cross-sectional area of the given slice,  $x$  is the solids concentration,  $q$  the liquid flow rate (being 'o' for overflow and 'u' for underflow or outflow).  $f$  is the settling flux and finally  $t$  is the time. Finally, the corresponding model for the soluble nutrients is either  $n$  corresponding well-mixed compartments for each modelled nutrient.

### Activated Sludge Model 2d

Tables A.2 and A.3 illustrate a simplification of the main state variables and processes contained into the RWQM1.

**Table A.2.** State variables of the model ASM2d.

State variable	Description
$S_{O_2}$	Dissolved oxygen
$S_F$	Fermentable readily biodegradable organic substances
$S_A$	Fermentation products, considered to be acetate
$S_{NH_4}$	Ammonium plus ammonia nitrogen
$S_{NO_3}$	Nitrate plus nitrite nitrogen
$S_{PO_4}$	Inorganic soluble phosphorus, primarily orthophosphates
$S_I$	Inert soluble organic material
$S_{ALK}$	Alkalinity of the wastewater
$S_{N_2}$	Dinitrogen
$X_I$	Inert particulate organic material
$X_S$	Slowly biodegradable substrates
$X_H$	Heterotrophic organisms
$X_{PAO}$	Phosphate-accumulating organisms
$X_{PP}$	Poly-phosphate
$X_{PHA}$	Cell internal storage product of PAOs
$X_{AUT}$	Nitrifying organisms
$X_{TSS}$	Total suspended solids
$X_{MeOH}$	Metal-hydroxides
$X_{MeP}$	Metal-phosphate

**Table A.3.** Processes of the ASM2d model.

	<b>Process</b>
1	Aerobic Hydrolysis
2	Anoxic Hydrolysis
3	Anaerobic Hydrolysis
4	Aerobic growth on $S_F$
5	Aerobic growth on $S_A$
6	Anoxic growth on $S_A$
7	Anoxic growth on $S_A$ , denitrification
8	Fermentation
9	Lysis (heterotrophs)
10	Storage of $X_{PHA}$
11	Aerobic storage of $X_{PP}$
12	Anoxic storage of $X_{PP}$
13	Aerobic growth of $X_{PAO}$
14	Anoxic growth of $X_{PAO}$
15	Lysis of $X_{PAO}$
16	Lysis of $X_{PP}$
17	Lysis of $X_{PHA}$
18	Aerobic growth of $X_{PAO}$
19	Lysis (nitrifiers)
20	Precipitation
21	Redissolution

Receiving body quality model

Concerning to the biochemical conversions, a simplified version of the IWA RWQM1 has been used. The full model contains 24 state variables and 23 processes. As happens with the ASM models, the quality model can be represented in a matrix taking into account which variables are governed to what processes and thus, being expressed as follows:

$$r_i = \sum_{j=1}^m v_{ij} \rho_j$$

Where the expression of reaction is  $r_i$  for the  $i$ th component,  $v_{ij}$  is the stoichiometric coefficient and  $\rho_j$  is the kinetic rate for process  $j$  (usually based on Monod kinetics).

Tables A.4 and A.5 illustrate a simplification of the main state variables and processes contained into the RWQM1.

**Table A.4.** Main state variables of the RWQM1.

<b>State variables</b>	<b>Description</b>
$S_I$	Inert soluble COD
$S_S$	Readily biodegradable soluble COD
$S_{O_2}$	Dissolved oxygen
$S_{NO_2}$	Nitrite nitrogen
$S_{NO_3}$	Nitrate nitrogen
$S_{PO}$	Phosphate
$S_{NH}$	Ammonia nitrogen
$S_{ALK}$	Alkalinity
$X_I$	Particulate inert COD
$X_S$	Particulate organic matter
$X_H$	Heterotrophic biomass
$X_{N1}$	First stage nitrifying bacteria
$X_{N2}$	Second stage nitrifying bacteria
$X_{ALG}$	Algae and macrophytes
$X_P$	Phosphate adsorbed to particles
$X_{II}$	Particulate inorganic matter

**Table A.5.** Main processes contained into the RWQM1.

<b>State variables</b>	<b>Description</b>
1	Aerobic growth of heterotrophs with ammonia
2	Aerobic growth of heterotrophs with nitrate
3	Anoxic growth of heterotrophs with nitrate
4	Anoxic growth of heterotrophs with nitrite
5	Aerobic endogenous respiration of heterotrophs
6	Anoxic endogenous respiration of heterotrophs
7	Growth of first stage nitrifiers
8	Aerobic endogenous respiration of first stage nitrifiers
9	Growth of second stage nitrifiers
10	Aerobic endogenous respiration of second stage nitrifiers
11	Growth of algae with ammonia
12	Growth of algae with nitrate
13	Aerobic respiration of algae
14	Death of algae
15	Hydrolysis
16	Aeration

## SECOND LEVEL AND THIRD LEVEL TREES

### Second level trees

The *sensors alert tree* has been implemented as an example of control tree for the sensor values within reasonable logics. In a real system, this kind of tree would be much more complex, and it should include those key sensors necessary to be monitored like gates, pumps, rain gauges, flow meters, etc. In the present application, just few sensors have been included as an example. Logically, the different lecture variables of this tree are rain gauges, flow sensor at the WWTP of VilaPrat entrance, tank volumes, COD sensors, etc.). The resulting messages are given to the operators in case of abnormal values measured in the sensors.

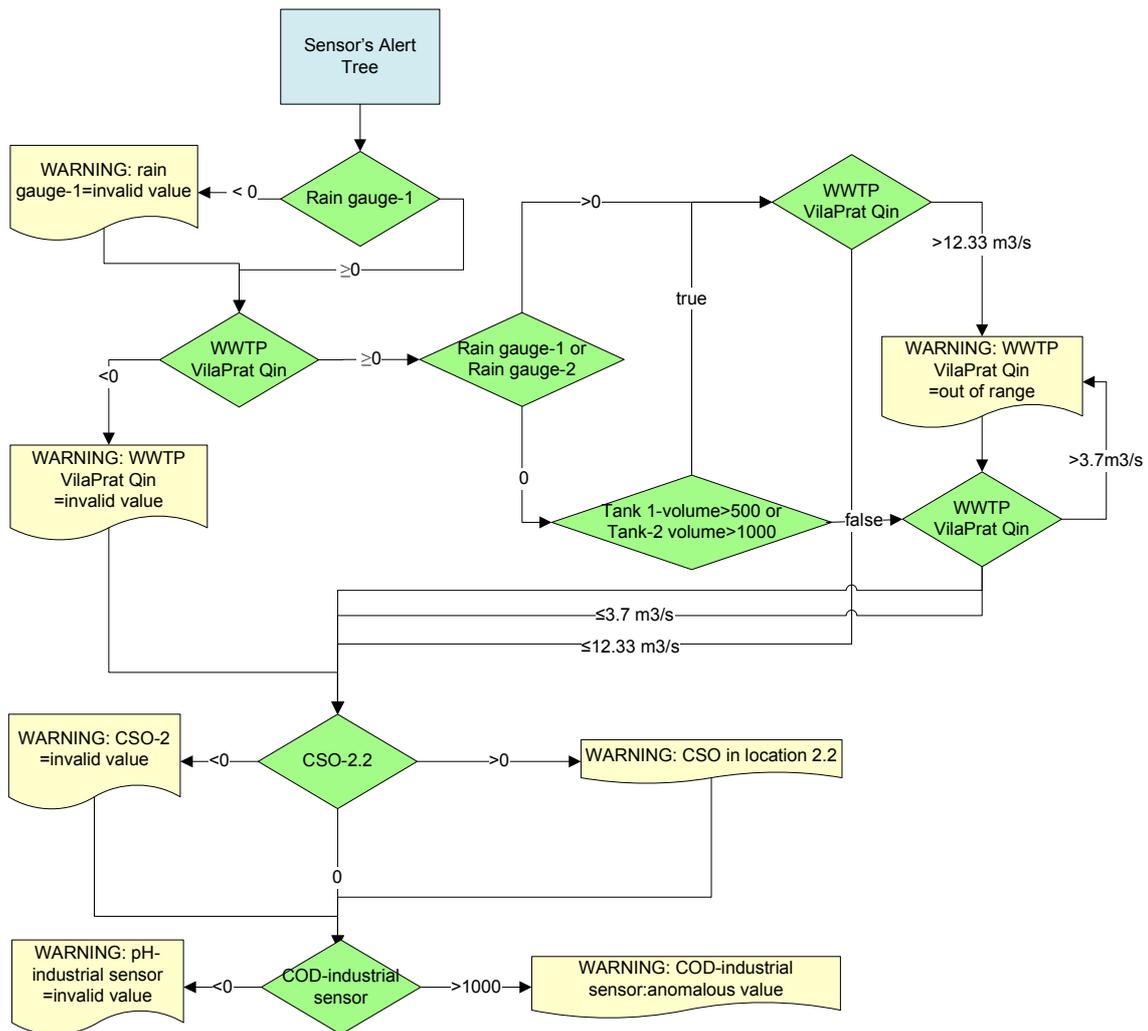


Figure A.1. Sensors alert tree.

The *emergency operation tree* (see **Figure A.2**) is responsible of informing the actions that must the operator apply depending of some defined variables. This tree is inspired on the actuation protocol of the sewer system company of Barcelona as an example that protocols of any complexity can be implemented into the EDSS prototype.

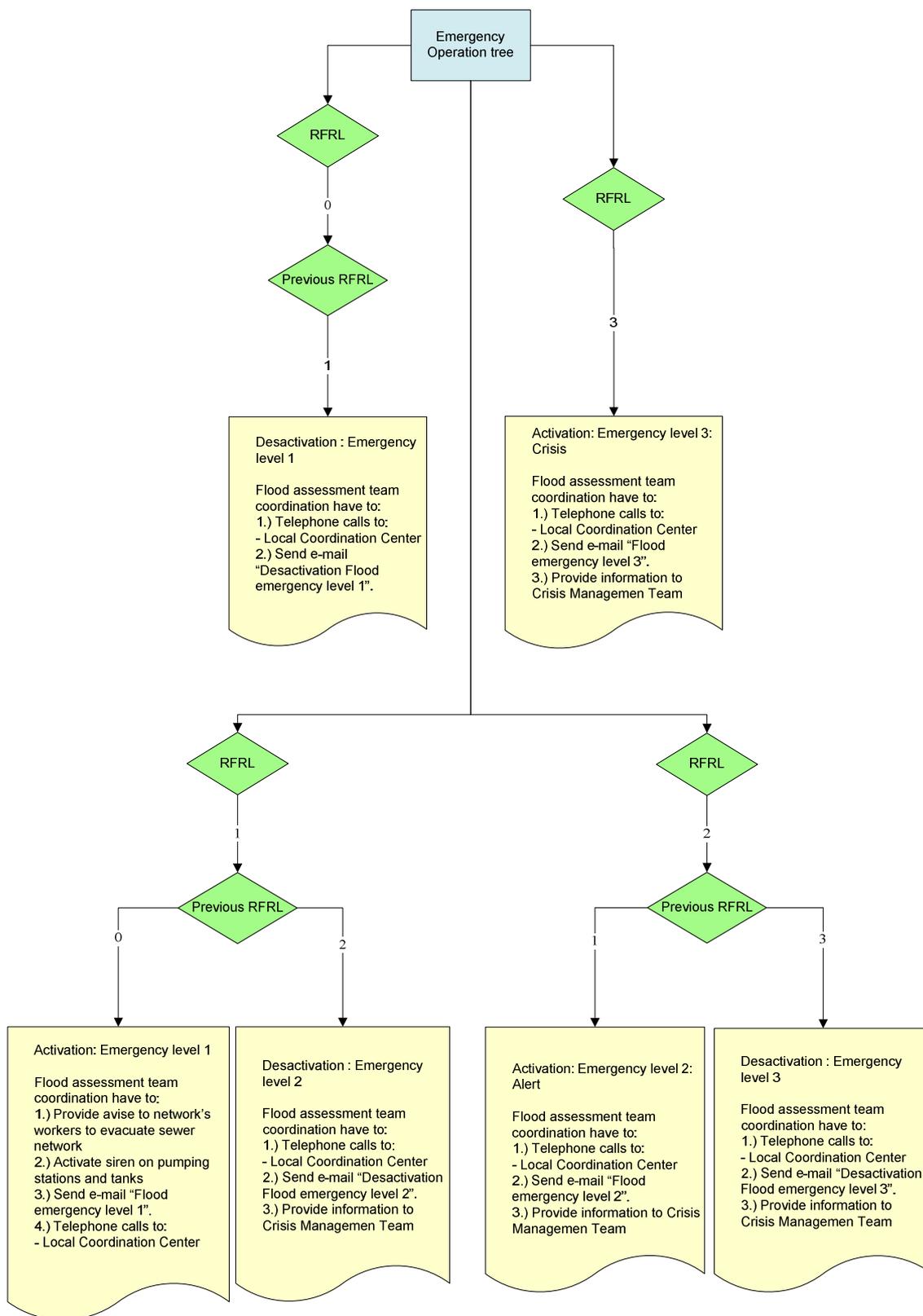
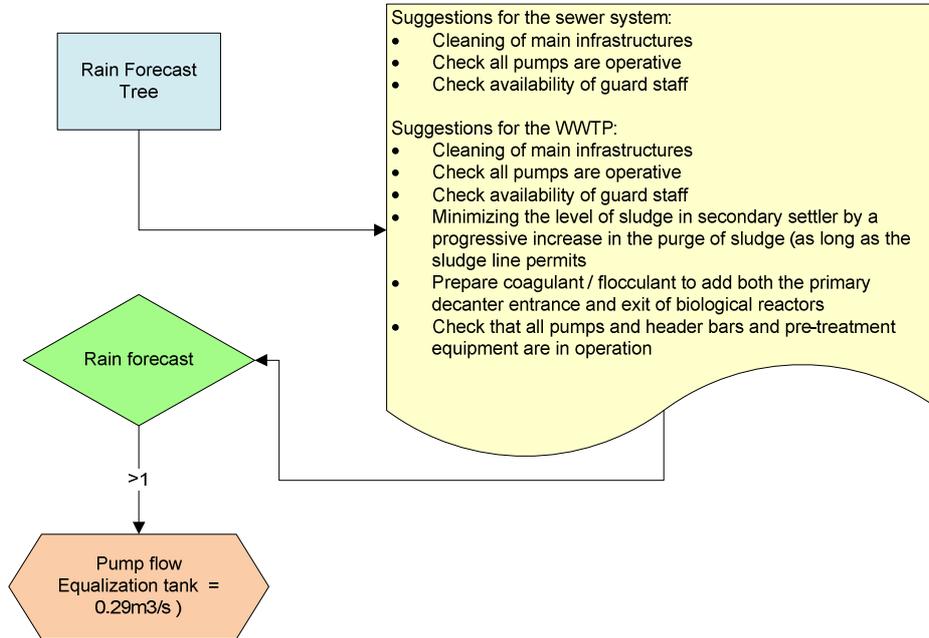


Figure A.2. Emergency operation tree.

The *rain forecast tree* which provides general suggestions to the operator and in case there is a heavy rain forecast, then the equalization tank is emptied as much as possible (tank pump flow is set to  $0.29\text{m}^3/\text{s}$ ) increasing the treatment capacity of Vilaconca WWTP. Additionally, this tree provides some suggestions to the sewer system and WWTP operation in order to prepare the systems for a heavy rainfall event. **Figure A.3** illustrates the rain forecast tree scheme.



**Figure A.3.** Rain forecast tree.

### Third level trees

Concerning to the rain event third level trees, the *WWTP VilaPrat tree* gives set points to bypass in order to modify the water path depending on the WWTP inflow. There are three possible streams which are (i) the normal position, where water flows through primary, secondary and tertiary treatment, (ii) parallel treatment primary and secondary, which operates treating up to  $3.7\text{m}^3/\text{s}$  directly through secondary treatment and then flowing to the river given that it has not enough good quality to go to tertiary treatment. The rest flows through primary treatment and is then discharged to the river. Finally, the third water path is the (iii) parallel treatment primary secondary and tertiary treating up to  $3.7\text{m}^3/\text{s}$  through the secondary and tertiary treatment while the difference is treated only with primary treatment.

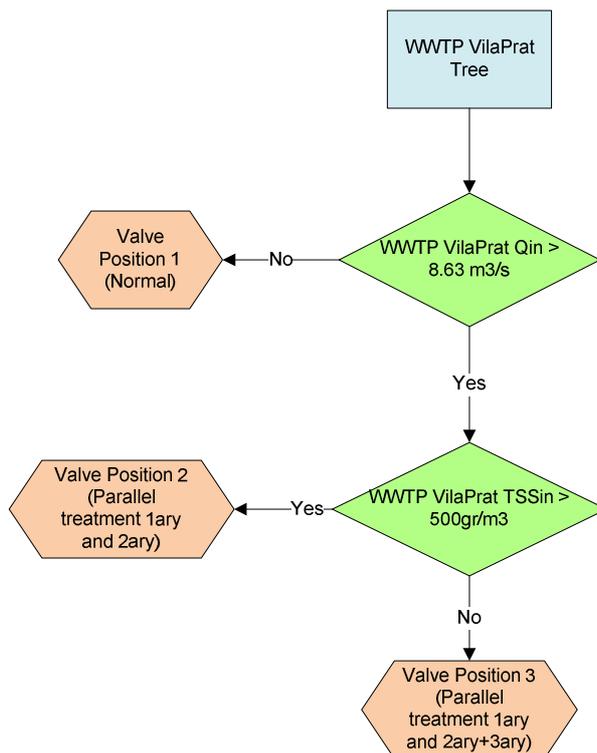


Figure A.4. WWTP VilaPrat management tree.

The other decision tree from the *rain event* third level trees is the *bypass gate tree* which controls the position of the bypass gate between the two systems (VilaPrat and VilaConca). The gate will only be opened when the volume in Tank 3 is above 90% or 30% (see Figure A.5) and there is no CSO in VilaPrat as it would not make sense to avoid CSO in VilaConca municipality and increase it in VilaPrat. Thus, the gate will only open when the by-passed water will not cause CSO because it can all be treated in VilaPrat WWTP.

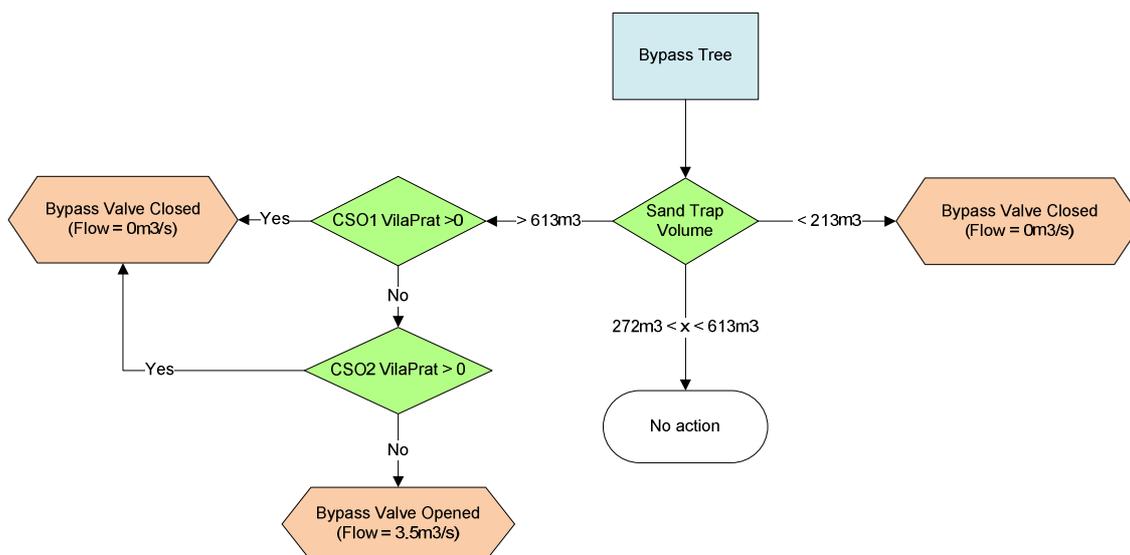
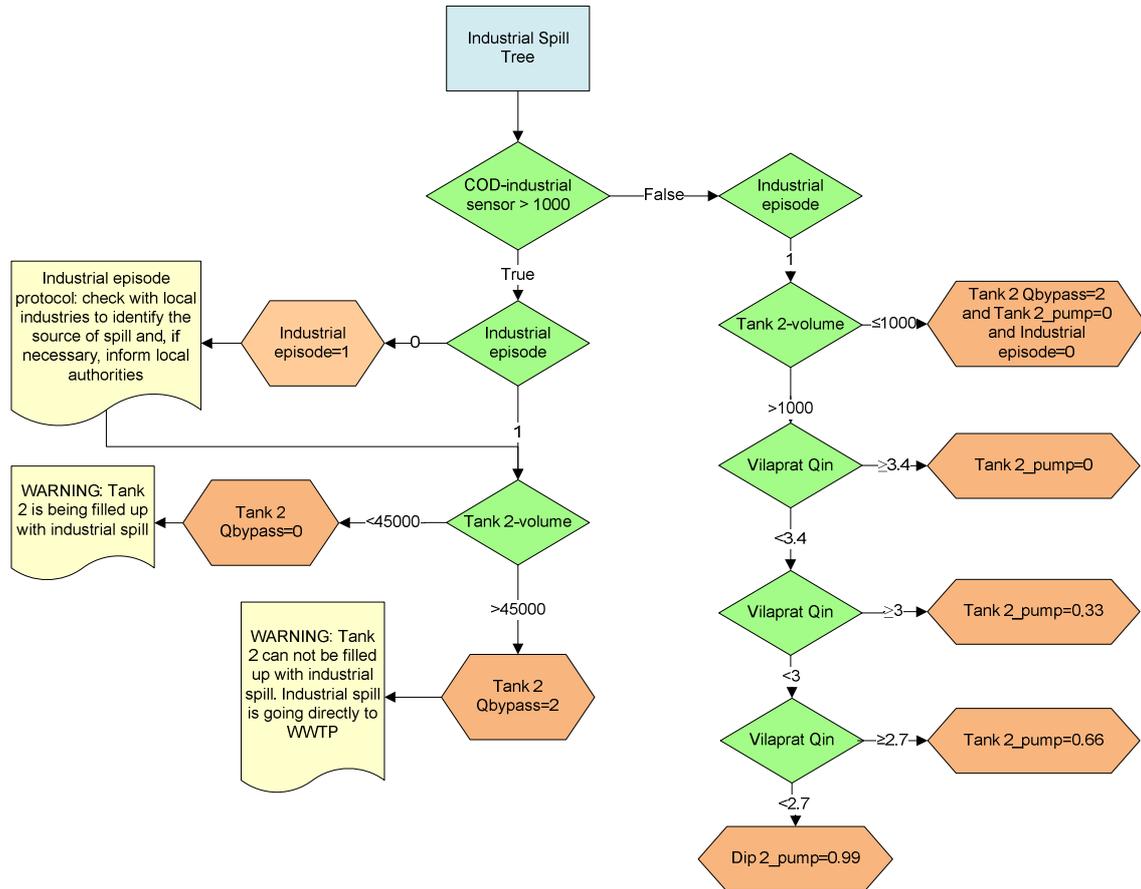


Figure A.5. Bypass tree.

On the other hand the set of trees of the coming from the *dry weather tree* are the *industrial spill tree*, which has been developed to detect and manage the system in case of any discharge episode at the industrial catchment (in VilaPrat).

Checking the COD sensor in the sewer system of this catchment, the tree detects if there is an industrial spill event. In such case, the water is stored in Tank 2 and pumped in a way that this industrial flow does not cause any dry weather flow discharge and that all waters are treated in the primary, secondary and tertiary treatment before being sent to the river. Moreover, the tree gives some alert messages in case of, Tank 2 filling or volume availability problems at Tank 2 during this kind of episode.

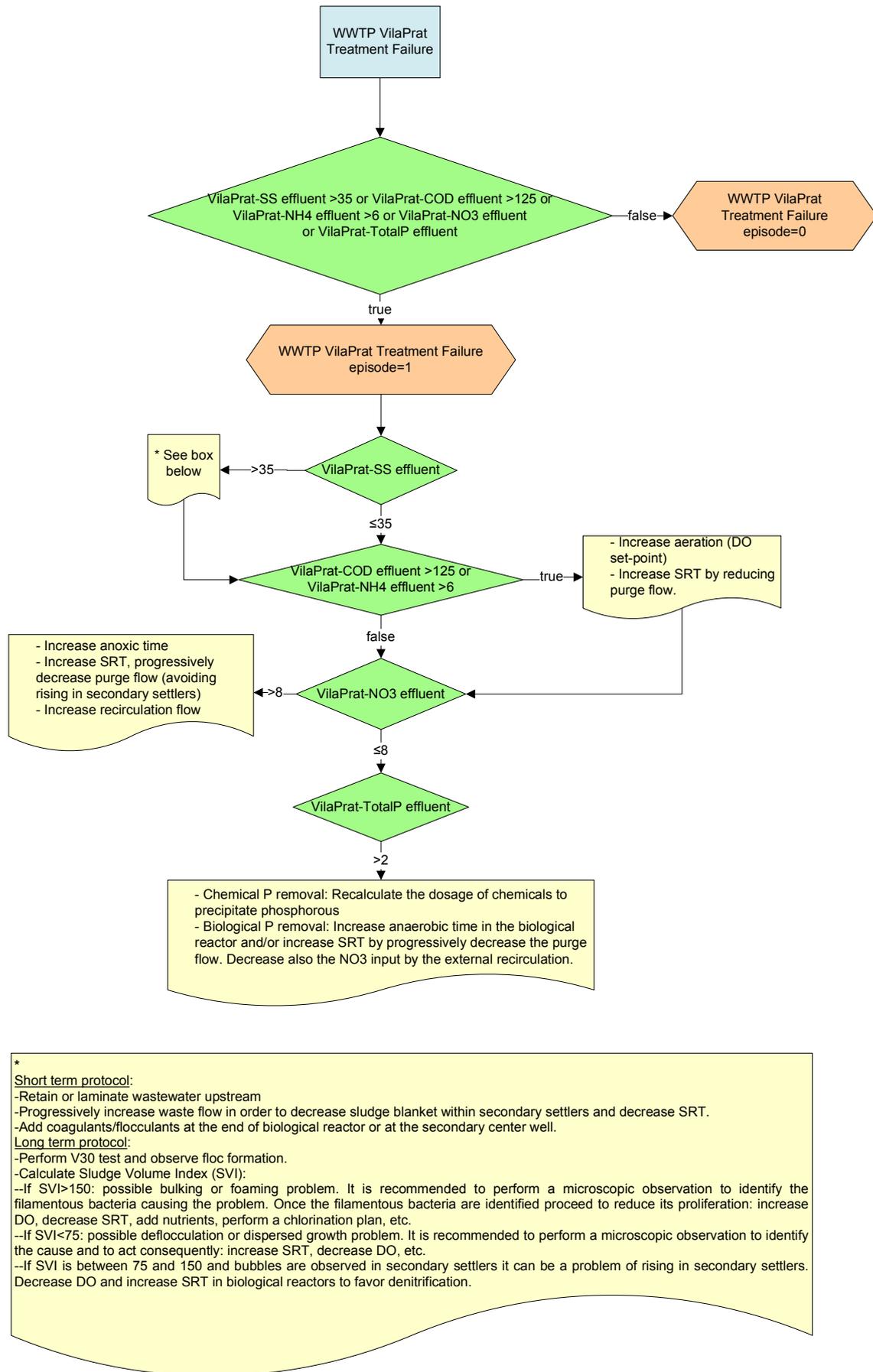
The next **Figure A.6** illustrates the management operation of this tree



**Figure A.6.** Industrial spill tree.

The next trees, *WWTP VilaConca treatment failure* and *WWTP VilaPrat treatment failure trees* check if the quality values at the outlet of the WWTPs after primary and secondary treatment fulfil the limiting standards for SS, COD;  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and  $\text{P}_{\text{total}}$ . In case these are not fulfilled it provides the WWTP management protocols to improve the treatment efficiency. These messages vary depending on the parameter that fails to fulfil the legislation limits providing specific WWTP management protocols to the operator (see **Figures A.7** and **A.8**).





\*  
**Short term protocol:**  
 -Retain or laminate wastewater upstream  
 -Progressively increase waste flow in order to decrease sludge blanket within secondary settlers and decrease SRT.  
 -Add coagulants/flocculants at the end of biological reactor or at the secondary center well.  
**Long term protocol:**  
 -Perform V30 test and observe floc formation.  
 -Calculate Sludge Volume Index (SVI):  
 --If SVI>150: possible bulking or foaming problem. It is recommended to perform a microscopic observation to identify the filamentous bacteria causing the problem. Once the filamentous bacteria are identified proceed to reduce its proliferation: increase DO, decrease SRT, add nutrients, perform a chlorination plan, etc.  
 --If SVI<75: possible deflocculation or dispersed growth problem. It is recommended to perform a microscopic observation to identify the cause and to act consequently: increase SRT, decrease DO, etc.  
 --If SVI is between 75 and 150 and bubbles are observed in secondary settlers it can be a problem of rising in secondary settlers. Decrease DO and increase SRT in biological reactors to favor denitrification.

Figure A.8. WWTP VilaPrat treatment failure tree.

The next third level tree, the *sensible receiving environment tree* checks the river flow and quality (according to the  $\text{NH}_4^+$  sensors in the river), and in case the values are under the recommended good quality standards, some recommendations are provided to the WWTP operator so as to increase the treatment efficiency and to spill treatment waters with a higher quality than the required by the legislation in order to minimize the ecosystem stress due to the WWTP spills.

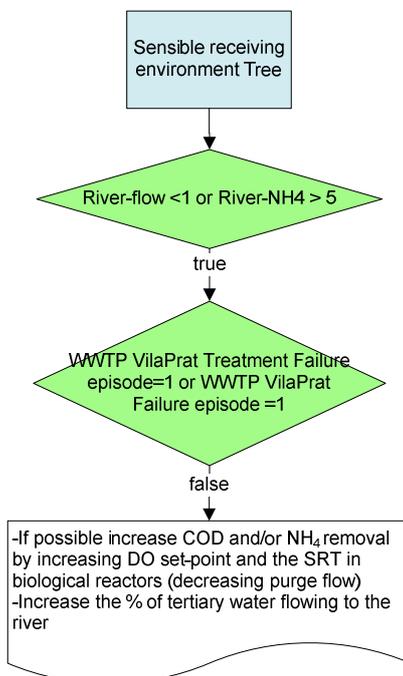


Figure A.9. Sensible receiving environment tree.

The last third level tree produced by the *dry weather flow tree* is the *WWTP VilaPrat failure tree*. This tree checks if there is any problem at the VilaPrat interceptor or the WWTP causing a reduction at the maximum treatment capacity of the plant. In such case, the water is temporarily stored in Tank 2 and slowly pumped to the WWTP at the exact flow to be accepted and treated by the WWTP.

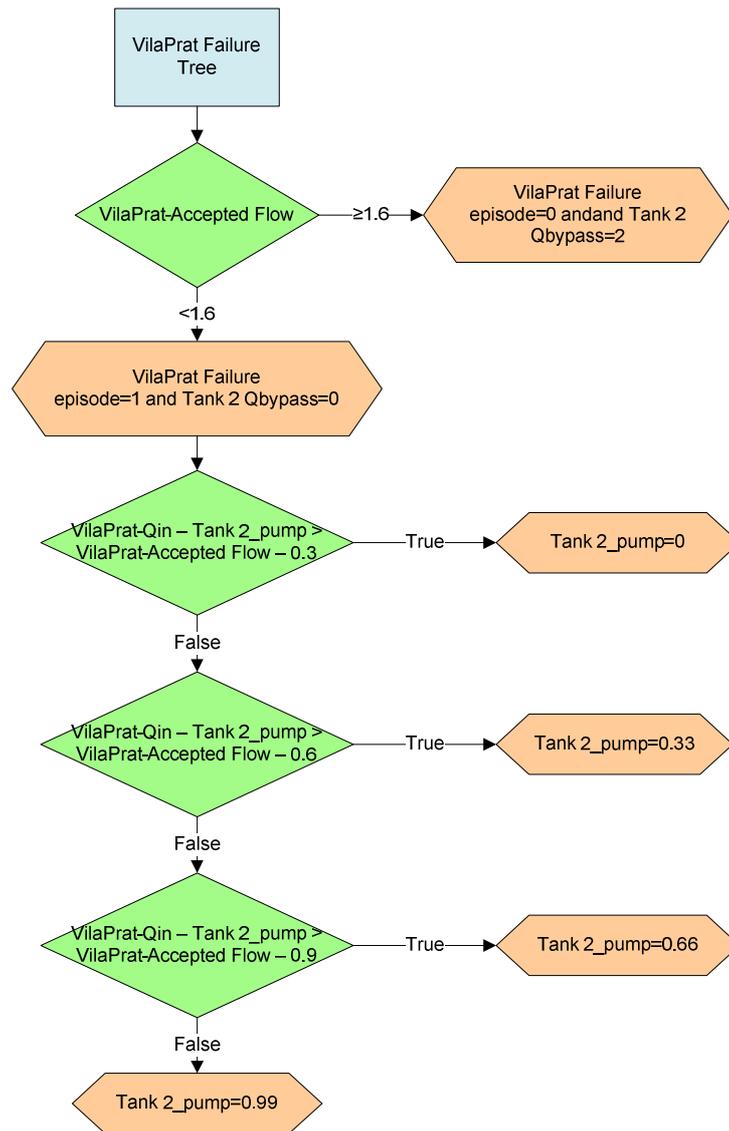


Figure A.10. WWTP VilaPrat failure tree.

As an example, the next figure displays the *diagnosis meta tree* being in the one hand, the small figure, the one represented in **subsection 4.6.3.1**, and the large figure, the one developed with the specific software LPA-WinProlog<sup>®</sup>. As it is shown in this figure, the tree starts reading a set of variables (Rain gauges 1 and 2) and depending on the reading results, the diagnosis meta tree switches or not the *emergency operation tree*, *rain event tree* and the *sensors alert tree*. After that, the diagnosis meta tree reads the value of the rain forecast variable and again, depending on its results, it switches or not the *rain forecast tree*, *dry weather tree*, the *storage capacity tree* and the *sensors alert tree*. If non of the abovementioned variables is positive, the tree finally switches the *dry weather tree*, the *storage capacity tree* and the *sensors alert tree*. As it has been explained, an LPA version of each of the decision trees has been developed within this thesis.

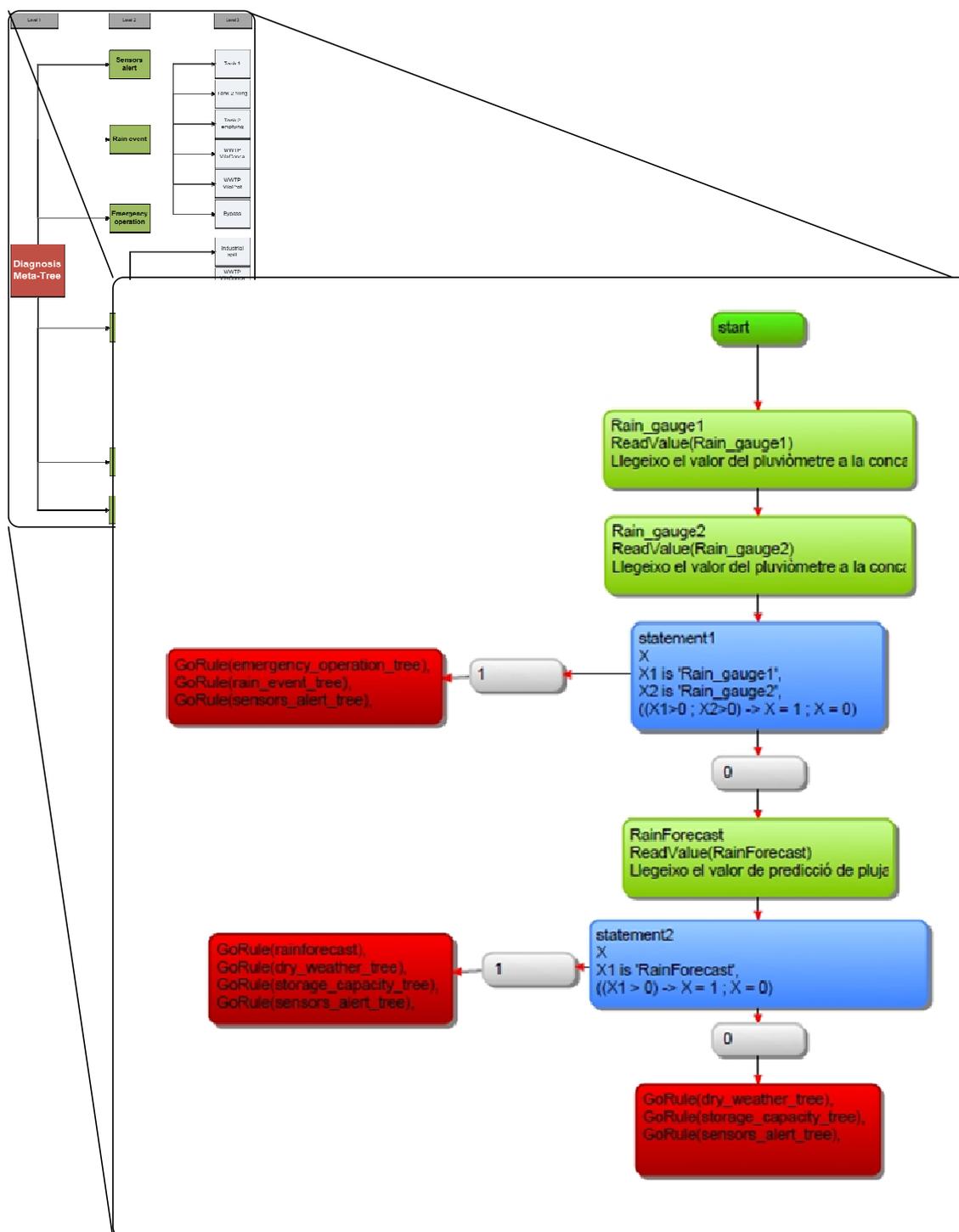


Figure A.11. LPA representation of the diagnosis meta tree.

## ADDITIONAL BASIC CONCEPTS OF THE EDSS PROTOTYPE

### *Time series*

Time series values are continuous in time according to the specified frequency interval configured by the user. Depending on the type of time series if no value is found into the DB, the EDSS provides a default value, for manual time series or no value (the rest). The absence of a value implies for the site specific and the expert system modules to use default values in contrast, no value is used when reporting results. Time series can also store set points but in this case, values don't need to be continuous in time.

After each simulation, WEST Exchange uploads the time series values into the DB. The way that WEST Exchange knows which values to upload is by searching the last value found into the DB for each time series configured to be read in WEST Exchange. After that, the module uploads these values from that date to the end of the simulation.

### *WestExchange and Expert System usage*

The main operation concepts of WEST Exchange and the Expert System (LPA<sup>®</sup>) within the EDSS system are defined.

*Run* is the execution of a component of the system along a specific time interval. The EDSS stores information of the execution (start date and end date) and if the execution has finished correctly or not. Additionally, set points given by the Expert System are associated to the component run.

Every event activated by the EDSS is controlled in time using the *scheduler time*. It can be virtual (offline mode) or the same as the system one (online mode).

The *component base time* is configured by the user and is used to synchronise the component to a specific time in an hour. It is particularly used for the first execution of the component.

The *component frequency interval* is the time configured by the user that determines the interval of time between the component executions.

The *component time out* is the time configured by the user to specify how much time has the scheduler wait for the component to finish before considering there is a problem and jump onto the next execution.

### *West Exchange concepts*

The *hindcast time* is the time interval of the run period which is relatively before the beginning of the simulation time. It is used to create the start date of the run period simulation.

The hindcast time is important because the WEST<sup>®</sup> software does not have any hot start option and in consequence, all simulations start empty (no water in it). For this reason, the hindcast time cannot be set to zero or to a very low value. The correct hindcast time depends on the size of the virtual system and must be fixed by an expert.

The *forecast time* is the time interval of the run period that is future to the current scheduler moment. It is used to create the end date of the run simulation period.

### *Expert System concepts*

Two different types of rule variables are found:

- Input variables: These variables read the values from their linked EDSS time series.
- Output variables: These variables read and write set points from their linked time series.

The expert who has created the rules can introduce *messages* which will be seen by the end user when the rules are executed.

### *Online/Offline/Player modes*

These are the different modes that the scheduler can work in the EDSS. For this prototype only Offline and Player modes are implemented.

The offline mode launches petitions to the Expert System or to WEST Exchange depending on what the user has previously configured. On the other hand, the player mode allows the user to show how the system performs during a specific pre established date time.

### *Site specific application / WestExchange*

If the EDSS prototype wants to be implemented online at any location, WEST<sup>®</sup> model and the WEST Exchange become unnecessary and instead of that, a site specific tool needs to be programmed on order to connect the EDSS database with the SCADA systems and/or the database of the location where sensors data are stored.

## EDSS OPERATION: SIMULATION RESULTS OF SCENARIOS 3 AND 4

EDSS rain scenario 3

This third testing scenario (Figure A.12), based on real data has a total precipitation of 35.6 mm spread in 1.41 h duration. The return period is of 1.5 years and the total rain input is of 16576.2 m<sup>3</sup>.

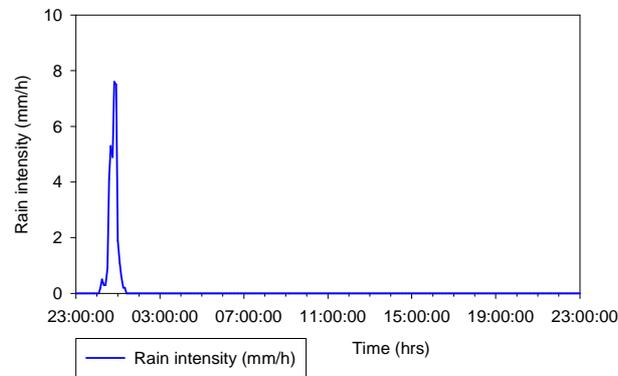


Figure A.12. Rain intensity plot of the testing scenario 3.

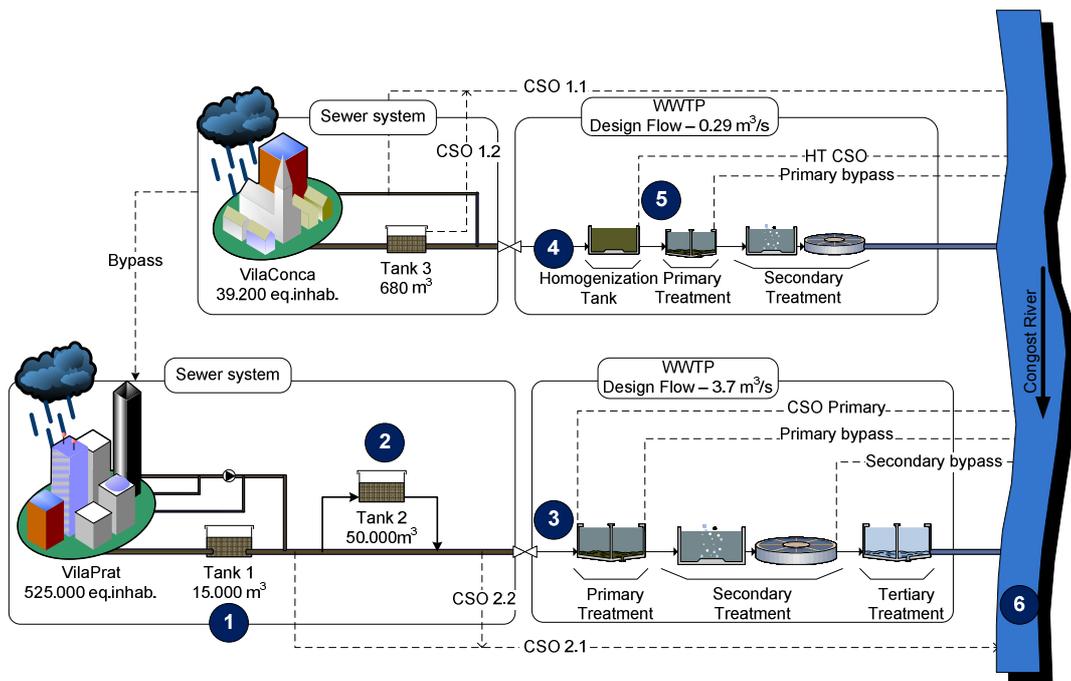
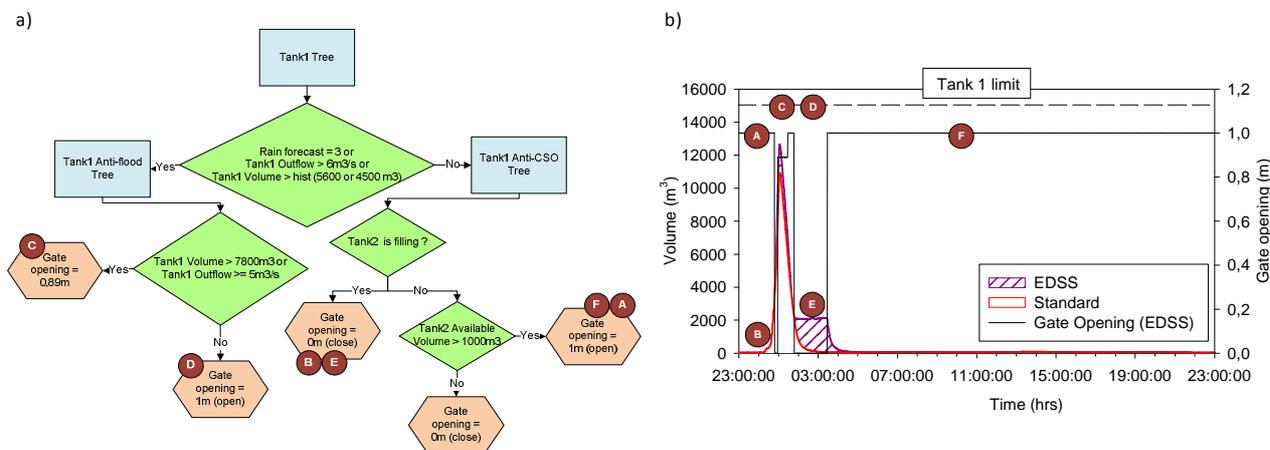


Figure 5.13. VilaConca and VilaPrat system scheme for scenario 3.

VilaPrat Tank 1 (1)

Figure A.14b shows the simulation results of Tank 1 management for the EDSS and Standard modes during scenario 3. Before the rain starts, the tank operates in DWF conditions with the gate fully opened (1 m) (A). Once the rainfall begins, the gate closes (0 m) since Tank 2 is filling in order to prevent CSOs (B). In consequence, the stored wastewater rises quickly and the volume overpasses 7800 m<sup>3</sup>. This makes the gate open to position 0.89 m in order to empty the tank and avoid possible flooding (C). Figure A.14a shows the Tank 1 decision tree and execution time line for this scenario.

Once the rain is over, the tank volume descends below  $7800 \text{ m}^3$  (and outflow is less than  $5 \text{ m}^3/\text{s}$ ) so the gate opens to 1 m, still with anti flooding purposes (D). After that, Tank 2 receives wastewater from Tank 1 and in consequence, the gate closes to 0 m (E). Once the second tank has more than  $1000 \text{ m}^3$  of free volume, the gate is switched to position 1 m in order to empty the remaining wastewater and return to normal DWF conditions (F).



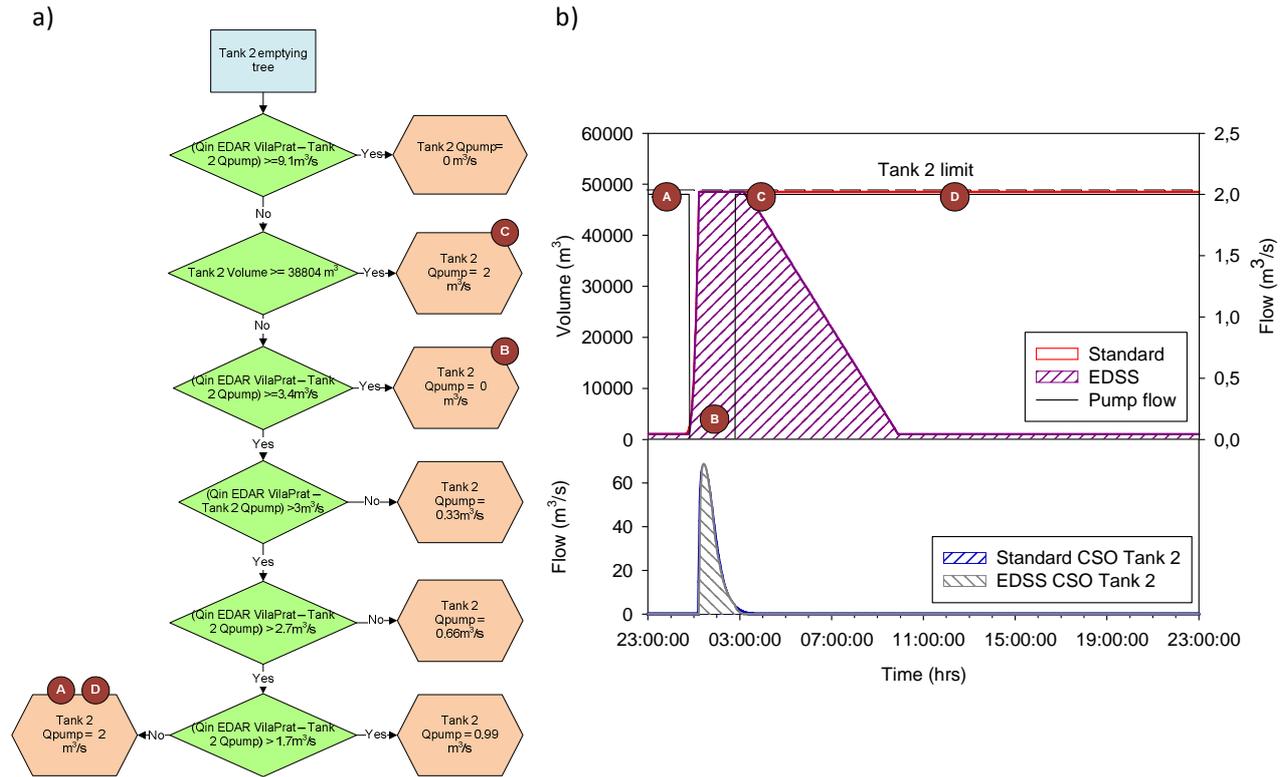
**Figure A.14.** (a) Tank 1 management tree and execution time line and (b) Tank 1 volume and gate position for scenario 3.

The management of Tank 1 for this scenario illustrates better results for the EDSS mode than for the Standard one. Since Tank 1 tree has two main stretches, one for anti flooding purposes and another for anti CSO purposes, it is possible to manage the tank depending on its inflow, its stored volume or to Tank 2 status. This gives the tank the ability to reduce the number and volume of CSOs which for this particular scenario, is of  $258365 \text{ m}^3$ .

#### VilaPrat Tank 2 (2)

With regard to Tank 2, Figure A.15b illustrates the simulation results during scenario 3 for both the EDSS in comparison with the Standard mode. Before the rain episode begins, the tank is empty operating in DWF conditions and its pumping set point is of  $2 \text{ m}^3/\text{s}$  (A). Once the rain starts (00:30), the inflow to VilaPrat WWTP rises above  $3.4 \text{ m}^3/\text{s}$  and according to Tank 2 emptying tree (Figure A.15a), the pumps stop (set point  $0 \text{ m}^3/\text{s}$ ) (B) and all wastewater is stored into the tank in order to allow the WWTP to treat all wastewater without causing CSOs. Round 02:50, the tank has less than  $1000 \text{ m}^3$  of free volume meaning that it has to be emptied as quickly as possible to avoid CSOs and thus, pumping set points turn to  $2 \text{ m}^3/\text{s}$  (C). Once the rain is over, inflow into VilaPrat WWTP returns to normal conditions so the tank can be emptied at  $2 \text{ m}^3/\text{s}$  (D).

The volume of spilled wastewater (CSO) during scenario 3 shown in Figure A.15a illustrates that there is not much difference between the Standard or the EDSS modes ( $186885 \text{ m}^3$  and  $188374 \text{ m}^3$  respectively). This is because in the Standard operation the Tank remains full within the 24h simulation. All the stored volume is not taken into account and is susceptible to produce CSOs. Considering this water volume, the difference between the EDSS and Standard mode is of  $48511 \text{ m}^3$ .



**Figure A.15.** (a) Tank 2 emptying tree and execution time line and (b) Tank 2 management (volume and pump flow) results during scenario 3.

Simulation results of Tank 2 during scenario 3 are quite different between the two operation modes. On the one side, the Standard mode, stores wastewater during the rainfall but as it has no given pumping set points, the tank remains full during the rest of the simulation. On the other side the EDSS mode is able to store wastewater as long as it does not produce any CSO discharges and is emptied gradually maintaining the performance of VilaPrat WWTP.

### WWTP VilaPrat (3)

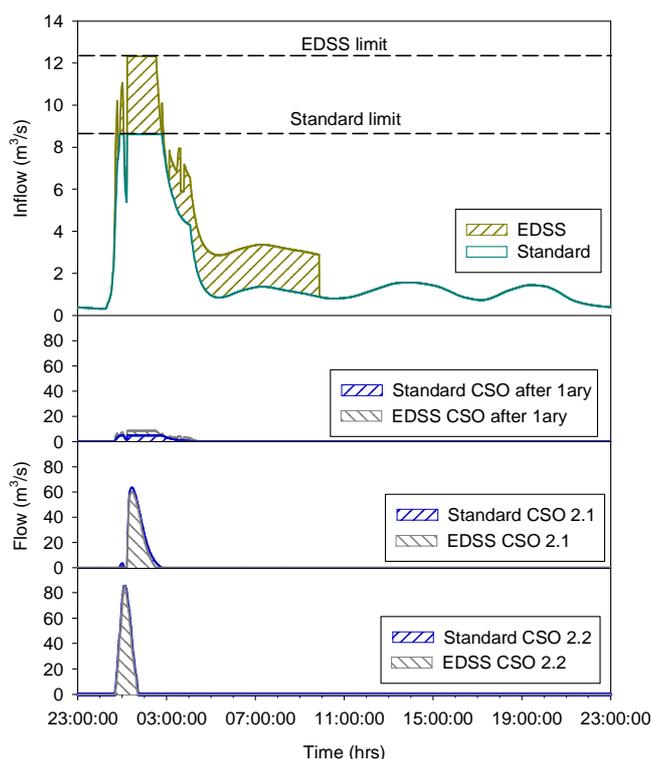
Figure A.16 shows the simulation results of the inflow of WWTP VilaPrat for the EDSS mode in comparison with the Standard one during scenario 3. At a first stage, before the rain begins, inflow of the WWTP is below  $8.63 \text{ m}^3/\text{s}$  and the plant operates in DWF conditions treating all wastewater through all stages.

Once the rainfall starts the plant inflow is between  $3.7 \text{ m}^3/\text{s}$  and  $12.33 \text{ m}^3/\text{s}$  so the plant operates in position 2, where  $3.7 \text{ m}^3/\text{s}$  are treated through the secondary treatment and the rest (maximum of  $7.4 \text{ m}^3/\text{s}$ ) through the primary treatment. The tertiary treatment can provide an additional treatment capacity of  $1.23 \text{ m}^3/\text{s}$  only when TSS concentration is below  $500 \text{ gr}/\text{m}^3$  (Position 3). The excess is directly discharged into the river without any treatment. When the rain is over, the inflow starts to descend but the effect of Tank 1 and then Tank 2 emptying phases can be observed before recovering DWF conditions.

Three different CSOs were detected for Scenario 3 in Figure A.16. CSOs spill after primary treatment is higher for the EDSS mode ( $72650 \text{ m}^3$ ) than for the Standard mode ( $43091 \text{ m}^3$ ).

Despite that, it must be taken into account that these discharges are partially treated wastewater and thus, they are less harmful to discharge to the receiving body than totally untreated wastewater from other CSO points. CSO 2.1 shows similar values for the Standard and EDSS modes in the figure. Despite that, the EDSS operation discharges a smaller volume of untreated water to the river and therefore the effect on the receiving body is smaller too.

The discharge values are of  $166036 \text{ m}^3$  for the Standard mode and  $142001 \text{ m}^3$  for the EDSS mode. CSO 2.2 discharges are very similar in volume of wastewater for both modes being their difference of  $76 \text{ m}^3$ . Finally, the stored wastewater into Tank 2 for the Standard mode must be also taken in regard as the tank remains full after the rain event and it is susceptible to produce CSO discharges.



**Figure A.16.** Simulation results for the WWTP of VilaPrat inflow and CSOs during scenario 3.

Results of the WWTP of VilaPrat during the third scenario illustrate how the plant has a higher treatment capacity in comparison with the Standard mode by the flow redirection during wet weather. Therefore, this new configuration allows the improvement of the receiving body by reducing the amount of untreated wastewater.

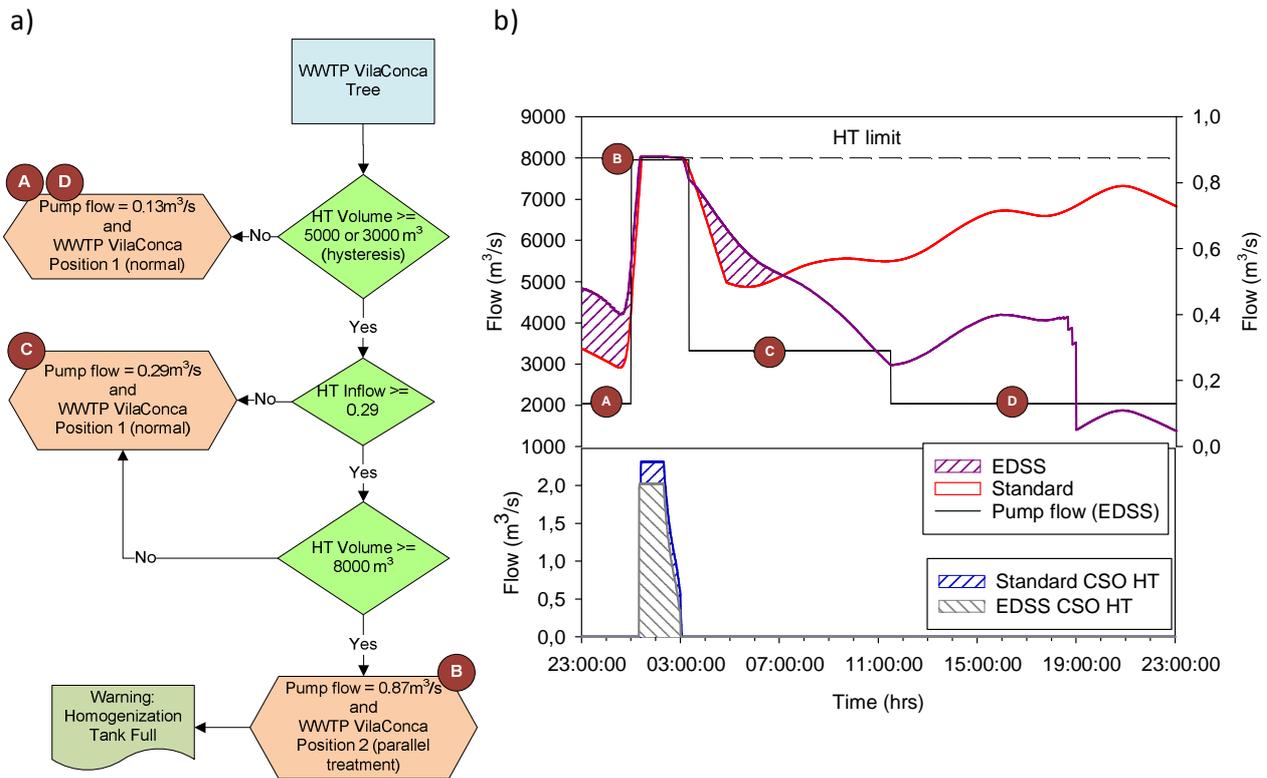
#### VilaConca Homogenization Tank (4)

Figures A.17b show the simulation results during scenario 3 of the stored wastewater volume on the HT for the EDSS mode in comparison with the Standard one. Decisions made for the HT management are directly related with the WWTP of VilaConca status and thus are represented in the decision tree of this WWTP (see Figure A.17a).

Before the rain begins, the tank operates in DWF conditions so the pumping set point is  $0.13 \text{ m}^3/\text{s}$  which is the average daily inflow of VilaConca WWTP (A). Once the rain starts (00:20), the tank inflow is over  $0.29 \text{ m}^3/\text{s}$  and the stored volume quickly reaches  $8000 \text{ m}^3$  so the pumping set point turns to  $0.87 \text{ m}^3/\text{s}$  (B).

When the rainfall is over, the tank inflow is still over  $0.29 \text{ m}^3/\text{s}$  but its volume is smaller than  $8000 \text{ m}^3$  so the pumping set point changes to  $0.29 \text{ m}^3/\text{s}$  (C) until the tank volume reaches  $3000 \text{ m}^3$  (11:30). After that, the HT recovers DWF conditions and the pumping set point is  $0.13 \text{ m}^3/\text{s}$  (D).

CSO discharged by the HT during this third rain event are illustrated in Figure A.17b. Results illustrate how the use of the EDSS mode produces better results in comparison with the Standard mode reducing the volume of spilled wastewater to the river. The total amount saved by the EDSS mode is of  $1267 \text{ m}^3$ .

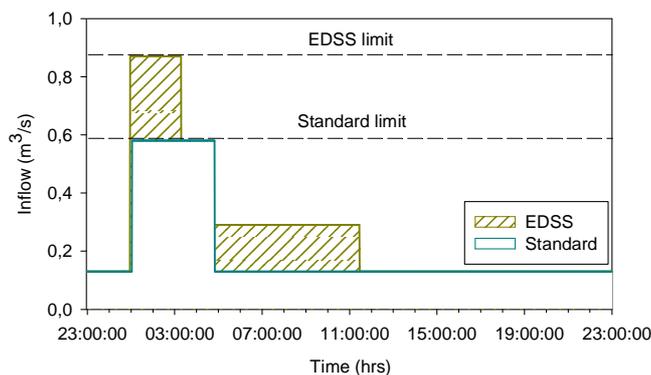


**Figure A.17.** (a) WWTP of VilaConca decision tree and execution timeline and (b) Simulation results for the stored volume, pumping set point and CSO of the HT during scenario 3.

Management of the HT for the EDSS mode during this rain event reduce the volume of untreated wastewater discharged into the receiving body. Additionally, the Standard mode has a constant pumping set point and after the rainfall, the tank is emptied in a different way the EDSS mode. The EDSS operation tries to empty the tank as fast as possible and changes set points depending on the status of VilaConca WWTP. This way, the probability of new CSO spills in case of another rain event is reduced.

### WWTP VilaConca (5)

Figure A.18 illustrates results of the management of VilaConca WWTP during scenario 3 for both the EDSS and Standard modes. At the beginning of the simulation, the plant operates in DWF conditions as the inflow is  $0.13 \text{ m}^3/\text{s}$  and wastewater is treated through all the processes. Once the rain starts (00:44) the plant inflow increases to  $0.87 \text{ m}^3/\text{s}$  and the WWTP operates separating flow into two independent streams. The first one of  $0.29 \text{ m}^3/\text{s}$  flows through secondary treatment and is then discharged into the river while the remaining wastewater (up to  $0.58 \text{ m}^3/\text{s}$ ) receives only primary treatment. After the rainfall (03:05), inflow decreases to the design flow of the WWTP ( $0.29 \text{ m}^3/\text{s}$ ) so wastewater can be fully treated. Approximately at 11:15, volume of the HT is low enough in order to send  $0.13 \text{ m}^3/\text{s}$  to the plant and return to DWF conditions.

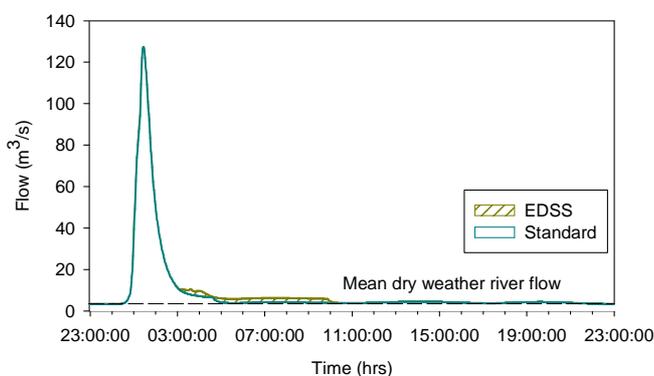


**Figure A.18.** Inflow of the WWTP of VilaConca during scenario 3.

Results of the WWTP of VilaConca management during this scenario with the use of the EDSS mode respect the Standard mode illustrate that for the one hand, the plant is able to increase inflow until the design flow ( $0.29 \text{ m}^3/\text{s}$ ) optimizing the plant to treat wastewater through the complete process. On the other hand, during wet weather, the plant rises its capacity ( $0.87 \text{ m}^3/\text{s}$ ) separating flow into two different stretches (only primary treatment or only secondary treatment) reducing the probability to produce CSOs or at least treat partially wastewater as far as possible. The EDSS mode represents an enhancement of  $4791 \text{ m}^3$  of treated or partially treated wastewater respect the Standard mode.

#### Receiving body (6)

Figure A.19 show the simulation results for the EDSS and the Standard modes of the river flow after the WWTP of VilaPrat during scenario 3. At the beginning of the simulation, the river flow is in DWF conditions ( $3 \text{ m}^3/\text{s}$ ). Once the rainfall starts, the water flow increases to approximately  $120 \text{ m}^3/\text{s}$  due to the different CSO discharges of VilaPrat system. When the rain finishes, flow decreases again to  $3 \text{ m}^3/\text{s}$  but in the EDSS mode, there is a small difference in comparison with the Standard mode due to two reasons. The first one is the contribution of Tank 2 stored wastewater, which is not taken into account in the Standard mode. The second reason is the small simulation errors due to model instabilities. The total discharged volume for both modes should be the same, for the EDSS mode it is of  $795438 \text{ m}^3$  while for the Standard mode the discharged volume is of  $750383 \text{ m}^3$ . The difference between them is  $45055 \text{ m}^3$ , corresponding approximately to Tank 2 capacity.



**Figure A.19.** River water flow after the WWTP of VilaPrat for scenario 3.

EDSS rain scenario 4

The last scenario (Figure A.20) is based on real data, has a length is of 1.91 h with a total precipitation of 58.53 mm (rain input of 17743.8 m<sup>3</sup>) and a return period of 5 years. In consequence, it can be considered a very strong rain event which may not occur so easily.

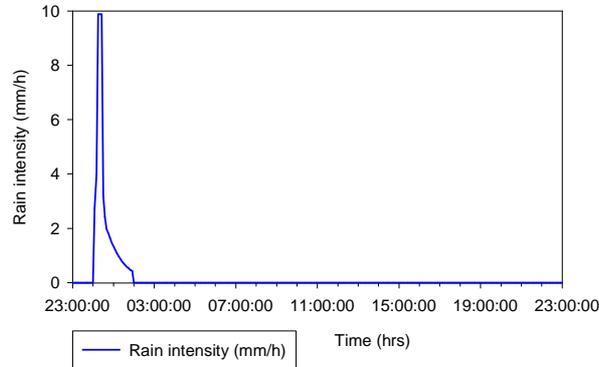


Figure A.20. Rain intensity of the rain scenario 4.

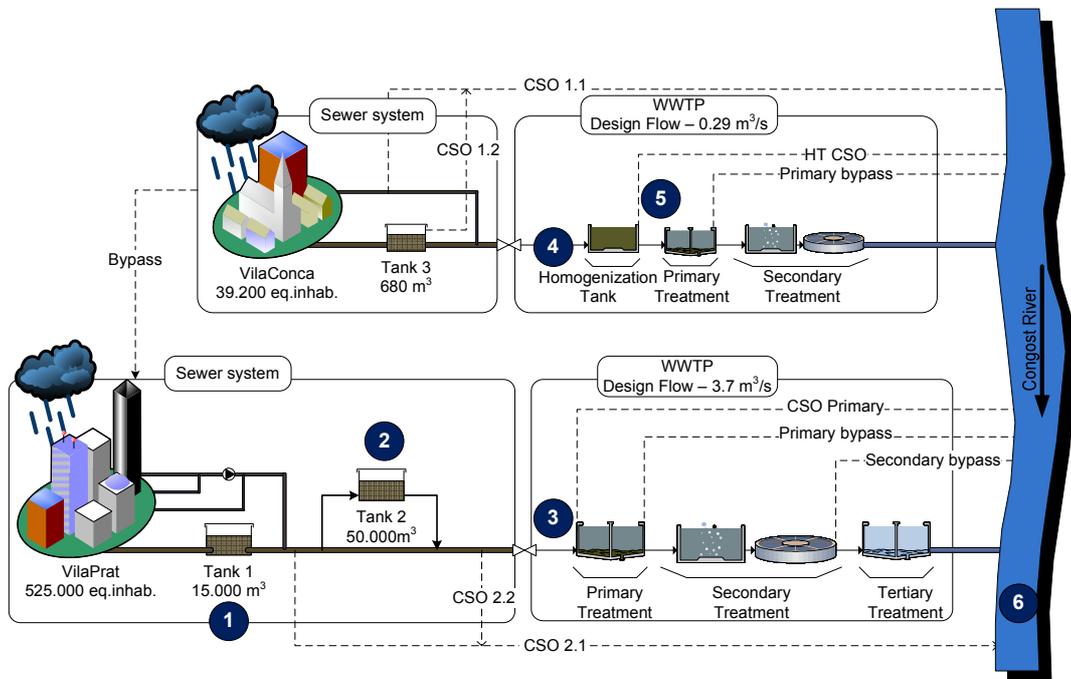


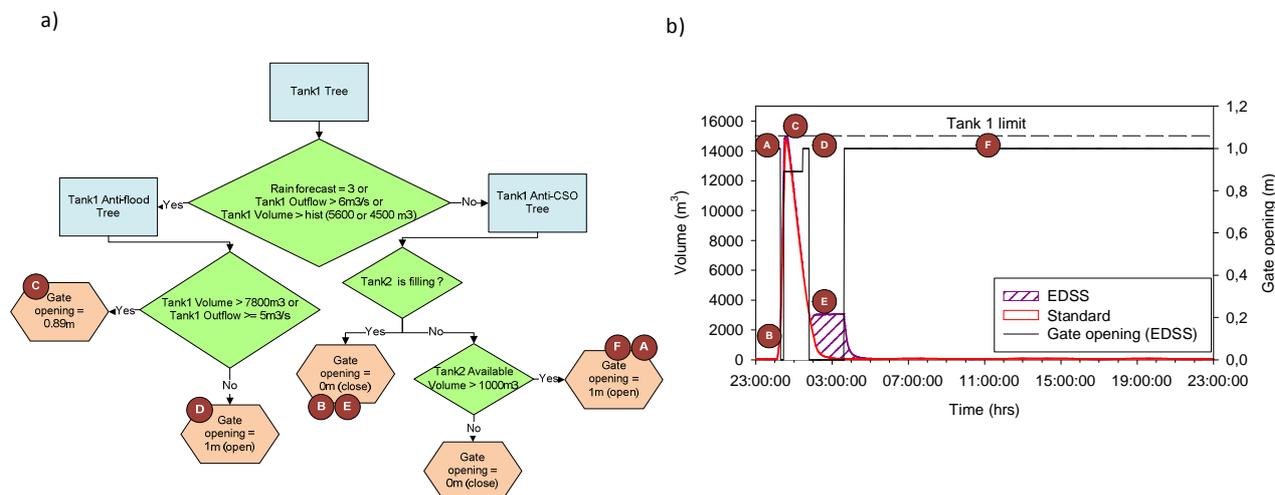
Figure A.21. VilaConca and VilaPrat system scheme for scenario 4.

VilaPrat Tank 1 (1)

Figure A.22b shows the simulation results of Tank 1 for the EDSS mode in comparison with the Standard mode during scenario number 4. The management of this tank is governed by Tank 1 management tree (see Figure A.22a). Before the rain starts, the gate is fully opened to position 1 m and the tank is operating in DWF conditions (A). When the rain begins, during 10 minutes (00:18 to 00:28) the tank operates with anti CSO purposes and the gate closes to position 0 m because Tank 2 is filling (B).

After that, the stored volume is over 7800 m<sup>3</sup> and according to Tank 1 decision tree, the set point for the gate position changes to 0.89 m (C), which is the maximum gate aperture without producing flooding during rainfall.

The gate remains in this position until the rain finishes and the tank volume decreases below 7800 m<sup>3</sup>. Then, the gate opens completely to position 1 m (D) in order empty the stored wastewater as fast as possible. As a result, Tank 2 starts to fill and the gate closes (0 m) again (E). Once Tank 2 has more than 1000 m<sup>3</sup> of free volume, the gate of Tank 1 opens to position 1m emptying the remaining wastewater and recovering DWF conditions (F).



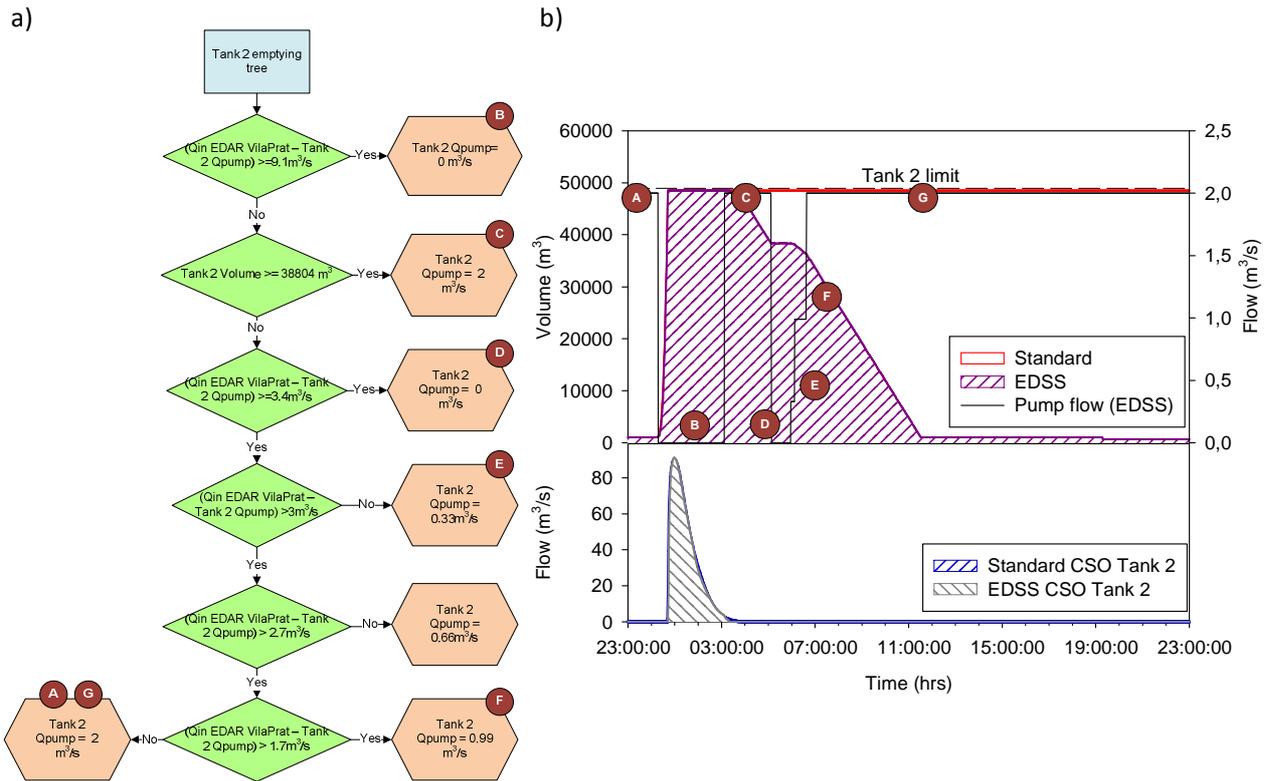
**Figure A.22.** (a) Tank 1 tree management and execution timeline and (b) Stored volume and gate position in Tank 1 during scenario 4.

Results of the EDSS mode for the management of Tank 1 during scenario 4 show that the maximum reached during the simulation is similar to the ones obtained in the Standard mode. After the rainfall, the stored volume differs from the Standard mode since the management of the tank with the EDSS avoids possible CSOs downstream (341397 m<sup>3</sup>) the tank and thus empties the stored wastewater as quickly as possible.

### VilaPrat Tank 2 (2)

Figure A.23b illustrates results of Tank 2 management during scenario 4 for the EDSS mode in comparison with the Standard mode. The management of this tank is governed by Tank 2 decision tree, which takes into account the stored volume of the tank itself and the inflow into the WWTP of VilaPrat (see Figure A.23a). Before the rain starts the tank is empty, the pumping set point is set to 2 m<sup>3</sup>/s and operates in DWF conditions (A). Once the rain starts, the tank starts to fill quickly and the set points change to 0 m<sup>3</sup>/s trying to protect from CSOs the WWTP of VilaPrat since its inflow is over 9.1 m<sup>3</sup>/s (B).

When the rain stops, the tank has to be emptied as quickly as possible in order to avoid unnecessary CSO spills and thus, pumping set points turn to 2 m<sup>3</sup>/s (C). After that, the tank has more than 1000 m<sup>3</sup> of free volume but since the plant inflow is over 3.4 m<sup>3</sup>/s, pumping set points are set to 0 m<sup>3</sup>/s in order to protect the WWTP from CSOs (D). Once the plant decreases its inflow, Tank 2 continues emptying and thus, pumps are set to 0.33 m<sup>3</sup>/s (E) and later to 0.99 m<sup>3</sup>/s (F). Finally, the inflow into the WWTP is below 1.7 m<sup>3</sup>/s and the pumping set point can be set to 2 m<sup>3</sup>/s operating in normal DWF conditions (G).



**Figure A.23.** (a) Tank 2 management tree and execution timeline and (b) Tank 2 volume, pumping set points and CSO during scenario 4.

Regarding to the CSOs discharged by the tank during this scenario, results show that they are very similar for both EDSS (349758  $\text{m}^3$ ) and Standard (346243  $\text{m}^3$ ) modes. Despite that, in the Standard mode the emptying of the tank is not considered, all the stored wastewater (50000  $\text{m}^3$  approximately) must be taken into account since it is susceptible to produce CSO discharges. Thus, the difference between the EDSS and the Standard modes is of 46485  $\text{m}^3$ .

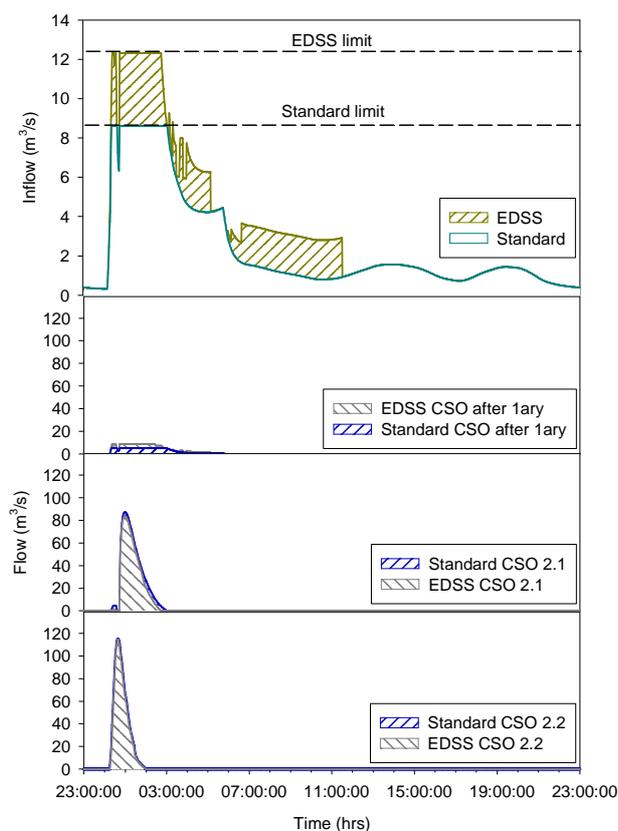
Results of Tank 2 management for the EDSS mode during scenario 4 are different in comparison with the Standard mode for the same scenario. The Standard mode does not consider any pumping set point to empty the tank and all wastewater remains stored during the simulation. During this scenario, wastewater is stored into the tank and is then emptied gradually taking into account the plant inflow and the volume of the tank in order to avoid CSO spills into the WWTP of VilaPrat.

### WWTP VilaPrat (3)

Figure A.24 illustrates the simulation results of the WWTP of VilaPrat for the EDSS mode in comparison with the Standard one during scenario 4. Before the rain starts, the inflow of the WWTP is below 8.63  $\text{m}^3/\text{s}$  so the plant operates in DWF conditions. Once the rain begins, the inflow increases between 3.7  $\text{m}^3/\text{s}$  and 12.33  $\text{m}^3/\text{s}$  so the plant operates at position 2 treating by the one hand 3.7  $\text{m}^3/\text{s}$  through the secondary treatment, 7.4  $\text{m}^3/\text{s}$  through the primary treatment. Position 3 (including tertiary treatment) is launched if TSS concentration is below 500  $\text{gr}/\text{m}^3$  treating an extra flow of 1.23  $\text{m}^3/\text{s}$ . The water excess is directly spilled to the river without treatment. Once the rain stops, the inflow of the plant descends gradually taking into account discharges of Tank 1 and Tank 2. After that, the plant recovers DWF conditions.

Three different CSOs are illustrated in Figure A.24. The first one is the CSO after the primary treatment which is higher for the EDSS mode (91211 m<sup>3</sup>) than for the Standard one (59293 m<sup>3</sup>). It must be taken in regard that this is a partially treated discharge and thus, is better for the receiving body than a totally untreated spill.

Results for the CSO 2.1 show that both modes have a very similar result. Despite that the volume of spilled wastewater into the river is smaller for the EDSS mode (284573 m<sup>3</sup>) than for the Standard one (319853 m<sup>3</sup>). CSO 2.2 results are very similar in volume for both the Standard and the EDSS modes. In this case, the difference of spilled wastewater into the receiving body is of 428 m<sup>3</sup>. Finally, the volume of stored wastewater into Tank 2 for the Standard mode must be also considered. During the simulation it remains into the tank and is thus susceptible to produce CSO discharges.



**Figure A.24.** WWTP of VilaPrat inflow and CSOs during scenario 4.

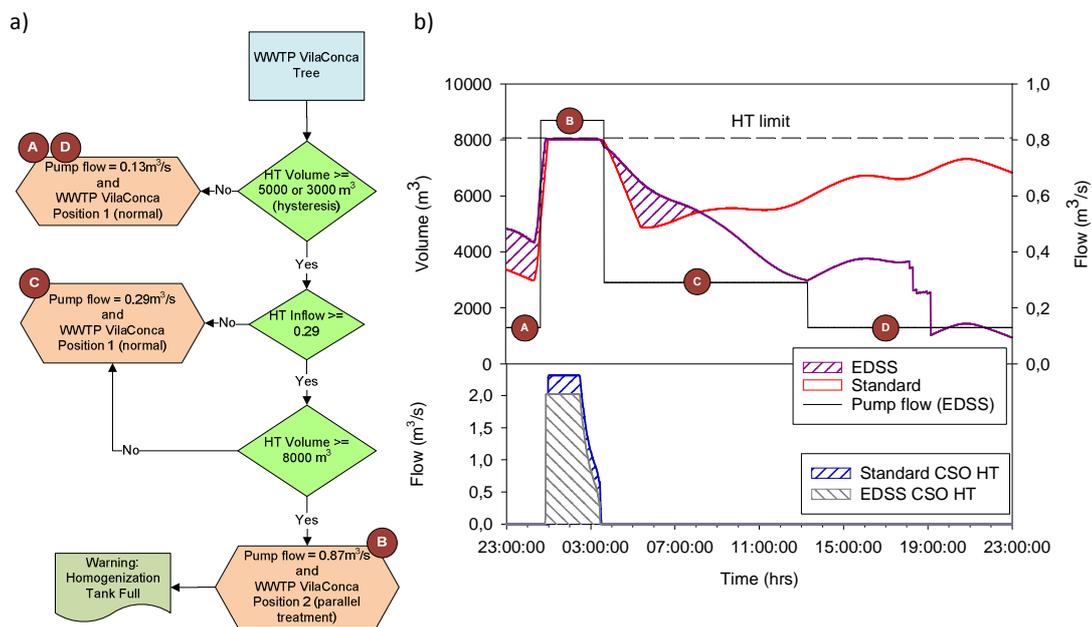
Simulation results of VilaPrat WWTP during scenario 4 show how the plant has a higher treatment capacity (from 8.63 m<sup>3</sup>/s to 12.33 m<sup>3</sup>/s) when compared with the Standard mode and in consequence has a greater potential during wet weather and more capacity for the river quality protection. However, this is a heavy rain scenario and the volume of discharged water in CSO 2.1 and 2.1 is high in comparison with the one after the primary treatment.

#### VilaConca Homogenization Tank (4)

Simulation results of the HT for the EDSS mode in comparison with the Standard one during scenario 4 are illustrated in Figure A.25b. The management of this tank is directly related with the status of VilaConca WWTP so decisions for this tank are represented in the decision tree shown in Figure A.25a).

Before the rain begins, the HT operates normally in DWF conditions pumping  $0.13 \text{ m}^3/\text{s}$  to the WWTP (A). Once the rainfall starts, the volume of the tank increases to  $8000 \text{ m}^3$  so the set point changes to  $0.87 \text{ m}^3/\text{s}$  during 3 h approximately (B). When the rainfall is over, stored wastewater starts to decrease but in contrast its inflow is still higher than  $0.29 \text{ m}^3/\text{s}$  so that the pumping set point is set to  $0.29 \text{ m}^3/\text{s}$  which allows the WWTP to fully treat the incoming wastewater through all the stages (C). This set point does not change for the next 9 h 40 min until the volume of stored wastewater of the tank is below  $3000 \text{ m}^3$  allowing the HT to operate in DWF conditions ( $0.13 \text{ m}^3/\text{s}$ ) (D).

CSO spilled by the HT during this rain event in Figure A.25b shows how the use of the EDSS mode produces better results in comparison with the Standard mode. Consequently protecting the river from untreated wastewater discharges. In this scenario, the saved volume by the EDSS mode is of  $1828 \text{ m}^3$ .



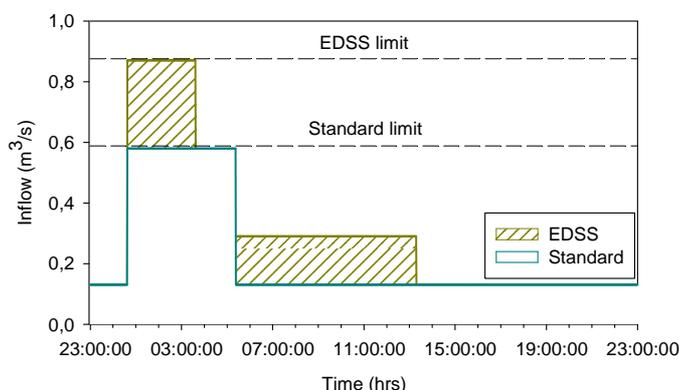
**Figure A.25.** (a) WWTP of VilaConca decision tree and execution time line and (b) Stored volume, pumping flow and CSOs of the HT during scenario 4.

Results of the stored wastewater into the HT during this scenario illustrate that there are some differences when comparing the EDSS and the Standard modes. On the one hand, the volume of CSOs is smaller for the EDSS mode and is thus better for the receiving body. On the other hand, the Standard mode does not consider any change in the pumping set points of the tank and in consequence, it takes more time to empty the tank after the rain event. In contrast, the EDSS mode empties the tank as quickly as possible as long as the WWTP of VilaConca can accept the flow.

### WWTP VilaConca (5)

Figure A.26 shows results of the VilaConca WWTP management during scenario 4 comparing the EDSS and the Standard modes. Before the rainfall starts, the plant inflow is of  $0.13 \text{ m}^3/\text{s}$  operating in DWF conditions thus, wastewater is treated through all processes. When the rain starts the inflow of the plant increases to  $0.87 \text{ m}^3/\text{s}$  and the WWTP operates redirecting flows into two independent streams during 3 h approximately. The first stream, of  $0.29 \text{ m}^3/\text{s}$  flows through the secondary treatment and is then discharged to the receiving body. The rest (up to  $0.58 \text{ m}^3/\text{s}$ ) receives only primary treatment and is then discharged into the river too.

Once the rainfall stops, the inflow of the plant decreases to  $0.29 \text{ m}^3/\text{s}$  during 9 h and 40 min which is the design flow of the plant so wastewater receives complete treatment. Finally, the WWTP inflow descends recovering DWF conditions ( $0.13 \text{ m}^3/\text{s}$ ).



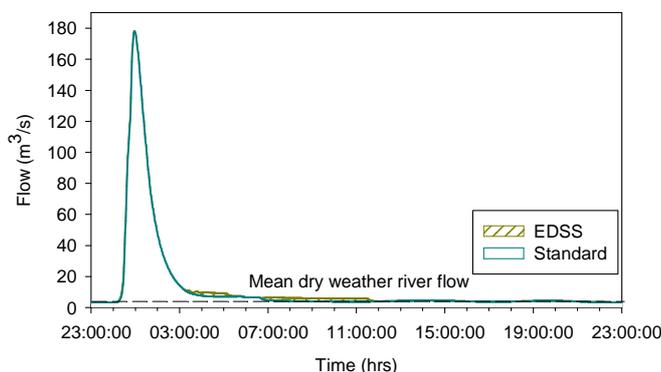
**Figure A.26.** Inflow of the WWTP of VilaConca during scenario 4.

In the EDSS mode, the plant increases its treatment capacity (from  $0.58 \text{ m}^3/\text{s}$  to  $0.87 \text{ m}^3/\text{s}$ ) and in consequence reduces the probability to produce CSO spills of untreated wastewater to the river. Additionally, the plant optimizes the complete treatment capacity up to its design flow ( $0.29 \text{ m}^3/\text{s}$ ). Both measures represent an enhancement in terms of volume of treated or partially treated wastewater, which for this particular scenario is of  $5865 \text{ m}^3$ .

#### Receiving body (6)

Figure A.27 shows the simulation results for the receiving body after the WWTP of VilaPrat for the EDSS and Standard modes during scenario 4. Before the rain starts, the river flow is near  $3 \text{ m}^3/\text{s}$ , which is its average daily flow. Once the rainfall starts, the flow increases up to  $180 \text{ m}^3/\text{s}$  approximately, corresponding to the total amount of CSOs produced within the sewer system. After that, the rain stops and the river flow descends to its normal DWF conditions.

Despite that, there is a small difference while the flow is descending with the EDSS mode. This is because of the emptying of the stored wastewater of Tank 2, which is not taken into account in the Standard mode within the 24 h simulation.

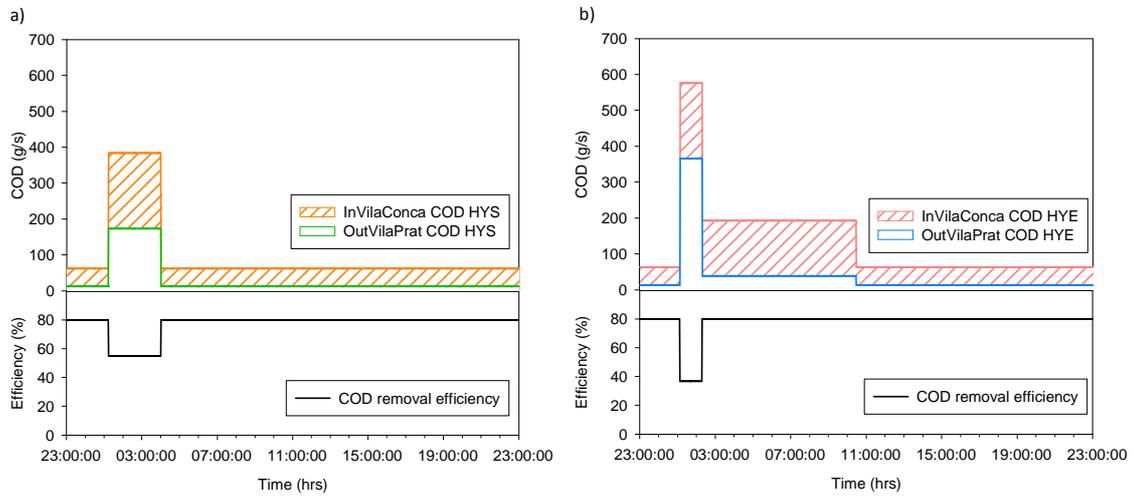


**Figure A.27.** River water flow after the WWTP of VilaPrat for scenario 4.

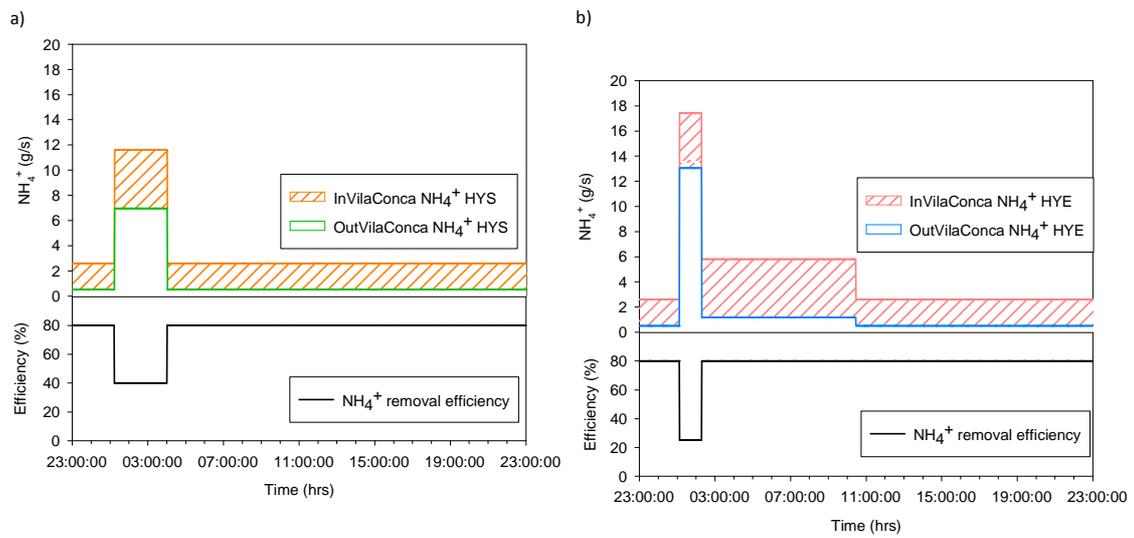
**ADDITIONAL RESULTS OF HYS AND HYE COMPARISON**

*Scenario 1*

*VilaConca*

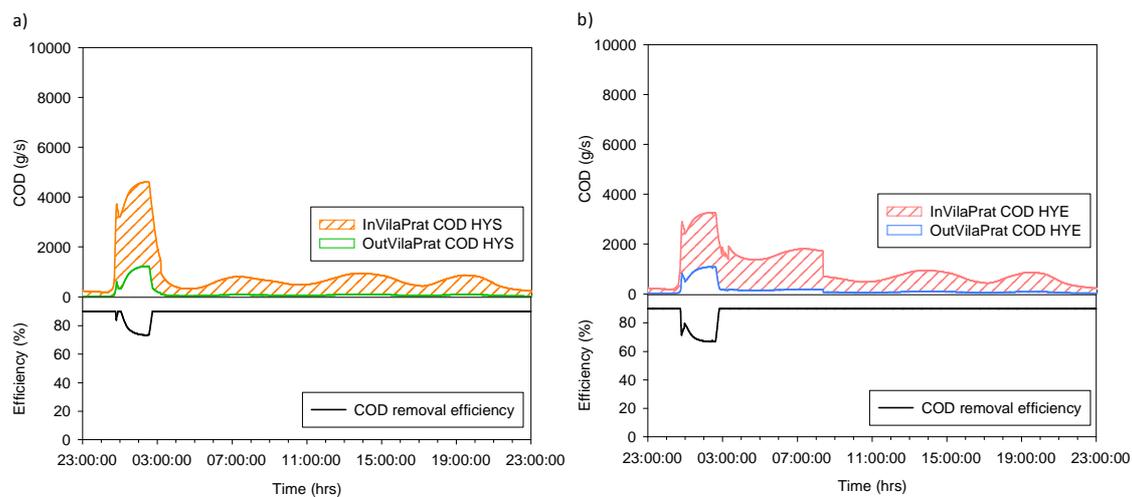


**Figure A.28.** COD mass flow and removal efficiency of VilaConca WWTP for (a) HYS and (b) HYE operation modes during scenario 1.

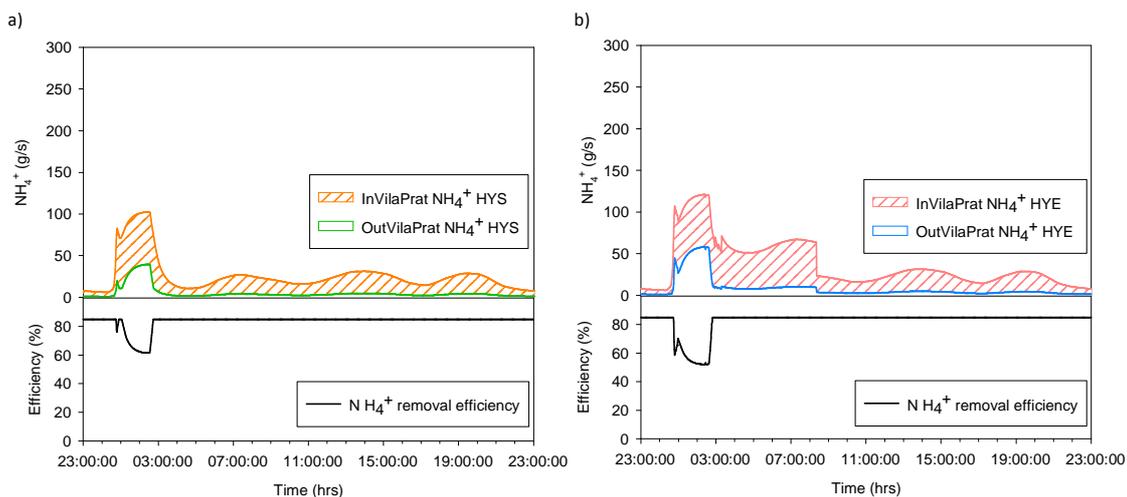


**Figure A.29.**  $\text{NH}_4^+$  mass flow and removal efficiency of VilaConca WWTP for (a) HYS and (b) HYE operation modes during scenario 1.

## VilaPrat scenario 1



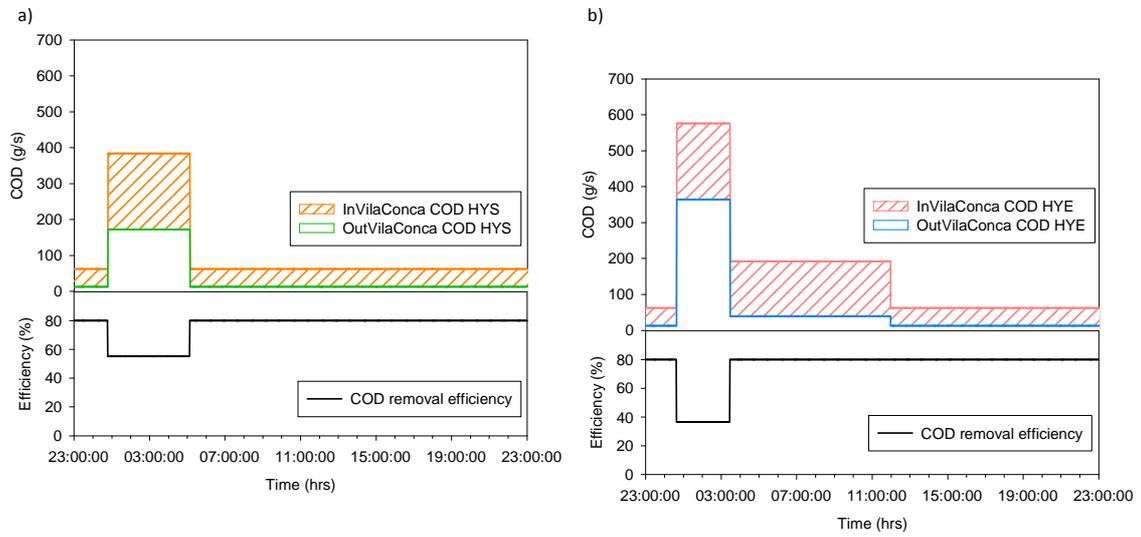
**Figure A.30.** COD mass flow and removal efficiency of VilaPrat WWTP for (a) HYS and (b) HYE operation modes during scenario 1.



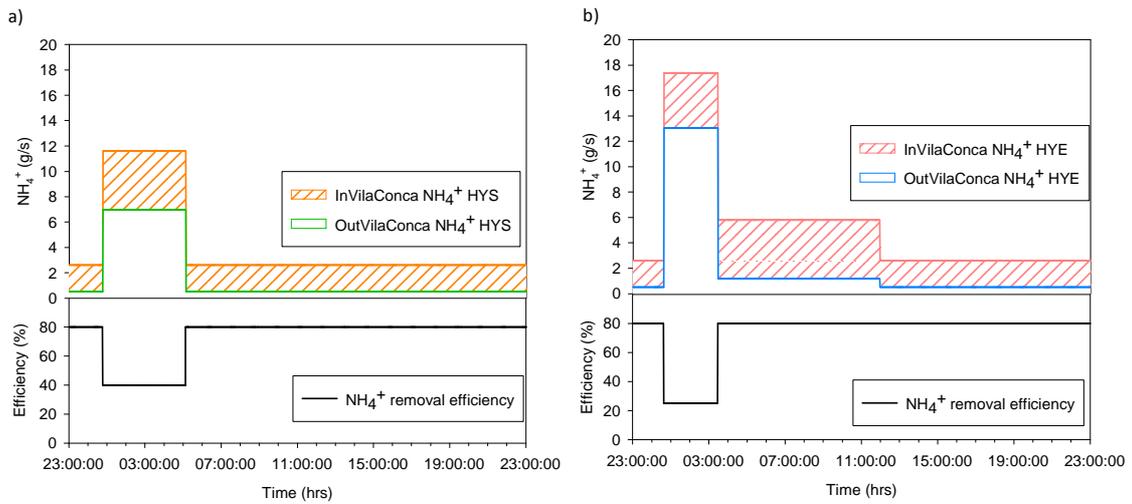
**Figure A.31.**  $\text{NH}_4^+$  mass flow and removal efficiency of VilaPrat WWTP for (a) HYS and (b) HYE operation modes during scenario 1.

Scenario 2

VilaConca



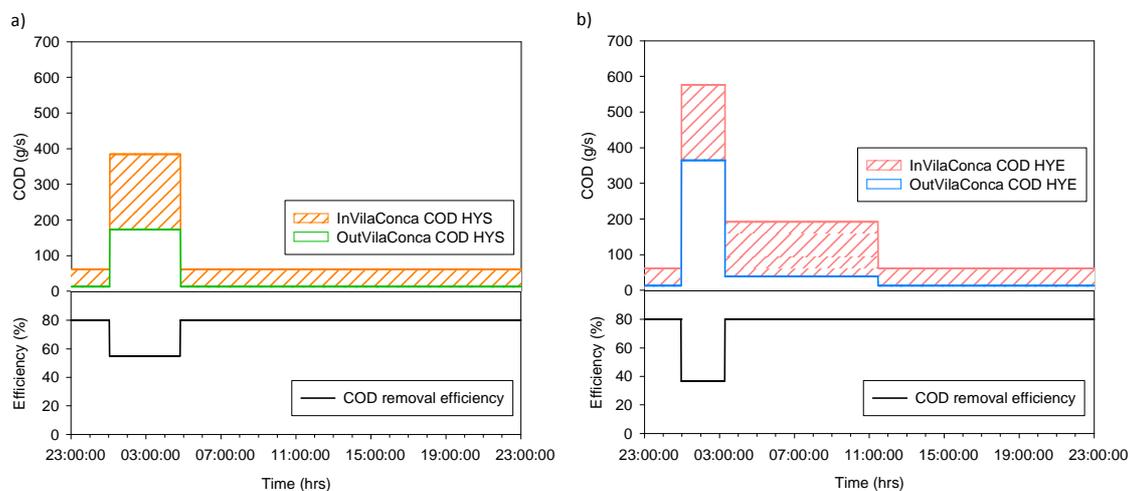
**Figure A.32.** COD mass flow and removal efficiency of VilaConca WWTP for (a) HYS and (b) HYE operation modes during scenario 2.



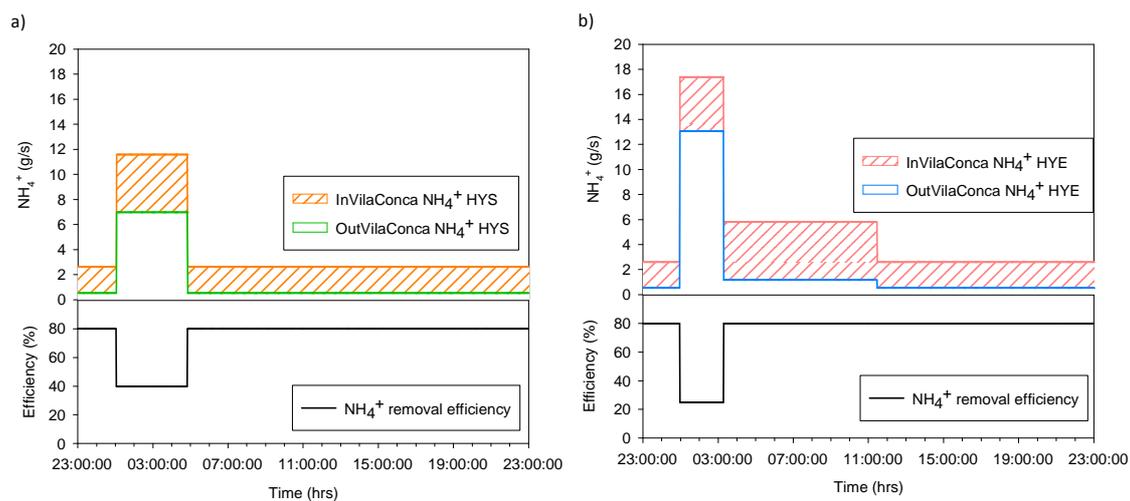
**Figure A.33.**  $\text{NH}_4^+$  mass flow and removal efficiency of VilaConca WWTP for (a) HYS and (b) HYE operation modes during scenario 2.

## Scenario 3

## VilaConca

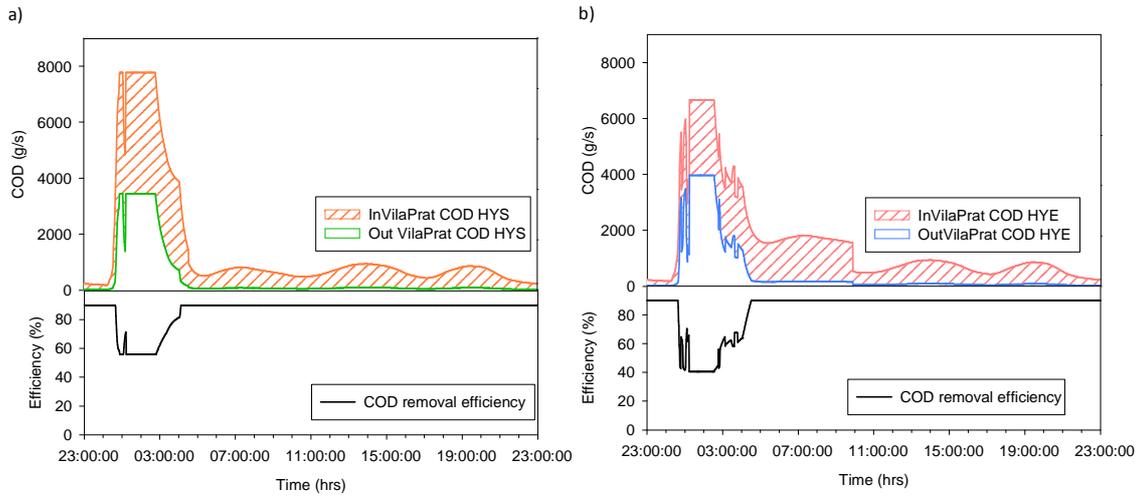


**Figure A.34.** COD mass flow and removal efficiency of VilaConca WWTP for (a) HYS and (b) HYE operation modes during scenario 3.

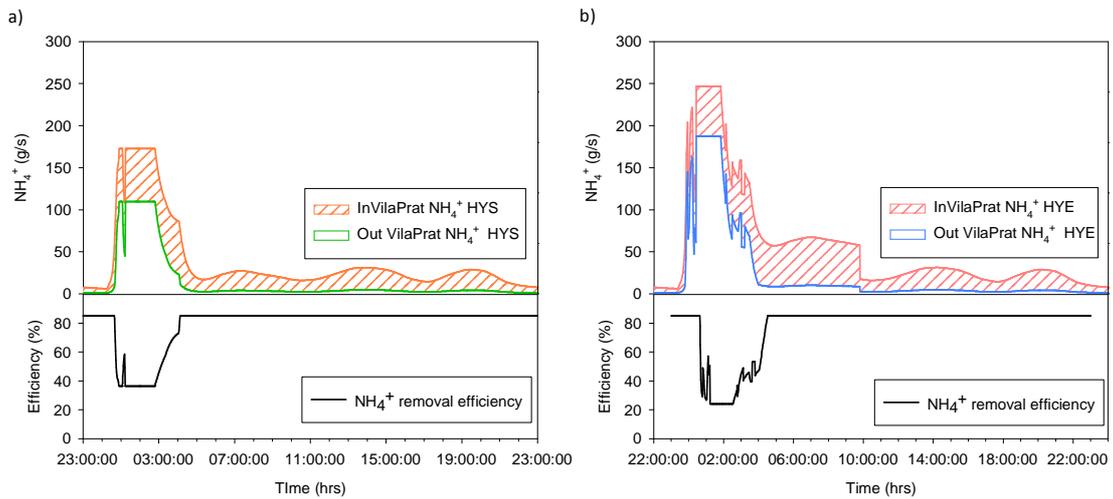


**Figure A.35.**  $\text{NH}_4^+$  mass flow and removal efficiency of VilaConca WWTP for (a) HYS and (b) HYE operation modes during scenario 3.

VilaPrat



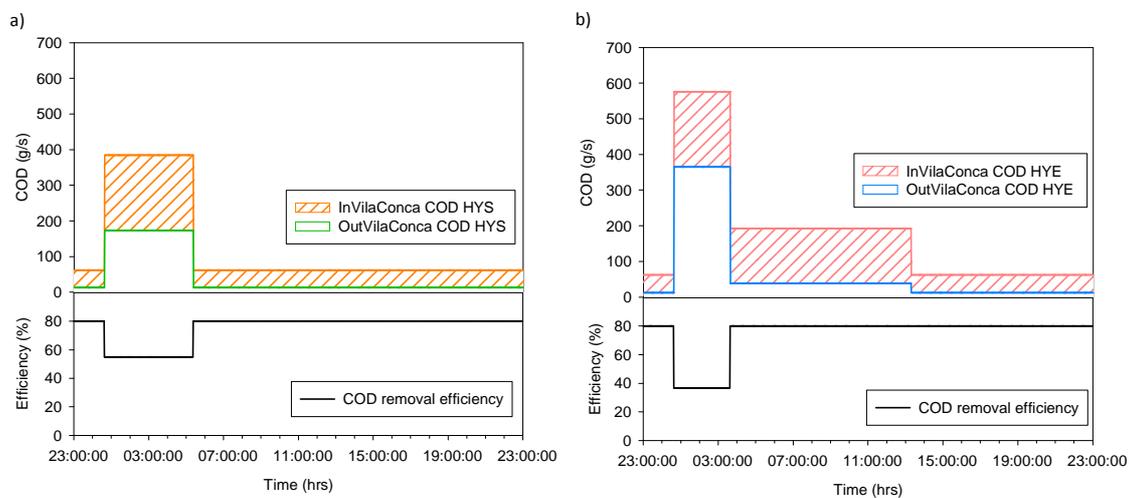
**Figure A.36.** COD mass flow and removal efficiency of VilaPrat WWTP for (a) HYS and (b) HYE operation modes during scenario 3.



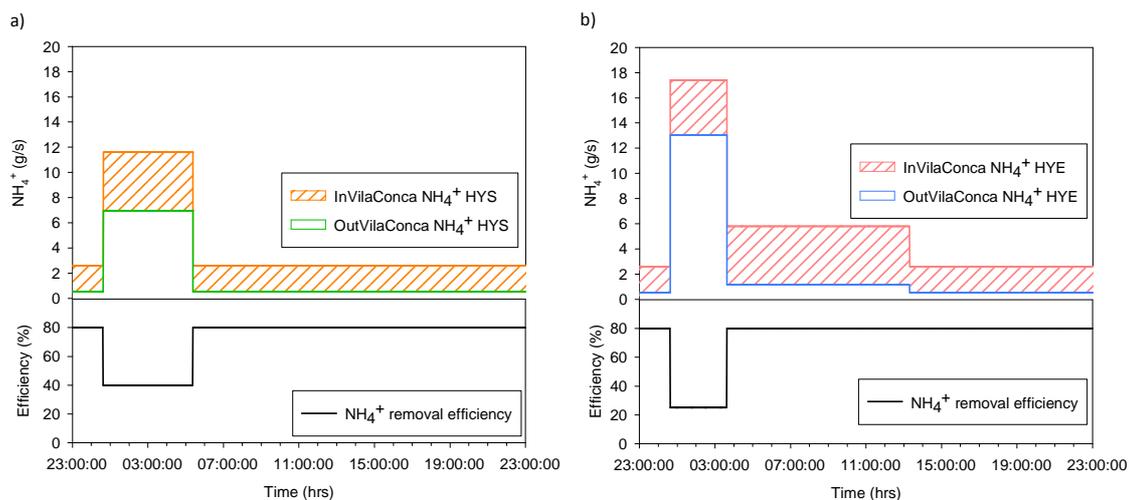
**Figure A.37.**  $\text{NH}_4^+$  mass flow and removal efficiency of VilaPrat WWTP for (a) HYS and (b) HYE operation modes during scenario 3.

## Scenario 4

## VilaConca

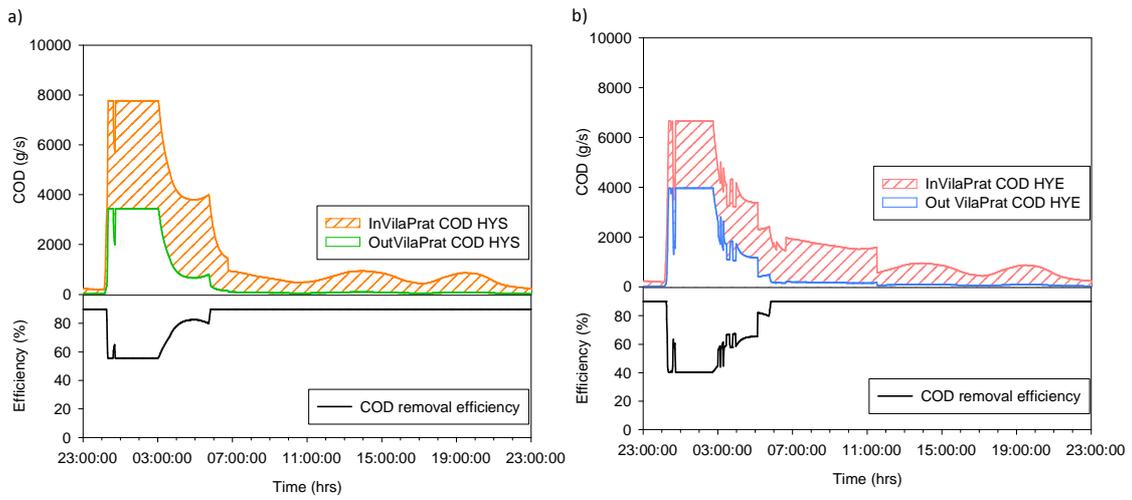


**Figure A.38.** COD mass flow and removal efficiency of VilaConca WWTP for (a) HYS and (b) HYE operation modes during scenario 4.

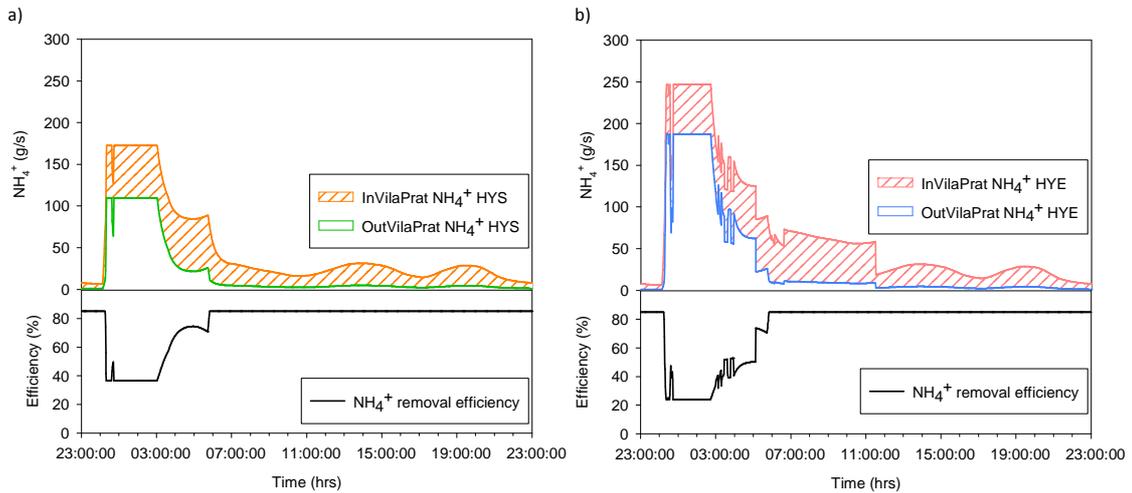


**Figure A.39.**  $\text{NH}_4^+$  mass flow and removal efficiency of VilaConca WWTP for (a) HYS and (b) HYE operation modes during scenario 4.

VilaPrat



**Figure A.40.** COD mass flow and removal efficiency of VilaPrat WWTP for (a) HYS and (b) HYE operation modes during scenario 4.



**Figure A.41.**  $\text{NH}_4^+$  mass flow and removal efficiency of VilaPrat WWTP for (a) HYS and (b) HYE operation modes during scenario 4.

## VIRTUAL SYSTEM LAYOUT

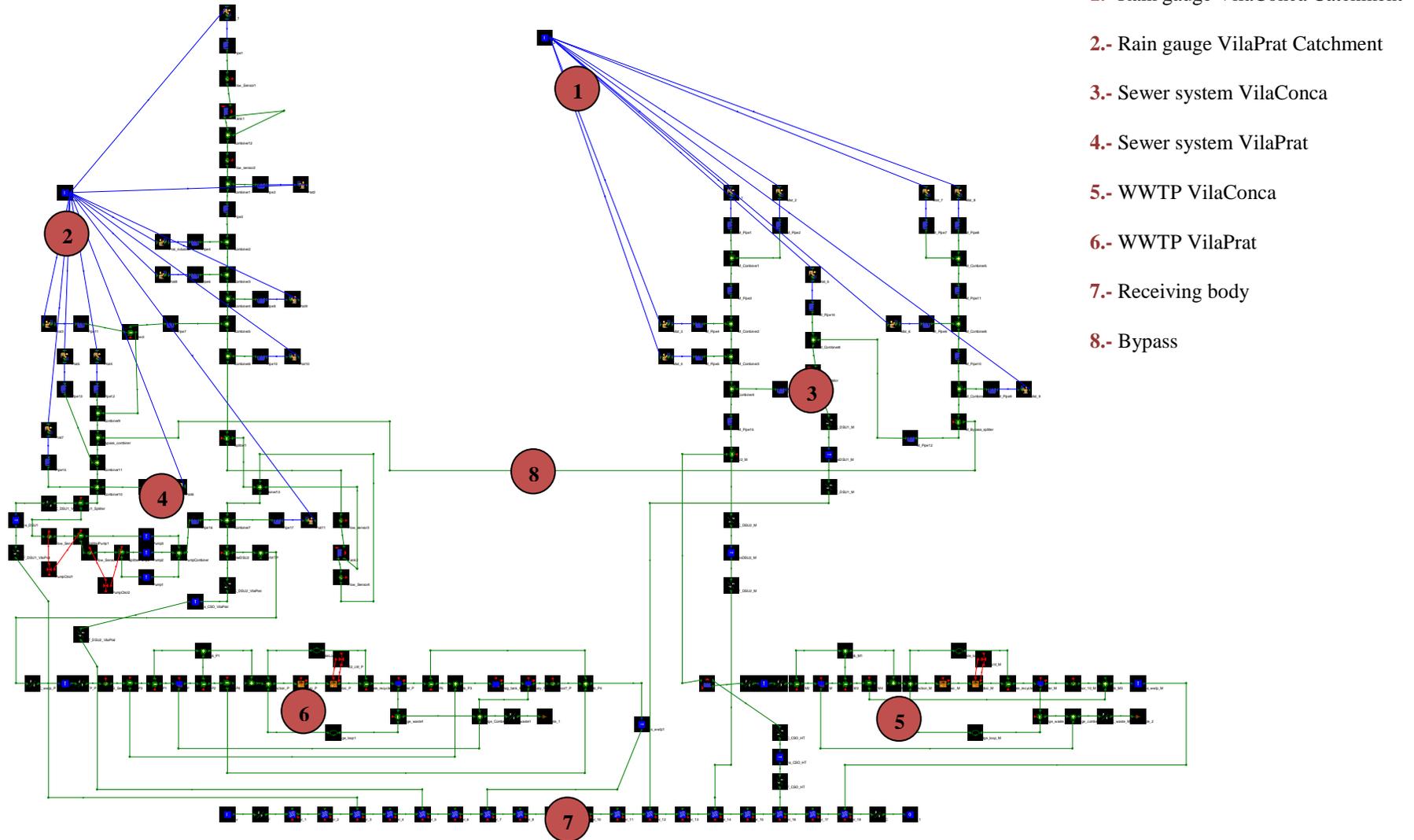


Figure A.42. Virtual system layout developed with WEST® modelling software.