RESILIENCE OF WATER RESOURCE RECOVERY FACILITIES: A FRAMEWORK FOR QUANTITATIVE MODEL-BASED ASSESSMENT

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DOCTORAL THESIS

RESILIENCE OF WATER RESOURCE RECOVERY FACILITIES

A FRAMEWORK FOR QUANTITATIVE MODEL-BASED ASSESSMENT

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Appendix A-D

November 30, 2018

SUPERVISION CERTIFICATE

Dr Peter Daldorph, of Atkins UK; Dr Arthur Thornton, of Atkins UK; Dr. Lluís Corominas, of ICRA

We declare:

That the thesis titles "Resilience of water resource recovery facilities: a framework for model-based assessment ", presented by Pau Juan-García to obtain a doctoral degree, has been completed under our supervision and fulfills the requirements for the degree of Doctor (and meets the requirements to opt for an International Doctorate).

For all intents and purposes, we hereby sign this document.

Signed: Peter Daldorph Arthur Thornton.

Girona, date: November 30, 2018

DECLARATION OF AUTHORSHIP

I, Pau JUAN-GARCÍA, declare that this thesis titled, "Resilience of water resource recovery facilities" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date: November 30, 2018

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"Resilience is all about being able to overcome the unexpected. Sustainability is about survival. The goal of resilience is to thrive."

—Jamais Cascio

"To expect the unexpected shows a thoroughly modern intellect."

—Oscar Wilde

ABSTRACT

It is widely believed that we are currently in a situation of high uncertainty regarding the challenges that lay ahead for our water infrastructure and services. Government bodies, utilities, practitioners, and researchers have shown interest in the incorporation of resilience into the management and operation of water resource recovery facilities (WRRFs). Current practice to enhance resilience in WRRFs is to ensure redundancy (or backup) for most critical equipment (e.g. pumps or blowers), but there is no objective manner on how to best allocate resources for enhancing resilience. The research sector is progressing to support resilience implementation, but slowly in comparison with the increasing demand from industry and government. In this thesis we provide a model-based assessment approach for the quantitative evaluation of different strategies for enhancing resilience and properly allocating resources.

The first part of the thesis presents a review of studies that deal with resilience in the wastewater treatment sector, with a focus on understanding how these have addressed the key elements for assessing resilience, such as stressors, system properties, metrics and interventions to increase resilience. The review shows that only 17 peer reviewed papers and 6 relevant reports directly address resilience. The lack of consensus in the definition of resilience, and the elements of a resilience assessment, hinders the implementation of resilience in wastewater management. To date, there exists no framework for resilience assessment that is complete, comprehensive and directly applicable by practitioners. The review clearly justifies the need for a framework, which is provided in the second part of the thesis. It focuses on model-based assessment and is built on top of the existing good modelling practices from IWA.

The framework provides guidance on the overall modelling approach from data collection, model selection, model calibration and scenario analysis. Biokinetic models have been traditionally more complex than aeration models for most modelling applications. However, the work on resilience assessment presented in this thesis focuses on equipment failure and control strategies. For this reason, a detailed mechanistic modelling of the air distribution system is used. This model enables understanding of the relationships between aeration equipment, control algorithms, process performance, and energy consumption, thus leading to a more realistic prediction of WRRF performance under stress conditions when properly calibrated. To illustrate this, a model-based energy audit has been performed for the Girona WRRF with the goal of assessing the ability of current models to provide an objective evaluation of energy reduction strategies. Results show that the implementation of an ammonia-based aeration controller, a redistribution of the diffusers, and the installation of a smaller blower might lead to energy savings between 12 and 21%, depending on wastewater temperature. The model supported the development of control strategies that counter the effects of current equipment limitations, such as tapered diffuser distribution, or over-sized blowers. The resilience of these strategies was tested against an ammonia peak.

In the fourth part of the thesis, the usefulness of the model-based framework for resilience assessment is illustrated by assessing the resilience of the WRRF of Girona against a storm event and a power outage. With regards to the WRRF of Girona, the model predicted that stormwater events could cause sludge washout if the plant had to increase the volume of water treated, but the overall impact highly depends on the sludge settleability. It was also predicted that recirculation of activated sludge (RAS) flow manipulation can potentially increase resilience against stormwater. Limited energy back-up can cause non-compliance in case of blower power shutdown of around 6 h, and around 12 h in case of recirculation pumps shut-down. Another option to enhance resilience would be to increase the power back-up by 260 kW, which allows the plant to run with recirculation pumps and blowers at minimum capacity. In that case, resilience can be further enhanced by optimizing the trade-off between balancing oxygen needs in each reactor while lowering system pressure. Model-based assessment of resilience showed great potential to become a standard tool to assist on the decision making of future investment. However, before it is adopted by the industry, further work will be required in standardization and validation of the modelling approach.

RESUMEN

Hay consenso en que nos encontramos en una situación de alta incertidumbre respecto a los futuros riesgos que afectarán nuestra infraestructura del agua y sus servicios. El gobierno, la industria y los investigadores muestran un creciente interés en la incorporación de la resiliencia en la gestión y operación de las plantas de tratamiento de aguas residuales; a partir de ahora conocidas como plantas de recuperación de recursos del agua (PRRA). La práctica actual para aumentar la resiliencia en las PRRA consiste en asegurar la redundancia de maquinaria crítica (e.g. bombas y soplantes). Sin embargo, no hay forma objetiva de determinar la mejor forma de dividir los recursos disponibles. El sector de la investigación está progresando en este campo, pero lentamente, si se compara con el continuo incremento en la demanda por parte de la industria y el gobierno. En esta tesis se ha diseñado un sistema cuantitativo de evaluación de resiliencia basado en la modelación de procesos, cuyo objetivo principal es la evaluación de estrategias para incrementar la resiliencia y optimizar los recursos.

La primera parte de la tesis presenta una revisión de estudios sobre resiliencia en el sector del tratamiento del agua, con énfasis en entender como los elementos clave de la teoría de resiliencia han sido abordados. Estos elementos son: los estresores, las propiedades del sistema, las métricas y las intervenciones para implementar resiliencia. Los resultados muestran que solo 17 artículos sujetos a revisión y 6 informes de organismos relevantes abordan la resiliencia. La falta de consenso en la definición de resiliencia y los elementos de su evaluación dificulta su implementación en la gestión del agua. Hasta la fecha, ningún procedimiento de evaluación de resiliencia incluye todos los elementos mencionados o es directamente aplicable por profesionales. La revisión de literatura claramente justifica la necesidad de un método de evaluación sistemático o framewok, que se presenta en la segunda parte de la tesis. El método se ha construido sobre la guía de modelación de la IWA.

El framework proporciona una guía en el proceso de modelación, desde la recolección de datos a la selección del model, calibración y análisis de escenarios. Los modelos biocinéticos son tradicionalmente más complejos que los de aireación para la mayoría de las aplicaciones de la modelación. No obstante, el trabajo en resiliencia presentado en esta tesis se centra en fallos de equipo i estrategias de control. Por este motivo, se ha utilizado un detallado modelo mecanístico del sistema

de distribución del aire. Este modelo permite entender la relación entre el equipo de aireación, los algoritmos de control, el rendimiento del proceso y el consumo energético. De este modo, la predicción del rendimiento bajo condiciones de estrés es más realista, siempre que el modelo esté debidamente calibrado. Para ilustrarlo, el modelo ha sido probado sobre la PRRA de Girona con el objetivo de evaluar la capacidad de proveer una evaluación de varias estrategias de reducción energética. Los resultados muestran que la implementación de un controlador en cascada basado en amonio en el efluente, la redistribución de los difusores de aire y la instalación de un soplante más pequeño tienen potencial para ahorrar entre 12 y 21% del consumo energético actual, dependiendo de la temperatura. El modelo es capaz de asistir en el desarrollo de estrategias de control que contrarrestan los efectos de las limitaciones actuales del equipo.

En la cuarta parte de la tesis, la utilidad del sistema de evaluación de resiliencia basado en modelación es ilustrado con un caso de estudio sobre la PRRA de Girona. Los estresores son agua de tormenta y fallos eléctricos. Los resultados predicen que una tormenta podría causar lavado del fango en la planta si el caudal a tratar tuviese que ser incrementado. El impacto final depende en la sedimentabilidad del fango. La manipulación de la recirculación interna del fango se ha identificado como una posible estrategia para aumentar la resiliencia de la planta. En cuanto a los fallos eléctricos, la planta podría verse en problemas a partir de 6 horas en un fallo del soplante, y 12 en el caso de bombas de recirculación. Otra opción para aumentar la resiliencia seria incrementar la energía de reserva hasta 260 kW, lo que permite a la planta funcionar con las bombas y la aireación al mínimo. En este caso, la resiliencia puede maximizarse optimizando la redistribución del aire y reduciendo la presión del sistema de aireación.

RESUM

Hi ha consens en que ens trobem en una situació d'alta incertesa respecte als futurs perills que afectaran a la nostra infraestructura de l'aigua i els seus serveis. El govern, la industria i els investigadors demostren un interès creixent en la incorporació de la resiliència en al gestió i operació de les plantes de recuperació de recursos de l'aigua (PRRA). La practica actual per augmentar la resiliència en les PRRA consisteix en assegurar la redundància de maquinaria critica (e.g. en bombes i soplants). No obstant, no hi ha forma objectiva de determinar la millor forma de dividir els recursos disponibles. EL sector de la investigació esta progressant en aquest camp, però lentament si es compara amb el continu increment de la demanda per part de la industria i el govern. En aquesta tesi s´ha dissenyat un sistema qualitatiu d'avaluació de la resiliència a partir de la modelació de procés, amb l'objectiu principal d'avaluar estratègies per a incrementar la resiliència i optimitzar els recursos.

La primera part de la tesi presenta una revisió d'estudis sobre resiliència en el sector del tractament d'aigua, amb èmfasis en entendre com els elements clau de la teoria de la resiliència han sigut emprats. Aquests elements son: els estressors, les propietats del sistema, les mètriques i les intervencions per implementar resiliència. Els resultats mostren que només 17 articles i 6 informes de organismes rellevants tracten de resiliència. La falta de consens en la definició de resiliència i els elements que la composen dificulta la seva implementació en la gestió de l'aigua. Fins ara, cap procediment d'avaluació inclou tots els elements esmentats o es directament aplicable per professionals. La revisió de literatura justifica clarament la necessitat d'un mètode d'avaluació sistemàtic, el qual es presentat en la segona part de la tesi. Aquest mètode s'ha construït sobre la actual guia de modelació de la IWA.

El framework proporciona una guia en el procés de modelació des de la col·lecció de dades a la selecció de model, cal·libració i anàlisi de escenaris. Els models biocinétics son tradicionalment mes complexos que els de aeració per a la majoria de les aplicacions de la modelació. No obstant, el treball en resiliència presentat en questa tesi es centra en fallades de equipament i estratègies de control. Per aquest motiu, s´ha utilitzat un model mecanistic del sistema de distribució de l'aire. Aquest model permet entendre la relació entre el equip d'aeració, els algoritmes de control, el rendiment el procés i el consum energètic. D'aquesta manera, la predicció de rendiment en condicions d'estrès

es mes realista, sempre que el model estigui ben calibrat. Per il·lustrar-ho, el model ha sigut testejat sobre la PRRA de Girona, amb l'objectiu de comprovar la capacitat d'avaluar varies estratègies de reducció energètica. Els resultats mostren que la implementació de un controlador en cascada basat en amoni en el efluent, la redistribució dels difusors d'aire i la instal·lació de una soplant mes petita tenen potencial per estalviar entre el 12 i el 21% del consum energètic actual, depenent de la temperatura. El model es capaç d'assistir en el desenvolupament d'estratègies de control que contraresten els efectes de les limitacions actuals de l'equip.

En la quarta part de la tesi, la utilitat del sistema d'avaluació de resiliència basat en la modelació es il·lustrat amb un cas d'estudi sobre la PRRA de Girona. Els estressors son aigua de tempesta i fallades elèctriques. Els resultats prediuen que una tempesta podria causar la pèrdua de fangs de la planta si el causal a tractar es veu incrementat. L'impacte final depèn de la sedimentabilitat del fang. La manipulació de la recirculació interna del fang s´ha identificat com una possible estratègia per a augmentar la resiliència de la planta. Respecte a les fallades elèctriques, la planta podria estar en problemes a partir de 6 hores de una fallada de la soplant i 12 hores en el cas de les bombes de recirculació. Un altra opció per augmentar la resiliència seria incrementar la energia de reserva fins 260 kW, el que permetria funcionar amb les bombes i la soplant al mínim de potencia. En aquest cas, la resiliència pot ser maximitzada optimitzant la distribució de l'aire i reduint la pressió del sistema d'aeració.

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It is not only those you work with, but also who sits next to you. During my stay in Girona I shared the lab with several incredible professionals, and each had a different impact in my life. Lluís Bosch, in showing me the programmer's path you rocked my world. The skills and the philosophy you instilled in me made me a better professional. Félix Hill, you have a special genius, style, passion, artistic skill and humility, to say the least. But most of all, I will treasure the friendship of us three. And of course, thanks to Silvia, Inma and Ignasi for being lovely lab companions and good friends. Thanks to all the great people at ICRA for making me feel at home. Many thanks to all the members of the TreatRec project. Special thanks to Alessio, for challenging my work and pushing me hard, to Jan Evert for all his help and interest and to Miyako for being so much fun.

I spent a long time in Atkins (during this project it was bought by SNC Lavalin, and UK voted to leave the EU; it has been an interesting time indeed). Many thanks to my team for their help and support. Carlos, Mike, and also those who moved on: Mark, Liz, Laura, Kathryn, Andrea and Olga. Thanks to all the people who took some time to help "that guy who is a PhD student but it is here for some reason". Special mention to Sinead McElroy and, of course, Vera Jones, the kindest consultant I have ever met.

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One needs friends to keep him sane during a PhD. I want to thank here my best friends ever since school: Evelio, Pablo and Montal. Thanks for keeping me up to date with Nintendo Games, so I could feel like a geek when I didn't have time to play, and telling me that I looked awesome in the conference pictures I put on facebook. You're the best guys. I also want to thank the incredibly friendly and easy-going group of "Bristol mates", composed by the best Spaniards in Bristol I could ask for. You are the sun that shines on this island. Special thanks to two special friends, with whom I don't speak as much as I would want to. Lo ic Ciol and Rubén Soler Moreno. People like you are rare treasures; you know why you are here.

Many thanks to Lluís and Cristina from Trargisa, currently managing the treatment plant of Girona. Without your help this project would not have been possible. Thanks to all the great professionals that collaborated with me, either through publications or in conferences.

And last but not least, I thank my parents, who will be even happier than me when I get this PhD. My brother Victor, for making me believe that I lived like a king –at least one who owns lots of comics. And my girlfriend Sylvia, whose legs have served as a desktop for so many wastewater process simulations.

My PhD has been a fantastic journey thanks to you all.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ABAC	**A**mmonia **B**ased **A**eration **C**ontrol
AIWW	**A**msterdam **I**nternational **W**ater **W**eek
API	**A**pplication **P**rogramming **I**nterface
ASR	**A**ctivated **S**ludge **R**eactor
BOD	**B**iological **O**xygen **D**emand
BSM	**B**enchmark **S**imulation **M**odel
CAS	**C**onventional **A**ctivated **S**ludge
COD	**C**hemical **P**hosphorus **D**emand
CSOs	**C**ombined **S**ewer **O**verflows
DO	**D**issolved **O**xygen
DWF	**D**ry **W**eather **F**low
ECC	**E**nvironmental **C**arrying **C**apacity
GLM	**G**eneralized **L**inear **M**odel
GMP - UP	**G**ood **M**odelling **P**ractice - **U**nified **P**rotocol
GUI	**G**raphical **U**ser **I**nterface
IAM	**I**nfrastructure **A**sset **M**anagement
Ifak	**I**nstitut **f**ür **A**utomation und **K**ommunikation
IR	**I**nternal **R**ecirculation
IWA	**I**nternational **W**ater **A**ssociation
LP	**L**inear **P**rogramming
MC	**M**onte **C**arlo
MLSS	**M**ixed **L**iquor **S**uspended **S**olids
MOV	**M**ost **O**pen **V**alve
ODE	**O**rdinary **D**ifferential **E**quation
OPE	**O**rdinary **P**ollution **E**mission
OREDA	**O**ffshore & Onshore **Re**liability **Da**ta
OTR	**O**xygen **T**ransfer **R**ate
OUR	**O**xygen **U**ptake **R**ate
PID	**P**roportional **I**ntegral **D**erivative (Controller)
RAS	**R**ecirculation **A**ctivated **S**ludge
RIO	**R**eal **I**n **O**ptions
ROI	**R**eturn **O**f **I**nvestment
SA	**S**ensitivity **a**nalysis
SCADA	**S**upervisory **C**ontrol **A**nd **D**ata **A**cquisition
SVI	**S**ludge **V**olume **I**ndex
SWMM	**S**torm **W**ater **M**anagement **M**odel
TN	**T**otal **N**itrogen
TSS	**T**otal **S**uspended **S**olids
UDS	**U**rban **D**rainage **S**ystem
UKWIR	**UK** **W**ater **I**ndustry **R**esearch

UWWS	**U**rban **W**aste **W**ater **S**ystem
VFD	**V**ariable **F**requency **D**rive
WAS	**W**astage **A**ctivated **S**ludge
WEF	**W**ater **E**nvironment **F**ederation
WERF	**W**ater **E**nvironment **R**esearch **F**oundation
WRRF	**W**ater **R**esource **R**ecovery **F**acility
WRRmod	**W**ater **R**esource **R**ecovery **M**odelling
WWTS	**W**aste **W**ater **T**reatment **P**lant
WWTmod	**W**aste **W**ater **T**reatment **M**odelling

To the wastewater sector.
It has been really fun,
let's keep up the good work

Part I

INTRODUCTION

Though this be madness, yet there is method in it.

Hamlet
—William Shakespeare

1

PROLOGUE

1.1 THE ORIGIN OF RESILIENCE

Resilience was first applied to systems theory by Holling (1973). In his seminal paper, he described resilience as:

> "a measure of the persistence of ecosystems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables."

The first field that used resilience was the psychology field, with extensive use in social-science (Olsson et al.*, 2015)*

A resilient ecosystem can stay within the stable state when facing a stressor, or can adapt and enter a new stable state – i.e. change the structure while maintaining its functionality – which guarantees its existence (fig. 1 on the following page, Images 1-3). This perspective is the result of using models to monitor and manage ecosystems changes, and has gained acceptance in other fields (Folke, 2006). Today, interdisciplinary discourse on resilience includes consideration of the interactions of humans and ecosystems via socio-ecological systems. Resilience is defined in the social-ecological systems field by Walker *et al.* (2004) as:

> "the capacity of a system to absorb disturbance and reorganize while undergoing change, so as to still retain essentially the same function, structure, identity and feedbacks"

Many other definitions of resilience exist across sectors, differing somewhat on the exact properties of resilience

The engineering sector has built on this early work, particularly from the division into ecological and engineering resilience developed in Holling (1996). Holling claimed that engineered systems are different from ecological systems, stating that the former are designed to provide specified services and should be efficient, continuously working and predictable, whereas the latter focus on survival though change.

Following a perturbation in engineered systems, service provision should ideally remain unaltered. Therefore, entering a new steady state, as might occur in a natural ecosystem, is unacceptable, and human intervention is required to return the system to the original steady state (as illustrated in fig. 1 on the next page).

A key insight gained from the social-ecological field, was the idea that resilience should consider disturbances as an opportunity to reorganize and adapt to change.

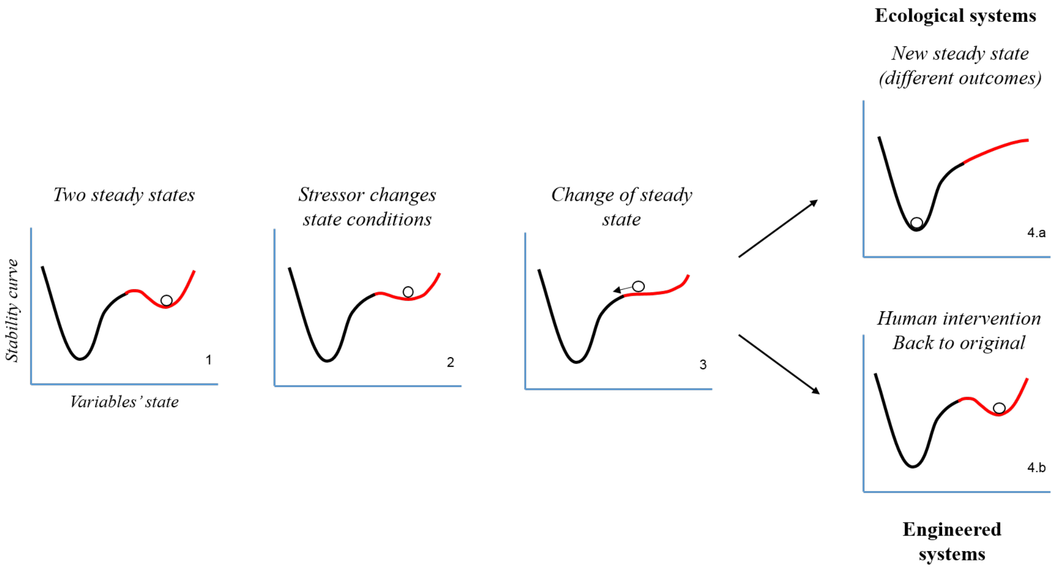

FIGURE 1. Evolution of a steady state in a system: Ecological resilience vs. Engineering resilience

Today, recent debates place resilience at the core of sustainability thinking, as systems need to become resilient to overcome future uncertainty (Moddemeyer, 2015), with the ambition that resilience is considered a boundary concept in sustainability research (Olsson *et al.*, 2015).

As a consequence, the concept of resilience in urban water management is gaining momentum in both academia and industry, drawing attention from international conferences and top level organisations [e.g. AIWW 2015 [1], WEFTEC 2015 [2], WERF [3] (Gay and Sinha, 2013), and the IWA [4] water wise cities initiative]. Other initiatives include the "100 resilient cities" project, pioneered by the Rockefeller Foundation (100RC, 2013), which gives expert support to cities around the world to become more resilient.

1.2 KEY RESILIENCE CONCEPTS IN ENGINEERED SYSTEMS

A more detailed description of the resilience elements and the state of the art of resilience assessment can be found in chapter 4 on page 51

An engineered system is a combination of components that work in synergy to collectively perform a useful function. Such a system can be represented as a set of variables, with a particular structure and relationship. Figure 2 illustrates the authors' conceptual representation of an engineering system within a resilience assessment framework.

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[1] Amsterdam International Water Week
[2] Water Environment Federation Technical Exhibition and Conference
[3] Water Environment Research Foundation
[4] International Water Association

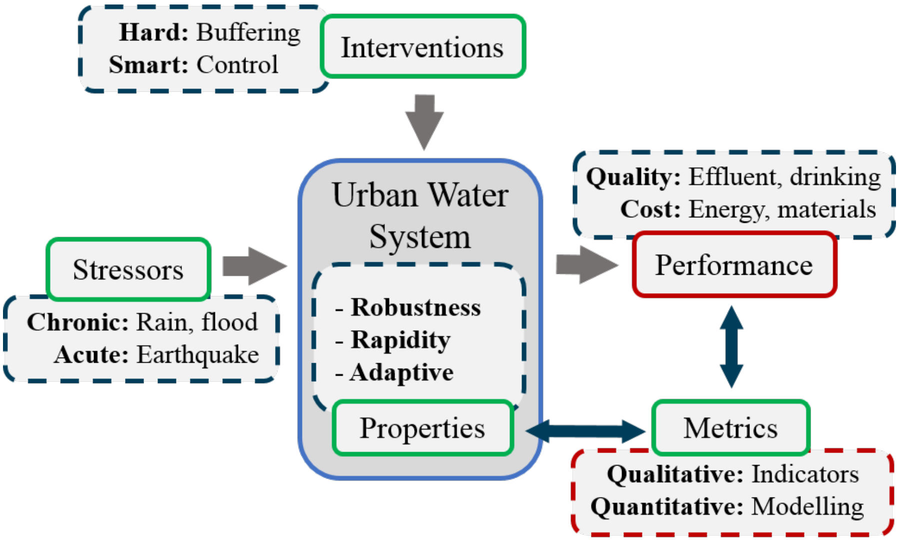

FIGURE 2. Diagram showing resilience elements and its context in an engineered system

There are four elements that need to be defined in order to grasp how resilience is understood within engineered systems: *stressors*, *properties*, *metrics* and *interventions*.

STRESSORS A stressor can be defined as a pressure on the system caused by human activities (such as an increase of pollution) or by natural events (such as occurrence of a drought), and is synonymous with other terms used in resilience literature such as threat, hazard and perturbation. These stressors affect the system performance. Whereas chronic stressors are well-known, recurrent and can often be estimated (e.g. urbanization and ageing of infrastructure), acute stressors are unpredictable, uncommon, and can have devastating consequences (e.g. floods, earthquakes, disease outbreaks and terrorist attacks).

PROPERTIES Resilient engineered systems may possess several properties that allow them to withstand, respond to, and adapt more readily to stressors, for example: robustness, redundancy, resourcefulness and flexibility. These properties may be considered indicators of resilience (e.g. Yazdani *et al.*, 2011) and have to be quantified either qualitatively or quantitatively through metrics.

METRICS Those used in resilience assessments, such as recovery time and failure magnitude, relate to the required performance or level of service of the system. Note the distinction between properties and performance. Whilst both may be quantified by metrics, the ultimate goal of resilience-based design focuses on achieving the required performance. This may be provided by properties assumed to provide resilience, but the effects of a given system property on performance are not certain without detailed analysis (Butler, Ward, *et al.*, 2016). Examples of such properties are given in section 4.2 on page 51.

INTERVENTIONS The performance of an engineered system with respect to resilience can be improved by means of interventions which alter its properties, such as installation of spare equipment, introduction of real-time control, or increasing of system capacities.

Recent work on resilience in engineering systems includes Hosseini *et al.* (2016), whose review on assessment studies provides two lessons: *i)* metrics to measure resilience are limited without a framework to guide their implementation; *ii)* urban infrastructure systems are connected and influence each other. In a recently published framework, Tran *et al.* (2017) aims to consider not only the ability of the system to absorb and recover, but also to adapt over time. To do this, they had to consider the evolution of the assets and the stressors over its entire life. The resilience definition adopted in their study is:

> "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events".

1.3 PROBLEM STATEMENT

Urban system design and optimization is evolving to reflect the consequences of natural disasters and extreme events, demanding that an increase in the level of resilience is built into infrastructure (Ganin *et al.*, 2016; Moddemeyer, 2015). Enhancing the resilience of water resource recovery facilities (WRRFs) has additional costs during design, operation and upgrade, but provides long-term savings through the recovery costs after process disruptions during the infrastructure's lifespan (Campbell, 2017). Studies have shown, that it costs approximately 50 percent more to rebuild infrastructure in the aftermath of a disaster (or any unexpected situations for which the infrastructure was not designed) than to design resilient infrastructure (Pandit and Crittenden, 2015). Methods are being developed to provide tools for objective resilience assessments. The current practice to enhance resilience in WRRFs is to ensure redundancy (or backup) for most critical equipment (e.g. pumps or blowers). However, without properly defining resilience and a common assessment method, it is impossible to ensure that the allocation of resources to enhance resilience is carried in the most efficient way. Using a model-based assessment approach allows for the quantitative evaluation of different strategies and properly allocating resources for the short, mid and long term.

Several attempts have been made to incorporate resilience in the design, operation and upgrade of WRRFs (e.g. Gay and Sinha, 2013; UKWIR, 2017) through frameworks that include "check-lists". Only three studies have proposed quantitative approaches to address resilience in WRRFs that make use of existing WRRF process models widely accepted by the community. Existing work focuses on reducing cost and enhancing resilience through real-time control (Meng *et al.*, 2017), design of resilient water management strategies (Butler, Ward, *et al.*, 2016) and system design (Sweetapple *et al.*, 2016). The proposed frameworks have been tested on virtual and semi-virtual systems [i.e. the BSM2 platform described in Gernaey, Ulf Jeppsson, *et al.* (2014) and virtual river models], and do not provide a generic framework on the overall modelling approach. Addressing this issue is one of the key goals of the thesis. A major outcome is a framework in the form of good practice guidelines to assist on model-based assessment of resilience.

1.3.1 *Measuring resilience*

There is no clear methodology to carry resilience assessments. Common practice consists of monitoring variables related to performance and then using expert knowledge to determine the level of resilience (P. Juan-García, D. Butler, *et al.*, 2017). Despite the use of quantitative measurements, the assessment is carried through "check-lists", and the experience of the technicians. This analysis is qualitative and provides evidence which is hard to compare (for example across stressors) and to use to justify investment.

Quantitative assessment provides evidence that can be used directly in decision making processes, especially around investment. The water industry has well established quantitative investment frameworks that can incorporate information relating to such stressors (UKWIR, 2017). A quantitative model –a model that uses real data to simulate a given water recovery plant– that is sufficiently accurate and fast, has the potential to support a range of decision making techniques, including sensitivity testing, scenario analysis and robust decision making. This approach would also improve understanding of the effects of stress events on the system, and be useful to test various mitigation strategies on a virtual plant.

Quantitative models have already been used for resilience assessment in WRRFs (i.e. Cuppens *et al.* (2012) worked on developing realistic disturbances to assess resilience in wastewater models). Butler, Ward, *et al.* (2016), Sweetapple *et al.* (2016) and Meng *et al.* (2017) have developed frameworks for water management, system design and integrated control respectively, which include resilience metrics. Some of the models used are stochastic and some deterministic, but common practice is to use state-of-the art deterministic models (e.g. ASM-family models). The main shortcomings of these studies are that they: *i)* do not connect to the previous and ongoing work done in ASM, *ii)* do not provide guidelines to extend their methodologies to other studies in a comparable way, *iii)* do not consider if such models can accurately reproduce acute stressors.

The WWTmod –wastewater treatment modelling– is a biennial modelling seminar series that started in 2008. In 2018 the name changed to WRRmod –water resource recovery– to reflect the change of philosophy of the industry from "treatment plants" to "water resource recovery facilities".

Concerning the third of these issues, there are many advances in the WRR modelling field which are normally presented at the WWTmod and WWRmod conferences [5]. These advances respond to challenges in process modelling, normally in view of enhancing process understanding or in view of process optimization. We believe that some of these advances are essential to deliver models capable to handle resilience assessment.

1.3.2 *An example of resilience implementation into legislation for wastewater infrastructure: United Kingdom*

England and Wales are the first countries to include resilience as a legal requirement for their infrastructure

In UK, water utilities are privatised, yet heavily regulated by the government. In 2014, the Water Act placed a requirement on Ofwat (England and Wales economic regulator) to ensure the long-term *resilience* of the water and wastewater systems. This has been identified as a priority for the Price Review 2019 (PR19), a 5-year periodic report in which the water utilities demonstrate how they are going to provide service for the next 5 years. Water and wastewater providers –as Category 2 Responders under the Civil Contingencies Act 2004– are required to cooperate and share information with other resilience and emergency response organizations.

A recent WIF seminar: resilience in the UK water industry was held to share learning around what has already been done to deliver improved resilience in UK, both within the water industry, and from other sectors.

Utilities are, however, struggling to understand what is expected from them in terms of demonstrating how they are going to be resilient for the next 5 years. To support legislation, guidance documents have been provided, such as: Ofwat "Towards Resilience" (Ofwat, 2015b), and the JESIP "Joint Doctrine and Keeping the Country Running". Further information and standardization of approaches can be found through ISO 55 000 Asset Management and ISO 22 301 Business Continuity. A summary of the UK legislation concerning water and wastewater service and resilience is illustrated in fig. 3 on the next page.

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[5] http://www.wrrmod2018.org/

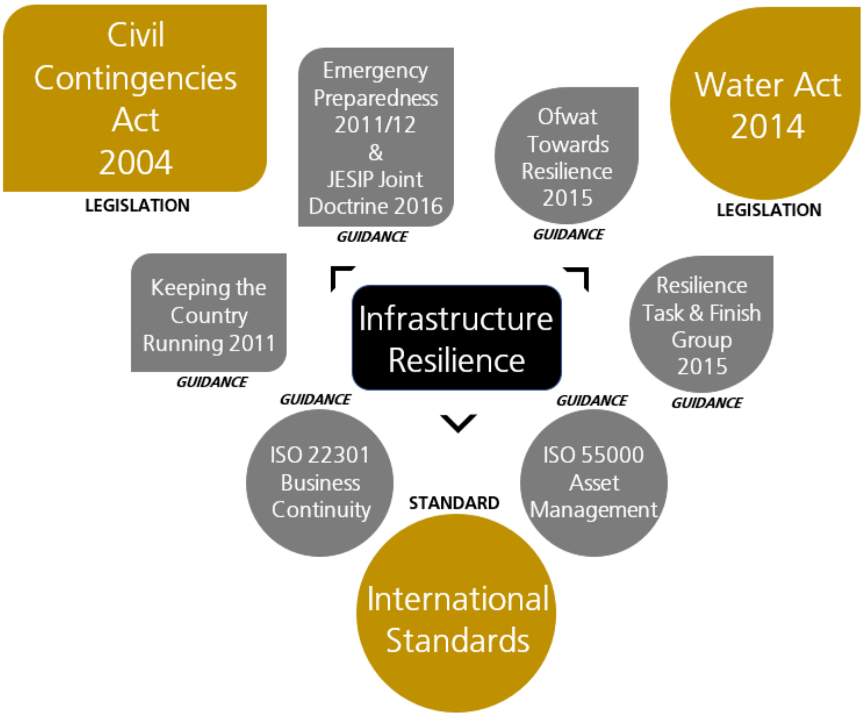

FIGURE 3. Diagram showing the legislative context around infrastructure resilience in UK

1.4 MY VISION

Water utilities have realized that any design is reliable only up to certain point. Even a design that is believed to be 99% reliable will fail eventually. On top of that, instrastructure needs to be periodically renewed and the future seems to be more uncertain that ever, in terms of both unknown threats (climate change) and stringent legislation (e.g. microcontaminants, microplastics, eutrophication). Rather than trying to predict and prepare for unobserved stressors, i.e. the unknown, the new philosophy for risk management is to create systems that can adapt to any stressors, minimise their impact, and recover fast. The focus changes from *predicting* the stressors, to studying how to create systems that are able to adapt, resist and recover to stressors. This is resilience.

The future of resilience assessment will invariably move towards a quantitative model-based approach. These tools have the ability to automate the simulation of different scenarios with varying model parameters, which enables the development and implementation of probabilistic design procedures (Belia *et al.*, 2009). Assigning uncertainty distributions rather than using a blanket safety factor approach will enable design engineers to take better informed decisions leading

In North America modelling is widely supported by the Water Environment Research Foundation (WERF) and the Modeling Expert Group of the Americas (MEGA) to designs that take the inherent uncertainties into account. This is a key factor that will lead to more resilient water resource recovery facilities, and ultimately to a more sustainable water management.

Other commercial software include: SIMBA$^{\#}$, SUMO, BioWin, GPS-X, WEST, STOAT, Lynx ASM and DESASS.

Ax explained in Hauduc *et al.* (2009), In North America modelling of wastewater treatment plants has become a standard engineering tool, with several companies developing their own commercial software. In Europe modelling is supported by the International Water Association, being used predominantly in academia, but advancing steadily into other sectors (i.e. wastewater management in United Kingdom).

However, the development of deterministic models for resilience assessment of WRRFs is not an easy task. There are guidelines to help practitioners carry out model-based assessments (Rieger, Gillot, *et al.*, 2012), but the study of resilience differs from other modelling applications. The main difference is that it is not possible to verify that the model can represent the effects of the stressors on the plant. It is important to develop guidelines during the early adoption of resilience assessment in water management practice, to create a standardized method that can be applied to several sites and allows comparison across sites and scenarios, as well as the evaluation of different strategies.

As a proof of concept, this thesis focuses on resilience enhancement against storm events and complete power outages. Protecting WRRFs against storm events has been widely studied in the literature (Schraa and Gray, 2017; Zhu and Anderson, 2017); however, the role of external recirculation sludge manipulation during hydraulic stress needs further assessment as pointed out by Zhu and Anderson (2017). Previous resilience studies use historical data to estimate the probability of stressors (Currie *et al.*, 2014). Instead, this work focuses on understanding the stressors' effects on the underlying processes that influence the performance of the plant, such as the air distribution and the system pressure.

1.4.1 *Goals*

The main goals that this thesis addresses can be summarized as follows:

1. Identify current problems and future challenges to put resilience in operation and propose a clear structure for resilience assessment studies in the wastewater field (fig. 2 on page 5). This has been achieved by means of a literature review on the state-of-the-art in wastewater treatment resilience.

2. Bring together academics and practitioners in the new field of wastewater resilience. This has been achieved by creating a collaboration between academic partners (ICRA, University of Girona), two practitioners (Atkins UK and InCtrl Solutions), and two utilities (Aquafin and Anglian Water).
3. Propose a framework for model-based resilience assessment that provides guidance on the overall modelling approach from data collection, model selection, model calibration and scenario analysis, and helps develop deterministic models for its use in real systems.
4. Validate the framework by evaluating the resilience of the Girona WRRF against two stressors: stormwater and power outage. This included calibrating and validating a model of the Girona WRRF that was used to assess plant performance, evaluate the effect of operational strategies, and capture the effects of stressors (i.e. equipment failure, stormwater).

1.4.2 *Organization*

The thesis is organized in the following way:

Chapter 1 provides the reader with an overview of the thesis topic, explains the historical background of resilience, introduces the problem statement and the researcher's personal view of the topic and summarizes the goals of the thesis, its organization and the published material produced during the thesis.

Chapter 2 provides a literature review on all the studies dealing with resilience in wastewater treatment, providing research directions and identifying those challenges relevant for the thesis.

Chapter 3 summarizes the materials and methods used in the thesis, including the data collection, the modelling approach and the software used.

Chapter 4 presents the framework for model-based resilience assessment developed during the thesis to undertake the study.

Chapter 5 contains the preliminary plant audit undertaken in the Girona plant with aims to test the dynamic air distribution model and identify stressors and vulnerabilities.

Chapter 6 contains the results of the case study on resilience assessment used as proof of concept for the framework. It features two applications: a storm event and a complete power outage.

Chapter 7 provides the general discussion of the results obtained throughout the thesis

Chapter 8 draws general conclusions on resilience theory applied to wastewater treatment management that can be inferred from this work.

1.5 PUBLISHED MATERIAL

During the 3 years of the thesis, a number of publications in peer reviewed journals and international conferences have been produced. The following list summarizes the literature produced, including both already published and ongoing projects:

PEER REVIEWED JOURNAL PUBLICATIONS The peer reviewed journal publications are the skeleton of the thesis. The first paper is the product of the literature review, which was needed to bring into context the current work. This concludes that the sector has a growing interest in resilience and provides details of the current state of research in this area. The second shows the potential of the modelling systems used in this research to represent the plant behaviour, with a focus on the aeration system. The third publication ties 3 years of research. It pulls together the knowledge acquired during the review and the understanding of wastewater systems developed in the modelling paper to create a framework on model-based resilience assessment. The framework is validated with a case study that features two of the most important stressors identified in the review and builds on the model developed during the first study.

- Peer reviewed journals
  - P. Juan-García, D. Butler, *et al.* (2017). "Resilience theory incorporated into urban wastewater systems management. State of the art". In: *Water Research* 115, pp. 149–161. ISSN: 18792448. DOI: 10.1016/j.watres.2017.02.047. URL: http://dx.doi.org/10.1016/j.watres.2017.02.047
  - P Juan-García *et al.* (2018). "Dynamic air supply models add realism to the evaluation of control strategies in water resource recovery facilities". In: *Water Science & Technology* in-press.September, pp. 1–11. DOI: 10.2166/wst.2018.356
  - Pau Juan-garcía *et al.* (In preparation). "Resilience of Water Resource Recovery Facilities: A Framework for Model-based Assessment". In: *Water Research*

INTERNATIONAL PEER REVIEWED CONFERENCES Two international conferences were attended; at which oral presentations where made. The first presentation was an early version of the second peer reviewed paper; the second a collaboration between different academic and industrial entities, showing the experiences in the application of wastewater process modeling in full-scale studies.

- Peer reviewed Conferences
    - P. Juan-García, Mehlika A Kiser, *et al.* (2017). "Exploring the potential of dynamic air supply models to evaluate control strategies: the experience at the Girona WRRF". in: *Instrumentation, Control and Automation 2017*. Quebec, pp. 303–316
    - Tamara Fernández-Arévalo *et al.* (2018). "Experiences in the application of mathematical models in full scale WWTPs: the modelling from the perspective of applied research". In: *Proceedings of the 6th IWA international conference on Water Resource Recovery Modelling*. Quebec, Canada

COLLABORATIONS Two more publications are foreseen. The first is a position paper that provides a perspective on the next generation of models. As a co-author, I have given my input on the needs of the models to be used for resilience assessment. The second publication is a reviewed version of the second conference paper to be published in a special issue of the journal *Water Science and Technology*.

- Foreseen publications
    - Position paper: Pusker Regmi *et al.* (Submitted). "The Future of WRRF modelling – Outlook and challenges". In: *Water Science and Technology*
    - Tamara Fernández-arévalo *et al.* (Submitted). "Experiences in the application of mathematical models in full scale WWTPs: the modelling from the perspective of applied research". In: *Water Science and Technology*

1.6 CONTEXT

The state of the art of resilience theory in the wastewater sector is discussed at length in chapter 2 on page 15

TreatRec is a European Industrial Doctorate (EID) project funded by Marie Skłodowska-Curie Actions (MSCA) programme of Horizon 2020.

At the time of writing this thesis, many consultancies (e.g. ARUP[6], Black & Veatch[7], Atkins UK) have expressed interest in water and wastewater resilience. Consequently, resilience was included as a research topic by the TreatRec project. This thesis is one of the 5 theses carried within the project.

TreatRec has a multidisciplinary nature as the researchers have had to spend at least 50% of their time in industry. My project is founded on the collaboration between Atkins UK and ICRA, both providing expert knowledge and training on different aspects of the wastewater sector. The project has been based in industry during 70% of the time,

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[6] City Resilience Index

[7] 2018 Strategic Directions: Water Report

and has extended the initial partnership of the project to InCtrl Solutions, a consultancy specialized in monitoring, modeling and control of wastewater treatment systems. InCtrl's technical knowledge and software capabilities have played an instrumental role in the development of this thesis.

2

LITERATURE REVIEW

2.1 STUDIES DEALING WITH RESILIENCE ASSESSMENT IN WASTEWATER TREATMENT

Resilience is increasingly used as a "buzzword" in water engineering and management, often as a synonym to sustainability, which makes difficult its use in a structured way

The literature review was carried out using SCOPUS and the keywords: 1) Wastewater OR Sewage OR Sewer AND Resilience (289 results); title, keywords and abstract were all considered. After manual filtering, only 16 papers were found that could be branded as "resilience assessment"; that is, those who directly applied resilience theory in wastewater management. A classification of the main characteristics of all studies considered is presented in table 1 on the next page. To complement the literature, 6 technical reports have been included from the following organisations: Infrastructure Asset Management Primer from WERF (Gay and Sinha, 2013) with collaboration of IWA. Ofwat, the economic regulator of the water sector in England and Wales (Ofwat, 2015a) and UK Water Industry Research (UKWIR) (Conroy, Von Lany, *et al.*, 2013).

TABLE 1. Classification of the main characteristics of the literature branded as resilience in wastewater treatment research

Authors	Resilience definition	Properties of a resilient system	Stressors	Scale[a]	Methodology and Scenarios[b]	Resilience measurement: metrics & equations[c]
Scott *et al.*, 2012	Resilience is the ability to gracefully degrade and subsequently recover from a potentially catastrophic disturbance that is internal or external in origin	None specified	Chronic: changing urban density, layout, water use/reuse; ageing of infrastructure, public perceptions	UWWS	Frame(Qual). /Yes	None specified
Butler, Farmani, *et al.*, 2014	Degree to which the system minimises level of service failure magnitude and duration over its design live when subject to exceptional conditions	Branded as characteristics: Redundant, Connected, Flexible Branded as attributes: Homeostasis, Omnivory, High flux, Flatness, Buffering, Redundancy	Chronic	UWWS	Frame.(Qual) /No	None specified
Butler, Ward, *et al.*, 2016	Degree to which the system minimises level of service failure magnitude and duration over its design live when subject to exceptional conditions	None specified	Chronic; acute	UWWS	Frame.(Qual) /No	None specified
Cuppens *et al.*, 2012	Reduced failure probabilities, reduced consequences, reduced time to recover	Robustness, rapidity, redundancy and resourcefulness	Chronic: Storm-water Influent variations	WwTS	Frame(Qual). /No	No, the focus of the paper is on definition of realistic stressors for resilience assessment
Currie *et al.*, 2014	Degree to which the asset base can perform and maintain its desired function under both, routine and unexpected circumstances	None specified	Chronic: Climate variability and machinery failures	WwTS	Quant. /Yes	Yes, performance of the treatment process and availability of the associated critical equipment.
Francis and Bekera, 2014	Ability to reduce the magnitude and/or duration of disruptive events.	Absorptive, Adaptive, Recovery	Chronic: Equipment malfunction	WwTS	Frame.(Quant) /Yes	Yes, accounts for speed to recovery and performance measured as functionality in time.
Gersonius *et al.*, 2013	None specified	Flexibility	Chronic Climate change, flood risk	UDS	Frame. (Qual) /Yes	None specified
Hopkins *et al.*, 2001	Degree to which the process can handle short-term stressors that affect the dynamics of the process	Flexibility	Chronic	ASR	Quant./ No	None specified
Hwang *et al.*, 2014	Resilience is a function of the system functionality loss and the failure event duration	Robustness, Rapidity	Chronic: Urban expansion, population growth	WwTS	Quant./ Yes	Yes, it accounts for functionality loss and event duration (time)

(continued on the next page)

TABLE 1. (continued)

Authors	Resilience definition	Properties of a resilient system	Stressors	Scale	Methodology and Scenarios	Resilience measurement: metrics & equations
Mabrouk *et al.*, 2010	Speed with which the reactor recovers following a perturbation.	Recovery	Chronic	ASR	Quant./Yes	Yes, it accounts for time to return to equilibrium of control variables.
Seith Mugume *et al.*, 2014	Ability of the UDS system to minimise the magnitude and duration of flooding resulting from extreme rainfall events.	Robustness, Rapidity	Acute: Flood risk	UDS	Quant./ Yes	Yes, robustness is represented as system performance, while recovery depends on both system performance and time.
Mugume *et al.*, 2015	Ability to maintain its basic structure and patterns of behaviour through absorbing shocks or stressors under dynamic conditions	Robustness, Rapidity	Acute: Flood risk	UDS	Quant. /Yes	Yes, robustness is represented as system performance, while recovery depends on both system performance and time
Ning *et al.*, 2013	Ability to recover from or to resist being affected by external shocks, impacts or stressors	Absorptive, Adaptive, Recovery	Chronic: Urban expansion, Runoff, Flow, Compliance	UWWS	Quant. /Yes	Yes, it accounts for pollutant thresholds in the environment of a control variable.
Schoen *et al.*, 2015	Ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions	Robustness, Adaptive, Rapidity, and Resourcefulness.	Acute events	UWWS	Quant. & Qual/ Yes	Yes, it accounts for the failure profile and time duration until recovery, measured as a control variable
Weirich *et al.*, 2015	Ability to recover from process upsets	Absorptive, Adaptive, Recovery	Chronic: Decentralization	UWWS	Quant. /Yes	Yes, cost function to evaluate the performance of a control strategy for shock recovery
Xue *et al.*, 2015	The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions	Robustness, Rapidity	Chronic: Nutrients removal, compliance	UWWS	Frame(Qual). /No	None specified
NYC Mayor's Office of Recovery & Resiliency, 2013	To adapt our city to the impacts of climate change and to seek to ensure that, when nature overwhelms our defenses from time to time, we are able to recover more quickly	None specified	Chronic and Acute: Catastrophes	UWWS	Frame.(Qual) /No	None specified
Gay and Sinha, 2013	Resilience is the ability to recover from disruption	Robustness, Redundancy, Rapidity, and Resourcefulness.	Chronic and Acute	UWWS	Frame.(Qual) /Yes	None specified
Ofwat, 2015a	Resilience is the ability to cope with, and recover from, disruption, and anticipate trends and variability in order to maintain services for people and protect the natural environment now and in the future.	Robustness, redundancy, resourcefulness, response , recovery	Chronic	UWWS	Frame.(Qual) /No	None specified

(continued on the next page)

TABLE 1. (continued)

Authors	Resilience definition	Properties of a resilient system	Stressors	Scale	Methodology and Scenarios	Resilience measurement: metrics & equations
Ofwat, 2015c	Resilience is the ability to cope with, and recover from, disruption, and anticipate trends and variability in order to maintain services for people and protect the natural environment, now and in the future.	Robustness, redundancy, resourcefulness, response, recovery	Chronic	UWWS	Frame.(Qual) /Yes	None specified
UKWIR Conroy, Von Lany, *et al.*, 2013	Resilience is the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event.	Resistance, Reliability, redundancy, Response and recovery	Chronic	UWWS	Frame.(Qual) /Yes	None specified

Table end

a Urban wastewater system: UWWS; Urban drainage systems: UDS; Water & Wastewater Treatment Works: WwTW; Activated Sludge Reactor: ASR

b (Type of model/Scenario analysis). Type of model: Semi-Qualitative (S-Qual.), Conceptual Framework (Frame.), Quantitative deterministic (Det.), Quantitative Probabilistic (Prob.); Scenario analysis included: Yes/No.

c Includes equation: (Yes/No); Description of measurement.

A graphical overview of the results is presented in fig. 4 on the following page. As the number of studies is limited, it is not recommended to extract sound conclusions from statistical data. In terms of organisation type, almost half the studies belong to academia, and the other half to government and industrial organisations fig. 4-a; only Currie *et al.* (2014), Schoen *et al.* (2015), and Xue *et al.* (2015) involve collaboration between academia, industry and government organizations. The scope of the studies fig. 4-b, includes reactors, urban drainage systems, water resource recovery facilities (WRRF) - formerly known as wastewater treatment plants and urban wastewater systems, being the last one the most common. The assessments are usually oriented to chronic stressors fig. 4-c, although general frameworks such as Butler, Ward, *et al.* (2016) were considered to target both chronic and acute stressors. Finally, there is an equal mix of qualitative and quantitative assessments, with a bias towards qualitative assessment being developed by industry, and quantitative algorithms by academia fig. 4-d. The studies have been classified in the following categories: those that propose frameworks/guidelines for water infrastructure asset management, and those that provide quantification methodologies.

2.1.1 *Studies that propose frameworks/guidelines for water infrastructure asset management*

ACADEMIA A total of 8 academic studies present a framework or guideline towards one or more resilience key elements (stressors, properties, metrics and interventions). Firstly, stressors have to be correctly defined, as stated by Cuppens *et al.* (2012). In his framework, resilience is proposed as a performance indicator for wastewater treatment, and a methodology for stressor identification is introduced, oriented to realistic modelling.

The second element is a definition for the system properties required to provide resilient performance, which is key to obtain a holistic assessment. In this respect, Butler, Farmani, *et al.* (2014) present a conceptual framework for urban water management which incorporates resilience as a main tool and discusses the qualities of a resilient system. A contribution is the classification of resilience as general or specific. General resilience refers to resilience assessment against any (all) stressors, and specific refers to assessment against a set of particular stressors. This framework is further developed in Butler, Ward, *et al.* (2016), where four different types of analysis are described: "top-down," "bottom-up," "middle based," and "circular". The framework also emphasises the difference between resilience and sustainability, and clarifies the relationship between properties of a resilient system and its performance.

A thorough description of the metrics used is presented in section 2.2.3 on page 26

Thirdly, metrics need to be established that quantify system performance, linked to system properties. Although there is no specific study on metrics for the wastewater sector, a comprehensive proposal

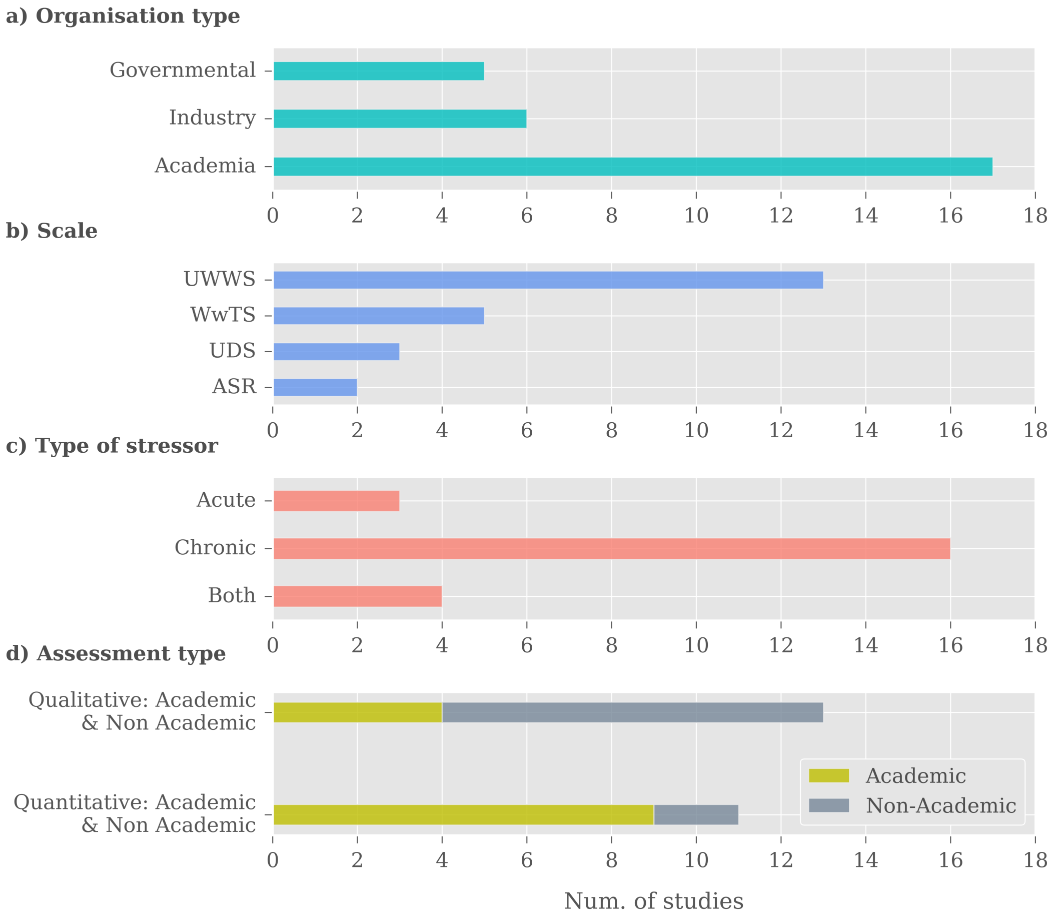


FIGURE 4. Literature review overview. The yellow line in fig. 4 represents academic studies, the grey line non-academic studies. The range of scale includes: Urban wastewater system (UWWS), Wastewater treatment system (WwTS), Urban drainage system (UDS), and activated sludge reactor (ASR)

can be found in Francis and Bekera (2014), which also includes stakeholder engagement and uncertainty assessment aspects. This framework is applicable to the assessment of resilience in wastewater sewer networks as demonstrated in Mugume *et al.* (2015). Sweetapple *et al.* (2016) also present a framework on resilience assessment, with a focus on the interplay between reliability, robustness and resilience in the context of control. In this study, robustness is measured independently to account for performance under extreme conditions, which are not considered under resilience. The study uses multiobjective analysis to assess these properties, and concludes that strategies that focus on reducing greenhouse gas emissions, may compromise total nitrogen concentration in the effluent under extreme conditions.

The last key point in resilience assessment is a guidance for benchmarking interventions used to increase resilience. No framework has addressed how to decide which interventions should be benchmarked, and which properties should be considered on each case.

Resilience is also incorporated within scenario planning for wastewater treatment in Scott *et al.* (2012) and Gersonius *et al.* (2013). The first is a pioneer in resilience theory, as it presents a measure (scenario planning) for better wastewater management within the context of resilience; the definition used is:

> "the ability to gracefully degrade and subsequently recover from a potentially catastrophic disturbance that is internal or external in origin"

It considers two properties: robustness and rapidity, and including reliability measurement. The second introduces Real In Option (RIO) analysis (a technique to handle uncertainties in infrastructure at managerial level) as a method to identify an optimal set of adaptive strategies to increase resilience to climate change. Lastly, Xue *et al.* (2015), places resilience as a key component in the evaluation of system sustainability and highlights the lack of standardization of resilience metrics.

INDUSTRY AND GOVERNMENT Resilience concepts are well embedded into infrastructure asset management as frameworks developed by industry and government bodies. The first example is from New York City, NYC Mayor's Office of Recovery & Resiliency (2013), which originated after the devastating effects of Hurricane Sandy. It includes the lessons learnt after the event with a specific section on water and wastewater. Another example is the comprehensive guide to water infrastructure management developed by the Water Environment Federation and International Water Association (WEF/IWA), which briefly introduces resiliency concepts, qualities and metrics (Gay and Sinha, 2013). In this case, resilience is simply defined as the ability to recover from disruption, and four properties are considered: Robustness, Redundancy, Resourcefulness and Rapidity. The guide stays at a general level and does not provide sufficient details for practical implementation; it also recognizes the need for future resilience implementation in the water sector and the integration within broader infrastructure management frameworks.

After Hurricane Sandy in October 2012, New Yorkers realized that a new approach was needed about the changing climate; one that considered future risks, which resulted in the New York City Mayor's Office of Recovery and Resiliency

The water economic regulator in the UK (Ofwat) produced two reports to incorporate resilience assessment, Ofwat (2015a,c). These two reports aim to set the role of resilience in wastewater, explain how service providers can implement it in their systems, and how to assess resilience and regulate it, from the point of view of the providers and the regulator. The UKWIR foundation produced two reports (Conroy and De Rosa, 2013; Conroy, Von Lany, *et al.*, 2013) presenting a set of Resilience Planning Guidelines intended to help introduce good practice concepts and approach to support development of water company business plans through resilience planning. These guidelines define resilience as the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event, and defines five properties: Resistance, Reliability, Redundancy, Response and Recovery.

2.1.2 *Studies that propose quantification methodologies*

A total of 9 studies were found that focused on quantification methodologies for assessment of resilience to various stressors. These studies are commonly used in optioneering projects for wastewater service options in urban planning. Ning *et al.* (2013), investigate wastewater infrastructure resilience to long-term changes (e.g. urban expansion and massive population movements). To this end, a grid-based database is used to build a map of land-use that estimates the impact over the years that these stressors will have on infrastructure systems. The study highlights the trade-off between infrastructure capacity, environment needs and urban expansion and suggests, governance and infrastructure resilience must be taken into account in urban planning. On a different line, three works have contributed to the study of performance of centralized versus decentralized wastewater systems. Weirich *et al.* (2015), presents a tool to predict resilience using probabilistic modelling. A 41 month data-base of effluent violations of BOD, TSS and ammonia in 211 WRRF was used to calibrate the model, which was then used to predict the effects of decentralized systems. Although the results are not conclusive, the study contributes to the resilience tools stockpile with an approach that uses time-series to predict current resilience levels at large scale, and can be complemented with other modelling approaches. Similarly, Hwang *et al.* (2014) investigate the resilience of a regional water supply system through a criticality analysis of five water supply components, of which wastewater reuse was analysed under two design conditions: *i)* centralized versus decentralized wastewater treatment, and *ii)* decentralized wastewater plant location. Schoen *et al.* (2015) on the other hand, carry out a technological resilience assessment that includes centralized/decentralized wastewater systems and centralized drinking water systems with water reuse scenarios. In this case, four system properties and performance measures assumed indicative of resilience were reviewed under a range of acute stressors such as extreme weather and wildfire. It is important to note that no "best" system was identified due to key uncertainties in the study.

The use of centralized vs. decentralized wastewater treatment is an ongoing debate. The right choice is case specific, which should be studied from a holistic perspective such as that of resilience

Another use for resilience assessment is in design studies, using resilience and its qualities as a criteria. Mabrouk *et al.* (2010) calculates reactor resilience considering time to recovery, instead of effluent limit restrictions, using influent variations as a stressor. It concludes that a reactor design that maximizes productivity may not be optimal in terms of resilience. A similar study is carried out by Hopkins *et al.* (2001), focusing only on flexibility analysis, defined as the degree to which the process can handle long-term changes to the steady state. This study develops a flexibility index that can be used to design resilient wastewater treatment. Resilience is also used in asset maintenance studies. It can be used as a means of assessing investment decisions, operational and maintenance planning to optimize budget. This is the case of Currie *et al.* (2014) in water treatment systems, which builds a reliability study on random component failures, considering actual failure rates with chronic stressors in all components. A complementary case for an acute stressor can be found in Mugume *et al.* (2015) and Seith Mugume *et al.* (2014). The first study describes a methodology to quantify resilience of Sustainable Drainage Systems (SUDs) that combines hydraulic performance with utility performance metrics during flooding (exceedance) conditions. In their second study, this methodology is used to evaluate the performance of an urban drainage system when subjected to a range of structural failure scenarios resulting from random cumulative link failures. Through detailed modelling of the SUDs, the study concludes that capital investments are insufficient to enhance resilience, unless they are combined with asset management strategies such as cleaning and maintenance.

WEFTEC is recognized as the world's largest annual water quality technical conference and exhibition

The AIWW is a biennial event towards a sustainable water environment that gathers experts from cities, industries, and utilities to combine real-life water cases with innovative solutions

Finally, some workgroups and conferences give consideration to resilience infrastructure either by studying the effect of acute stressors or resilience challenges. From WEFTEC 2015, Goldbloom-Helzner *et al.* (2015) has developed a guide to identify flood resilience vulnerabilities in the United States based on real flooding experiences, and Wood *et al.* (2015) analyses the interventions that San Francisco's combined sewer system needs to implement in order to cope with climate change. From conference proceedings in the AIWW 2015, Schellekens and Ballard (2014) present a new planning methodology to improve financing of resilience projects that takes into account stakeholders involvement early in the project.

2.2 ANALYSIS OF THE REVIEWED ACADEMIC STUDIES

A comprehensive analysis of the 17 reviewed academic studies was conducted, covering stressors evaluated, system properties analysed, metrics (i.e. the different methodologies, equations and scenario analysis) and interventions proposed to implement resilience. The low number of papers matching the characteristics of the search is relevant in itself. A recent study on the use of resilience as an engineering concept in literature undertaken by Hosseini *et al.* (2016), showed that the engineering sector is a late adopter of the term, compared to environmental, ecology and psychology sectors; and it is only within the engineering fields of oil, gas and nuclear that resilience assessment has become common practice OREDA (2009).

2.2.1 *Stressors assessed*

Detailed information on the studies and the stressors they assess can be found in table 1 on page 16.

All case studies assess a particular system under one or more stressors. As has been indicated in fig. 4 on page 20, chronic stressors are far more commonly studied than acute, with eighteen studies giving consideration to them. The most common stressor is *influent variation*, including *stormwater*. In second place *chronic equipment failures* (including ageing infrastructure) and *urban changes*. In third place, concern is also given to *increasing water use* and *climate change*. Other stressors mentioned are *run-off*, *stringent legislation* and *public perception*. On the other hand, only five studies considered acute stressors. The most common acute stressor is *flooding*, although it can be considered chronic in certain regions of the world such as England. Other acute stressors assessed in literature are: *cold weather event, storm event, power outage, short-term drought and wildfire* (Schoen *et al.*, 2015); the WERF report (Gay and Sinha, 2013) also mentions *hurricanes, severe thunderstorms, blizzards, and tornadoes*.

All the studies can serve as a set of examples for similar case studies. However, a methodology should be used to systematically characterize stressors in a way that can be used in models, such as the one proposed in Cuppens *et al.* (2012).

The number and type of stressors studied to date, is still a small subset of all the possible stressors that can affect wastewater infrastructure. Furthermore, perhaps due to the predominance of physical models, the range of stressors includes mainly those of physical nature. Regards have been given to compliance and public perception (Weirich *et al.*, 2015), but only from a scenario analysis point of view, there is no methodology to include them in the metrics analysis yet.

2.2.2 *Properties of a resilient system*

As shown in table 2, the most commonly studied properties were *rapidity* (12 out of 17 academic studies), followed by *robustness* (11) and *flexibility* (7). All the other qualities such as *connectivity* and *redundancy* were considered in less than 3 studies, and 4 qualities only are defined

TABLE 2. Overview of the properties found in the current resilience literature, and the studies including them

Properties	**Definition**	**Studies**
Robustness or absorptive	Ability to reduce severity of unexpected perturbation and to maintain its function operating in dynamic conditions	Cuppens *et al.*, 2012; Francis and Bekera, 2014; Hwang *et al.*, 2014; Mugume *et al.*, 2015; Seith Mugume *et al.*, 2014; Ning *et al.*, 2013; Schoen *et al.*, 2015; Weirich *et al.*, 2015; Xue *et al.*, 2015; Scott *et al.*, 2012; Sweetapple *et al.*, 2016
Rapidity or recovery	Time to recover from a perturbation to the previous steady state	Cuppens *et al.*, 2012; Francis and Bekera, 2014; Hwang *et al.*, 2014; Mabrouk *et al.*, 2010; Mugume *et al.*, 2015; Seith Mugume *et al.*, 2014;Ning *et al.*, 2013; Schoen *et al.*, 2015; Weirich *et al.*, 2015; Xue *et al.*, 2015; Scott *et al.*, 2012; Sweetapple *et al.*, 2016
Flexibility or adaptive	Accommodate changes within or around the system; and establish response behaviours aimed at building robustness and recovery	Butler, Farmani, *et al.*, 2014; Francis and Bekera, 2014; Gersonius *et al.*, 2013; Hopkins *et al.*, 2001; Ning *et al.*, 2013; Schoen *et al.*, 2015; Weirich *et al.*, 2015
Connectivity	Degree of interconnectedness or duplication	Butler, Farmani, *et al.*, 2014; Butler, Ward, *et al.*, 2016; Francis and Bekera, 2014
Redundancy	Degree of overlapping function in a system	Butler, Farmani, *et al.*, 2014; Butler, Ward, *et al.*, 2016; Cuppens *et al.*, 2012; Francis and Bekera, 2014
Homeostasis	Effective transmission of feedbacks between component parts	Butler, Farmani, *et al.*, 2014
Omnivory or resourceful	Diversifying resource requirements and their means of delivery	Butler, Farmani, *et al.*, 2014; Cuppens *et al.*, 2012; Schoen *et al.*, 2015
High Flux	High availability of resources through a system	Butler, Farmani, *et al.*, 2014
Flatness	Avoiding hierarchical systems to adjust behavior quicker in front of sudden disturbances	Butler, Farmani, *et al.*, 2014
Buffering	Design with studied excess capacity	Butler, Farmani, *et al.*, 2014

by Butler, Farmani, *et al.* (2014) and not applied to a case study. When this list is compared to system properties or performance associated with resilience in other fields (e.g. urban resilience), three properties are still missing: *reflective* understood as using past experience to inform future decisions. *Inclusive*, in the sense of social action, such as prioritize broad consultation to create a sense of shared ownership in decision making. Lastly, *integrated*: a system that brings together a range of distinct systems and institutions. The 'reflective' property is addressed indirectly by Butler, Ward, *et al.* (2016), who identify 'learning' as an important step in increasing resilience .System properties considered in urban resilience studies typically have a broader scope (IWA, 2017), which may be attributed to the inclusion of social and political stressors.

Figure 2 on page 5 identifies the relationship between the variables of the system and how they relate to properties that make the system resilient. Current literature only covers a small set of properties, with fewer studies covering multiple properties. The system properties and/or performance attributed to resilience, their definitions and scope, varied depending on the project. This has been observed not only in the wastewater field, but throughout the whole engineering sector Hosseini *et al.* (2016). Consensus on these subjects is the cornerstone of resilience assessment benchmarking. Although not every study has to include all the potential properties and performance measures, it is good practice to specify which ones will be covered. Studies such as infrastructure system reliability and vulnerability assessments, are currently conducted without reference to resilience. The integration of properties and performance contributing to resilience into a standard framework, will allow all the studies to be linked in a holistic assessment.

2.2.3 *Metrics*

12 studies have developed a methodology to calculate resilience, either with qualitative or quantitative metrics. In the reviewed studies, qualitative assessments tend to be "top to bottom"; they start big, and then draw conclusions on the small components. Quantitative assessment, on the other hand, has required in-depth knowledge and characterization of the different parts of the system under study.

QUALITATIVE There are 3 studies dealing with qualitative metrics. Butler, Farmani, *et al.* (2014) proposes an assessment that is intended to be descriptive, by means of a study of the properties and performance of a resilient system. In this framework, further developed by Butler, Ward, *et al.* (2016), four types of resilience analysis are considered: top-down, middle-based, bottom-up and circular. These approaches are classified and recommended based upon the following elements: emerging threats, intervening water system, system performance, and social, economic, and environmental consequences. The third study, Schoen *et al.* (2015) actually uses both qualitative and quantitative assessments. The qualitative part of the study is carried out by evaluating the critical functions of the system for the following properties: robustness, adaptive capacity/redundancy, rapidity, and resourcefulness, against the following short-term events: (1) extreme cold-weather event ; (2) storm event; (3) power outage; (4) widespread wildfire; (5) drought; and long term (climate change): (6) temperature increases; (7) changes in precipitation; and (8) sea level rise.

QUANTITATIVE All the studies proposing a metric, including the previous 3 studies in the qualitative section, also considered a quantitative measurement of resilience. The quantitative approach typically consists of linking the properties of the system to its performance, which is done by monitoring system variables affected by stressors. The most common system variables used to measure the performance of the system are: effluent quality/pollution units, level of service, energy consumption and monetary loss. This may result into a mathematical equation that assigns a value to resilience, although often the equation is not provided and the analysis is done by direct comparison of results between scenarios. Thus, depending on the case study, specifically the properties considered, the variables monitored and the level of detail needed, the resulting approach might be very different. Nevertheless, these studies have three clear points in common: they contain a model of the system; develop a range of possible scenarios, and one or several state variables are monitored to serve as indicators of system performance. Scenarios can be created randomly, using Monte-Carlo (MC) techniques, arbitrarily, or deliberately, using a consistent methodology from literature such as Lempert *et al.* (2015).

Cuppens *et al.* (2012) puts an emphasis on stressors. It proposes a methodology to identify and generate the stressors, characterise and monitor them. Resilience is then calculated through the modelling of the system after the affected processes of the plant are studied, and their dynamics modelled under a range of scenarios. Metrics which contribute to resilience assessment are loss of functionality (considered a measure of robustness), and recovery time (rapidity). This approach can be expressed mathematically in eq. (1), which has in turn been illustrated in fig. 5 on the next page. It has been adapted and put into practice by 6 studies in the literature review.

$$Res = \int_{t_0}^{t_n} (M_0 - M_t)\,dt \tag{1}$$

Where t_n is the total duration of the perturbation until recovery; t_0 is the initial time when the perturbation occurs; M_0 is the initial state of the chosen metric (a state variable representative of the state of the system) and M_t is the value of the metric at a measured time t.

This methodology has been applied to the whole range of scales, from reactor to UWWS. Francis and Bekera (2014) builds on this system and includes also the adaptive capacity; the study assesses resilience of any system above reactor level, using an equation that considers 3 properties: absorptive (robustness), adaptive and restorative (rapidity). This is done by giving consideration to the profile of the recovery curve through a set of parameters shown in eq. (2) on the following page.

$$Res = \rho_i = S_p \frac{F_r}{F_o} \frac{F_d}{F_o} \tag{2}$$

Where S_p is the speed recovery factor, F_o the original stable system performance level, F_d the performance level immediately post-disruption, and F_r the performance at a new stable level after recovery efforts have been exhausted.

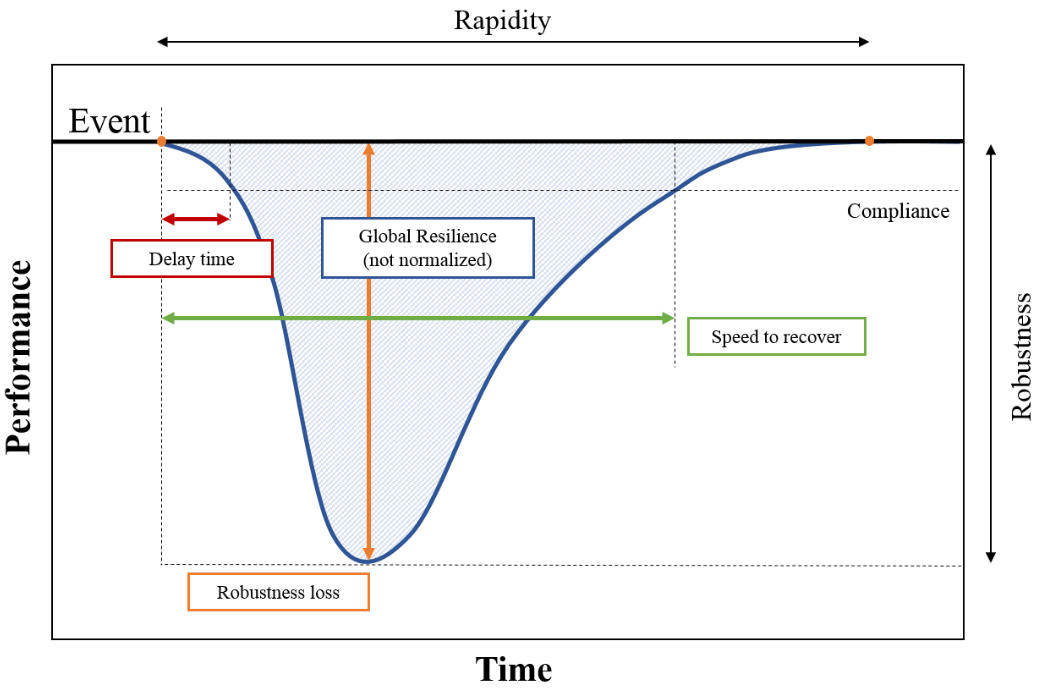


FIGURE 5. Graphical representation of assessment of resilience to a stressor. Adapted from Mugume *et al.*, 2015

At WRRF level, Sweetapple *et al.* (2016) uses this methodology to evaluate the trade-off between resilience and reliability by means of a virtual case study. Two resilience indicators, $R_{deficit}$ and $R_{duration,max}$, are used, based on performance deficit and maximum performance failure duration respectively under a range of disturbance magnitudes. These are calculated as follows:

$$R_{deficit} = \sum_{k=0}^{1} \frac{\sum_{i=1}^{N}(T_i - E_i)}{\sum_{i=1}^{N} T_i} \tag{3}$$

$$R_{duration,max} = \sum_{k=0}^{1} \frac{T_{total} - \max\limits_{k=1...M}(F_k)}{T_{total}} \tag{4}$$

Where k is the normalized disturbance magnitude, N the number of time steps, T_i the threshold at time step i, E_i the threshold exceedance at time step i, T_{total} the total duration of the evaluation period, F_k the duration of failure event k, and M the number of times failure state is entered.

The novelty of their approach is the use of multiobjective optimization to assess the cost-function of an intervention to build resilience, and further evaluation by means of multiobjective visualization tools.

This approach can be extrapolated to balance the cost/value between resilience implementation with other objectives in a project, such as reliability in this case.

Ning *et al.* (2013) use the method in fig. 5 on the preceding page to calculate the resilience of an urban wastewater system, with a focus on urban drainage, against long-term changes of chronic stressors. Resilience is calculated by the Storm Water Management Model (SWMM) and empirical models based on land-use to monitor pollution levels under a range of future urban development scenarios. Two metrics are used: Environmental Carrying Capacity (ECC) and the Ordinary Pollution Emission (OPE). The advantage of this approach is that allows to calculate severity on account of a specific threshold. The implementation is shown in eq. (5).

$$R_v = \frac{(O_{in} + D_{in}) - In^{ECC}}{DL} < 0, \text{ If } OPE - ECC > 0, \tag{5a}$$

$$R_v = 0, \text{ If } OPE - ECC = 0, \tag{5b}$$

$$R_v = \sqrt{\frac{(DP^*_{in} \times DR^*_{in}) - In^{ECC}}{DL^2}} > 0, \text{ If } OPE - ECC < 0 \tag{5c}$$

Where OPE is the ordinary pollution emission; O_{in} is the quantity of the ordinary influent caused by the residential population; D_{in} is the quantity of the disturbance influent caused by the floating population and urban runoff; In^{ECC} is the quantity of virtual wastewater that contains the threshold amount of pollutants to achieve the maximum requirement of the environmental constraint; DL refers to the designed load of a WRRF; DP^*_{in} and DR^*_{in} represent the maximum quantity of domestic wastewater and urban runoff, respectively.

Also on sustainable urban drainage systems (SUDs), Seith Mugume *et al.* (2014) applies this methodology fig. 5 on the preceding page using as the main indicators flood intensity and duration. The model is a combination of a linked network and the previous SWMM. In a second study, Mugume *et al.* (2015) runs the model across a range of scenarios to benchmark interventions for SUDS resilience to floods. At a smaller scale, Mabrouk *et al.* (2010) applies this it at reactor level; using a model obtained by deriving the mass balances of biomass and pollution. The objective is to show the effect of small chronic stressors (e.g. influent variability) on the rapidity (property) of a reactor, and how it affects the optimum design parameters. Finally, Schoen *et al.* (2015) used it for a resilience assessment focused on technology benchmarking, of an urban wastewater system. The qualitative analysis is complemented with a quantitative model (eq. (6)); the equation draws two profiles: a failure-profile accounting for robustness and redundancy, and a recovery profile accounting for resourcefulness and rapidity. Unlike the previous cases, this model also considers the lifespan of the infrastructure.

$$\text{Resilience (RI)} = \sum_{j} \left(Ti_j + F_j \Delta Tf_j + R_j \Delta Tr_j \right) / \text{lifespan} \tag{6}$$

Where j is the challenge index, T_i is the time to the incident, F is the failure profile, T_f is the duration of the failure, R is the recovery profile and T_r is the duration of the recovery. The main drawback of the approach presented in fig. 5 on page 28, is that it requires a physical characterization and accurate knowledge of the process dynamics of the system. An alternative to this method is statistical modelling. Weirich *et al.* (2015) used a statistical approach based on a Generalized Linear Model (GLM) for predictive modelling of WRRF performance. It uses pollutant concentrations in the effluent as indicators and 10-year long series scenarios. A second example of a statistical approach is Hwang *et al.* (2014), this time using a Linear Programming (LP) model. The LP model computes the resilience of a water supply system in different case scenarios, such as decentralized versus centralized wastewater treatment. Although these models do not have the level of detail of an in-depth, white-box model, this approach can be used for first-pass simulation purposes, mainly at planning level.

Resiliece assessment needs a more broad definition of properties that includes social and economical aspects, and a flexible, *yet* structured *approach to design resilience assessment*

Overall, the key insights that could be drawn on to increase the understanding in the wastewater sector are: first, the "linking properties to performance" approach is limited, in the sense that it cannot take into account non-physical variables of the system that cannot be directly measured, such as public involvement. In this area, complementary qualitative approaches are necessary. Secondly, different levels of model detail should be used depending on the project. At planning level, statistical models are more appropriate, whereas at small scale, physical models provide better understanding and prediction power, at the expense of increased data requirements and calibration costs.

2.2.4 *Proposed measures to increase resilience*

As can be seen in many of the studies that presented a practical case study, a resilience assessment not only focuses on assessing the overall resilience of the system qualities, but also benchmarking its current state against interventions that can potentially increase resilience. This point of view is also directly stated in the WERF foundation report: Water Infrastructure Asset Management Primer Gay and Sinha (2013). A classification of the interventions found in the literature have been presented in table 3.

TABLE 3. Summary of interventions to enhance resilience found in current literature.

Measure	Type	Description	References
Buffering. Storm water tanks	Natural risks	Adequately planned overcapacity and storm tanks for extra storage	Currie *et al.*, 2014; Mabrouk *et al.*, 2010; Mugume *et al.*, 2015; Technical reports
Spare replacement equipment and back-up	Mechanical failures	Overlapping in key equipment, storage of spare parts	Currie *et al.*, 2014; Mugume *et al.*, 2015; Technical reports
Asset renewal	Mechanical failures	Removal of old, and installation of new equipment.	Currie *et al.*, 2014; Schoen *et al.*, 2015; Technical reports
Active asset management	Preventive maintenance	Sensors and real time control, multiobjective optimisation	Butler, Farmani, *et al.*, 2014; Sweetapple *et al.*, 2016; Technical reports
Centralized/ decentralized	Planning	Centralize/decentralize a system when appropriate depending on the system's needs	Butler, Farmani, *et al.*, 2014; Hwang *et al.*, 2014; Schoen *et al.*, 2015
Assets protection	Natural risk (climate change and floods)	Proofing critical assets from natural risks by means of hardened infrastructure, barriers and water-proofing pumps	Currie *et al.*, 2014; Technical reports
Increased repair strategy	Mechanical failures	Identifying the most sensitive equipment and increasing its checking/calibration times	Currie *et al.*, 2014; Technical reports
Energy production	Planning	Cogeneration facilities and other energy interventions	Butler, Farmani, *et al.*, 2014

The most common intervention is *buffering* (extra capacity), straightforward and widely used, particularly when dealing with variable influent (the most common stressor). In second place, *equipment back-up and asset renewal*, which are directly related to equipment failures (second common stressor). Other interventions include *increased repair strategy, active asset management and asset protection*. The first one is also related to equipment failures, the second one to long-term changes (such as the third most common stressor: climate change); and the last one concerns protection against acute stressors (catastrophic events) such as flooding. Finally, *energy production* is also mentioned in one study. As with the properties discussed in the current literature, the interventions proposed focus on technical aspects. Changes in the behavioural, social or governance paradigms are rarely considered, and only if the previous interventions did not work. Social education towards water reuse for example, plays a vital role in budget constraints (Hering *et al.*, 2013).

A key point is that an intervention that contributes positively to one property of resilience may impact negatively on another (Sweetapple *et al.*, 2016). In order to test the effectiveness of interventions, these have to be assessed holistically against a range or properties and scenarios of stressors. As an example, automated control and storm tanks increase system's robustness and rapidity, but active control requires higher maintenance costs and trained staff requirements, which create an added vulnerability. In countries lacking qualified personal or with high energy prices, it may not be the best solution. On the other hand, having active control entails data gathering which might enhance reflectivity (learning from past experiences) and resourcefulness (e.g. flexible catchment permitting).

2.3 FUTURE RESEARCH DIRECTIONS

Chapter 4 on page 51 proposes a methodology to solve some of the problems in this section, including identify relevant stressors and choose metrics in a resilience assessment case study

The use of resilience as a sustainability concept in wastewater systems management is at an early age. Academia, industry and government agencies need to work together for a successful implementation. Based on the outcomes of this review and the mentioned reports from US and UK water organisations, the following research directions have been identified to help the research community and the professionals working in resilience of urban wastewater systems. Each category falls under one element of resilience assessment.

2.3.1 *A comprehensive lens of system stressors*

The current literature review considers stressors in areas such as: natural risk, mechanical failures, and planning. However, this is still a small subset of the whole range of stressors the wastewater sector will be facing in the future. Climate change is likely to affect wastewater treatment in several ways and the underlying climate variability is anticipated to increase (Milly *et al.*, 2008). Flooding is also expected to increase in future (Campos and Darch, 2015a), prolonged periods of dry weather will lead to sedimentation in sewerage systems, followed by increased 'first flush' pollutant loads (Campos and Darch, 2015b). More treatment may be required if consents are tightened to reflect changes in environmental flows. Mechanical failures and preventive planning are rarely considered in water management, and neither are trends within the systems such as wearing or reduced efficiency. The challenge is to develop a comprehensive study of stressors affecting wastewater treatment, to understand all the potential vulnerabilities. A special case is that of the unknown stressors, unpredicted stressors that have profound effects on the performance of a WRRF during its lifetime (Dominguez, 2008). For known stressors, the challenge is to properly combine available tools (e.g. influent generators, reliable WRRF models and cost models) to economically evaluate alternatives in the operation/design/upgrade. However, in order to deal with extreme uncertainty, instead of adapting the system for one stressor, a qualitative assessment to enhance the system properties is more appropriate. Complementary approaches include using adaptive planning techniques such a scenario analysis, and flexible managerial perspectives.

2.3.2 *Common framework for resilience properties and assessment*

The main challenge in resilience assessment is to have a framework that manages resilience effectively, making possible the comparison between cases. Resilience should be defined as a change in our philosophy to assess and prevent risk. This way, the need for standardization is combined with the need for being flexible, namely, an appropriate methodology for each study. Having a common definition that reflects all properties would constrain resilience assessment, since each case has specific necessities and thus will assess different properties. Each system is different and therefore different solutions are necessary, whereas a unique methodology would constrain the effectiveness of the solutions. A framework should act as a guideline that: *i)* contains a study of possible stressors, *ii)* summarizes different methodologies, sets of properties, tools, metrics and cases study, *iii)* includes interventions to increase resilience to be benchmarked. This would help companies to adapt their assessments to the requirements of the project. Hitherto, only Butler, Ward, *et al.* (2016) has considered different types of interventions of resilience assessment under the same framework. Complementary, wastewater systems are still part of a bigger picture, where they integrate with other urban resources. A functional framework should not only understand and manage resilience as asset based, but also provide feedback to broader frameworks (i.e. Infrastructure Asset Management (IAM) frameworks).

2.3.3 *A comprehensive lens of system metrics, and how to measure them*

As stated in the analysis section, in order to take into account the whole set of properties of a resilient system it is necessary to use both qualitative and quantitative assessment. The challenge is on developing a set of metrics that link to all the properties, and create an algorithm or equation to monitor and measure them. The set of metrics should include alternatives for each property, and also account for different scales, and levels of detail depending on the goals of the study. To date, there is no clear method to link non-physical properties to the performance of the system. Qualitative assessment has a key role in incorporating economic, social, legal and governmental variables into the assessment.

There are a number of tools available that have already been used in the literature review, such as deterministic or probabilistic modelling techniques, influent generators, adaptive planning techniques, Monte Carlo algorithms, sensitivity analysis, multi-objective optimisation, and sets of stressors and measures, to mention but a few. The challenge is to reorient these tools to resilience assessment, taking into account resilience metrics and quantitative algorithms. A second challenge will be choosing state variables for monitoring the performance; we need to identify which variables are representatives of the system's state, and develop efficient technology and procedures to monitor them. The third challenge resides on the integration of academic tools into practice. Quantitative assessment (modelling) is mainly developed in academia, and often disconnected from practitioners.

2.3.4 *Interventions to increase resilience: investment is both the main barrier and driver to resilience planning*

The level of acceptable resilience in the system is determined not only by the needs identified in a resilience assessment, but also by the cost-assessment of the interventions. Investment in wastewater infrastructure is one of the biggest challenges for the water sector. Therefore, the uncertainty on the cost-assessment will be decisive in the decision making, and potentially the main barrier to resilience implementation.

However, water industries should not see investing in resilience as an extra cost, but as a means to encourage further investment by other stakeholders. By understanding the resilience of the plan, we understand the risk profiles, which might attract new investment opportunities. Resilience financing needs to be involved in the project as early as possible (Schellekens and Ballard, 2014). The challenge is to design a framework to appropriately benchmark and demonstrate the effectiveness of interventions. This will unlock new investment opportunities, whereas not understanding resilience will be the actual barrier to the investment.

2.4 CHALLENGES ADDRESSED IN THIS THESIS

Some of the challenges outlined in this section have been addressed during the thesis, specifically:

1. The critical literature review provided in chapter 2 on page 15 summarizes the state of the art in resilience applied to the wastewater sector and recommends the use of quantitative resilience

assessment for future applications. Figure 2 on page 5 provides a roadmap for the structure of resilience assessment.

2. Chapter 4 on page 51 proposes a framework for model-based resilience assessment that provides guidance on the overall modelling approach from data collection, model selection, model calibration and scenario analysis; based on the GMP unified protocol of the IWA (Rieger, Gillot, *et al.*, 2012). This will serve as a first step to develop a comprehensive framework to study resilience in the wastewater sector. The goal is to provide guidelines on the development of deterministic models for quantitative resilience assessment in real-life systems.

3. Unlike most modelling applications, in resilience assessment there is no guarantee that the model will represent the behaviour of the stressor. Chapter 4 will explore how to obtain an acceptable degree of fidelity, and how to make the best use of models by studying the effect of stressors rather than its outcome. Likewise, model selection is of paramount importance for this process. In case of equipment malfunction and power shortcut, the model needs to be able to respond realistically. For this reason, the thesis explores the use of State of the Art dynamic aeration modelling and mechanistic equipment models, available in SIMBA$^{\#}$, with the support of InCtrl. In chapter 5 on page 59, the dynamic aeration model is tested for resilience studies within a case study oriented to energy optimization.

4. Proofs of concept for the framework are provided in Chapter 6 on page 81. Two stressors have been assessed: *i)* Stormwater event with sludge washout and *ii)* Complete Power Outage. This exercise includes screening of relevant stressors for the plant and models available for simulating them.

Part II

METHODOLOGY

Mathematics is the key and door to the sciences.

* * *

Measure what is measurable, and make measurable what is not so.

UNSOURCED
—Galileo Galilei

3

MATERIALS AND METHODS

This section contains: *i)* detailed information about the data campaigns carried out on-site, *ii)* an introduction to the Girona WRRF, *iii)* the approach used to simulate the plant and measure resilience and *iv)* to the software used to build-up a model and run the simulations.

3.1 THE GIRONA WRRF: PLANT LAYOUT AND OPERATION

The Girona WRRF receives a DWF of $55\,000\,\mathrm{m}^3\,\mathrm{d}^{-1}$ of domestic and industrial wastewater, and has the capacity to serve a population equivalent of 275 000 (currently serving a population of around 206 250 from the following municipalities: Bescano, Fornells de la Selva, Girona, Sant Gregori, Salt, Sant Julia de Ramis, Sarria de Ter, Vilablareix, and Aiguaviva). Figure 6 on the following page shows an aerial picture of the plant. The plant is an activated sludge system in a five-stage Bardenpho configuration. Even though this configuration is designed for biological removal of nitrogen and phosphorus, currently phosphorus is removed chemically. Per legislation, the plant is allowed a maximum total nitrogen concentration of $10\,\mathrm{mg\,L}^{-1}$ in the effluent (measured as 24-hour composite samples). Typical influent pollutant concentrations are presented in section 3.1. Plant detailed schematics for layout, pumps and volumes can be found in figs. 8 to 10 on pages 46–48 respectively.

The activated sludge process was discovered in the UK: experiments on treating sewage in a draw-and-fill reactor (the precursor to today's sequencing batch reactor) produced a highly treated effluent. Believing that the sludge had been activated, in a manner similar to activated carbon, the process was named "activated sludge"

The biological stage consists of two parallel treatment lanes. Each lane has a total volume of $14\,360\,\mathrm{m}^3$ split into 7 zones, of which 4 are aerated, as shown in fig. 7 on page 41. Sludge is wasted from secondary settlers and is anaerobically digested. Reject water from

TABLE 4. Average pollutant concentrations in the Girona WRRF influent

Pollutant	**Concentrations**	
mg/L	Average	Peak
BOD_5	225	300
COD	550	725
TSS	250	320
TKN	58	69
TP	8	10

FIGURE 6. Aerial of the WRRF in Girona

the centrifuges is sent back to the head of the plant. A first analysis showed that the load profile of the plant is heavily dependent on the schedule of the reject water, which varies depending on the usage of the sludge dewatering centrifuges. On average, the reject water represents up to 11% of the incoming nitrogen load and 0.5% of the phosphorus load.

The aeration system consists of a main blower and a support blower that service two main header pipes, each controlled by an automatic valve, which are followed by 4 manual valves, one per aeration zone. The list of air supply equipment can be found in table 5 on page 42. The reactors are aerated using fine-bubble diffusers. Air distribution is controlled by online measurements of dissolved oxygen (DO) currently placed at the end of the biological reactor (AER4). The air supply is controlled by the average DO of both lanes by varying the speed and guide vanes of the blowers (fig.7: Signal). The DO measurement in each lane manipulates the positions of the automatic main header valves. A *most open valve* (MOV) algorithm makes sure that at least one valve is kept open. Generally, the algorithm maintains the valve in lane 1 at 70% opening, and the valve in lane 2 oscillates to redistribute the air between the two lanes.

The idea of MOV is to gradually decrease the airflow pressure so that the most open air flow valve becomes almost fully open. Then the pressure drop will be minimised and further energy savings are possible

The facility has been designed with diffuser tapering and non automated control valves to each of the individual aeration grids; the highest airflow is therefore delivered to the first aerated zone and then diminishes with each successive zone. The number of diffusers in the aerobic zones are 480 in AER1, 366 in AER2, 180 in AER3 and 144 in AER4, respectively. Likewise, the piping system also decreases in diameter from 0.25 m to 0.15 m, as well as the valves' maximum flow capacity. As a result, the air distribution of the plant is significantly biased towards reactors AER1 and AER2.

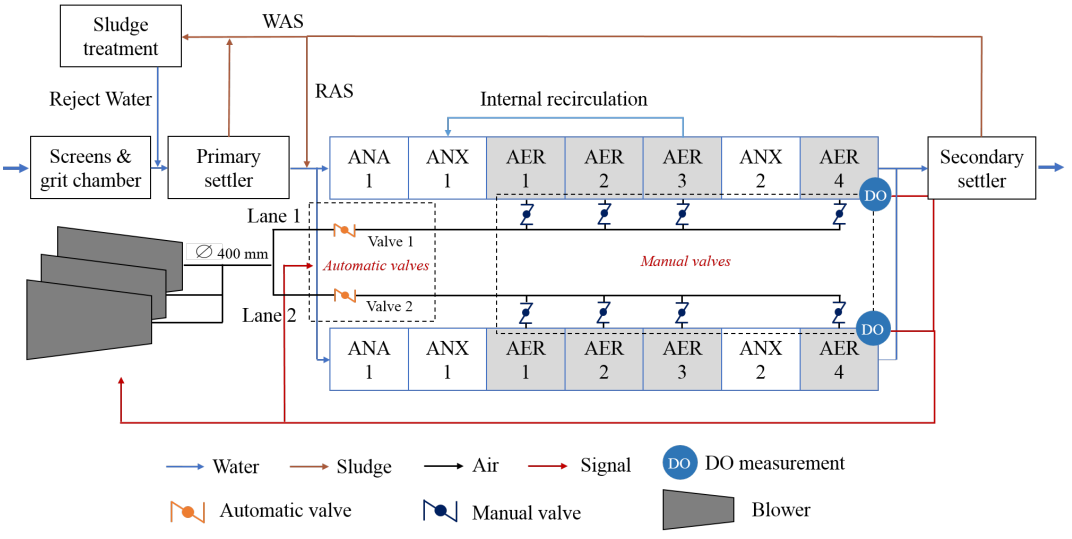


FIGURE 7. WRRF configuration (water line) & aeration system. ANA: Anaerobic, ANX (Anoxic), AER (Aerobic), WAS & RAS (Waste and return activated sludge respectively)

The WRRF in its current form has been in operation since 2008. Since then, operators have been manually optimizing the aeration system by adjusting the manual valves in each lane and changing the location of the DO sensor. The DO sensor was finally placed in AER4, and the DO setpoint set to $2\,\mathrm{mg\,O_2\,L^{-1}}$. This configuration results in concentrations in reactors AER1 and AER2 around 1 to $2\,\mathrm{mg\,O_2\,L^{-1}}$ and reactor AER3 shows very low DO concentrations (0.5 to $1\,\mathrm{mg\,O_2\,L^{-1}}$).

Overall, this results in an energy consumption in the biological reactors of about $0.2\,\mathrm{kWh\,m^{-3}}$ of treated wastewater. This is at the lower end of typical ranges, which are between 0.13 and $5.5\,\mathrm{kWh\,m^{-3}}$ (Enerwater, 2015), albeit the system is unable to maintain the DO setpoint during influent peaks. In low load situations, a blower turn-down limitation forces the air control valves to close as much as possible, which results in the blowers working against an increased system pressure and therefore reduced efficiency. The loss of control authority leads to an oscillation of the oxygen concentrations in reactors AER1-3. The response of the plant to stressors is slowed down as the only sensor is located at the end of the lane (and after an anoxic zone). Another effect of having AER1 and AER2 at higher DO concentrations to compensate for low DO in AER3 is more energy consumption. Oxygen transfer is more efficient at low airflow rates and low DO concentrations (Diego Rosso *et al.*, 2008).

TABLE 5. List of air supply equipment modelled (technical specifications and SIMBA# model

Equipment	**Brand**	**Num. Units**	**SIMBA# parameters**
Blower	Turbocompressor ABS HST 9000 Sulzer	1 (2 standby)	Efficiency curve, surge curve, max. and min. airflow
Automatic valves	Butterfly, centered axis. Belgicast	2	Kv values, max. and min. airflow
Manual valves	Butterfly, centered axis. Belgicast	8	Kv curves, max. and min. airflow
Diffusers	ABS Nopon disc diffuser system PIK 300	2280	# of diffusers per grid, pressure drop and SOTE[a]curves, submergence, oxygen transfer parameters
Pipes	-	2 lines (8 reactors)	K factor, roughness, length, diameter, fittings

[a] Standard oxygen transfer efficiency

TABLE 6. Number of diffusers, pipe diameter and valve setting on each aerated reactor

Reactor	**Diffusers** (#)	**Valve diameter** (m)	**Valve opening** (%)
AER1	480	0.25	0.325
AER2	366	0.2	0.45
AER3	180	0.15	1
AER4	144	0.15	1

3.2 DATA COLLECTION

The data used in this thesis consists of a tracer test and two data campaigns. In the following subsections each data collection process is described in detail. The fist data collection was used to calibrate the model described in chapter 5; the second data collection was used to calibrate the model in the resilience case study (chapter 6).

3.2.1 *Tracer studies of the anaerobic digester and waterline*

Two tracer studies were conducted in the Girona WRRF. The first one was in one of the anaerobic digesters of the plant. The purpose of the tracer study in the digester was to determine its hydraulic retention time, assess its mixing performance, and verify the flow rate of the reactor. These factors are important for the model and discovering ways to improve the performance of the anaerobic digester. The second was in the liquid stream of the Girona WRRF. The purpose of the waterline tracer study was primarily to determine the flow distribution between the two lines of biological treatment and quantify the hydraulic retention time of the plant, both of which are important for building a model that accurately represents the plant. The plant is currently being run by the company *Trargisa*.

The tracer study of the anaerobic digester showed that the reactor had very good mixing (no dead zones or short-circuiting), a hydraulic retention time of about 18 days, and a flowrate of approximately 380 $\mathrm{m^3\,d^{-1}}$, which verified the value that the managers of the plant had given us.

3.2.2 *First data campaign*

Firstly, plots of dynamic data from 2013 were collected and data was manually extracted using a program that converts graphical plots into digital values. Secondly, 2015 data from the plant's SCADA system was extracted. This data include the required parameter values at 5-minute intervals, which was an improvement over the once-per-day interval of the 2013 data. Thirdly, sensors were installed to measure ammonia, COD, pH, and temperature in the influent and two aerated zones in the biological reactor. The sensors collected 18 months of data. In addition, detailed information about the plant's aeration system, such as pipe lengths, diameters, blowers, valves, and diffusers were also collected. This information was critical to calibrate a dynamic air distribution model of the plant's aeration system.

3.2.3 *Second data campaign*

The second data campaign included the collection of SCADA data and PDF plot digitalization from 2016-2017. Additionally, electrical consumption data was collected from the aeration system, and an intensive data sampling campaign of 3 days was carried, from July 18th to July 20th of 2017. The data collected are listed below:

ENERGY AUDIT Reports and registers on energy consumption at the WRRF made available by *Trargisa*

ONLINE SENSORS NH_x, pH, K, Temperature, and COD at the inlet of the bioreactor at Girona WWTP and in the second aerobic zone were continuously monitored utilizing two on-line ion-selective electrodes (ammo::lyser^{TM}) coupled to a monitoring station (S::CAN Messtechnik GmbH, Austria).

ENERGY READINGS Files created by the energy monitoring system (referred to as fluke) on the energy consumed by the blowers at the WRRF. The data span 10 months, and measure the consumption of the 3 blowers.

LAB ANALYTICS Grab samples were taken 4 times a day at 3h intervals (starting at 9:00am to 18:00pm) during 3 days. A visual aid of the grab samples timing and zones is available in appendix A on page 115 in fig. 37 on page 119. Automatic samplers took samples every 3 hours during a 72h period. All the samples were analysed for NH_x - N, NO_2 - N, NO_3 - N, K and PO_4 - Pby ionic chromatography. Samples were filtered at 0.2 µm.

GAS HOOD READINGS Three hoods were placed in the plug-flow reactor in the aerated zone 1, 2 and 3, respectively. N_2O and CH_4 emissions were monitored online using a multi-hood gas system.

The history of the BOD_5 test dates back to 1908, when the Royal Commission on Sewage Disposal (UK) chose the parameter as an indicator for organic pollution in the Thames River, which in turn, has a nominal temperature of 20 °C and retention time of five days at the tidal zone.

TRARGISA DATA Registers of the company in charge of the treatment plant (Trargisa), containing COD, BOD_5, MLSS and nutrients data of the clarifier, reactors and effluent daily average. All samples were analysed according to standard methods (APHA, 1999).

SCADA SYSTEM SCADA data containing the following information:

- Hydraulic system
  - MDC-125: Influent Flow
  - MDC-339B: Biological Influent Flow
  - MDN-315B: Internal Recirculation Flow, Lane 2
  - MDN-315C: Internal Recirculation Flow, Lane 3
  - MDC-318A: External Recirculation Flow, Sec. Clarifier 1
  - DC-318B: External Recirculation Flow, Sec. Clarifier 2
  - DC-318C: External Recirculation Flow, Sec. Clarifier 3
  - DC-601: Sludge Flow into Centrifuges
  - DC-517: Primary Solids Flow
  - DC-319: Wastage Flow
  - DC-520: Thickened Sludge Flow
- Aeration system
  - DP-316: Blower frequency
  - DC-342: Airflow delivered from blowers
  - RA-308B: Proportional Valve, Line 2
  - RA-308C: Proportional Valve, Line 3
  - DO-317B: Dissolved Oxygen, Lane 2, Aerated Zone 1
  - DO-317E: Dissolved Oxygen, Lane 2, Aerated Zone 4

  - DO-317C: Dissolved Oxygen, Lane 3, Aerated Zone 1
  - DO-317F: Dissolved Oxygen, Lane 3, Aerated Zone 4

3.3 PROCESS MODELLING WITH SIMBA#

SIMBA# is a modern simulation platform for the mathematical modeling, simulation, optimization and management of wastewater treatment plants. It provides a fully integrated simulation platform with libraries for the dynamic modeling and simulation of wastewater treatment plants, collection systems, and rivers. Key functionalities for this project include:

- Integration of static design, dynamic simulations, equipment sizing and selection
- Development and testing of real-time control strategies
- A full library of wastewater treatment unit processes
- Advanced settling, control and aeration equipment models
- Capability for inline scripting

The process model developed using SIMBA# includes all the previously mentioned sub-models. The plant schematics used to build the main model layout are shown in figs. 8 to 10 on pages 46–48, corresponding to the plant layout, pumps and volumetric information respectively. The model layout as seen in the graphical user interface is shown in figs. 12 to 14 on pages 62–64. Appendices C and D on page 143 and on page 145 show the complete workflow automation in SIMBA# from data collection, influent generation, scenario analysis, sensitivity analysis and data extraction, processing and plotting.

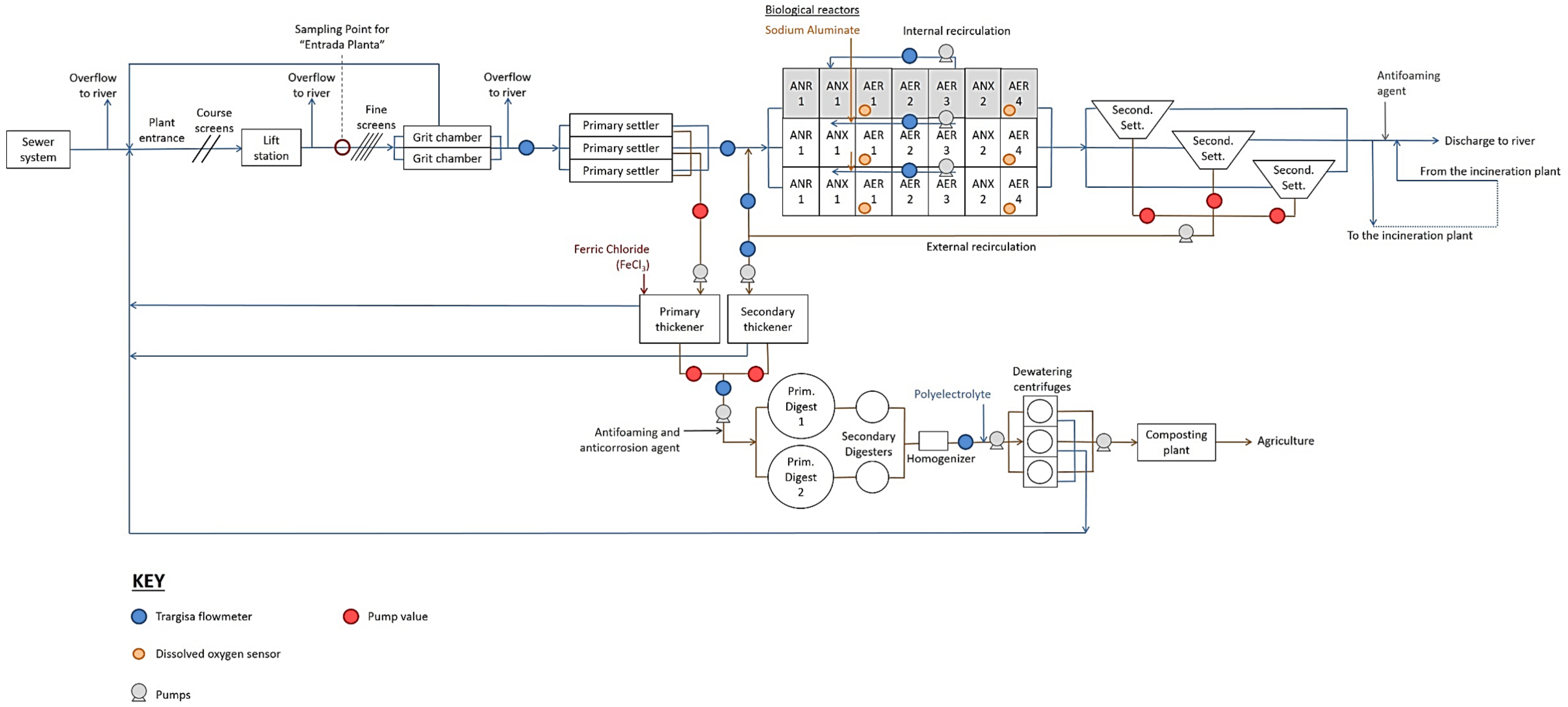
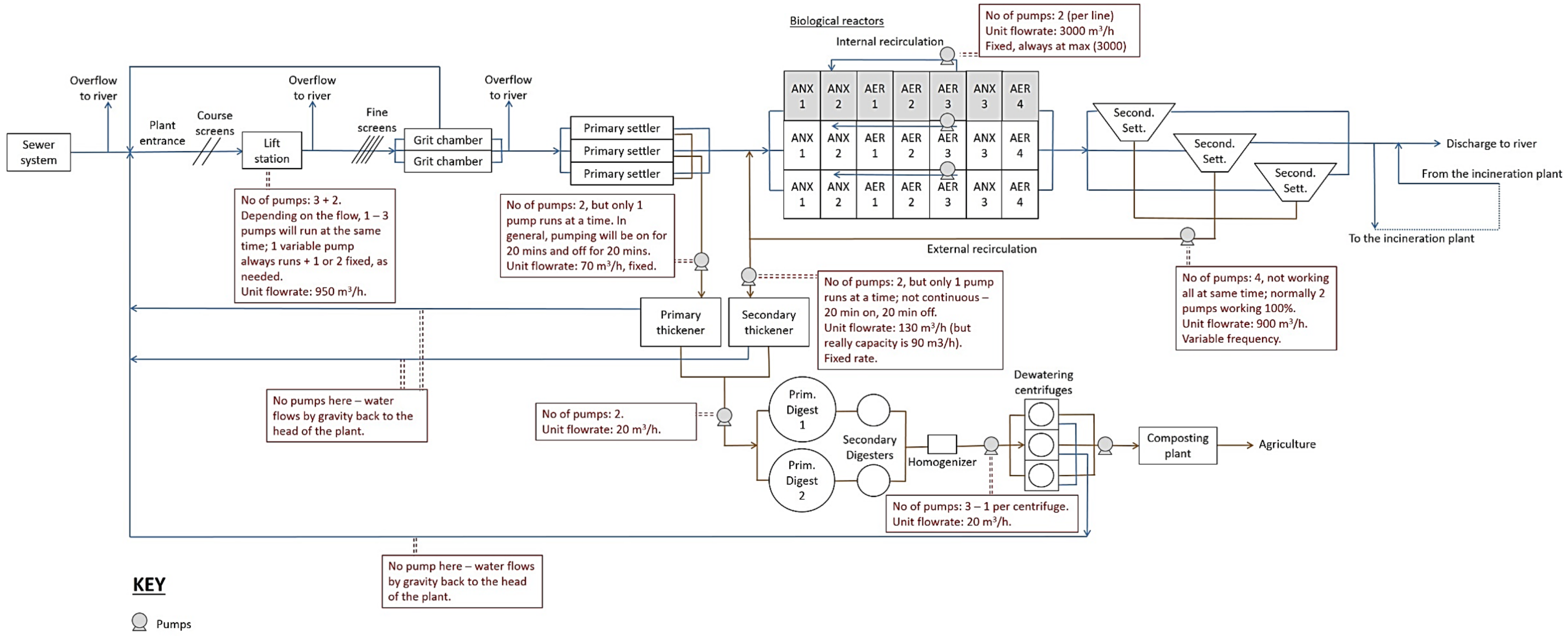


FIGURE 8. Girona WRRF: Detailed Schematic



No of pumps: 3 + 2. Depending on the flow, 1 – 3 pumps will run at the same time; 1 variable pump always runs + 1 or 2 fixed, as needed. Unit flowrate: 950 m³/h.

No of pumps: 2, but only 1 pump runs at a time. In general, pumping will be on for 20 mins and off for 20 mins. Unit flowrate: 70 m³/h, fixed.

No of pumps: 2 (per line) Unit flowrate: 3000 m³/h Fixed, always at max (3000)

No of pumps: 2, but only 1 pump runs at a time; not continuous – 20 min on, 20 min off. Unit flowrate: 130 m³/h (but really capacity is 90 m3/h). Fixed rate.

No of pumps: 4, not working all at same time; normally 2 pumps working 100%. Unit flowrate: 900 m³/h. Variable frequency.

No pumps here – water flows by gravity back to the head of the plant.

No of pumps: 2. Unit flowrate: 20 m³/h.

No of pumps: 3 – 1 per centrifuge. Unit flowrate: 20 m³/h.

No pump here – water flows by gravity back to the head of the plant.

FIGURE 9. Girona WRRF: Overview of pumps

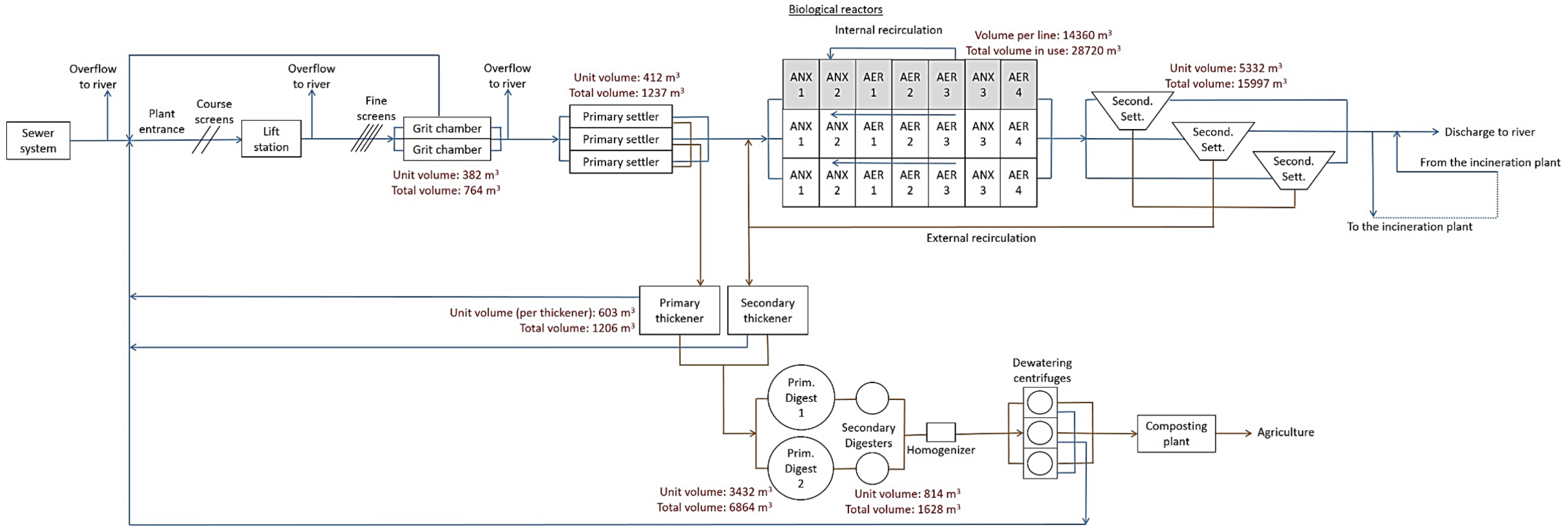


FIGURE 10. Girona WRRF: Overview of volumes

Part III

RESULTS

Sometimes science is more art than science

RICK AND MORTY
—Rick Sanchez

4

FRAMEWORK FOR MODEL-BASED RESILIENCE ASSESSMENT

4.1 OVERVIEW

This section presents a framework in the form of good practice guidelines to assist on model-based assessment of resilience. It builds on the GMP protocol, adding a new application for wastewater treatment modeling

The framework has been developed after *i)* extensive literature review on the state of the art in resilience modelling (chapter 2) and *ii)* practical experience in performance modelling realism (chapter 5).

4.2 TERMINOLOGY AND DEFINITIONS

The following terminology should be used for a resilience assessment:

RESILIENCE

Several definitions of resilience exist within the engineering field, but the definition applied in this work is: "Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same predisturbance process, form, identity, and feedbacks" (Walker *et al.*, 2004).

RESILIENCE ASSESSMENT

Resilience assessment is a study that aims to measure the degree of resilience of any given asset, network or system against one or multiple stressors in combination (P. Juan-García, D. Butler, *et al.*, 2017).

STRESSORS

Stressors are any disturbances that pose a risk to a system's function and performance. In the case of wastewater this might be: storm events, industrial spills or equipment failures to mention a few. The definition of a stressor in this study covers extreme events, not daily or seasonal variations.

Stressors can also be distinguished into *Observed Stressors* (an event has occurred in the past and data is available) and *Unobserved Stressors* (the stressor has been identified by a theoretical

Although this thesis focuses on physical stressors, it must not be overlooked how these are sometimes originated from human causes. A clear example would be the Aquiris case, a ghastly story of how the disagreement between an industrial corporation and a government caused a major environmental scandal analysis, but no observations exist). Especially for *Unobserved Stressors*, a model-based analysis of the impact is beneficial as the model should represent (if properly set up) the behaviour of a plant.

LEVELS OF FUNCTIONALITY

The level of desired performance that a WRRF must maintain under normal operation (full functionality) and under the impact of a stressor (reduced but accepted functionality). The plant may also change its function temporarily to better cope with the situation and prevent long-lasting performance reduction, e.g. if the plant receives a storm flow above the capacity of the full treatment (biological treatment), part of the flow can receive primary treatment and then be diverted to a storm tank. However, this strategy involves a state of temporal reduced functionality, and therefore must be specified in the compliance permit.

PROPERTIES OF RESILIENCE

Resilience is an emerging property of a system, it arises from the combination of different characteristics that are linked and act together. The most relevant in water resource recovery systems are:

ROBUSTNESS

Ability to reduce the severity of the impact of an unexpected stressor (e.g. robustness against equipment failure can be improved by redundant equipment, against power outage by having emergency generators or multiple power sources and industrial spills can be attenuated by early warning systems and diversion tanks).

RAPIDITY

Time to recover from a stressor to an accepted state (e.g. nitrification capacity may be limited by the available volume than can be aerated, or be hindered by a breakdown in the biological process). The time to recovery is defined as the period of time since the stressor is detected until the system recovers the level of performance it had before the stressor.

ADAPTABILITY

Ability to accommodate changes within or around the system and establish response behaviours aimed at building robustness and increasing the speed of recovery. Starts in the design phase and incorporates flexibility and redundancy in operation.

IMPACTED VARIABLES

A variable that is sensitive to the effects of the stressor under study. The ideal variable will be easily measurable and relevant for the desired level of functionality, i.e. effluent quality, energy and resource consumption, cost.

RESILIENCE METRICS
Resilience metrics are indicators of the performance of the system, relative to the desired level of functionality. Metrics link the value of the impacted variable to the properties, and provide quantitative meaning (i.e. if studying clarifier performance under storm conditions, the maximum total suspended solids (TSS) in the effluent can be an indicator of robustness).

4.3 FRAMEWORK STEPS EXPLANATION

The GMP unified protocol (Rieger, Gillot, *et al.*, 2012) provides an application matrix where various model applications are described. In this section, resilience assessment is added as a new application. Each step is developed with a focus on those aspects of resilience assessment that are relevant to the GMP unified protocol. A diagram that illustrates the revised protocol is shown in fig. 11 on the following page.

4.3.1 *Project definition*

The first step involves identifying the *goal* of the resilience assessment, the *stressors* to be included in the study (e.g. related to a previous simulation study), and the required *level of complexity* of the model to execute the resilience assessment. The goal may vary in scope from understanding the effect of a stressor, to undertaking a thorough evaluation of strategies to enhance resilience against one or various stressors. Various procedures to decide which stressors should be included in the study have been developed in quantitative frameworks, such as Conroy, Von Lany, *et al.* (2013). Firstly, an initial study of system and environmental characteristics is used to short-list relevant stressors; secondly, historical failure data is used to define the probability of a stressor happening, and expert opinion is used to assess the potential disruption level. Finally, stressors are prioritised for detailed assessment depending on the potential service loss, as an indicator of relevance. If a previous model is available, it can be used to identify the main vulnerabilities. A list of stressors in a conventional Activated Sludge (CAS) plant is provided in table 7 on page 57.

1. Project definition

GMP

- Problem statement
- Objectives
- Requirements

Resilience

- Level of complexity
- Identify main stressors

2. Data collection

GMP

- Plant audit
- Data collection
- Verification

Resilience

- Collect data from *observed stressors*
- Stress tests to measure *unobserved stressors*

3. Plant model set-up

GMP

- Model selection
- Control actions and time constraints
- Prepare outputs

Resilience

- Base-line model
- Model *observed stressors*
- Model Operator response
- WRRF behaviour and adaptation model

4. Calibration and Validation

GMP

- Uncertainty propagation
- Calibration & Validation

Resilience

- Stress tests to calibrate *unobserved stressors*

5. Simulations and results

GMP

- Set up of scenarios
- Interpret results

Resilience

- Dynamic simulations
- Set-up metrics
- Sensitivity analysis

FIGURE 11. Proposed structure of a resilience assessment

4.3.2 *Data collection*

It is recommended to carry out a monitoring campaign during the occurrence of an *observed stressor* to calibrate the model. This involves close monitoring of the magnitude of the stressor (e.g. duration of a power outage, or duration and intensity of a storm event), and of the loss of performance (e.g. a time series of pollutants discharged to the environment or energy consumption). With regards to unobserved stressors (e.g. equipment failure) it is necessary to design specific experiments to measure the impact of these stressors in a measuring campaign. For stressors which cannot easily be created, model-based tools can be used. A special case is a change in the influent to the plant; WRRF influent generators are valuable tools to generate temporal series of input variables to the system (Martin and Vanrolleghem, 2014). Examples are the generation of inputs for the models describing a storm event (Talebizadeh *et al.*, 2016), or the presence of inhibition or toxic substances (Pons, 2007; C. Rosen *et al.*, 2008).

4.3.3 *Plant model set-up*

The model of a WRRF consists of a series of sub-models, for example, influent, bioreactors, pumps, airflow, sensors, hydraulics, settling tanks. In the case of resilience, 3 sets of sub-models need to be set up and calibrated:

1. sub-models for observed stressors, which include the perturbance itself (i.e. stormwater, catchment, spill, power outage, equipment malfunction). These models can be complex, such as a rain generator that takes into account the catchment characteristics, or simple, such as a timer to schedule the blower shut-down period;
2. sub-models for the operator response to the occurrence of a stressor, commonly simulated with a slowly tuned controller on any available operational parameters. Examples of such models are the DO setpoint control based on effluent ammonia, or wastage pump flow control based on reactor's MLSS;
3. the baseline model, composed of various sub-models to represent the adaptation of the operational settings by the operators (i.e. biokinetic, air-supply, equipment, sensors, and operational settings such as RAS variations, change of probe position for DO control).

For each process there exists different sub-models available with varying levels of complexity, which must be correctly balanced to be fit for the project definition (Nopens, Arnaldos, *et al.*, 2014). The process models have been developed to be used during normal operating conditions, whilst resilience deals with extreme conditions. A screening of the current sub-models available for each process should be carried out, with emphasis in ensuring that the model can describe the conditions and behaviour triggered by the stressor. For the case study in chapter 6 on page 81, a power outage is simulated, which requires equipment models (sensors, actuators, blowers, piping system) that are able to represent the behaviour of the aeration system accurately. This feature was considered to be so critical, that the models were tested a priory in a previous study, to understand the relationship between energy, performance and equipment. In table 7 on the next page, the stressor screening is linked to literature on ongoing research of each relevant sub-model.

4.3.4 *Calibration and Validation*

Ideally, calibration/validation should be carried out firstly without the occurrence of stressors and secondly against the stressors. Only *observed stressors* for which there is data available can be calibrated. For *unobserved stressors*, preference is given to designing specific experiments or *stress tests* to gather data on stressors and system responses accurately, and particularly under extreme conditions. These can be generated through changes in operational settings (valve positions, blower capacity, position of DO probe for control). The timing and specific actions must be carefully registered, and ideally be accompanied by detailed monitoring of the impacted variables.

4.3.5 *Simulation and results*

Table 8 on page 58 shows a metric proposal to account for robustness, rapidity and adaptability in a conventional activated sludge (CAS) plant. A visual representation of the metrics is shown in fig. 5 on page 28.

Studying the effect of an unobserved stressor adds deep uncertainty to the model. In order to reduce the uncertainty first principle models of equipment like pumps and blowers can be used. Beyond adding realism, the usefulness of a detailed integrated process and equipment model lies in its ability to capture the plant's behaviour under the effect of stressors. By carrying a sensitivity analysis of the stressor intensity and mitigation strategy parameters, it is possible to find thresholds in the behaviour of the system, and understand why they occur (e.g. how the settling capacity is impacted by different combinations of stormwater flows, settleability, and storage capacity). A description of the uncertainties in a modelling project and options to deal with them can be found in Belia *et al.* (2009) and Talebizadeh *et al.* (2016).

TABLE 7. Screening of physical stressors and sub-models affected, including recent developments towards model-based resilience assessments in ASM. This is by no means a comprehensive list of all possible stressors but a working example for the treatment plant that will be assessed in the case study

Process	Stressor	Sub-Model	Description	Reference
Hydraulic & settling	Stormwater	Primary and secondary settlers	Layered settler models need to be used to represent the effect in performance and hydraulic stress of storms for which there is no data available	Torfs *et al.*, 2017; Bürger *et al.*, 2013
			If we need quick decision making and real-time control for wet weather, empirical settler models for fast simulation are needed	Benedetti, 2016
		Mixing	Stormwater affects mixing in reactors, which effects can be assessed e.g. with computational fluid dynamic (CFD) modelling	Rehman *et al.*, 2016
Biokinetic	Influent fractionation and temperature variations	Population dynamics and microbial diversity	Many processes in WWTPs (e.g. microbial diversity) are governed by population dynamics that depend of influent, process and control dynamics. Abrupt changes need to be considered as they may have an important effect on the process performance	Vannecke *et al.*, 2016; Nopens, Torfs, *et al.*, 2015
	Toxics	Inhibition dynamics	Reduced bacterial growth due to toxins in the influent	Pons, 2007
		Toxicity	Increase in decay rate due to toxins in the influent	U. Jeppsson *et al.*, 2013
	Low alkalinity	Physicochemical & pH processes	Lack of alkalinity (e.g. due to industrial spill or a change of the drinking water source) might cause pH values that could destabilize chemical nutrients removal and EBPR	H. Hauduc, I. Takacs, *et al.*, 2015; Latif *et al.*, 2015
Equipment	Machinery failure	Aeration system	Mechanical failures and performance loss in blowers, valves and diffusers needs to be considered with physical models	Amerlinck *et al.*, 2016; Schraa, Rieger, *et al.*, 2017; Amaral, Bellandi, *et al.*, 2018
			Energy audits and system optimisation have mechanical constraints that need mechanistic models to be assessed	P. Juan-García, Kiser, *et al.*, 2017
		Pumping system	Mechanical failures and performance in the pumping system must be assessed with pump models	Alex *et al.*, 2008
	Sensor failure	Sensor model	A realistic sensor model is beneficial to capture the behaviour of the plant's control system in detail	Leiv Rieger *et al.*, 2003
		Fault sensor modelling	Sensors and actuators often present faults in dynamic simulations that need to be taken into account to represent plant performance	Christian Rosen *et al.*, 2008

TABLE 8. Proposal of metrics for a resilience assessment of a common Activated Sludge Water Resource Recovery Plant. CV stands for Controlled Variable. A visual representation of the resilience metrics is shown in fig. 5 on page 28.

Property	Metric	Equation	Description	Reference
Robustness	Robustness loss	$\mathrm{RL} = \max_t(\mathrm{CV}_{stress})$ (7)	Where RL is *Robustness Loss*, and CV_{stress} is the maximum value of the CV time-series on a given scenario	Adapted from Tran *et al.*, 2017
Rapidity	Speed to recovery	$\mathrm{STR} = last\ \Delta t\ when \left[\frac{\mathrm{CV}_{stress}}{\mathrm{CV}_{compliance}} \geqslant 1\right]$ (8)	Where STR is *Speed to Recovery*, calculated as the last moment in the time-series when the controlled variable (CV_{stress}) has a value above the compliance limit	Developed for current study
Global resilience	Global resilience Index	$\mathrm{GRI} = \frac{\int_{t_0}^{t_F} \mathrm{CV}dt}{\mathrm{STR}}$ (9)	Where GRI is *Global Resilience Index*, STR is the *Speed to Recovery* (8), and CV is the value of the monitored variable. The *Global Resilience Index* in calculated by integrating the CV value over the STR time, and then normalizing by the STR	Adapted from Francis and Bekera, 2014; Tran *et al.*, 2017

5

TESTING DYNAMIC AERATION MODELS FOR RESILIENCE STUDIES

5.1 MOTIVATION

A model capable of reproducing the behaviour of a WRRF plant against stressors, needs a high level of detail in every sub-model that will be affected by the stressor under study. To understand the stressors' effects on the underlying processes that influence the resilience of the aeration system, model complexity in this area needs to be balanced. Apart from biokinetics, a detailed mechanistic modelling of the air distribution system is used. This model enables understanding of the relationships between aeration equipment, control algorithms, process performance, and energy consumption, thus leading to a more realistic prediction of WRRF performance under stress conditions. To illustrate this, a model-based energy audit has been performed for the Girona WRRF with the goal of testing the ability of the model to evaluate control strategies and how these increase plant reliability. The reliability of these strategies is tested against an ammonia peak, showing that well designed control can enhance the reliability of the plant. This work has been published in Water Science & Technology (Juan-García *et al.*, 2018).

The 12th IWA Specialized Conference on Instrumentation, Control and Automation (ICA) is a forum to exchange methodologies and international experiences on all aspects of sensor technology, instrumentation, control and automation for water and wastewater treatment and transport systems

5.2 MECHANISTIC MODELLING OF EQUIPMENT

The use of dynamic models to reduce energy consumption in WRRFs is common in our field, normally carried out using a combination of experimental work and modelling studies. Such optimisations often include the implementation of a new control strategy, as seen in Corominas (2006) and Thornton *et al.* (2010). Recent studies have been published on control system design (Odriozola *et al.*, 2017; Rieger, Alex, *et al.*, 2016); yet current studies use simplified aeration system models that include oxygen transfer and oxygen demand, but assume ideal air supply and distribution with no equipment constraints. Not including these constraints such as blower, valve, or diffuser limitations can hide extra costs or even mask the inability of a control strategy to reduce energy consumption. Oftentimes, optimisations carried out with simplified aeration models overestimate the potential for energy savings by 5 to 10%, due to missing equipment constraints (Schraa, Rieger, *et al.*, 2017).

Recent research has focused on more detailed models of the aeration system and its energy consumption (Jens Alex *et al.*, 2016; Amaral, Oliver Schraa, *et al.*, 2017; Amerlinck *et al.*, 2016; Schraa, Rieger, *et al.*, 2015). Within this context, only the work of Schraa, Rieger, *et al.* (2015, 2017) uses a fully dynamic model for the piping network, which recalculates the system curve based on the changing pressure drops throughout the system. Simulating the air distribution system dynamically, enables the possibility of conducting troubleshooting analyses, and evaluating the components and limitations of the system for different optimisation options and load and temperature scenarios. Hence, integrated models can be used to find solutions for energy and process optimisations that are more realistic and tailored to a specific facility.

5.3 MODEL SET-UP

A model was built following the recommendations of the IWA Guidelines for Using Activated Sludge Models (Rieger, Gillot, *et al.*, 2012) using the modelling platform SIMBA$^{\#}$. First, mass balances on TSS, COD and TP were conducted to verify that no gross error was present in the data. The model was built using SIMBA$^{\#}$'s activated sludge model ASM-inCTRL, and a simplified anaerobic digester model developed by the Institut für Automation und Kommunikation (Ifak, 2015). To build the layout of the aeration system, mechanistic models were used for each actuator in table 5 on page 42. The piping system is modelled using the Darcy-Weisbach equation with the friction factor calculated using the Swamee and Jain (1976) equation. The model calculates pressure drops across each element using polynomial functions based on airflow rate, which have been calibrated using manufacturer-supplied data. Aeration control was accounted for by means of PI controllers. Concerning the automatic valves, a MOV algorithm was implemented following the configuration proposed in Jens Alex *et al.* (2016); one lane was fixed at 70% open and the other oscillated to adjust the required airflow.

Table 9 on the next page shows a detailed summary of the procedure and characteristics of the simulation exercise. The layout of the process model and sub-models developed in SIMBA$^{\#}$ is shown in figs. 12 to 14 on pages 62–64, corresponding to the general model layout (influent, biokinetics, pumps, effluent, sensors), the aeration system and the control system of the plant.

TABLE 9. Summary of the procedure to calibrate and simulate the Girona WRRF

Plant data	Period used for calibration	2 years
	Plant routine data SCADA	15-min flow measurements, flowrates throughout the plant, DO (2 reactors). Daily average composite samples of nutrients (COD, TSS, VSS, TKN, NH_4-N, NO_3-N, TP, PO_4-P)
	Online data	NH_x, NO_3, COD, pH, and temperature (7 months)
	Additional lab measurements	No
	Additional measurement campaigns	No
Data Management	Software tools	inCTRL influent characterisation spreadsheet used for determination of influent fractionation and development of diurnal patterns
	Others	Visual analysis (figures) of raw data and calculated metrics (ratios, averaged values, etc.)
Models selection	Biochemical models	ASM_InCtrl
	Transport model	CSTRs in series
	Settler model	Otterpohl and Freund model for first calibration, layered Takacs model for second calibration
	Aeration model	Mechanistic blower + pipes + valves + diffusers model + fully dynamic airflow and pressure
	pH model / Alkalinity model	Alkalinity included in ASM model. Metal salt addition modelled with equilibrium chemistry model. General pH model not required for study.
	Control loops	Direct DO control (PI) + Ammonia-based aeration control (PID)
	Cost models	Aeration, Sludge, Effluent Compliance
Simulation platform	Simulation platform	SIMBA#
	Solver	Backward differentiation method for stiff ODE systems
Wastewater characterisation and model calibration	Wastewater characterisation procedure	Used inCTRL influent characterization tool combined with influent measurements, experience with typical influent fractions, and initial modelling to check observed and measured sludge production and O2 consumption
	Main tuning parameters	Influent COD and nutrient fractions Aeration: specification of equipment curves (e.g blower, valve, and diffuser), alpha values Aeration control parameters

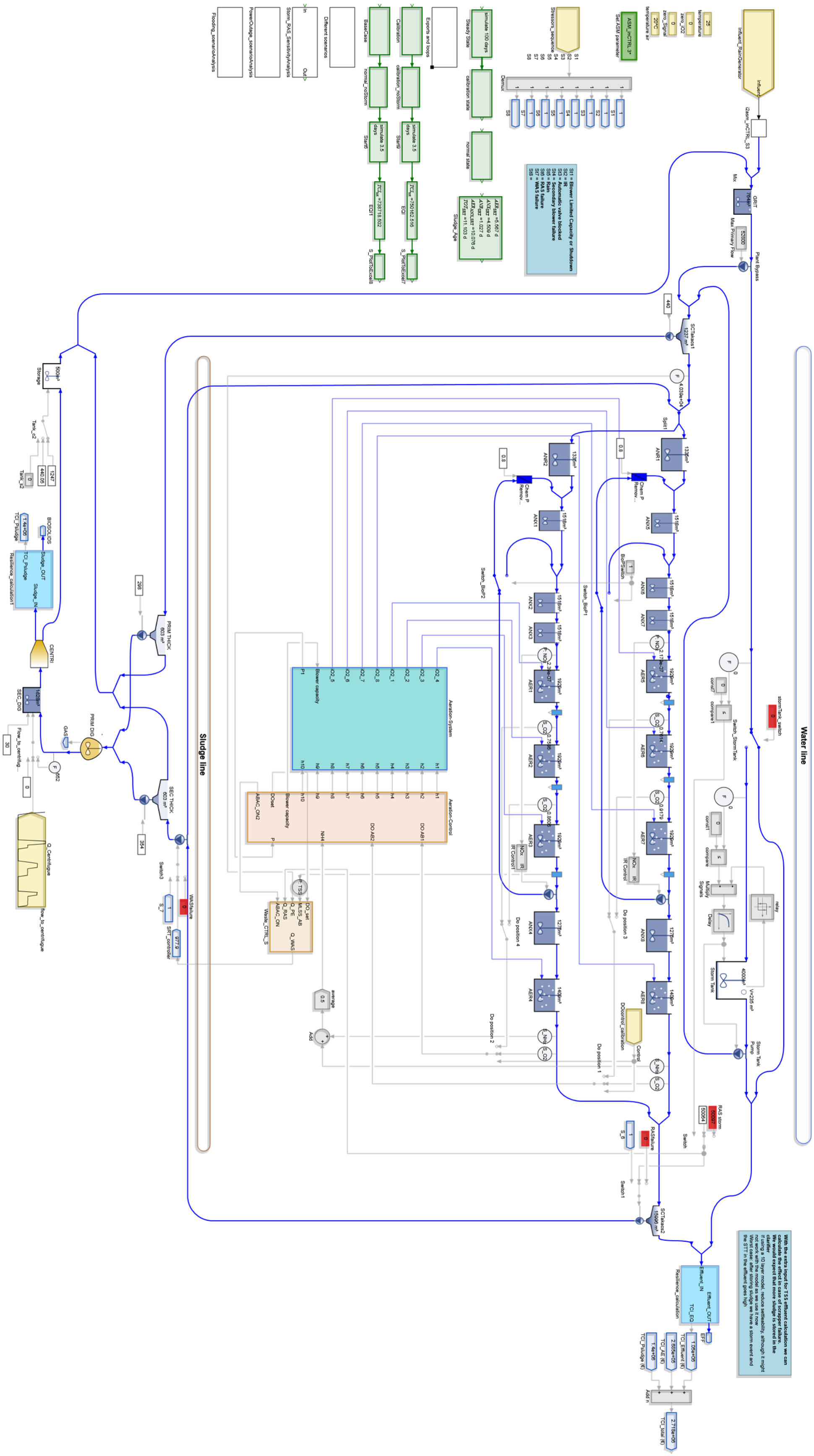


Figure 12. General view of the SIMBA# model of the Girona WRRF

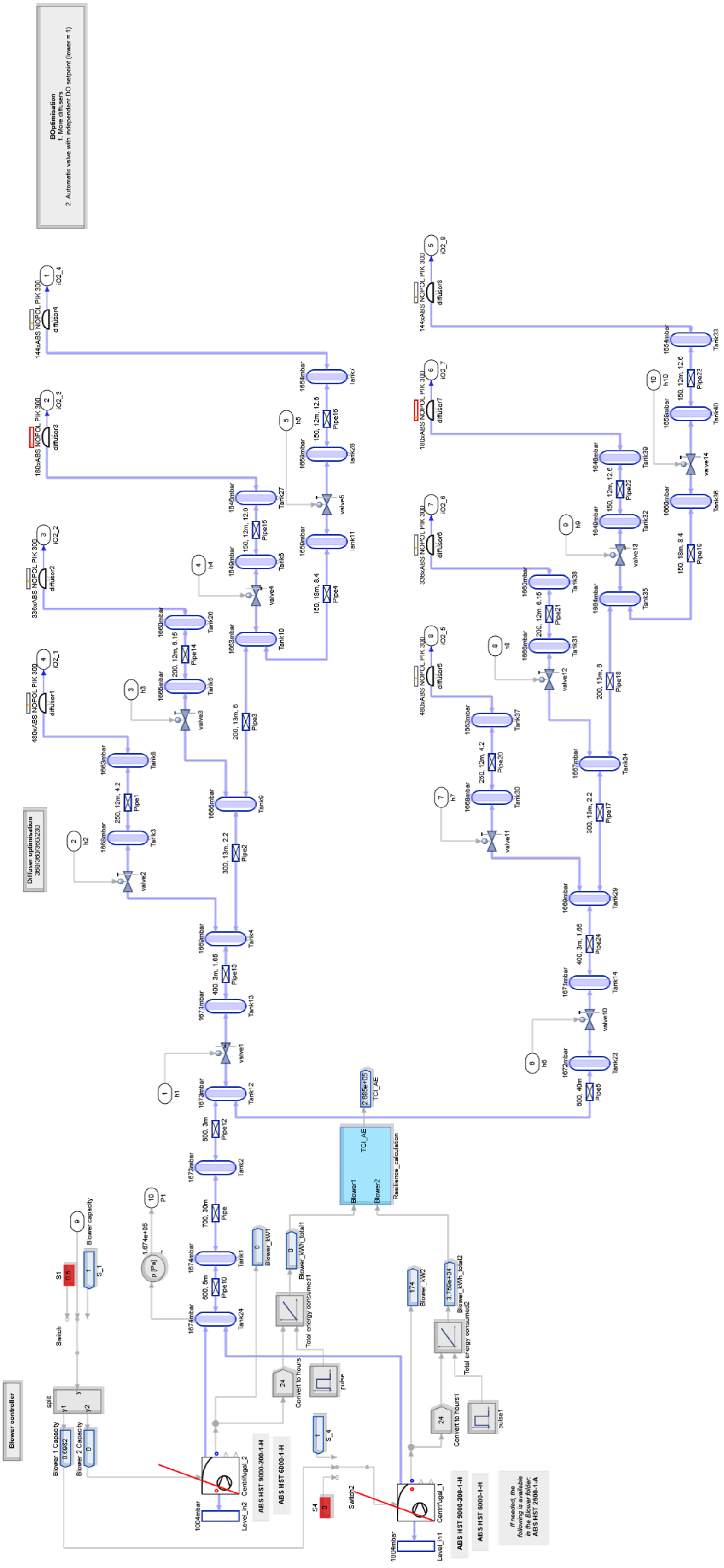


FIGURE 13. General view of the aeration model of the Girona WRRF

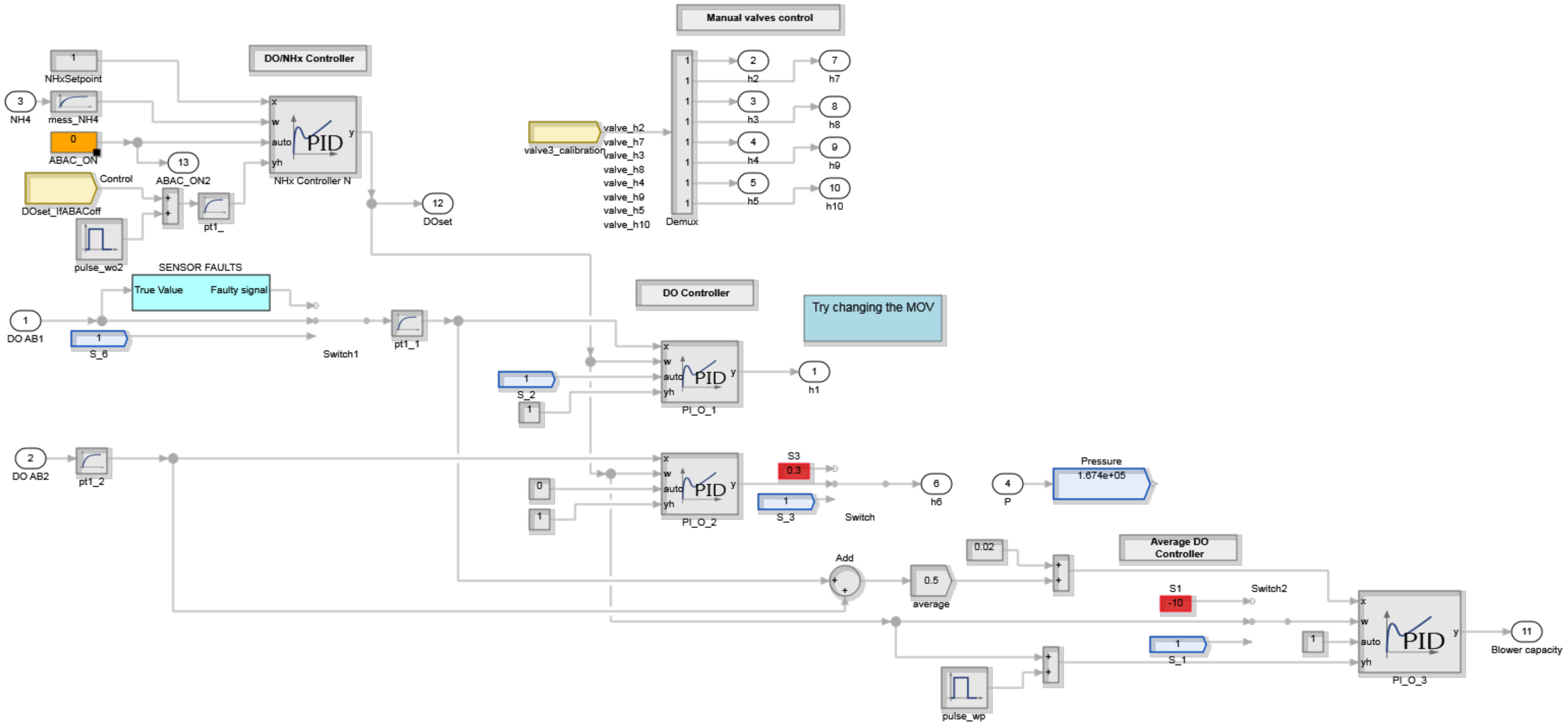


FIGURE 14. General view of the control model of the Girona WRRF

5.3.1 *Calibration*

General schematics of the plant were used, including the treatment processes, the design volumes for each treatment process, water and sludge lines, and the locations of flow meters, dissolved oxygen sensors, and pumps (figs. 8 to 10 on pages 46–48). The number, type, flowrate, and general operation of the pumps were also described in the schematics. Most of the necessary input and performance data for 2013 was also acquired from the Girona WRRF model. Input data were influent flow as well as concentrations of influent organics, nutrients, and suspended solids. Performance data included effluent flow, organics, and nutrients, as well as data for sludge production.

After building the model, a steady-state calibration was conducted to fit the sludge production (using full-scale data from January until December 2015). The results of the steady state calibration are available in appendix A.1, which show the calibration of the sludge production and the biokinetic parameters used in it. Calibration in dynamic state was executed by using real dynamics from the period between the 7th and the 13th of December 2015, described in section 3.2.2 on page 43. It comprises a period of dry weather data, with detailed flow measurements (every 15 min) and daily nutrient measurements (1 sample per day). Hourly nutrient dynamics were incorporated by scaling an hourly ammonia profile gathered in February 2016. For the dynamic calibration period, we had available DO concentrations in reactors AER1 and AER4, as well as blower airflow, system pressure and valve positions. Calibration focused on equipment instead of biokinetics, which should improve the validity of the predictions. A list of parameters calibrated is in table 5 on page 42.

5.3.2 *Calibration results*

The goodness of fit of the airflow during the calibrated week can be seen in fig. 15 on the following page. The model describes the airflow dynamics of the system and the behaviour of the main blower overshooting 1-2 times per week on average entering and on/off behaviour. A better fit of the blower overshooting would be possible if we would have had the real hourly measurements for nutrients and COD at the inlet of the reactor. The support blower on the other hand starts 2-3 times a week during peak moments and runs for short periods, even though this is not accurately captured by the SCADA system recordings (days 5-7). The importance of the effect of delayed ammonia peaks during the weekends' nutrient profiles is appreciated in the delayed airflow curve (days 6-7).

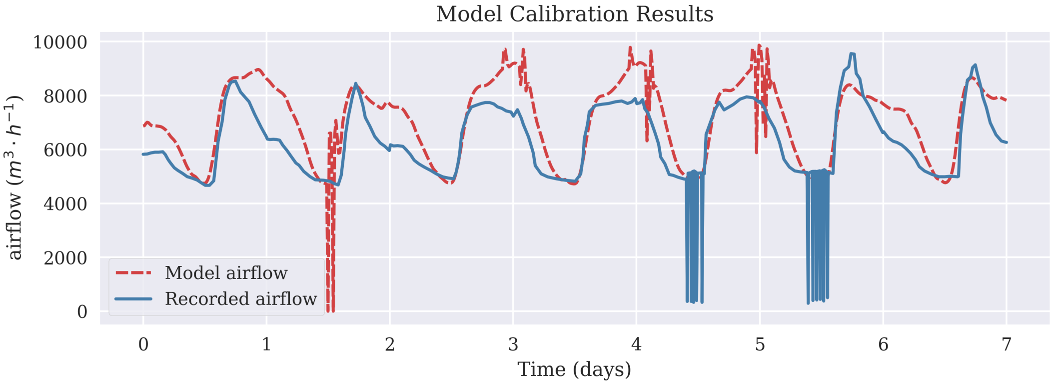


FIGURE 15. Comparison of airflow results obtained from one week of real data and the modelled base case. Days 6 and 7 correspond to a weekend.

5.4 CASE STUDY: MODEL-BASED PROCESS PERFORMANCE

The Girona WRRF's 2013 energy consumption record shows that 63% of the plant's energy consumption was due to aeration. The existing DO control system has already been optimised by the plant operators by trial and error, but it was hypothesised, that further optimisation using the dynamic air supply model would lead to extra energy savings and a better dynamic response to disturbances (i.e. load peaks, temperature variation, operational settings).

After assessing the current performance (Base Case SC0), three different optimisation scenarios were selected: SC1) Ammonia-based Aeration Control (ABAC) (Rieger, Jones, *et al.*, 2014), SC2) Optimisation of the air distribution system, and SC3) Installation of a smaller blower. The optimisation scenarios were compared for three different temperature variations and a stress test in the form of an ammonia peak. This is the first published application of the aeration system model library developed by Schraa, Rieger, *et al.* (2015, 2017) at a full-scale WRRF.

5.4.1 *Water lane energy audit*

A liquid train of a WWTP often makes use of conventional devices such as: mixers, influent pumps, sludge recycle pumps, internal recycle pumps, blowers. In this paragraph the energy audit of the most used and consuming devices is reported. Despite several other devices being present that allow the regular functioning of a WWTP, these devices do not generally consume more than the 5% of the WWTP consumed energy. Moreover, as they are operated continuously, they

TABLE 10. Pumps energy consumption as measured during the energy audit campaign

Device	**Time** d/d	**Config**	**Current** A	**Flow** m^3/h
External recycle pumps (in 2 lanes)	24/24	2+2	58	3000
Internal recycle pumps (in 2 lanes)	24/24	2+0	28-28.5	3000
Waste pump	Intermitent	2+0	9	fixed

TABLE 11. Blowers energy consumption as measured during the energy audit campaign

Frequency %	**Current** A	**Voltage** V	**Power** kW	**Flow** m^3/h	**Air pressure** Bar
54	171	414	118	4764	0.704
60	190	413	132	5387	0.712
70	222	412	158	6524	0.718
80	260	407	186	7563	0.72
90	301	406	216	8275	0.72
97	337	405	239	8820	0.729

cannot be part of a strategy aimed at energy reduction. For this reason, they are never considered in an energy audit.

Each biological lane makes use of 2 mixers with an instantaneous energy consumption of 25 A, and 4 mixers with an instantaneous energy consumption of 17 A. They also make use of pumps to keep the activated sludge process under control. Energy consumption was measured as in table 10.

The blowers are Sulzer HST 9000, with an operational configuration 2 + 1. They are mostly operated at a dissolved oxygen set-point of $1.5\,mgO_2L^{-1}$. An hysteresis cycle of +/- 0.1 is applied on the blowers control, as to prevent over aeration of the biological lane. Blowers are operated with a minimum turning speed is 55%. If the frequency stays at 92% for more than 15 minutes, a second blower is automatically activated in parallel. If the blowers' frequency stays at 55% for more than 15 minutes, they are automatically switched off. Energy consumption of the blowers depending on frequency was audited as in table 11.

The influent pumping station at the entrance of the WWTP was audited. Five pumps of equal capacity are operated in configuration 3+2. In particular, 1+1 frequency controlled pumps and 2+1 fixed frequency controlled pumps are adopted. The pumping control starts always with the frequency control until the water level reaches 2.1 m. Once this level is reached, if the active pump stays at 100% for more than 5 minutes, the second (fixed) pump starts. If the lever reaches 3.6 meters, all 3 pumps will be started. The relationship between the %

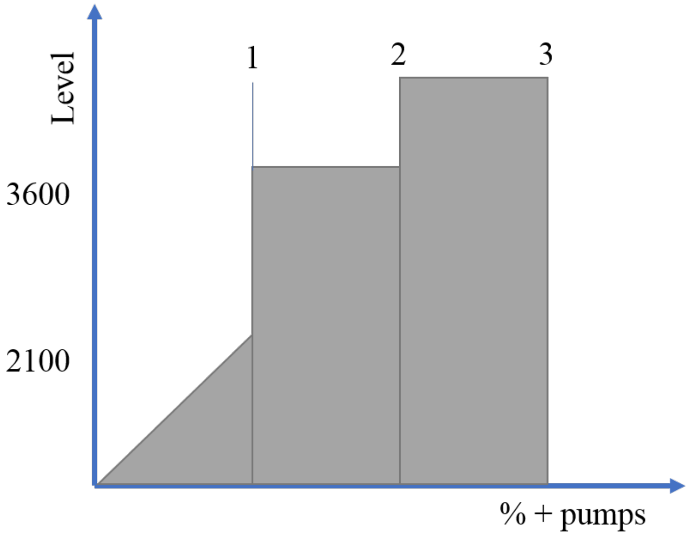


FIGURE 16. Relation between the % influent pumping capacity and water level (in mm) in the influent pit

TABLE 12. Pumps energy consumption as measured during the energy audit campaign

Frequency Hz	**Current** A	**Level** mm	**Flow** m^3/h
37	40	1690	
40	56	2490	
50	107	3594	1100

influent pumping capacity and water level (in mm) in the influent pit is summarized in fig. 16. Energy consumption of these devices was audited as in table 12

5.4.2 *Scenario analysis*

Several virtual options were evaluated to reduce energy consumption while maintaining or even improving effluent quality. The options were grouped into three cumulative scenarios of increasing financial investment. An overview of the options and the scenarios is shown in table 13 on the next page. To guarantee the robustness of the control strategies, all scenarios were stress-tested by an artificial ammonia peak, which increased the influent ammonia concentration from the average ($40\,mgNL^{-1}$) to $80\,mgNL^{-1}$ for 4 hours, starting on the 8^{th} day of the simulation. Variations in ammonia loading are commonplace in the WRRF and the peak is the maximum concentration registered in the plant's historical data.

TABLE 13. Summary of optimisation options and scenarios (SC).
+ Aeration system upgrade + Blower downscaling

	Ammonia-Based Aeration Control (ABAC)			+ Aeration system upgrade		+ Blower downscaling	
	DO probe	ABAC	Fixed valve at 100% open	Optimised pipe and valve sizes	Diffuser distribution	Downscaled blower	Blower scheduling
SC0	AER4						
SC1	AER2	X	X				
SC2	AER2	X	X	X	X		
SC3	AER2	X	X	X	X	X	X

SC1: AMMONIA-BASED AERATION CONTROL (ABAC) A cascade controller where ammonium, in the primary loop, modifies the DO setpoint in the secondary loop. Following the strategy described in Rieger, Jones, *et al.* (2014), an ammonia probe is used to measure ammonia concentrations in the last aerated reactor. The ammonia measurement is then used to adjust the DO setpoint with a PID controller, in a range of $0.1\,\mathrm{mgO_2L^{-1}}$ to $2.5\,\mathrm{mgO_2L^{-1}}$. The DO sensor is moved from AER4, where it was in the Base Case (SC0), to AER2, in the middle of the main aerated reactors where most of the load is being removed. To reduce the pressure drop, the valve in the lane that has more air requirement is now fixed at 100% open, and the valve in the controlled lane is now operating between 20% to 90% open.

SC2: AERATION SYSTEM UPGRADE To improve the airflow distribution in the system, the number of diffusers was optimised and redistributed as follows: from 480 to 360 in AER1, from 366 to 360 in AER2, from 180 to 360 in AER3, and from 144 to 230 in AER4. A second optimisation step was to adapt the diameter of the pipes that feed AER3 from $0.15\,\mathrm{m}$ to $0.2\,\mathrm{m}$to minimise the pressure drops and improve air distribution. The valves feeding these pipes, which were designed for a maximum airflow of $1194\,\mathrm{m^3\,h^{-1}}$ were re-sized to allow for up to $2111\,\mathrm{m^3\,h^{-1}}$.

SC3: BLOWER DOWNSCALING This scenario addressed the problem of not being able to turn down the blower to match the requested air demand at minimum load conditions. It includes the previous strategies, plus replaces one of the blowers another of lower capacity: TDS Turbo compressor type ABS HST 9000 to type ABS HST 6000. This reduces the lower limit of the aeration system's air flowrate. The blower scheduling was adapted to the new configuration and simulation results showed that this setup was not prone to surge of the smaller blower.

To assess the performance of each scenario, the model was first initialised by a steady-state simulation with the scenario's conditions, and then dynamically simulated for 11 days including an ammonia peak on day 8 at 10am. The equation used to calculate the return of investment (ROI) in the optioneering assessment is:

$$\mathrm{ROI} = \frac{Investment\ Cost}{Savings\ per\ year - Maintenance\ cost\ per\ year} \tag{10}$$

5.5 RESULTS

The first results are for the Base Case (SC0) and have been used to calibrate and diagnose the current shortcomings of the plant. The subsequent three scenarios are presented and the results of the strategies are discussed below. Finally, the effects of temperature in each scenario are discussed, and an optioneering assessment is performed to evaluate the strategies from an economic point of view.

BASE CASE SC0: CURRENT OPERATION AND SYSTEM SHORTCOMINGS The blowers are controlled based on the average DO of the last reactor of the two lanes, which is outside of the internal recycle loop, and with a fixed DO setpoint of $2\,mgO_2L^{-1}$. To minimise pressure drops due to both control valves closing when the minimum blower capacity is reached, the control algorithm fixes the valve in lane with more oxygen requirement at 70% open, while the valve in lane 2 is controlled to redistribute the air between the two lanes.

The facility has been designed with diffuser tapering and manual control valves to each of the individual aeration grids. The header pipes and the valve diameters decrease in diameter from $0.25\,m$ to $0.15\,m$. With all manual valves completely open, the highest airflow would therefore be delivered to the first aerated zone and then diminish with each successive zone. To compensate the mismatch between airflow and load, the airflow distribution has been adjusted by the operators by setting the first two manual valves on the reactor's grid to be partially open, at 32.5% and 45% of the total opening capacity respectively. Consequently, the reactors with the highest airflows have a high pressure drop which results in increased system air pressure requirements -the system usually operates at $1650 - 1800\,mbar$. The loss of control authority leads to an oscillation of the oxygen concentrations in reactors AER1-3, and the response of the plant to stressors is slowed down as the only sensor is located at the end of the lane (and after an anoxic zone). The minimum blower turn-down is above the minimum airflow requirements during low load periods, so the blower switches

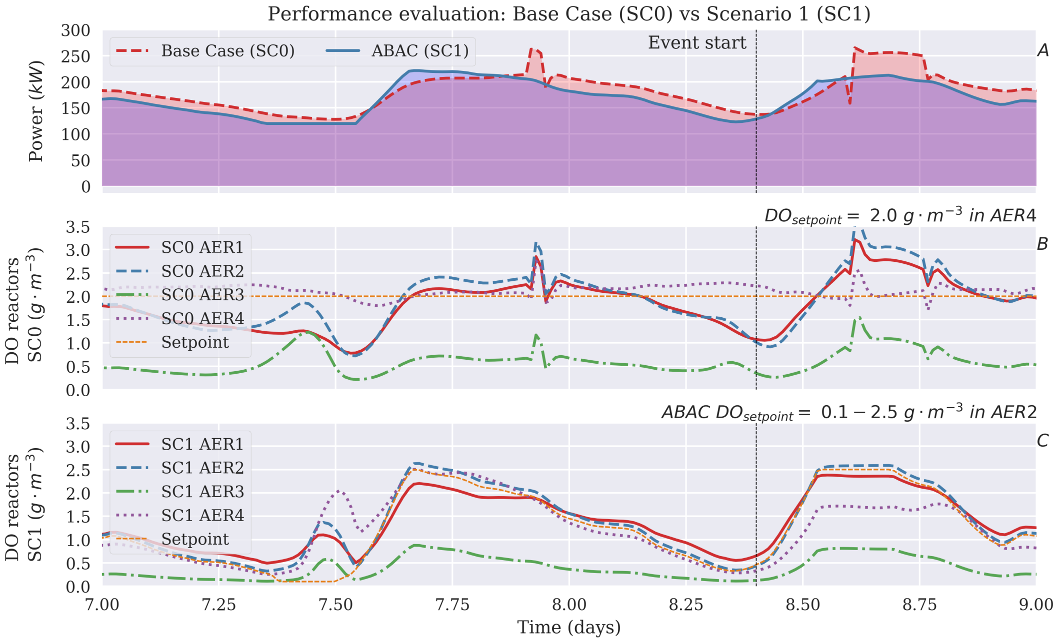


FIGURE 17. Performance evaluation of Scenario SC1 over the Base Case (SC0). A: Power consumption; B: Oxygen profiles across reactors in Lane 1 for the Base Case; C: Oxygen profiles across reactors in Lane 1 for Scenario SC1.

on and off intermittently when the load is low for extended periods of time. This reduces the blower life and creates instabilities in the DO concentration.

The Base Case scenario displays periods of insufficient DO concentrations throughout the reactors (fig. 17 - B SC0: Base Case in page 71); AER4 maintains the setpoint, except during peak loading. Reactors AER1 and AER2 vary around 1 - 3 $\mathrm{mgO_2L^{-1}}$, depending on the load, and AER3 is lacking airflow capacity as can be seen from the DO concentration. Although most of the COD and ammonia load is treated in AER1 and AER2, the aeration capacity is not sufficient to maintain an acceptable DO concentration in AER3. Only at low load situations does the DO in AER3 increase to around 1 $\mathrm{mgO_2L^{-1}}$, which limits the ability of the plant to fully realise its nitrification capacity.

Overall, the Base Case (SC0) results in an energy consumption in the biological reactors of about 0.2 $\mathrm{kWh\,m^{-3}}$ of treated wastewater. This is at the lower end of typical ranges, which are between 0.13 and 5.5 $\mathrm{kWh\,m^{-3}}$ (Enerwater, 2015), however, the system is unable to maintain the DO setpoint during influent peaks. In low load situations, the blower turn-down limitation forces the air control valves to close as much as possible, which results in the blowers working against an increased system pressure and therefore reduced efficiency. Another effect of having AER1 and AER2 at high DO concentrations to compensate for low DO in AER3 is a higher energy consumption, as oxygen transfer is more efficient at low airflow rates and low DO concentrations (Rosso *et al.*, 2005).

5.5.1 *Evaluation of the optimisation scenarios*

SCENARIO SC1: ABAC. The implementation of ABAC results in both energy savings of up to 7% and improved controller response. Savings are obtained by the DO setpoint varying between 0.1 and 2.5 $\mathrm{mgO_2L^{-1}}$, increasing the airflow when higher ammonia loads enter the reactor, and saving aeration power otherwise. The system's improved reaction to ammonia peaks can be appreciated in fig. 17 - C SC1: Scenario 1. Right after the "Event Start" mark, the ABAC controller reaches a high DO concentration faster than the Base Case, despite having a much lower DO setpoint before the event. The ability of the ABAC controller to increase the DO setpoint up to 2.5 $\mathrm{mgO_2L^{-1}}$ instead of 2 $\mathrm{mgO_2L^{-1}}$ at peak load conditions, allows the aeration system to draw more capacity in moments of need.

By controlling the oxygen supply to always maintain a minimum ammonia concentration in the effluent of 1 $\mathrm{mg/L}$, the load is distributed over the entire reactor causing a more balanced oxygen demand. As can be seen in fig. 17 - C, the DO profile shows that the load is removed gradually in each reactor. Nevertheless, AER3 still presents a critical limitation in reaching the required DO concentration (fig. 17 - C: SC1 AER3).

Despite the improvements with the ABAC scenario (SC1), the manual valves in reactors AER1 and AER2 still must remain partially closed to compensate for the flawed airflow distribution generated by the tapering. Figure 4A shows that the ABAC controller is properly working and reacts quickly to the measured ammonia most of the time. However, at low load situations the minimum blower turn-down prevents the system from maintaining the low DO concentrations requested by the ammonia controller. The DO controller (fig. 18 - B) works well until the ammonia controller is limited, and then the DO concentration spikes in the lane with the fully opened valve. The valve control (fig. 18 - C) shows that the automatic valve in lane 2 closes to regulate the airflow. Yet, the valve in lane 1 must be fixed at 100% open to prevent the blowers working against closed valves. This would reduce blower efficiency and may lead to blower surge. After this in-depth analysis of the controller and actuator performance, the two main system constraints can be identified: 1) the airflow distribution and 2) the minimum blower turn-down. Overall, the model confirms the benefits of ABAC reported in other studies (Amand *et al.*, 2013).

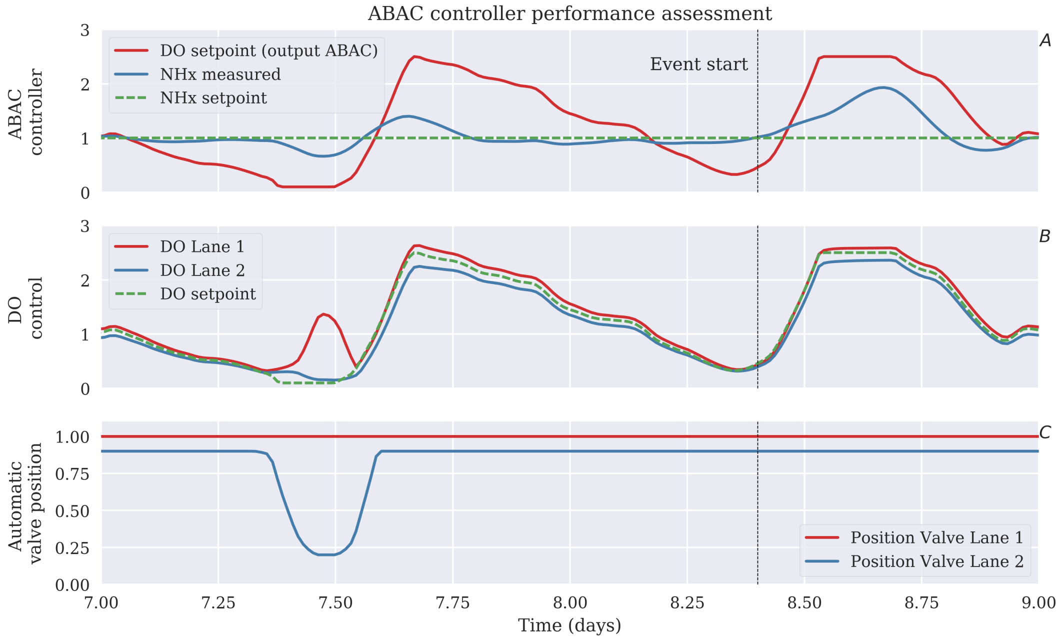


FIGURE 18. ABAC performance evaluation in scenario 1. A: Input-output signals; B: Oxygen profiles of each lane; C: Valve position in % 0-1. DO in mgO_2L^{-1}, Ammonia NHx in $mgN\text{-}NHxL^{-1}$

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SCENARIO SC2: AERATION SYSTEM UPGRADE. Scenario SC2 upgrades the aeration system to overcome airflow limitations in reactor AER3 by (i) reducing the number of diffusers in the first two reactors, (ii) increasing the number of diffusers in the last two reactors, and (iii) resizing the pipes and valves, as described in table 13 on page 69. According to the model predictions, this allows the plant to operate with the manual valves fully open, which translates into reduced system pressure. Although some form of diffuser tapering still exists, the limitation of delivering air to AER3 has improved, and the reactor can now reach higher DO concentrations fig. 19-B. The airflow distribution changes were simulated and analysed as shown in fig. 20-A. The diffuser distribution has been calculated to the current loading patterns but could change if the loading patterns were to change significantly over time.

The model predicts that improving the airflow distribution would increase energy savings up to 12%, due to several reasons. Firstly, reducing the system pressure allows the blowers to supply the same airflow with less energy consumption. Secondly, by increasing the nitrification capacity in AER3, there is more nitrite and nitrate being recirculated to the anoxic reactors, thus more organic matter is removed

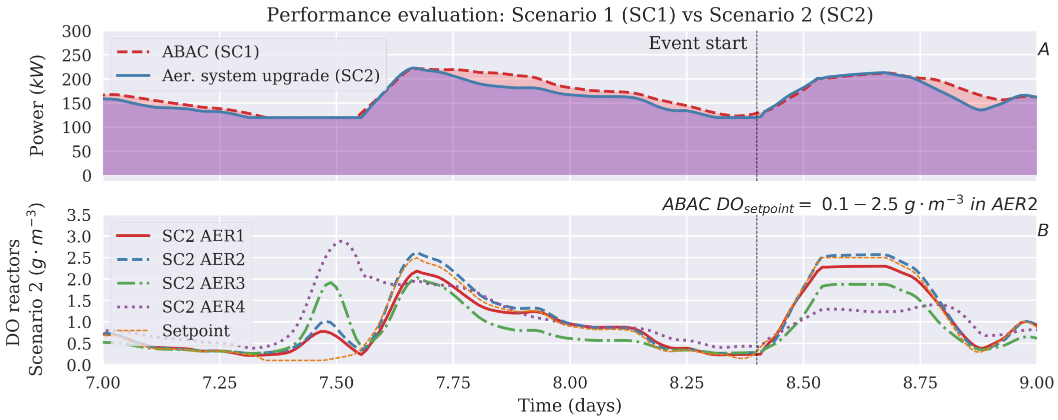


FIGURE 19. Performance evaluation of Scenario SC2 over Scenario SC1. A: Power consumption, B: Oxygen profiles across reactors in Lane 1 for Scenario SC2.

anoxically instead of aerobically. This NO_x was previously being produced in AER4, and thus its oxidizing capacity was lost. The increased denitrification activity can be seen in fig. 21 on page 76, which shows the ratio of kWh per kg NHx-N removed and total nitrogen removed. Both nitrification and denitrification become more efficient with each scenario, which translates to less blower usage (fig. 19-A) and reduced effluent concentration of total nitrogen. Finally, a more balanced load allows the plant to run with a lower DO setpoint overall, which increases the oxygen transfer driving force.

The only remaining constraint is the minimum blower turn-down. Upgrading the aeration system lowered the air demand during low peak periods. However, the blower can only decrease its capacity to 40% of the full capacity of one blower, which is already over the minimum air demand. The turn-down capacity of the blower is reached during low load periods, as seen in the airflow measurements in fig. 20 on the facing page, which cause the DO spikes in low peak periods in reactors AER3 and AER4 fig. 19.

There are three main solutions to this problem. The first one would be implementing intermittent blower operation, using control based on effluent ammonia as in Rieger, Takacs, *et al.* (2012). The second solution is to implement a blow-off valve, and the third solution is to replace the main blower by a smaller one. In this study we have explored the third solution, as it is considered the most efficient in terms of design.

SCENARIO 3, BLOWER DOWNSCALING The last scenario solves the minimum blower turn-down limitation by downscaling the main

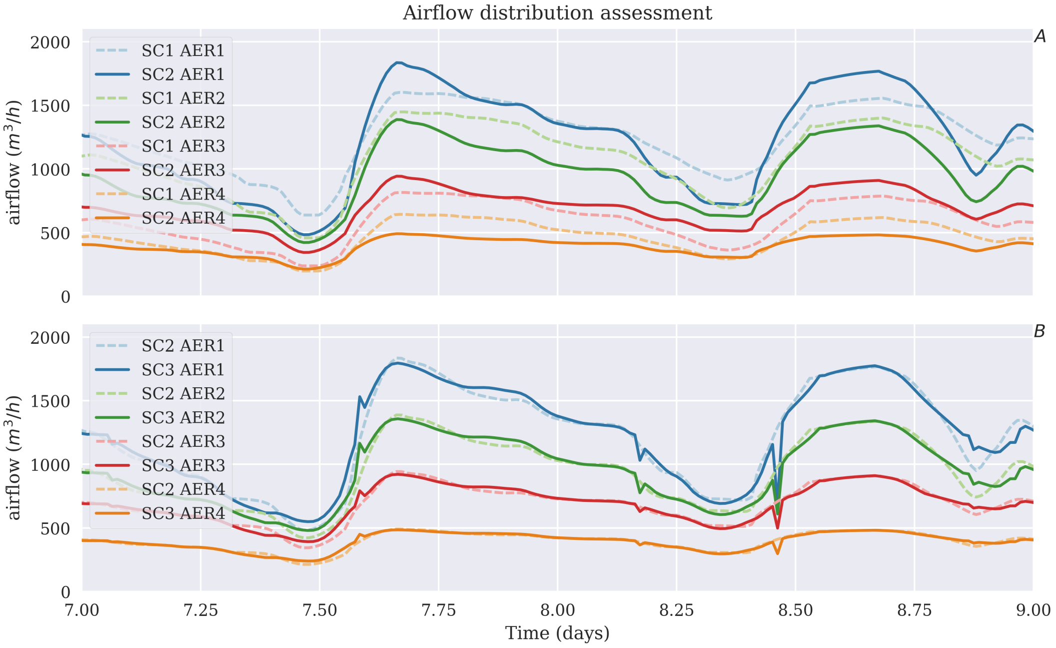


FIGURE 20. Airflow distribution analysis. A: Scenario SC1 (ABAC) and Scenario SC2 (Aeration system upgrade); B: Scenario SC2 (Aeration system upgrade) and Scenario SC3 (Blower downscale)

blower. The virtual system now has a lower minimum airflow (fig. 20-B), which results in energy savings at low peak periods (fig. 22-A, fig. 23) and improves the DO profile across the reactors (fig. 22-B). The system dynamics are also smoother.

All scenarios are more energy-efficient as the temperature increases, both in terms of raw energy savings (fig. 23 on page 77-A), and kWh per pollutant removed (fig. 21 on the next page). This is mainly due to increased bacterial activity, which allows the reactor to be run at a lower suspended solids concentration, and lower DO setpoint. The base case at 25 °C consumes 8% less energy than at 16.5 °C. In fig. 23 on page 77-B, the performance of each strategy is analysed in comparison to the base case at that temperature.

Results show that not every scenario behaves similarly with temperature changes. Upgrading the aeration system (Scenario 2) shows less savings variation across temperatures, whereas the ABAC (Scenario 1) is significantly more efficient at high temperature. Downscaling the blower (Scenario 3) provides no increased savings at low temperature, but is more efficient at high temperatures when the minimum capacity of the blower is reached more often. This shows the trade-off between flexibility and energy savings. The perfect design would be running

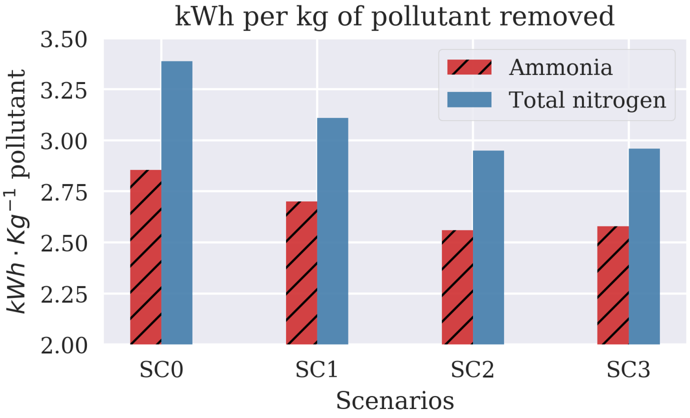


FIGURE 21. kWh consumed per kg of ammonia/total nitrogen removed in each scenario

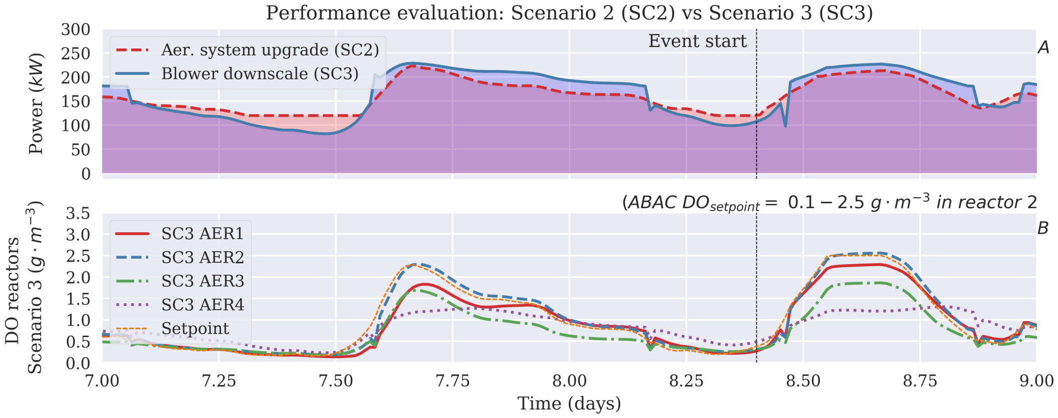


FIGURE 22. Performance evaluation of Scenario 3 over Scenario 2. A: Power consumption, B: oxygen profiles across reactors in Lane 1 for scenario 3.

several "small" blowers in a more efficient range, allowing maximum process modularity and improving energy savings.

5.5.2 *Optioneering assessment*

Table 14 on page 79 summarises the results for the tested scenarios, considering the effluent quality and system response to ammonia-peaks. A return of investment for each enhancement has been calculated using the following details: *i)* maintenance costs for the ABAC controller during a 10-year period amount to 25'000€/year,*ii)* Energy price is

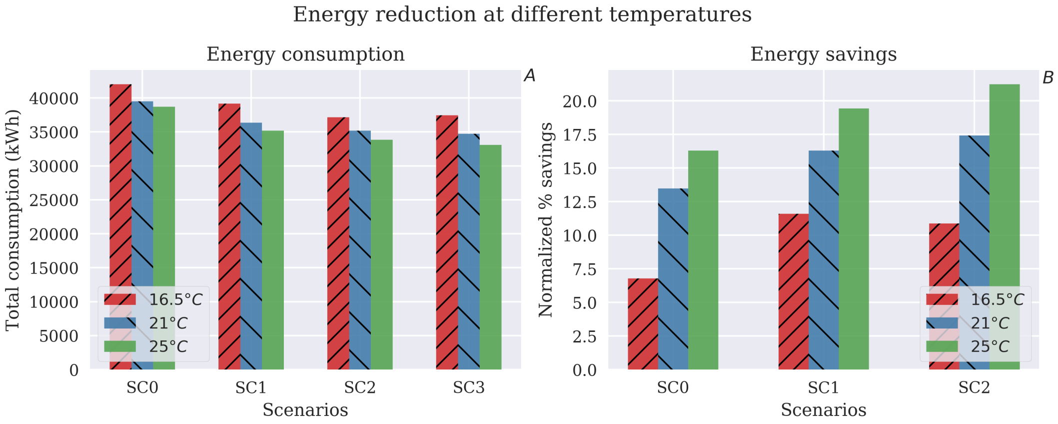


FIGURE 23. Energy consumption and the percentage of energy savings of each scenario compared to the Base Case at three different temperatures. A: Weekly aeration energy consumption. B: Percent savings, normalised to the savings of the base case at the given temperature.

considered to be 0.1 €/kWh, *iii)* cost of piping, valves and installation is estimated at 52’000 €[values obtained from a personal communication with the consultancy Banc Bedec (ITeC)]; *iv)* blower cost estimated at 155’000 €(obtained through a personal communication based on recorded data from the Belgian water utility Aquafin). Results show that Scenarios 1 and 2 are recommended as valid optimisation options to save energy. Replacing a blower needs to be evaluated based on a cost-benefit analysis; however, this highlights the importance of designs including low load scenarios, and the cost of over-sized equipment. Results on mean effluent ammonia and total nitrogen show that the base case was not making use of the plant’s full denitrifying capacity, which is improved when aeration is optimised.

The ammonia stress test is generated in a low-load period, and thus the DO setpoint set by the ammonia controller, right before the ammonia peak, was at the lower end of the range. This is the most disadvantageous moment for the ABAC system to receive an ammonia peak. Still, all scenarios handled the ammonia peak and maintained effluent quality (table 14 on page 79: NHx peak).

5.6 CONCLUSIONS

The ability of the model to simulate the aeration system has been used to gain understanding on the relationship between the aeration system, control system and process stability. The model is able to react realistically to changes in equipment settings and enables the simulation of different scenarios, including drastic changes in settings, equipment and system characteristics. This case study has focused on energy savings and system performance, including a resilience assessment against ammonia peaks.

TABLE 14. Summary of modelled cases and performance obtained. [1]Scenarios are cumulative. Each new scenario includes the optimisation options of the previous scenario. [2]The range of savings for each scenario is calculated over the base case for each temperature.

Scenario description	**Energy savings** %	**Effluent** NHx **daily average** gN/m^3	**Effluent NHx peak** gN/m^3	**Effluent TN mean** gN/m^3	**Return of investment** years
SC0: Base Case	–	0.59	1.19	6.85	–
SC1: ABAC	6.8 – 16.3	0.99	1.40	6.22	0.88
SC2: Aeration system opt.	11.6 – 19.4	0.98	1.29	6.20	6.29
SC3: Blower downscaled	10.8 – 21.2	1.02	1.33	6.12	15.64

6

FRAMEWORK VALIDATION

6.1 OVERVIEW

This section applies the methodology described in chapter 4 in a full-scale resilience assessment of the WRRF of Girona. Each step of the framework is, hereby, contextualized. Allowing the work carried out in the previous chapters to be related to the framework. The validation consists of a case study with two applications: to enhance resilience in the Girona WRRF against -two stressors- *stormwater* and *power outage*.

6.2 APPROACH FOLLOWING THE PROPOSED FRAMEWORK

6.2.1 *Project definition*

Although the plant complies with current effluent limits, the effect that extreme events can have on the plant is unclear. The WRRF managers are considering building up resilience and wants to know to which stressors their work is most vulnerable to, and how to increase resilience in the most cost-effective way. After personal consultation with operators, the main sources of concern are:

RESILIENCE AGAINST STORMWATER The weather in Catalonia is characterized by short but intense rainfall events. Due to the limited capacity of the plant to treat all wastewater during these events, untreated water is discharged to receiving water bodies through combined sewer overflows (CSOs). Currently the plant bypasses flow over 1.5 times dry weather flow (1.5X DWF). The plant has the capacity to treat up to 3 times the dry weather flow, which would prevent various kg of pollutants being discharged to the river, with the consequent environmental benefit. However, clever manipulation of the RAS is necessary during wet weather to avoid sludge washout. The *objectives* of the study are to: *i)* assess the effects of extreme weather events where the plant treats an influent of 3 times the dry weather flow (3X DWF as it is commonly required by design guidelines (Woods, 2010)); *ii)* explore a new strategy to mitigate sludge washout based on RAS manipulation, as suggested by Zhu and Anderson (2017).

The virtual plant is tested against an eight hours storm. A sensitivity analysis of RAS-influent ratios was carried to study the effect of the RAS during the storm. A sensitivity analysis of the sludge volume index (SVI) was conducted, from 60 to 160 $\mathrm{mL/g\ sludge}$, to understand the effect of reduced settleability on the RAS analysis. The impacted variable used to assess resilience in this scenario is TSS ($\mathrm{mg/L}$) in the effluent. The metrics are: *i)* Rapidity: time it takes for the plant to recover TSS below compliance (<35 $\mathrm{mg/L}$); *ii)* Robustness loss: maximum concentration of TSS in the effluent; and *iii)* Global Resilience Index: Accumulated effluent TSS above compliance, normalized by recovery time in days (see table 8 on page 58).

RESILIENCE AGAINST POWER OUTAGE The plant experiences occasional power outages and events of limited power supply. As accurs in many WRRFs, the Girona plant relies on external sources of energy. During a power outage the plant has backup generators to power the influent pumps, but recirculation pumps and blowers remain incapacitated. Building resilience against these events is one of the most important priorities for the WRRF managers. The objective is, first, to assess how much time the system can withstand critical equipment shut-down and where further investments in back-up energy should be prioritized; second, to explore a mitigation strategy in case of limited back-up power supply for the blowers.

Two sets of simulations were designed. The first set of simulations carried out a sensitivity analysis on equipment shut-down duration for blowers and recirculation pumps. Although the Girona plant uses diffusers as the main source of mixing, in case the aeration stops the real plant is equipped with low speed mixers which are assumed to be functional. The second set simulates the plant during a 48 h power outage, where an investment has been made in back-up energy to power recirculation pumps and blowers. The blower capacity is set to a minimum to preserve back-up power and thus limit the necessary generators, keeping investment costs low. A scenario analysis is carried out on different strategies of airflow distribution using the manual valves as control handles:

- Base Case: No changes with respect to current settings in airflow distribution, which already favours aerating the head of the plant.
- Favour head: Airflow towards the head of the plant (two first aerated reactors)
- Only head: *Limit* airflow to the head of the plant (two first aerated reactors)

- Favour rear: Favour airflow towards the rear of the plant (two last aerated reactors)
- Only rear: *Limit* airflow to the rear of the plant (two last aerated reactors)
- Open valves: Open all valves (manual and automatic) to minimize system pressure

It must be stressed that this type of granular analysis of the aeration system, including strategies that involve manipulating equipment, is only possible thanks to the mechanistic model for dynamic aeration supply calibrated and tested in chapter 5.

The impacted variable in this case is total nitrogen in the effluent (TN). The same metrics have been applied as in the stormwater case study: *i)* Rapidity: time to recover TN effluent values under compliance limits ($< 10 \mathrm{mg/L}$); *ii)* Robustness loss: Max. TN effluent concentration during event; *iii)* Global Resilience Index: Accumulated Kg of Nitrogen in the effluent above compliance limit, normalized by recovery time.

6.2.2 *Data collection*

Caveats on how to collect data to calibrate and validate a model to assess resilience in section 4.3.2 on page 55

Plant dynamics were collected from a period between the 18th and the 20th of July 2017, as described in section 3.2 on page 42. It includes a period of dry weather data, with detailed flow measurements (every 15 min) and a data campaign consisting of: *i)* online measurements of DO in all reactors, and NH_x at the entrance of the biological treatment and AER2; *ii)* composite sampling of influent and reactors: 4 grab samples per day in all 7 reactors plus hourly samples in reactors ANA1 and AER2; *iii)* energy consumption monitoring; *iv)* SCADA system files; *v)* influent wastewater characterization; *vi)* reject water characterization; *vii)* daily averages of effluent quality from the plant's lab. Stress tests included a 30 min power outage in blowers and recirculation pumps, a change in the valve opening of AER3 in one lane, and a change of the controlled reactor (from rear to head), which includes lowering the DO setpoint from 1.5 to 1 $\mathrm{mg/L}$. These tests are intended to collect system performance information against sudden changes. Figure 25 on page 87 shows the stress tests in time, appendix A.3.2 on page 120 shows the SCADA report during the power outage event. As no data from storm weather was available, the sensitivity analysis used on the stormwater scenario is used to compensate for the lack of information. Figure 24 on the next page shows an overview of DO and ammonia online measurements.

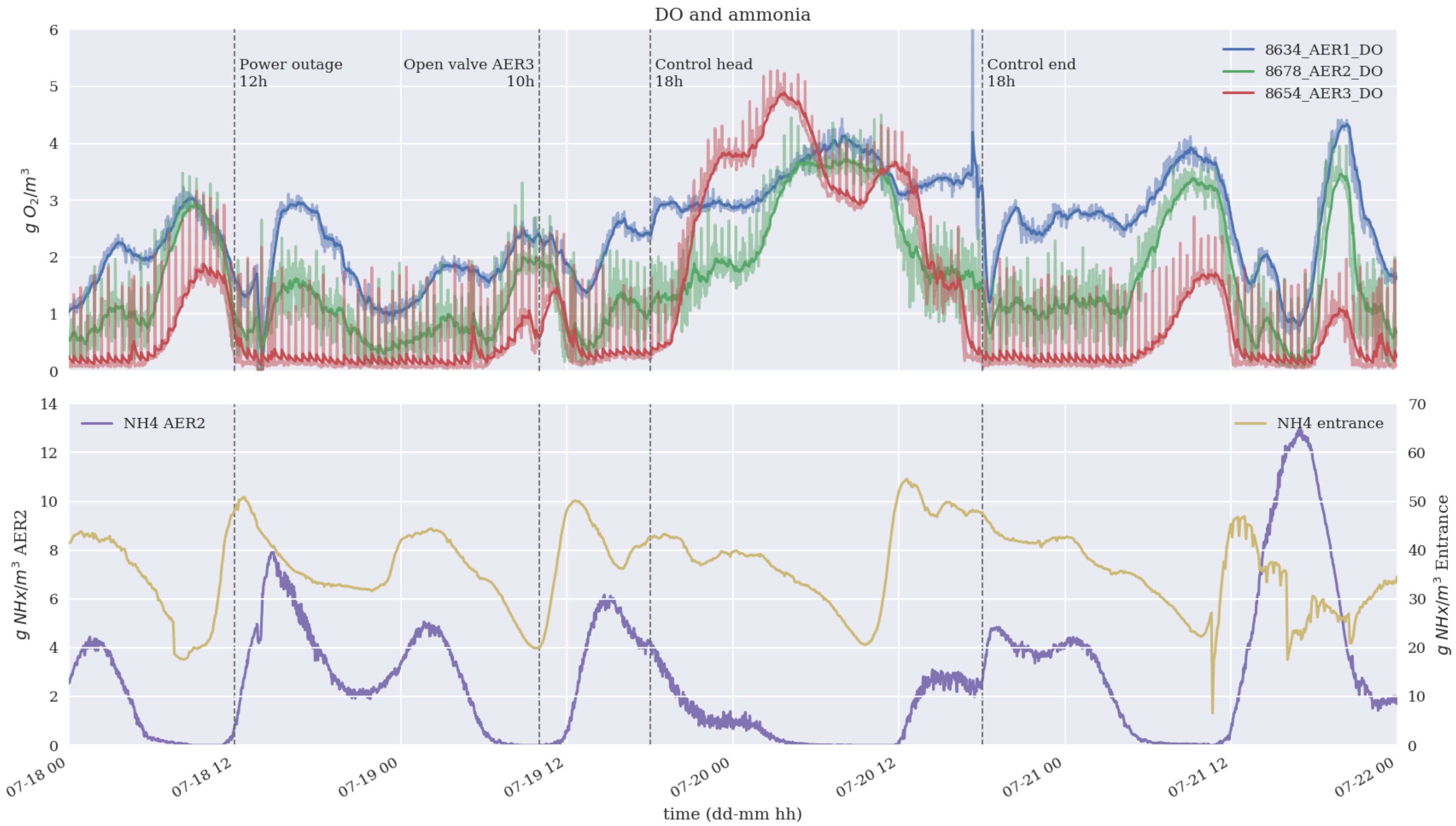


FIGURE 24. Online DO and NHx measurements during data campaign

6.2.3 *Influent generation*

A 3-day dynamic influent was built using direct measurements of COD, NH_x, PO_4, suspended inorganic, alkalinity and flow, available from the eSCAN sensors, SCADA system, and laboratory analysis from the data campaign. Dynamics for nutrients were adjusted to the plant influent timing by calculating the hydraulic retention time from the plant entrance to the biological treatment. The influent time interval was 15 min and has been adjusted by interpolation when needed. Influent fractionation was prepared using SIMBA# "Influent Helper spreadsheet" for raw influent. Data handling and processing of the campaign and influent set-up was carried out using the Python programming language. Code is available in appendix B.1 on page 135.

6.2.4 *Plant model set-up for resilience*

Starting from the calibrated model described in P. Juan-García, Kiser, *et al.* (2017), various considerations were taken into account to upgrade the model to assess resilience. To model the propagation of the storm wave through the plant, settling is accounted for by an improved 10 layer Takacs model (I. Takacs *et al.*, 1991) clarifier model, implemented in SIMBA# by explicitly taking the sludge concentration of the lower layer into account to model the exchange streams between layers. Full details of this implementation are available in Alex (2011). The $N_2\ (gas)$ concentration and the sludge blanket level and concentration are monitored, as indicators of clarifier breakdown.

The models for the stressors include *i)* the wet flow, generated using the SIMBA simulation platform by adding a stormflow influent, and using a plug-flow reactor to account for the catchment dilution and mixing; *ii)* the power limitation and outage in various equipment, created by adjusting the input in equipment model blocks through the graphical user interface, excel files and C# code scripts. The operator response to the stressor is simulated with slowly tuned controllers for: *i)* internal recirculation based on NO3- concentration in the anoxic reactor; *ii)* DO setpoint in monitored reactor based on effluent ammonia; *iii)* wastage pump flow controlled by TSS in AER4. Settings for all PID controllers are in table 15 on the next page. The adaptation of operational settings by the operators facing stressors include the previously mentioned controllers plus a sensitivity analysis of RAS-Influent ratios, and automating the position of the manual valves regulating the airflow in each scenario as previously described.

TABLE 15. PI/PID settings of the SIMBA# model. ABAC: Ammonia Based Aeration Control; IR: Internal Recirculation; WAS: Waste Activated Sludge

Controller name	**Setpoint**	**Type**	**Gain**	**Integral name constant**	**Derivative time constant**
IR Pumps	1 mg/L NO_x	PI	10 000	$15/(24*60)$	0
ABAC $DO_{setpoint}$	1 mg/L NH_x	PID	2	$120/(24*60)$	$30/(60*24)$
Automatic valves	$[0-1]$	PI	0.2	$20/(24*60)$	0
Blower	$[0-2]$	PI	0.08	$30/(24*60)$	0
WAS Pump	$[\approx 3600]$	PI	10	5	0

6.3 CALIBRATION

6.3.1 *Results calibration*

A second and more exhaustive data campaign including stress tests (section 6.2.2) was used to calibrate the model and calibrate the submodels (section 6.2.4) used for: the stressors, the reaction of the plant against them, and the operator response. This calibration also focused on influent fractionation instead of adjusting biokinetic parameters, which should improve the validity of the predictions. The software was automated to recreate a 30 min power outage in all modelled equipment except influent pumps and mixers. Changes in manual valve position, DO setpoint and control DO probe position were set to replicate those registered during the stress test experiment. The goodness of fit of the kWh consumed by the blower can be seen in fig. 25 on the facing page. The loss of fit during the last part of the calibration (07-21 18h) is explained by a direct communication with the plant operator, who confirmed that at the moment the plant control was returned to the rear (AER4), the DO sensor in lane 2 had suffered a drift and needed cleaning. This is clearly appreciated in fig. 27 on page 88, which shows the DO sensors readings during the last day of the data campaign. The complementary goodness of fit of the NH_x concentrations across the primary clarifier and activated sludge reactors is presented in fig. 28 on page 89.

6.3.2 *Results validation*

To validate the model, it was tested against the first dataset used in chapter 5. Results can be seen in fig. 26 on the next page. The plant dynamics remain exactly the same, and the effect of the blower overshooting is better captured with the upgraded model.

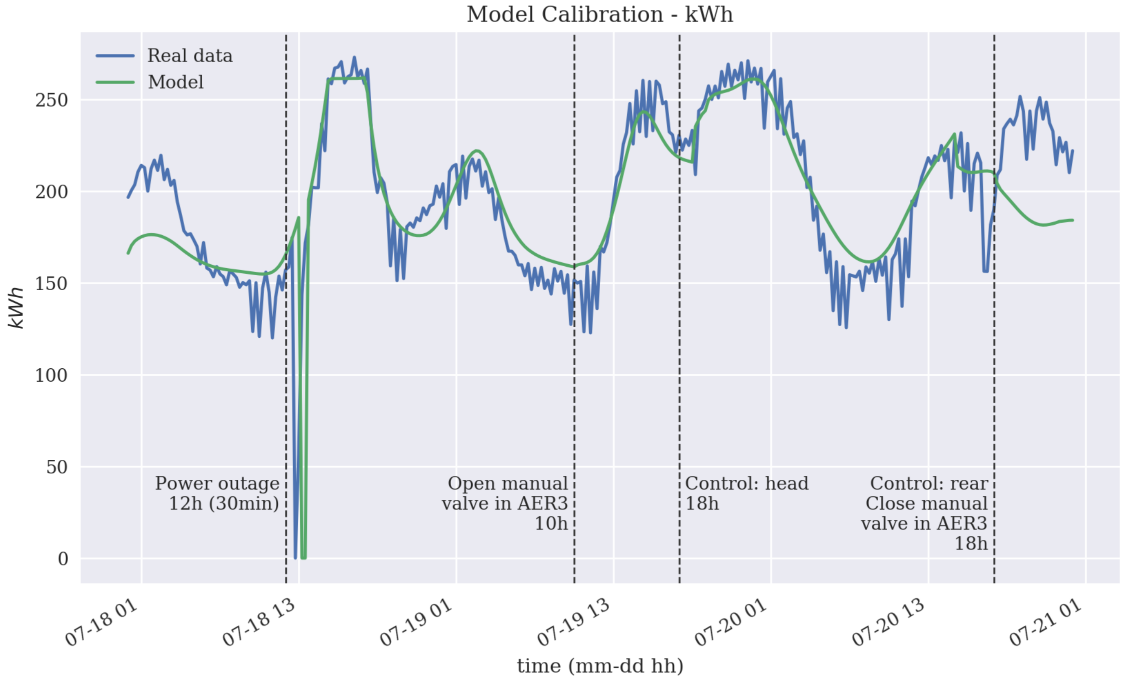


FIGURE 25. Comparison of kWh results obtained from three days of real data and the modelled base case.

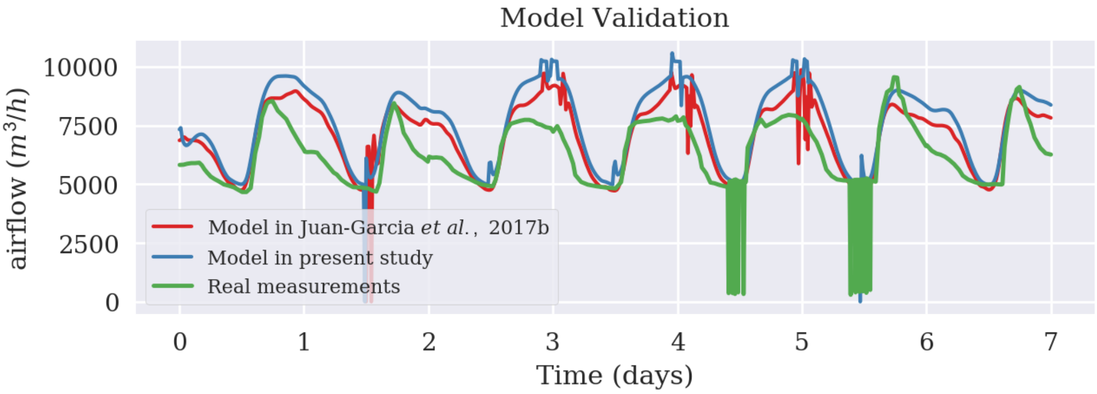


FIGURE 26. Comparison of airflow results obtained from the calibration, re-calibration and real data

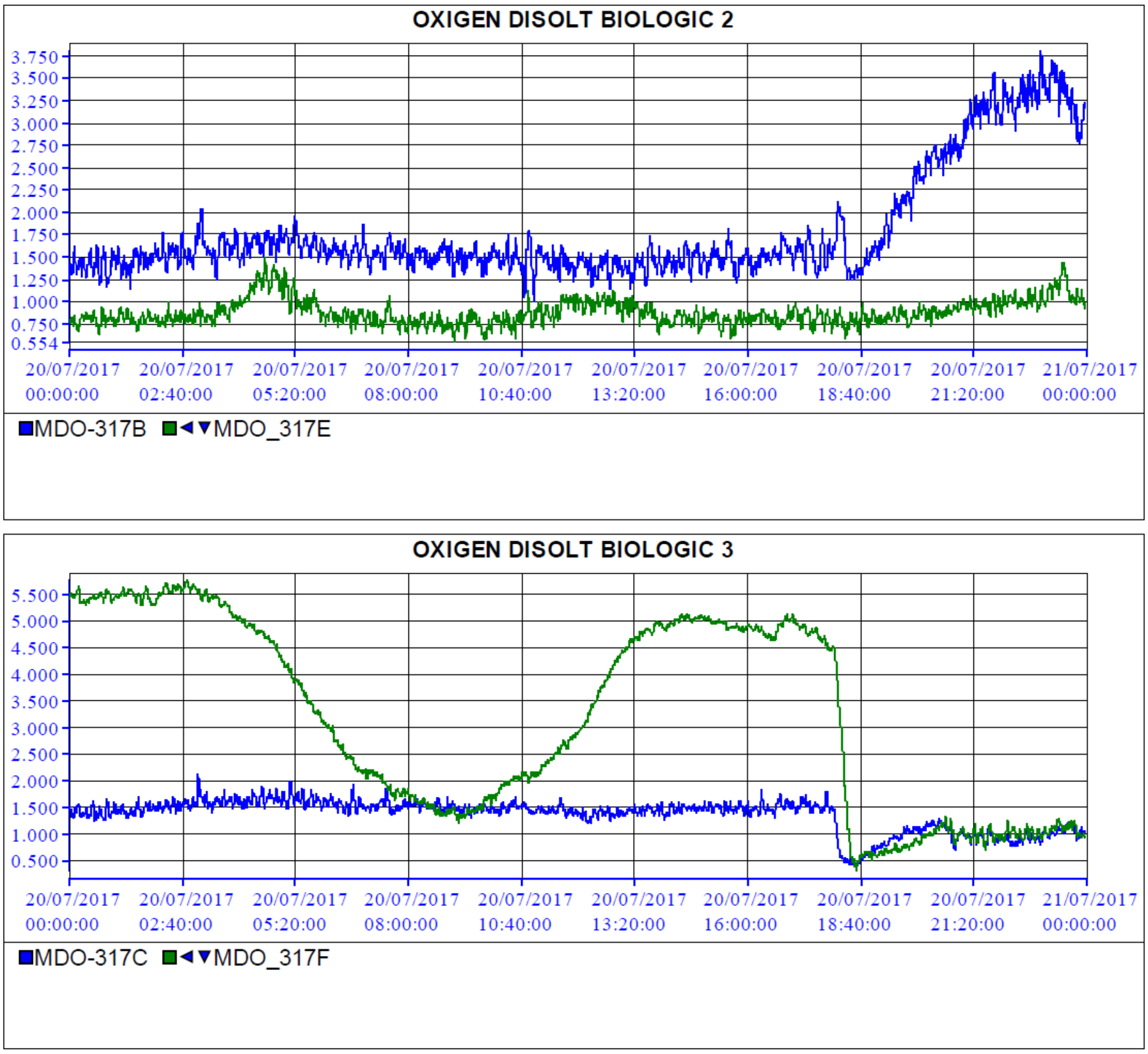


FIGURE 27. Snapshot of the SCADA system during the last day of the data campaign. Oxigen disolt biologic: dissolved oxygen in biological; MDO-317C: DO concentration in AER1, lane 2; MDO-317B: DO concentration in AER1, lane 1. MDO-317F; DO concentration in AER4, lane 2; MDO-317E DO concentration in AER4, lane 1.

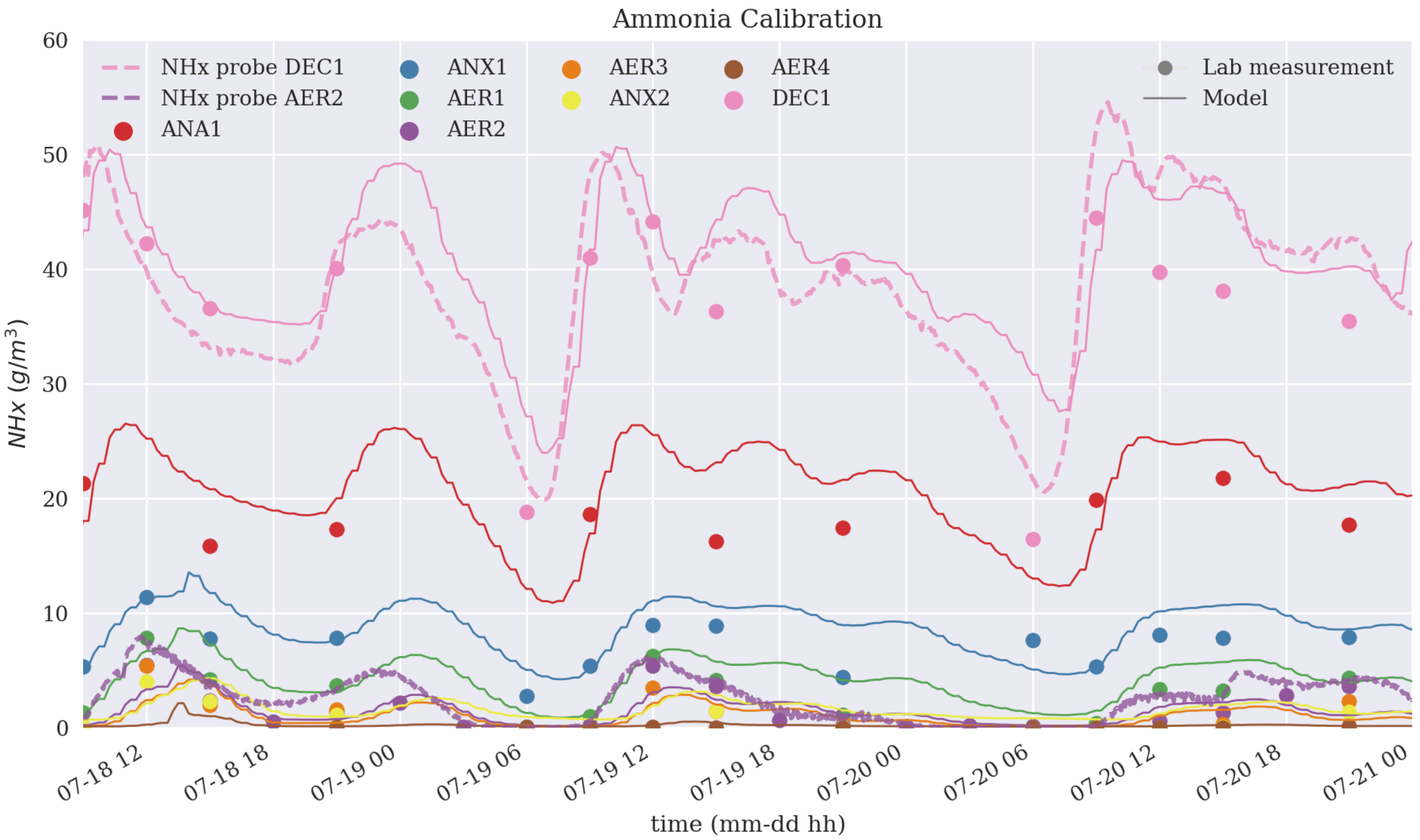


FIGURE 28. Comparison of NHx measurements obtained from the calibrated and the validated model

6.4 DISCUSSION ON MODEL SET-UP AND CALIBRATION

Calibration efforts need to be adapted to the objective of the model (Rieger, Gillot, *et al.*, 2012). As has been previously discussed, in the case of resilience assessment it is impossible to guarantee that the model will reproduce the effect of unobserved stressors. The calibration effort for a resilience assessment is thus larger than is required for most model applications, particularly the data collection and reconciliation steps. The two calibrations carried out in this project present different levels of accuracy, corresponding to the necessary level of detail to undertake the analysis. The first calibration represents the blower dynamics and on-off behaviour that we are interested in, and is therefore relevant to the objectives (see chapter 5 on page 59 for further details). The second calibration faces the challenge of having to represent the system under the effect of *unobserved stressors* (fig. 25 on page 87).

For more information on unobserved stressors see the framework in section 4.3.4 on page 56

As reported by Solon *et al.* (2015), detailed influent dynamics are the main influencing factor on calibration accuracy. A major improvement in calibration detail was, correspondingly, observed by increasing the data collection efforts during the second calibration. The knowledge acquired with the first calibration was, however, useful to prioritize data collection efforts towards critical points:

REJECT WATER The reject water has a strong influence on the nutrients load and profile of the plant. Sampling the reject water had a major impact in the influent profile and therefore model accuracy.

PLANT PHYSICAL CHARACTERISTICS Volumes, hydraulic retention time, equipment characteristics and other physical data is critical, as this could cause systematic errors if not verified. Direct communication with plant operators is necessary during this step; the schematics normally contain errors, or there may be unrecorded upgrades. This is particularly true when mechanistic models *based on first law principles* are used, since they need no calibration, and depend only on equipment data.

NUTRIENT PROFILE A detailed nutrient profile is fundamental to calibrate the model and test accuracy. Particularly important is the NH_x concentration in reactors, due to its effect on oxygen consumption.

COD PROFILE The influent load is paramount to match oxygen requirements and plays a major role in most processes, such as bacterial growth and phosphorus removal.

INFLUENT FRACTIONATION The fractionation of the influent components determines in which form they are available, and how they will be used by the biokinetic model.

SCADA EQUIPMENT DATA SCADA data is vital to verify flows, close mass balances and check equipment functioning (blower schedulling, valve position, etc.) to mention but a few. In this case, the Girona WRRF uses an intermittent pump to recirculate the sludge towards the head of the plant. SCADA data is necessary to know the exact recirculation pattern, critical due to its influence on the influent profile.

An outcome has been the calibration of a detailed model that balances the biological model (biokinetics), the aeration system model (dynamic aeration) and the settling model (10-layer Takacs) with enough accuracy to follow the pattern of $\mathrm{NH_x}$ consumption across the primary clarifier and 7 reactors with different characteristics.

The use of *stress tests* has been particularly useful in testing the model capacity to representing the recovery of the plant after a 30 min power outage. They also demonstrated its capacity to follow a drastic change in aeration strategy (changing the controlled DO reactor from AER4 to AER1), which is instrumental to test mitigation strategies related to the response of a reactor.

Stress tests are discussed in section 4.3.4 on page 56

6.5 RESULTS

6.5.1 *Stormwater*

Treating up to 3 times the dry weather flow translates into great environmental benefits. However, without a proper handling of the RAS, the resilience of the plant may be compromised. The sensitivity analysis on SVI and RAS ratios allows to study the plant behaviour under different system conditions.

Concerning the SVI, higher values translate into worst settling, and hence higher TSS concentration in the effluent, recovery time and total TSS loss (fig. 29 on the following page), which increase exponentially when the capacity of the plant is surpassed. The effect of the RAS is not as straightforward, and the optimal ratio of re-circulation depends on the SVI -how well the clarifier is settling. A turning point has been identified which shows how to best manipulate the RAS to avoid sludge washout. Figure 29 shows that the simulated system perform better with lower RAS ratio for low SVI values, until a change of behaviour occurs for SVI values over 125 $\mathrm{mL/g}$. This turning point is better appreciated in fig. 30 on page 93, which shows the same trend

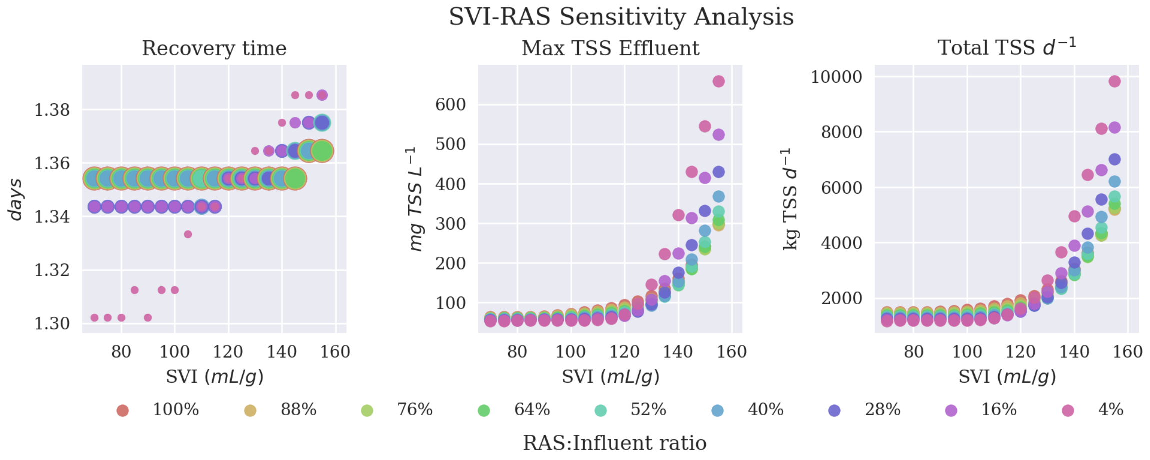


FIGURE 29. SVI-RAS sensitivity analysis results in the stormwater scenario. Left: Recovery time in days for each scenario (Rapidity); Centre: Maximum TSS concentration in the effluent during the event (Robustness loss); Right: Total kg released during event, normalized per recovery time (Global Resilience Index). The SVI ratio 100% corresponds to the normal RAS flow.

in a logarithmic graphic, with the RAS in the X axis. For low SVI (below 115 mL/g) a smaller RAS increases resilience, but if settleability is poor (SVI above 145 mL/g) the system‘s resilience is increased by a higher RAS-ratio.

To further analyze the extent of this change of behaviour, and the relationship between the 3 variables (resilience metrics, RAS and SVI), 3D plots of the Effluent TSS at each point of the RAS-SVI plane were created (fig. 31 on page 94). Figure 31A to D show the change of behaviour as we consider an SVI range from 70 to 120, 130, 140 and 160 mL/g respectively. Figure 31A shows that reducing RAS during storm events increases resilience against sludge washout, as long as settleability is not compromised. As the SVI increases to values of 130-140 mL/g (fig. 31B-C), the optimal RAS:influent ratio increases to 25% and 60% respectively; reducing the RAS still increases resilience. However, with very poor SVI values (fig. 31D, 160 mL/g) keeping a high RAS becomes a better strategy to keep the sludge in the bioreactors.

To understand why this happens, it is necessary to analyse the movement of the sludge blanket. A 10-layer clarifier model was used (I. Takacs *et al.*, 1991) that can represent the effects of two competing processes: *i)* increased overflow [where particles with higher settling velocity (i.e. larger particle diameter) are fluidized and carried upward] and *ii)* sludge recirculation. The model shows how an increase in flow raises the sludge blanket height and, consequently, produces high effluent suspended solids. The implementation of the model in

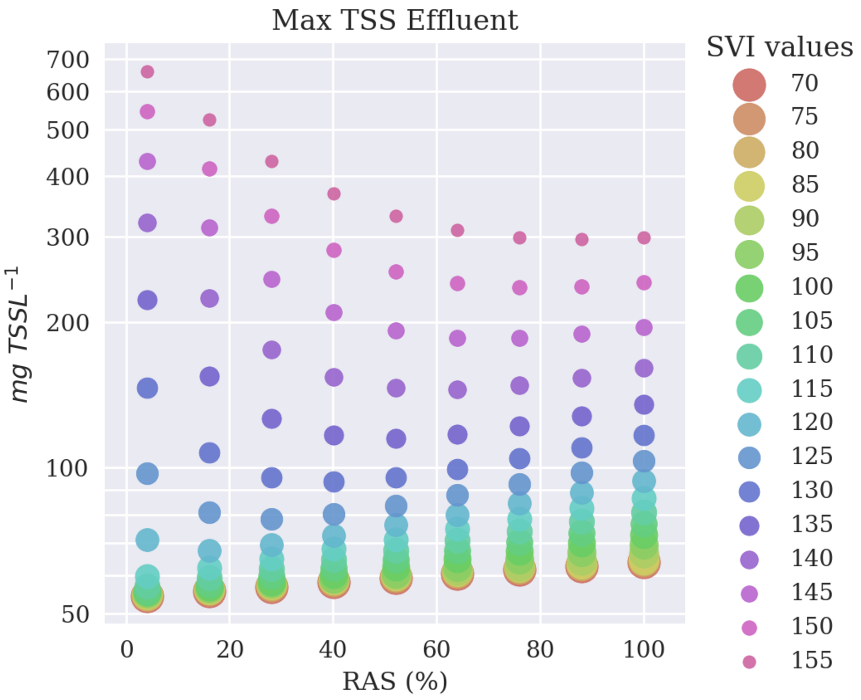


FIGURE 30. Max TSS in the effluent plot of the SVI-RAS sensitivity analysis. Logarithmic view interchanging the axes of RAS and SVI.

SIMBA# explicitly takes the sludge concentration of the lower layer into account to model the exchange streams between layers, which partially accounts for the reduction of disturbance in the underflow when reducing the RAS. Clarifier breakdown was considered by monitoring the blanket level, the sludge concentration in each layer and the N_2 (gas) produced by denitrification. A high rise in the sludge concentration at the high layers suggests clarifier malfunctioning. High nitrogen gas production would cause sludge flotation. No obvious signs of breakdown were observed in any scenario.

In scenarios with good settleability (SVI 70 to $100\,mg/L$), the sludge blanket at low RAS values is lower than at high values, as the sludge compresses more efficiently with reduced hydraulic stress (see fig. 32 on the next page). fig. 33 on page 95A-D shows the sludge distribution in each layer of the clarifier for the scenarios at SVIs 70 and 150, with RAS-influent ratios of 100% and 4%. At low SVI, reducing the RAS will cause the sludge to accumulate in the lower layers, further increasing settleability by reducing the hydraulic stress and improving effluent quality. On the contrary, when SVI is high the upper layers contain more sludge, which is then lost in the effluent. Lastly, the reduction of disturbance in the settler achieved with reduced RAS:influent ratios should further improve settleability in the lower layers.

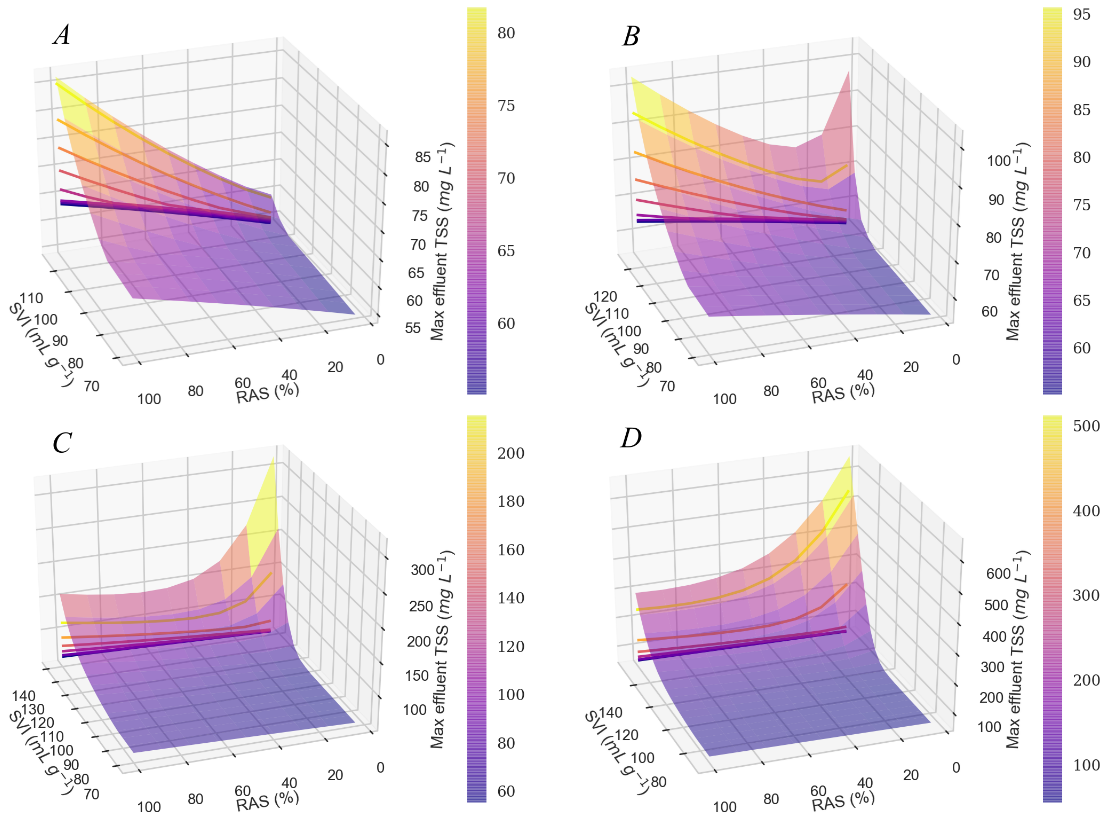


FIGURE 31. 3D plot of the Max TSS in the effluent from the SVI-RAS sensitivity analysis. X axis shows RAS % reduction, Y axis shows range of SVI values, Z axis shows Max. TSS effluent. The bottom layer shows a 2D projection of the plane on the Y axis. Each projection A, B, C, D shows SVI ranges from 70 to 120, 130, 140 and 160 respectively.

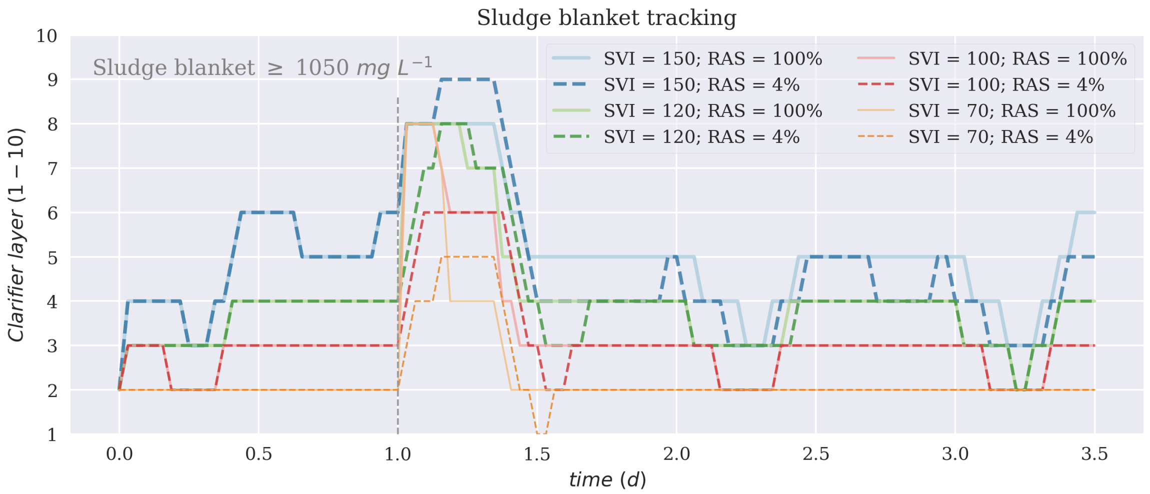


FIGURE 32. Sludge blanket level in clarifier (represented as the first layer with a concentration of 1050 or more mg/L, for SVI values of 70, 100, 120 and 150, for RAS values of 4% and 100% of the recirculation flow. Storm event starts at day 1, marked by a dashed grey line.

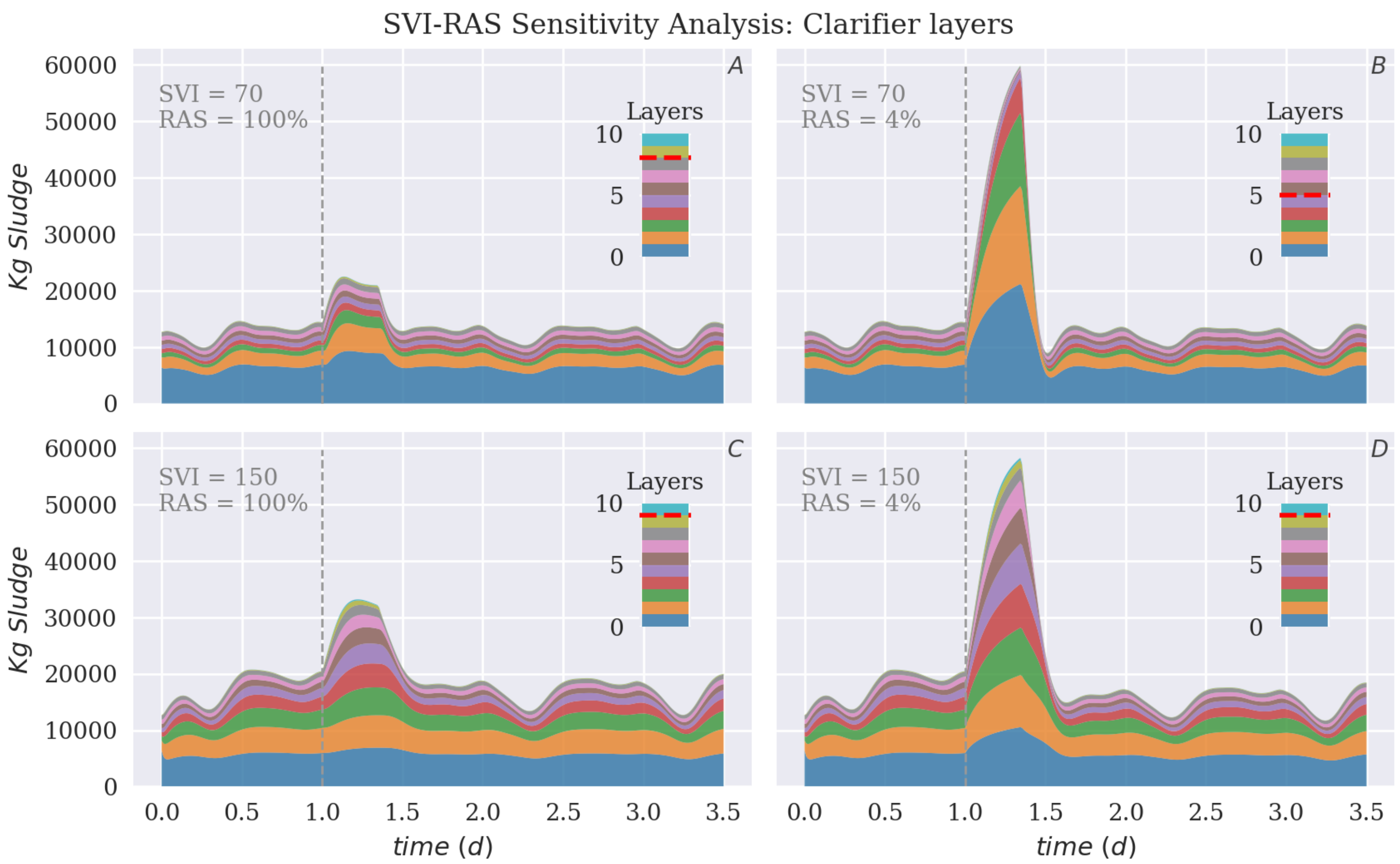


FIGURE 33. Total amount of sludge (in kg) per level in clarifier. The inner subplot shows the 10 layers and indicates the higher layer the sludge blanket reaches (dashed red line). Storm event starts at day 1, marked by a dashed grey line.

The sensitivity analysis helps analyse the effect of the storm within a range of scenarios of SVI and RAS. The model identifies that there is a turning point in the system behaviour, after which the optimal RAS strategy affects in a completely different manner the model performance. The effect of SVI and RAS values is described by the model, as the turning point depends on the storage capacity and the sludge settleability (density). This approach allows the modeller to understand the behaviour of the plant without needing to identify specific points of plant breakdown.

6.5.2 *Power Outage*

Equipment vulnerability assessment

Both the maximum effluent TN and total kg of nitrogen that have been spilled above the compliance limits are larger in the blower shut-down scenarios than the recirculation pumps scenarios, for each power outage duration (fig. 34 A-centre, right). The plant can recover in a short period of time (around 3 days) for any equipment shut-down up to 2 days. The overall resilience loss increases linearly with the duration of the stress event, regardless of the equipment failing.

Aeration strategy assessment with limited energy back-up

Those scenarios which favour redirecting airflow towards the head of the plant ("Favour head", "Only Head") perform worse than the "Base Case" (fig. 34 on the next page). The best scenarios in terms of effluent quality are "Favour rear" and "Open valves".

The dynamic air supply model simulates the changes of pressure in each part of the piping system at limited blower capacity, and calculates the airflow supplied to each reactor. To understand the effect of airflow redirection on the process, fig. 35 on the facing page shows the average oxygen effectively supplied to each aerated reactor [oxygen transfer rate (OTR)], minus the average oxygen used by the process [oxygen uptake rate (OUR)]. In the open valves scenario, due to the specific airflow distribution of this plant, opening all valves redirects the airflow distribution towards the head of the plant. This creates an imbalance in air supply-demand, that is further accentuated in those scenarios where airflow is favoured towards the head of the plant: Base Case, Favour head, Only head.

By closing the manual valves in reactors AER1 and AER2, it is possible to balance the airflow to maintain a minimum DO concentration in all reactors (fig. 35: Favour rear). This maximizes oxygen use and oxygen transfer driving force, at the expense of increased system pressure.

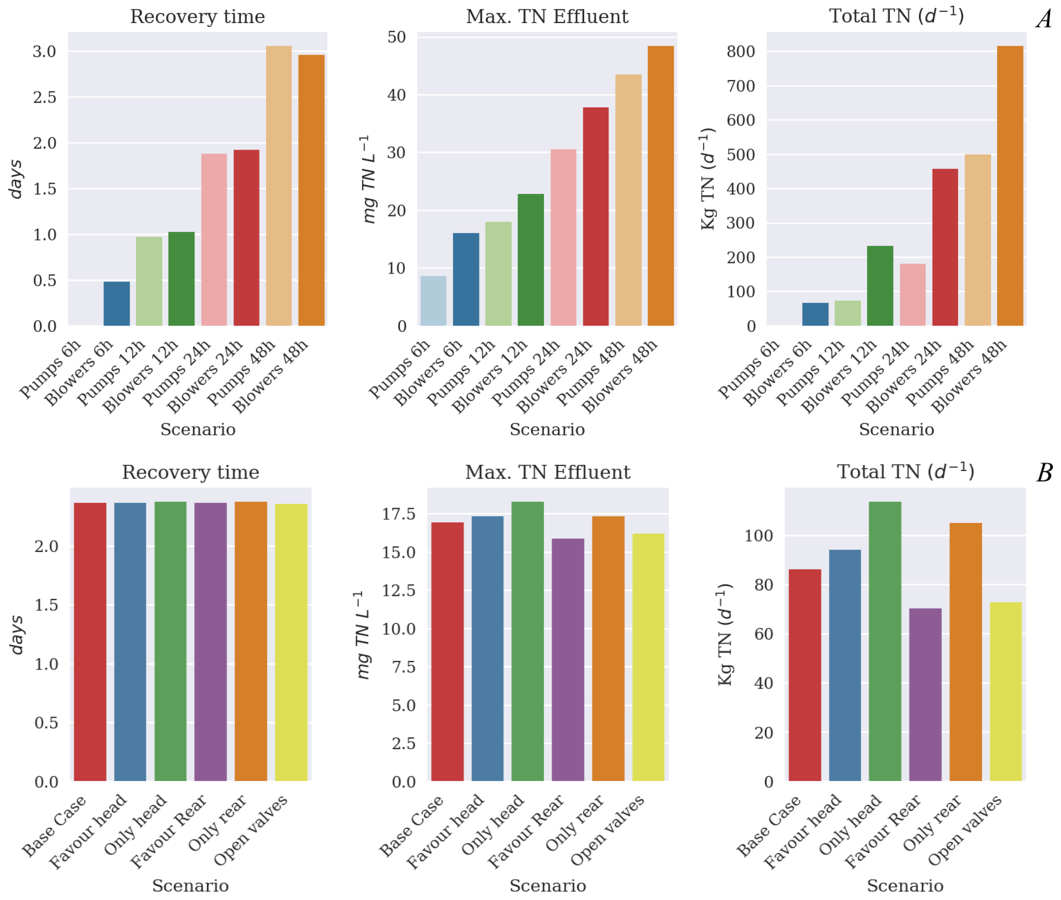


FIGURE 34. A: Sensitivity analysis of equipment and power outage durations; B: Scenario analysis of aeration strategies for a 48h power outage with limited blower energy back-up. *Left*: Recovery time in days for each scenario (Rapidity); *Centre*: Maximum TN concentration in the effluent during the event (Robustness loss); *Right*: Kg of TN released during event, above the 10 mg/L compliance limit, normalized by recovery time (Global Resilience Index)

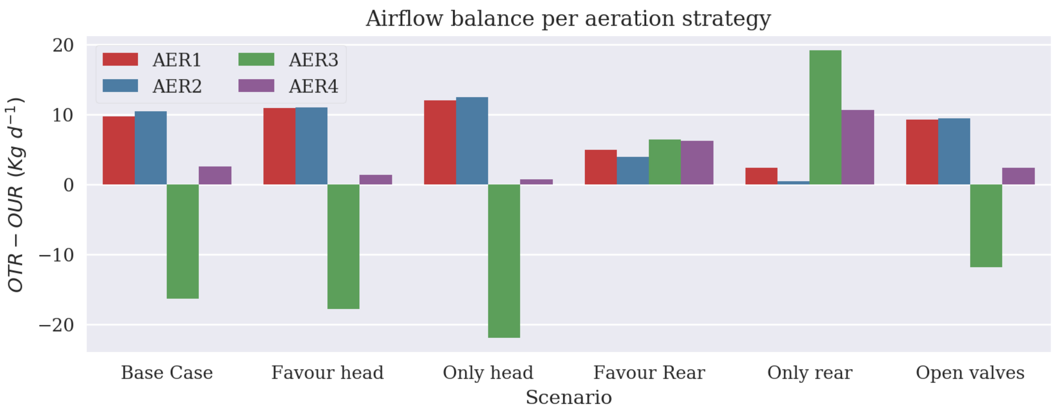


FIGURE 35. OTR – OUR per aerated reactor in each scenario of the sensitivity analysis of equipment and power outage durations. OUR: Oxygen Uptake Rate; OTR: Oxygen Transfer Rate

6.6 DISCUSSION

6.6.1 *Stormwater*

The common tendency is to increase RAS during storm events to work against the sludge inventory shift and recycle more sludge back to the reactors, but this may not be the best strategy for short-term storm events. Increasing the RAS ratio recirculates more sludge to the reactors, but it also increases the hydraulic stress due to increased recirculation flow. Reducing the RAS reduces hydraulic stress and may improve settling; this allows to store more sludge in the clarifier for short periods of time, improving the robustness against washout events and the recovery time. If daily SVI tests are carried out ahead of a storm event and the clarifier is properly functioning, reducing the RAS can potentially increase plant resilience. Considering the recent developments in sludge blanket measurement in real time (Derlon *et al.*, 2017), a control strategy may be possible by monitoring the sludge blanket to keep the external recirculation pump to a minimum during storms.

This first case illustrates the importance of using sensitivity analysis in resilience assessment. As no data is available to calibrate the clarifier response against a storm, and there are no predictive settling models available, regardless of which settling model is used a sensitivity analysis on the SVI index is critical to handle the uncertainty of the model.

6.6.2 *Power outage*

The main effect of recirculation pump shut-down is the performance loss due to accumulation of sludge in the clarifier and loss of MLSS, progressively reducing all biological activity in the reactors. Up to 2 days, the clarifier shows no signs of breakdown. Blower shut-down has a more immediate effect on effluent quality, as the lack of oxygen completely stops aerobic activity. The plant would enter non-compliance after around 6h of blower shut-down, and 12 h in case of pump recirculation shut-down.

There are Back-up generators for the wastewater industry available by a range of suppliers (e.g. HIPOWER; and also resale alternatives (e.g. WPC)

In the case of larger power outages, resilience can be enhanced by increasing the back-up energy available. For power outages up to 12 hours blowers should be prioritized, which would require a generator up to 230 kW for full blower functionality. If longer power outages are considered a better option is to run the plant with recirculation pumps and the blower at minimum capacity. In this case, the plant requires extra back-up of 260kW, obtaining much better performance for

TABLE 16. Energy consumption of various equipment at the Girona WRRF. VFD: Variable Frequency Drive

Equipment	**Power** (kW)
Internal recirculation pump (VFA)	30
Blower (minimum capacity)	150
Influent pump	55
Internal recirculation pump	15
External recirculation pump	39.9
Sludge surplus pump	9
Pump to tank for supernatant of secondary clarifiers	3
Pump to tank to empty biologic sludge	7.23
Pump to dose Poly-Aluminium Chloride	0.55
Pump dose FERRICLAR (Iron)	0.75

power outages up to 48h (fig. 34 on page 97). A list of relevant equipment with the power consumption for the Girona WRRF is presented in table 16.

When the blower is run at limited capacity, the operational settings of the aeration system can be optimized to increase resilience. The two competing processes are the system pressure and the oxygen transfer driving force which depends on optimizing airflow supply-demand. The fact that similar effluent quality is obtained in the scenario that balances airflow and the scenario that minimises pressure (fig. 35 on page 97), suggests that both driving forces have equal weight in plant performance, and should be considered when deciding the best operational strategy or design.

Part IV

DISCUSSION AND CONCLUSIONS

The saddest aspect of life right now is that science gathers knowledge faster than society gathers wisdom.

ISAAC ASIMOV'S BOOK OF SCIENCE AND NATURE QUOTATIONS
—Isaac Asimov & Jason A. Shulman

7

DISCUSSION

7.1 GENERAL CONTRIBUTIONS OF THIS THESIS

This work is the result of an industrial doctorate program and, as such, it is expected to contribute not only in the academic sector, but also to provide industrial benefits. The main contributions of the thesis can be summarized as:

A complete overview of the goals of this thesis can be found in section 1.4.1 on page 10. This section discusses how the contributions are of use to the wastewater sector

1. Providing an overview of the current paradigm of resilience theory in wastewater management
2. Providing a standard structure and elements for resilience assessment of WRRF
3. Identifying the advantages and challenges of model-based resilience assessment
4. Testing the ability of mechanistic models to reproduce the behaviour of a WRRF under sudden changes
5. Developing a framework as good modelling practices for model-based resilience assessment, which add a new model application to the current GMP protocol
6. Testing the framework to provide insight on resilience strategies against stormwater and power outage

In addition, it is expected that the work carried out will be useful to:

UTILITIES that seek to assess how resilience can be implemented in their works in the most cost-effective way, or that want to learn which stressors their sites are most vulnerable to.

CONSULTANTS that are interested in helping the utilities overcome the challenges of uncertainty planning through resilience as a new business opportunity.

ACADEMICS who are interested in resilience theory, particularly in the water sector. Also modelers in the water sector, interested in state of the art in the limits of using ASM for WRRF performance.

MANUFACTURERS that want to know how the new technologies in development fit within the new resilience-risk management paradigm.

7.2 A NEW PARADIGM IN RISK MANAGEMENT

Resilience implies a change of paradigm towards risk management, switching the focus from *predict* and *prepare* to *adapt* and *recover* (Tran *et al.*, 2017). This new perspective assumes that no design is 100% reliable, and therefore the plant will experience stressors during its lifespan for which it has not been designed. The *predictive* capacity of current risk management approaches and modelling studies based on historical data is limited, as the outcome of unobserved stressors is, by definition, impossible to predict with certainty. Instead, systems have to be build with inherent resilience, which allows them to adapt to unpredicted stressors and recover fast from service disruption.

Figure 36 on the facing page shows the domain of resilience over the current paradigm. For stressors of small magnitude, the probability is higher; this is the domain of reliability (fig. 36-green). As the magnitude increases, the probability decreases. This area has been considered risk management so far, and it is now being transformed by new ideas from resilience theory (fig. 36-blue). But the new domain hitherto unexplored is that of black swans; stressors to which no probability is associated, able to cause major process disruption. This is the domain of resilience (fig. 36-orange). This thesis studies mainly those stressors in the shared area of risk-management and resilience. Future research should be directed towards the study of resilience against low-probability stressors and black swans.

7.3 THE FUTURE OF WASTEWATER TREATMENT

Wastewater treatment plants are slowly but steadily being transformed into WRRF, a term that is already being applied to encourage society to accept this change of philosophy. This new type of infrastructure will run more complex and, arguably, more vulnerable processes, producing products that have to comply with tighter standards of quality. In this context, a process disruption may not only cause a compliance breach, but also spoil a batch of product causing extra financial consequences. For development of WRRF to happen, an understanding of process resilience is critical. Securing investment is already problematic in the water sector, and resource recovery requires costly technology that increases its cost. Building resilience in every stage of the project (planning, design and operation) is the only way to foster investment under deep uncertainty.

To assist in implementing resilience in the design and upgrade of water infrastructure, modelling software will become the norm, as it already is for so many other applications. Models are useful tools to test new technologies, especially when there are no design guidelines

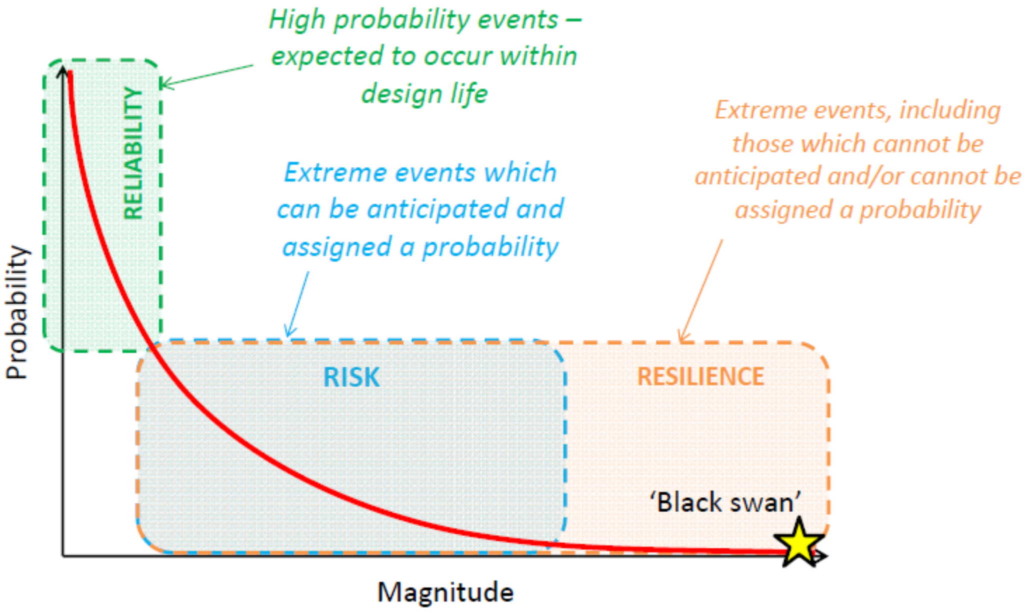


FIGURE 36. Graphical description of resilience definitions and metrics in the context of the water industry [Adapted from Butler, D. (2018): The Resilience Journey: The Safe & SuRe Project. At *Water Industry Forum: Delivering Resilience in PR19 and Beyond.* Birmingham, 23 May 2018.]

for innovative technologies. Modelling enables the use of a range of strategies such as: probabilistic design, scenario analysis, stressor testing and more. The models of the future will also combine WRRF models with catchment and river models, to carry out integrated assessments that will provide more comprehensive solutions (Regmi *et al.*, Submitted). It is also foreseen that utilities will have models for their largest and most vulnerable works. These will act as a tool to help practitioners understand to what stressors the plant is most vulnerable to, and how to build resilience against them in the most efficient way; not only in the design phase, but also in terms of operational strategies and allocating investment for upgrades.

7.4 MODELLING EXTREME EVENTS

For extreme events such as extensive flooding, tornadoes or wildfire, where the plant undergoes total breakdown, the capability of existing models to describe the plant recovery is unknown. To validate such models, it will be necessary to collect worldwide experiences of stress events and plant breakdown, with emphasis on their recovery time.

The effect of *unobserved stressors* on plant resilience cannot be predicted nor validated with certainty, but this does not signify that models cannot be used to improve our understanding and decision making with respect to such stressors. One of the main risks of this practice is that often too much effort goes into the set-up and simulation of models, and not enough into thinking about the assumptions in place. A professional modeller brings special skills and techniques in order to produce results that are insightful, reliable, and useful. He/she applies quantitative reasoning to observations about the world, in hopes of seeing aspects that may have escaped the notice of others (Silvert, 2000).

7.5 FUTURE WORK

Two main areas of work are identified to standardise the use of model-based resilience assessment in the water sector. The first one concerns the quality of current models to measure resilience and plant performance under stressors. The second one concerns the approach the water industry will take towards resilience to deal with uncertainty.

7.5.1 *Future of modelling*

Identifying an appropriate level of model complexity is a key point in any modelling project; this is no different in the case of resilience. The two applications presented in the case study in chapter 6 have different requirements at sub-model level. Model selection and set-up has been carefully discussed (section 5.3) and tested (chapter 5) to justify their use. The results interpretation has been discussed in detail (section 6.6) with extensive analysis on how to draw conclusions. Since it is not possible to validate the exact effect of the stressors on the plant, a high level of effort has been put into validating that the model is sensitive to them. This approach is necessary to draw meaningful conclusions, and has been carefully described in the framework (chapter 4).

Modelling resilience is at a very early stage. As the field advances, new models will appear that will be able to describe the resilience of a WRRF in more detail. Two important candidates to take into account are:

MECHANISTIC MODELS Historically, model development of ASM has been focused on biokinetics and hydraulics. Model calibration often accounts for discrepancies in data by adjusting lumped parameters, which often masks the effect of equipment response.

Mechanistic models of equipment are appearing that can improve prediction quality in this area. These models are based on first-principles (i.e. physical laws and well understood engineering equations); they need detailed data of the system characteristics to be set-up, but require no calibration. If properly used, this can reduce model uncertainty, and represent the behaviour of equipment more accurately.

GRAY-BOX MODELS The impact of big data and data science methods is arriving to wastewater modelling. The next generation of models will combine the current deterministic approach of *process knowledge-based* models with the predictive capacity of *data driven* models. These *grey-box* models have endless possibilities, but to draw meaningful conclusions their use will require a multidisciplinary team to reconciliate process knowledge with data science and its computational implementation.

Finally, the feasibility of ASM models and future models to describe performance under extreme events (e.g. start-up of a the biological treatment after a sludge washout event) will need to be documented. To this end, a global database of stress events has to be created, with emphasis of plant status before and after disruption, and recovery time. Research efforts are needed in monitoring the recovery/start-up of a treatment plant. The ability of the current biokinetic models to represent the recovery of a full-scale plant or even a simple reactor has never been tested.

The Water Environment Federation Podcast: Words on Water produced this fantastic episode Hurricane Harvey and Houston Water where employees of Houston Water explain their experience during the catastrophic flooding in Houston, caused by Hurricane Harvey, which caused $125 billion in damage

7.5.2 *Bringing resilience into operation*

ADOPTION BY INDUSTRY Regardless of how the existing tools such as process modelling are adapted to resilience, their value needs to be demonstrated before the water industry will adopt them. Likewise, current frameworks need to be able to interact with wider asset management frameworks such as Butler, Ward, *et al.* (2016).

FUNDING Resilience entails increased costs in system design, upgrade and operation. In a sector where successful bids are normally the most cost competitive, this is a clear constraint. The main objective of resilience assessment is not to allocate resources in the most effective way, but *to demonstrate that not allocating any resources at all will result in more expense in the long term*. Resilience needs to be implemented very early in the design project, and involve all stakeholders. From an economic point of view, the objective of resilience is to secure efficient and cost effective investment of water and wastewater infrastructure.

CONSENSUS Despite all the effort from Ofwat, the water companies are not yet using the same vocabulary and metrics for resilience. There is no framework for resilience assessment that is complete, systematic and comparable across sites that can be used directly by practitioners. Unless consensus is achieved and common guidelines agreed, the use of resilience will be no different from the current allocation of funding.

STANDARDIZATION The final step towards standardization of resilience assessment is to help the users define a *standard level of resilience*; that is, the minimum level of resilience that needs to be attained in a simulation against a set of stressors in a range of metrics. Only then, will the utilities be able to compare objectively the level of resilience in their works, and benchmark interventions to achieve the desired level of resilience in the most cost-efficient way.

8

CONCLUSIONS

8.1 STATE OF RESILIENCE THEORY IN WATER MANAGEMENT

It is widely believed that we are currently in a situation in which there is a high degree of uncertainty regarding the challenges that lay ahead for our water infrastructure and services. This creates a new need for WRRFs; to be able to resist and recover from stressors for which no probability can be assigned, the so called *unobserved stressors* or *black swans*. To reflect these extreme events, a new approach to risk management is necessary. Today, resilience is a new concept in water management that builds on risk assessment and is steadily becoming part of how the sector designs, upgrades and operates water infrastructure.

The response of the UK water sector to their newly acquired resilience responsibility is at an early stage. Utilities are implementing a wide range of measures to prepare for the forthcoming years, but the effect that these measures have on plant resilience is unknown. Without a standardized approach for resilience assessment it is impossible to benchmark different alternatives, which is key to prioritize and optimize investment in the short, mid and long term. More effort is needed to incorporate resilience research into the industry sector.

8.2 DYNAMIC AERATION MODELLING FOR RESILIENCE

The goal was to demonstrate that the use of mechanistic modelling of the aeration system provides a better estimate of plant performance, and helps gain understanding of the relationships between process performance, aeration equipment, control and energy consumption. The plant model was set up with a dynamic air distribution model together with a process model and a control system model. Prior to the audit, the plant's aeration system was already controlled and considered to be optimised following a trial-and-error approach by operators. Using the model, a set of strategies was designed which reduced energy consumption by 12-21%, while improving effluent quality. Furthermore, in the simulated scenario with no equipment limitations, the DO profile is the same across reactors and follows the DO setpoint in all aerated tanks, and the aeration system can respond faster to disturbances and draw more aeration capacity when needed. This is the first full-scale validation of the dynamic mechanistic model of the air distribution system.

The study highlights the importance of considering equipment constraints when designing control strategies. Often the system constraints are hidden as they cannot or are not measured, such as the positions of the manual valves, or the effect of pipes and valves sizing. The mechanistic dynamic air supply model accurately represents the current system, showing airflow distribution and pressure drops as they occur in the plant. This enables in-depth analysis of the aeration together with the treatment performance and the control system, diagnosing the main bottlenecks in the existing aeration system (i.e. the piping size, diffuser distribution and blower minimum turn-down).

8.3 RESILIENCE ASSESSMENT OF THE GIRONA WRRF

This work provides a framework for the development of deterministic models for quantitative resilience assessment in real-life systems, providing a new application to the GMP UP. Model-based resilience assessment has great potential, but to be applicable to real case studies special care is needed in data collection, model set-up and calibration. As a proof of concept, two cases of extreme events are modelled: an extreme stormwater event and a power outage event of varying duration. The most important results are summarized as follows:

1. During wet weather, the Girona WRRF has potential to treat up to 3 times the dry weather flow. However, this may compromise the resilience of the plant if sludge washout occurs.

2. RAS manipulation can increase resilience against wet weather events, while treating the desired flow, but its implementation depends on sludge settleability. The sensibility analysis on RAS and SVI has identified a turning point in the system's behaviour that indicates how to manipulate RAS to increase resilience. Full-scale studies are needed to evaluate how to implement it. The possibility of a control strategy using automatic registration of the sludge blanket height via image analysis should be investigated.

3. The plant would enter non-compliance in case of a blower power shut-down of around 6h, and around 12h in case of recirculation pumps shut-down.

4. The best option to enhance resilience would be to increase the power back-up in 260 kW, which allows the plant to run with recirculation pumps and blowers at minimum capacity. In such

case, resilience can be further enhanced by optimizing the trade-off between balancing oxygen needs in each reactor while lowering system pressure.

5. More effort is needed in data collection of real stress events and plant recovery to help validate models that study resilience
6. First law mechanistic models of equipment are a vital tool in resilience modelling to reduce uncertainty and improve the ability of the model to simulate stressors.
7. The use of resilience in wastewater management is still at its infancy. More work and engagement between all the stakeholders is needed to bring resilience into practice.

Part V

TECHNICAL APPENDIX

I am a brain, Watson. The rest of me is a mere appendix.

THE ADVENTURE OF THE MAZARIN STONE
—Arthur Conan Doyle

A

META-DATA COLLECTION AND ORGANIZATION

A.1 RESULTS OF THE INITIAL STEADY STATE CALIBRATION

The results of ICRA's steady-state calibration (Table 17), with a focus on sludge production and effluent quality, show that the model is well-calibrated and can be used for testing various control strategies.

TABLE 17. Results of the steady-state calibration of ICRA's basic steady-state model

Target variable (mg/l)	**Measured**	**Acceptable Error** %	**Acceptable Error Range**	**Modeled**
MLSS	2850	±10	2565 to 3135	2919
Wasted Sludge	5200	±5	4940 to 5460	5323
Effluent Total N	6.9	±1.0	5.9 to 7.9	7.3
Effluent PO4-P	0.35	±0.5	0 to 0.85	0.68

The primary full-scale sludge production in the reference period accounts up to 2055 tons with a production of 6.8 ± 2.7 $tons/day$. The secondary sludge production in full-scale in the reference period accounts is up to 1964 tons with a production of 6.6 ± 2.6 $tons/day$. The amount of sand was not recorded. Operators recorded a sand production of about 70 $m^3/year$.

A number of simulations were run in order to define optimal influent parameters to match primary and secondary sludge production. The results are presented in table 18.

TABLE 18. Optimal parameters combination for the ASM model influent characterization. F_{iN-SS}: fraction of inorganic SS in the total SS. $f_{Sol-COD}$: fraction of soluble COD. ST f_{XAN}: fraction of inorganic trapped in the sandtrap.

K_{BOD}	F_{iN-SS}	$f_{Sol-COD}$	f_{XAN}
0.20	0.15	0.15	0.85
0.2	0.15	0.25	0.85-0.95
0.2-0.4	0.05	0.05	0.75
0.3-0.5	0	0.05	0.75
0.3	0.05	0.15	0.95

A.2 OBTAINING AND PROCESSING DATA FROM SENSORS

The *eSCAN* sensors produced multiple `.xlsx` files per day with the collected measurements. Data was arranged in columns, with the first column being the date-time of sampling. In order to collect and arrange this data in a more usable way, a *bash* script was created by the research technician in ICRA and further modified during this PhD.

Bash is a Unix shell and command language written by Brian Fox for the GNU Project as a free software replacement for the Bourne shell. A Unix shell is a command-line interpreter that provides a traditional Unix-like command line user interface. "Bash scripting" is widely used in the Linux community for string manipulation, given the wide array of programs embed in the language for this purpose. The Bash shell can be made available in Windows operative system through *cmder*, a console emulator for the Bash shell.

Cmder is a software package that features a powerful Unix-like console emulator on Windows; it is available for free in its website

The following bash scripts (`.sh`) consitute a small program run in *cmder* that can produce a single `.xlsx` with the time in the first column and the samples of one or more measurements in the subsequent columns.

`Multijoin.sh`

```
#!/bin/bash

# multijoin - join multiple files

alias join='join -t\;'

join_rec() {
        if [ $# -eq 1 ]; then
                join -t\; - "$1"
        else
                f=$1; shift
                join -t\; - "$f" | join_rec "$@"
        fi
}

if [ $# -le 2 ]; then
        join -t\; "$@"
else
        f1=$1; f2=$2; shift 2
        join -t\; "$f1" "$f2" | join_rec "$@"
fi
```

`Find_col.sh`

```
#!/bin/bash
#FInd the column "n" containing the keyword inside a
    .csv file
```

```
if (( $#<2 )); then echo "Usage: $0 paraula arxiu";
   exit; fi
paraula=$1
arxiu=$2

#In the second row of the file there are the names of
   the columns
headers=$(cat $arxiu | sed -n 2p)

#Check that we have the keyword inside the headers
trobat=$(echo $headers | grep -c -e "$paraula")

if (( $trobat==0 )); then
        echo "Error, keyword not found in any column"
           1>&2 #write to stderr
        exit
fi

#Start iterating through columns
i=1;
while :;
do
        #Check the column "$i"
        columna=$(echo $headers | cut -d ’;’ -f$i)

        if [[ $i>1 && $columna == "" ]]; then break; fi

        #Does it match the keyword
        trobat=$(echo $columna | grep -c -e "$paraula")

        #If we find it then
        if (( $trobat==1 )); then
                echo $i;
                exit
                break;
        fi
        ((i++))
done
```

Print_col.sh

```
#!/bin/bash
#Print the first column and the column where the
   keyword has been found in the .csv

if (( $#<2 )); then echo "Usage: $0 keyword file";
   exit; fi
paraula=$1
arxiu=$2

#Find the column with the keyword
col=$(bash troba_col.sh $paraula $arxiu);
```

```
#Do not print the last 2 lines
#Print the found column ($col)
sed 1,2d $arxiu | cut -d ';' -f 1,$col
```

Print_all.sh

```
#!/bin/bash
#print the first column and the found column of many
   .csv

if (( $#<2 )); then echo "Usage: $0 paraula
   arxiu_1.csv arxiu_2.csv ... arxiu_n.csv"; exit; fi
paraula=$1

#Traverse all the arguments (files) starting by the
   2nd (first file)
for (( i=2; i<=$#; i++ ))
do
        arxiu=${@:$i:1};
        #echo $arxiu;
        bash print_col.sh $paraula $arxiu;
done
```

Keywords.sh

```
#!/bin/bash
if (( $#<1 )); then echo "Use: $0 paraula1 paraula2
   ..."; exit; fi

cd programa

i=1
for paraula in "$@"
do
        echo "[+] Searching $paraula..."
        #Creates a temporary file 1.join, 2.join, etc
        bash print_tots.sh $paraula ../arxius/* | tee
           "$i.part"
        echo
        ((i++))
done

if (( $#==1 ))
then
        mv 1.part ../out.csv
else
        bash multijoin.sh *.part > ../out.csv
        rm *.part
fi


#final
echo "+----------------------+"
```

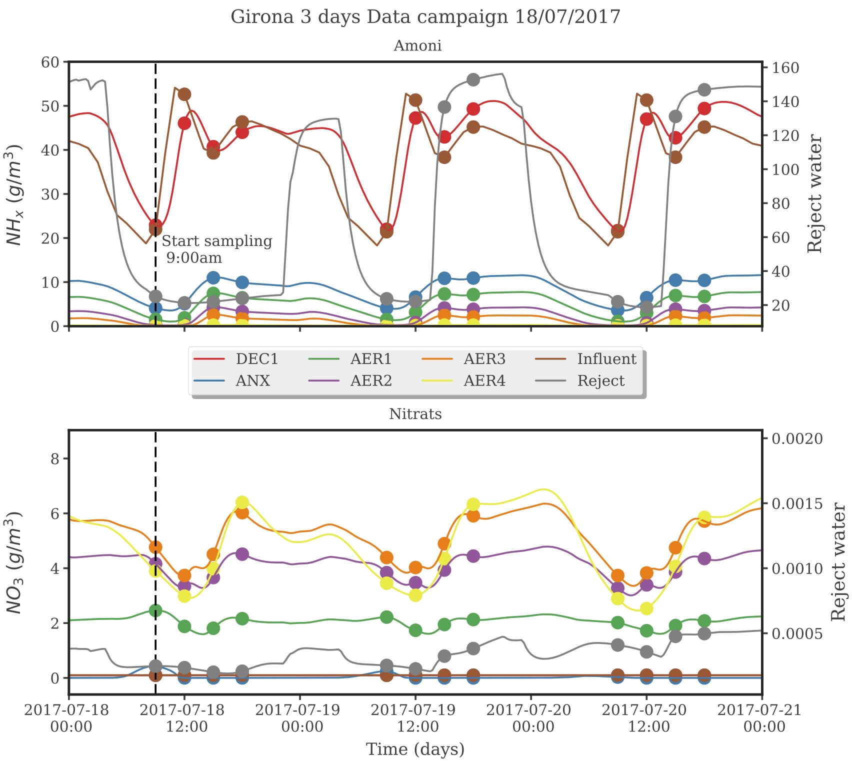


FIGURE 37. Graphic of the second data campaign sampling times for ammonia and nitrates. Amoni:Ammonia; Nitrats: Nitrates

```
echo "| File  out.csv created |"
echo "+-----------------------+"
cat ../out.csv
```

A.3 ORGANIZING DATA FROM A SAMPLING CAMPAIGN SYSTEMATICALLY

In section 3.2 on page 42, a thorough description of the data collection files is given. Figure 37 shows the timing of the data sampling during the second data campaign.This chapter will explain how the data has been organized. The system chosen consists of a series of Python scripts that take the original data files as input and carry the analysis, producing a new `.csv` to output the analysis if necessary. This will ensure that all data is traceable, and creates a data architecture that for the long-term needs of the project. All data has been labeled and recorded as a time series, which ensures that asynchronous data collection will be possible if extra data was to be collected.

The Python language has been chosen on account of being a general-purpose programming language that is becoming more and more popular for doing data science. It is open-source, well documented and counts with extensive libraries for data analysis and visualization such as *numpy*, *pandas* and *matplotlib*.

The coding style follows the recommendations of the PEP (Python Enhancement Proposals) 8 protocol, which describes coding conventions for code in the standard Python library. This PEP covers how code should be commented, use tabs or spaces to indent code, naming convention, the use of non-semantic white space, etc. Other documentation and coding practices include the following books and websites:

- Python Data Science Handbook. *Jake VanderPlas*
- Python for Data Analysis. *William McKinney*
- Think Stats: Exploratory Data Analysis in Python *Allen B. Downey*
- Matplotlib examples gallery

In order to carry the analysis, the Graphical User Interface *Spyder* has been used, as part of the Anaconda distribution package, a free and open source distribution of the Python and R programming languages for large-scale data processing, predictive analytics, and scientific computing.

A.3.1 *Script to organize the data campaign in one pandas dataframe*

The data from the campaign is scattered in a series of `.csv` and `.xlsx`. The following script traverses the folders where the Data Campaign is stored and loads the data as a `pandas dataframe`. The dataframes columns are renamed and stored following the corresponding date and time they were collected (using *pandas* `Timeseries` and `timestamp` objects. Finally, all data is joined into a single dataframe. Since the sample timing is not always constant, all values are re-sampled to a common time interval by interpolation. The script used is available in GitHub as `dataCampaign.py`.

A.3.2 *SCADA data in PDFs*

The following pages contain the information from the Girona plant SCADA system available in PDF concerning the days of the data campaign.

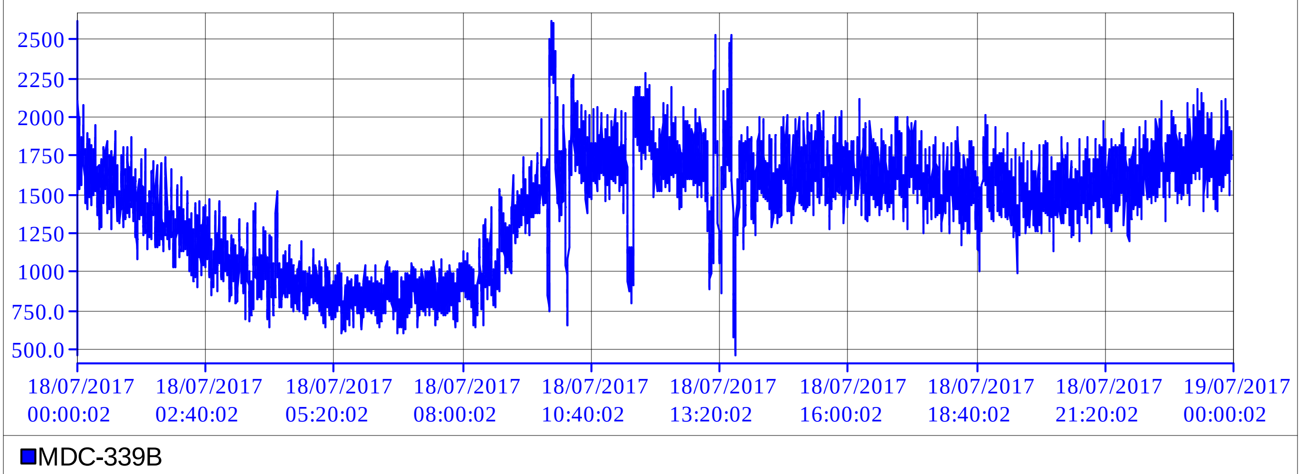
Translation from top to bottom:

- *Caudal entrada biologic*: flow entering biological treatment
- *Recirculacio interna*: internal recirculation
- *Cabal Recirculacio Externa*: External recirculation flow
- *Bombes recirculacio externa*: External recirculation pumps
- *Soplants*: Blowers
- *Valvules proporcionals*: Valve position (automatic valves) Oxigen disolt biologic: solved oxygen in biological (reactor)
- *MDO-317C*: DO concentration in AER1, lane 2
- *MDO-317B*: DO concentration in AER1, lane 1
- *MDO-317F*: DO concentration in AER4, lane 2
- *MDO-317E*: DO concentration in AER4, lane 1

Data inici 18/07/2017 00:00:02
Data final 19/07/2017 00:00:01

BIOLOGIC

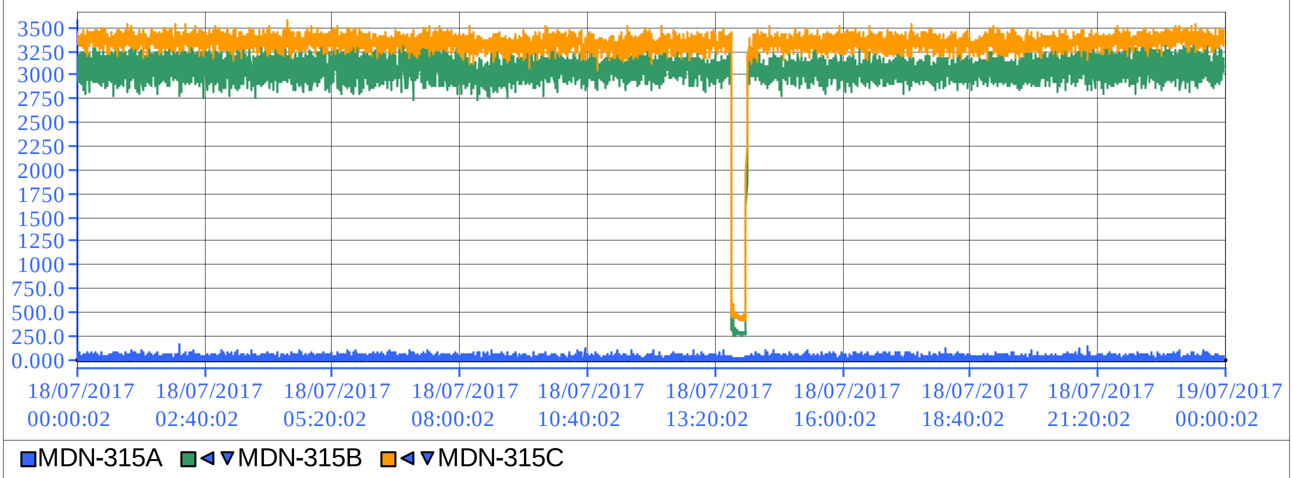
CAUDAL ENTRADA BIOLOGIC



Valor Maxim 2617 m3/h **Hora** 18/07/2017 09:52:20 **Valor Mig** 1424 m3/h
Valor Mínim 467 m3/h **Hora** 18/07/2017 13:40:10

Contador Inici m3	Contador final m3	Caudal Diari m3
81238584	81277056	38472

RECIRCULACIO INTERNA

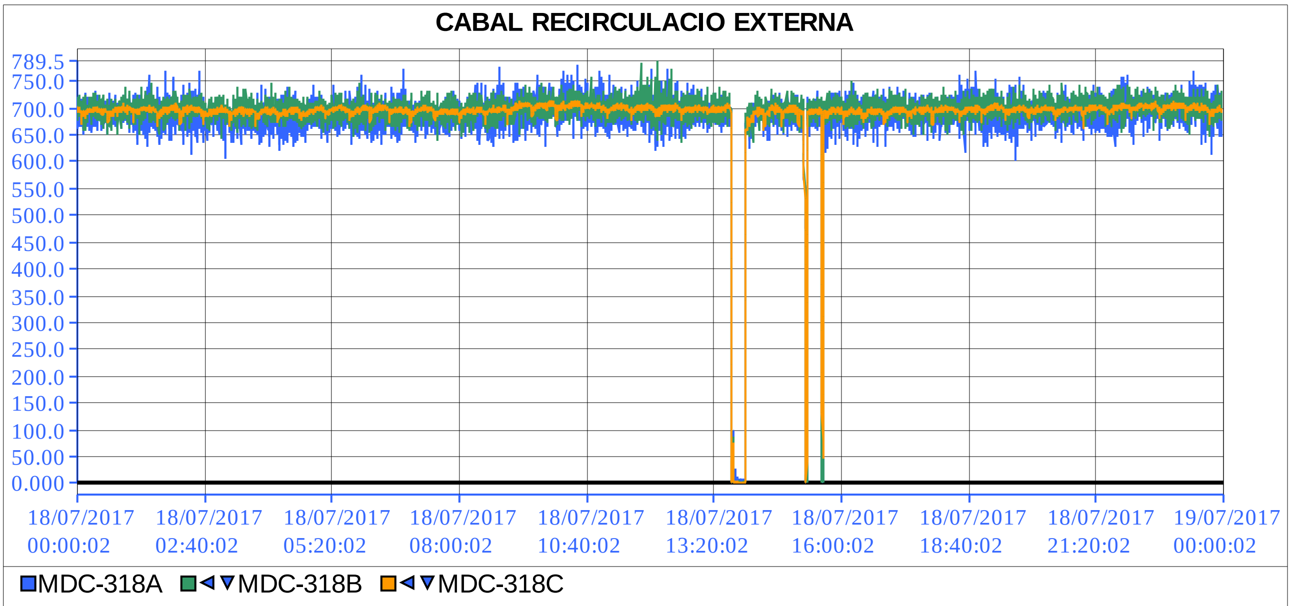


Valor Maxim 158 m3/h **Hora** 18/07/2017 02:09:00 **Valor Mig** 18 m3/h
Valor Mínim 0 m3/h **Hora** 18/07/2017 00:00:10

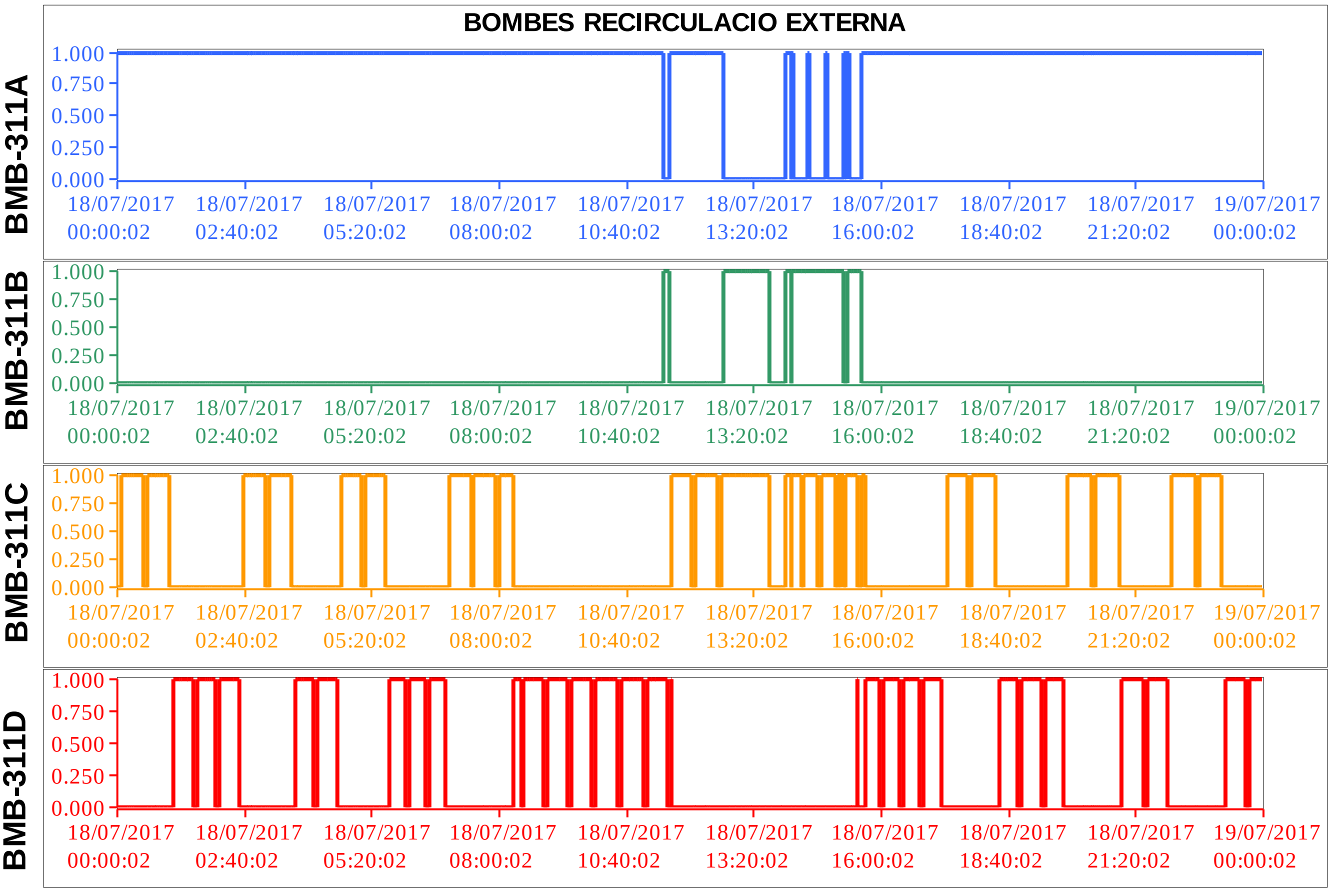
Valor Maxim 3382 m3/h **Hora** 18/07/2017 22:41:20 **Valor Mig** 3021 m3/h
Valor Mínim 248 m3/h **Hora** 18/07/2017 00:00:10

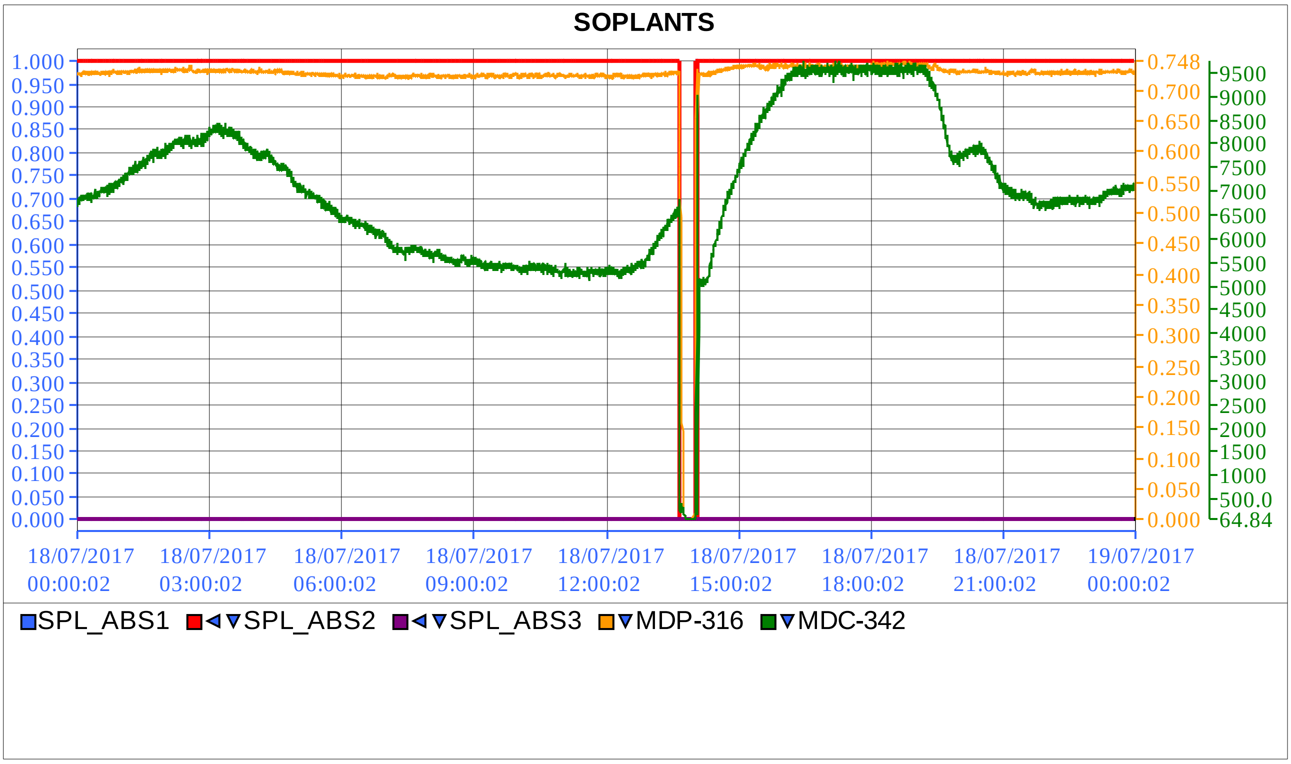
Valor Maxim 3569 m3/h **Hora** 18/07/2017 04:24:20 **Valor Mig** 3305 m3/h
Valor Mínim 410 m3/h **Hora** 18/07/2017 13:53:30

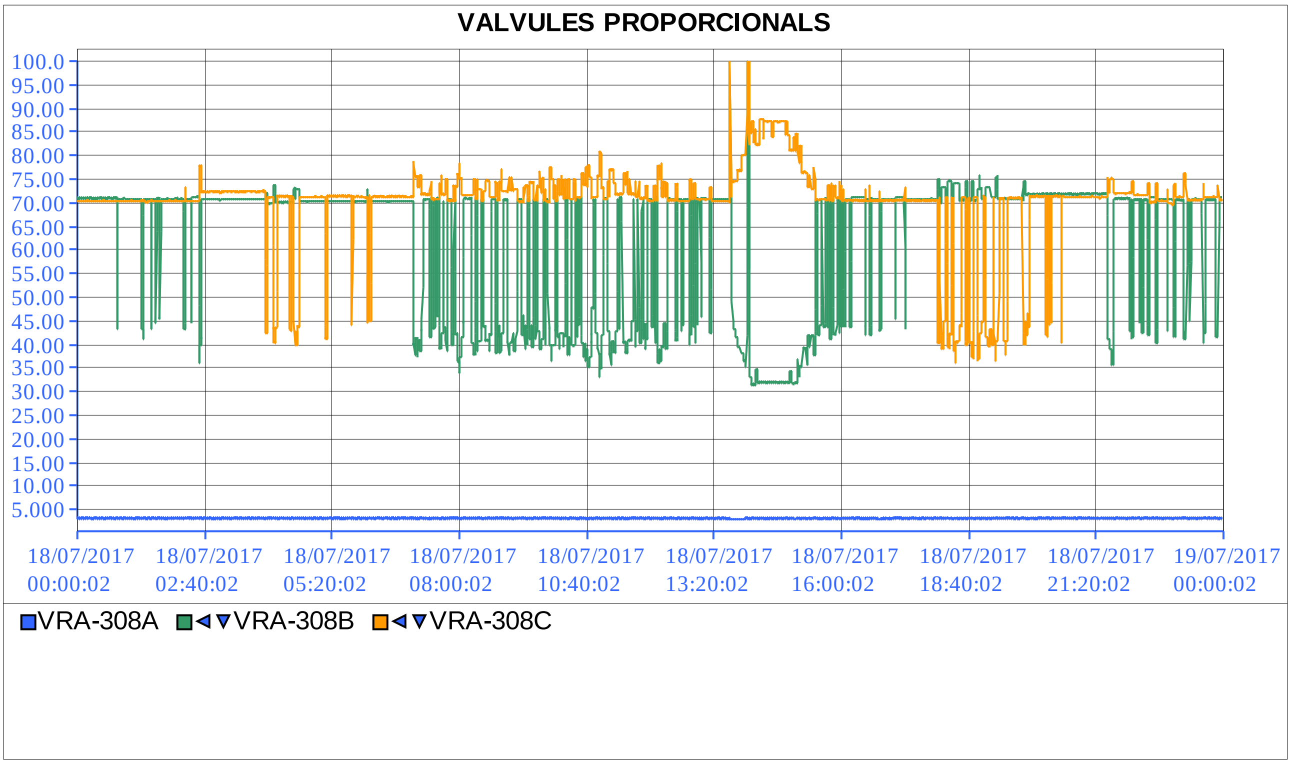
Data inici	18/07/2017 00:00:02
Data final	19/07/2017 00:00:01



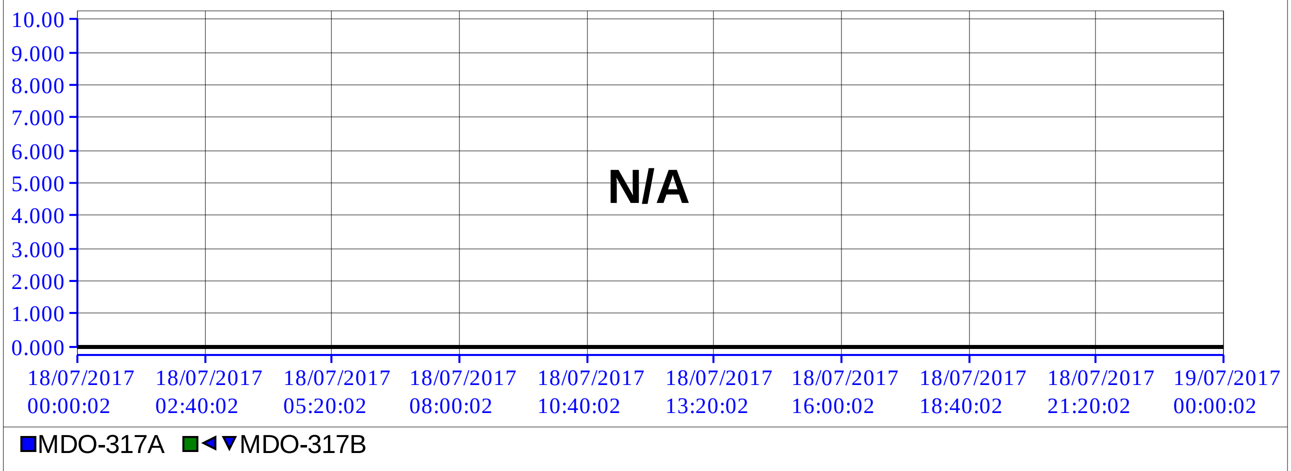
Valor Maxim	780 m3/h	**Hora**	18/07/2017 10:29:10	**Valor Mig**	681 m3/h
Valor Mínim	0 m3/h	**Hora**	18/07/2017 13:43:40		
Valor Maxim	790 m3/h	**Hora**	18/07/2017 12:10:50	**Valor Mig**	689 m3/h
Valor Mínim	0 m3/h	**Hora**	18/07/2017 13:43:40		
Valor Maxim	714 m3/h	**Hora**	18/07/2017 10:26:00	**Valor Mig**	687 m3/h
Valor Mínim	0 m3/h	**Hora**	18/07/2017 13:44:00		



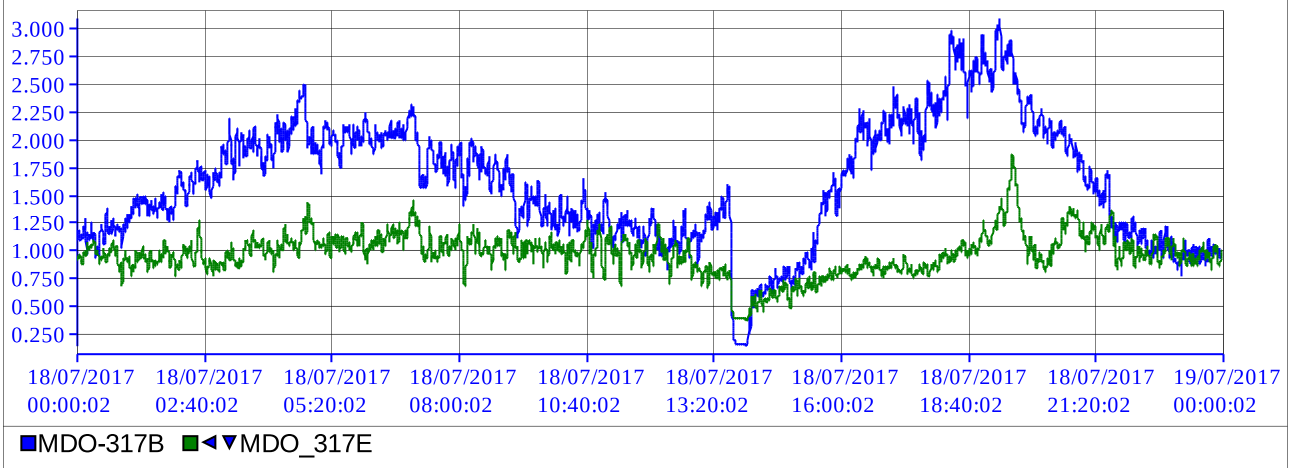

SOPLANTS


VALVULES PROPORCIONALS

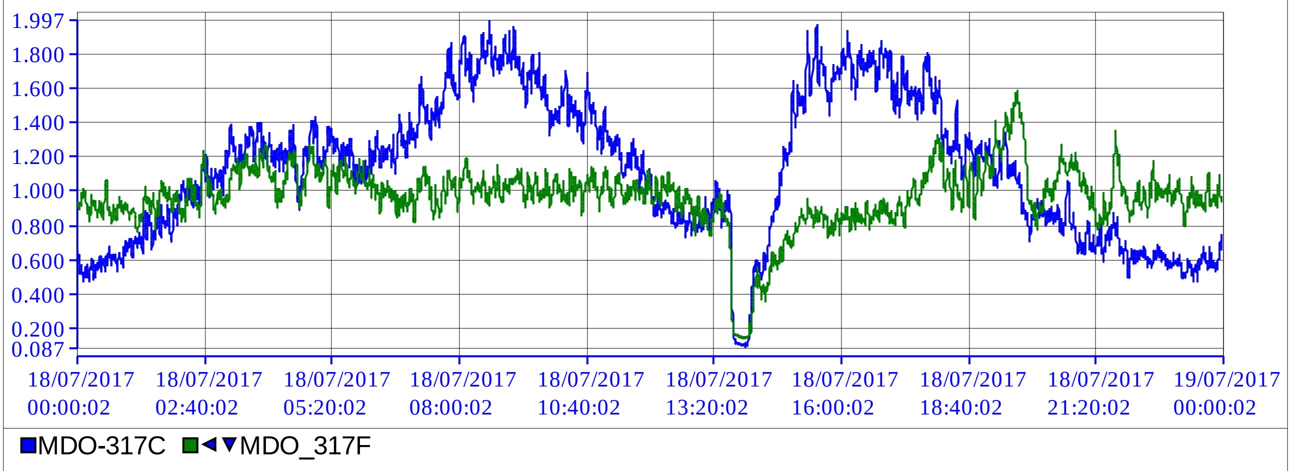
OXIGEN DISOLT BIOLOGIC 1



OXIGEN DISOLT BIOLOGIC 2



OXIGEN DISOLT BIOLOGIC 3

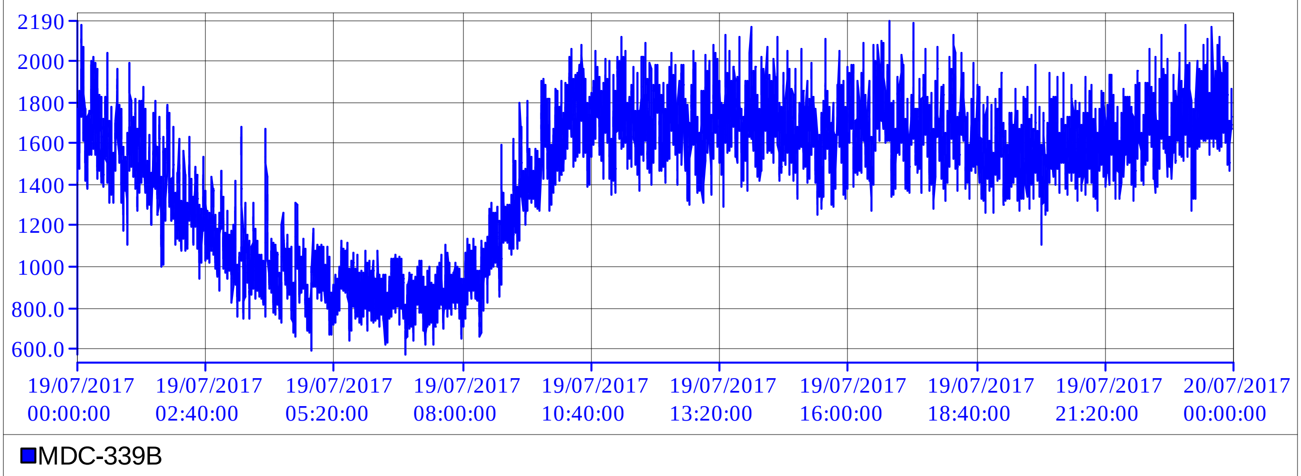


TRARGISA
Tractament de Residus i d'Aigües Residuals
del Sistema de Girona, S.A.
AREA DE SANEJAMENT

Data inici	19/07/2017 00:00:00
Data final	19/07/2017 23:59:59

BIOLOGIC

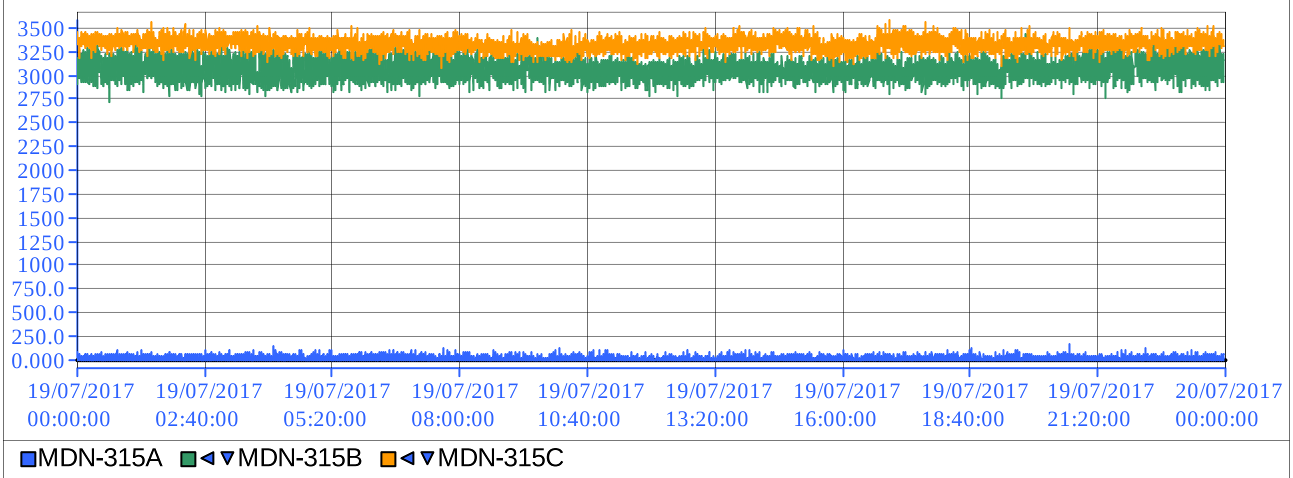
CAUDAL ENTRADA BIOLOGIC



Valor Maxim	2190 m3/h	**Hora**	19/07/2017 16:53:40	**Valor Mig**	1451 m3/h
Valor Mínim	575 m3/h	**Hora**	19/07/2017 06:49:50		

Contador Inici m3	Contador final m3	Caudal Diari m3
81277056	81318664	41608

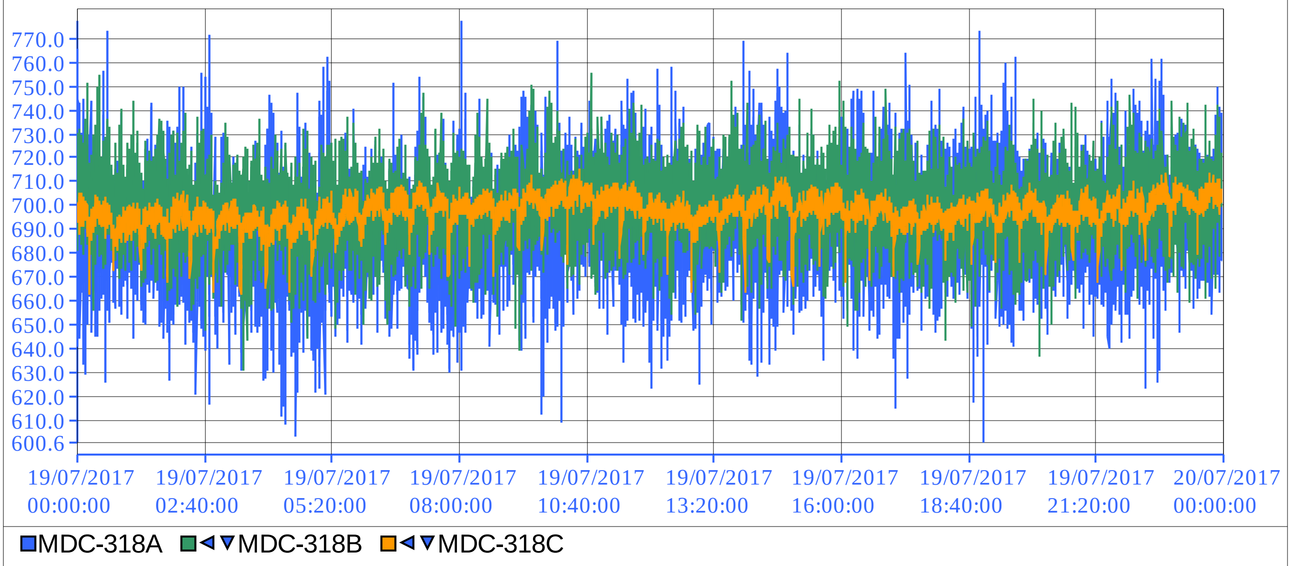
RECIRCULACIO INTERNA



Valor Maxim	165 m3/h	**Hora**	19/07/2017 20:47:10	**Valor Mig**	18 m3/h
Valor Mínim	0 m3/h	**Hora**	19/07/2017 00:00:30		
Valor Maxim	3431 m3/h	**Hora**	19/07/2017 19:51:00	**Valor Mig**	3059 m3/h
Valor Mínim	2717 m3/h	**Hora**	19/07/2017 00:00:30		
Valor Maxim	3573 m3/h	**Hora**	19/07/2017 16:59:30	**Valor Mig**	3330 m3/h
Valor Mínim	3070 m3/h	**Hora**	19/07/2017 07:38:00		

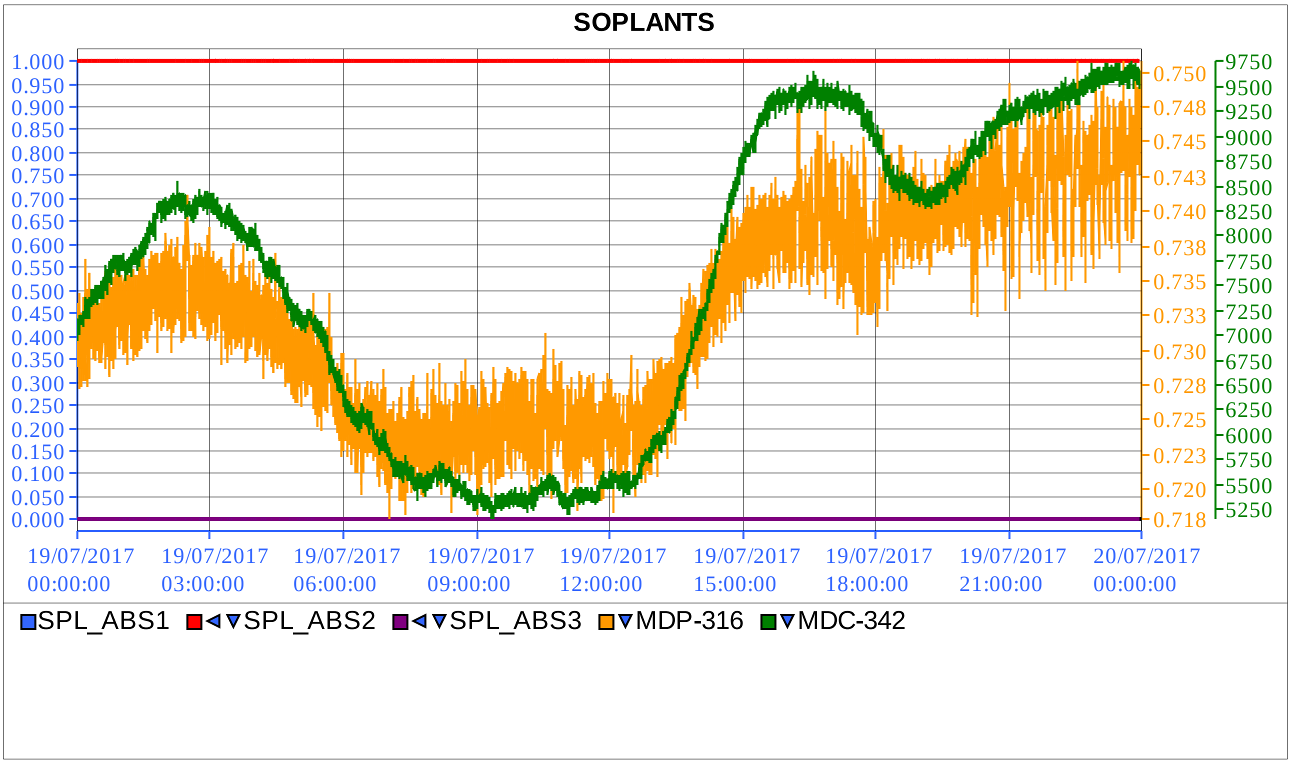
Data inici 19/07/2017 00:00:00
Data final 19/07/2017 23:59:59

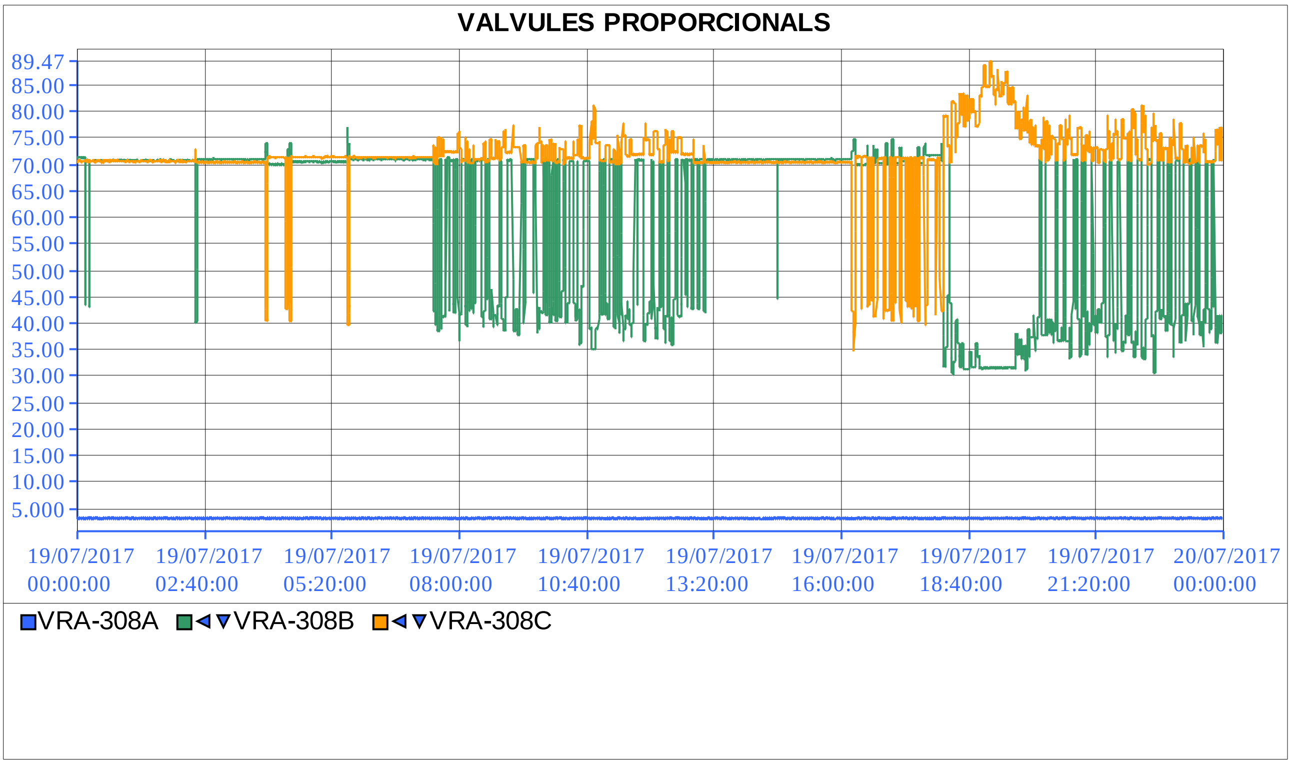
CABAL RECIRCULACIO EXTERNA

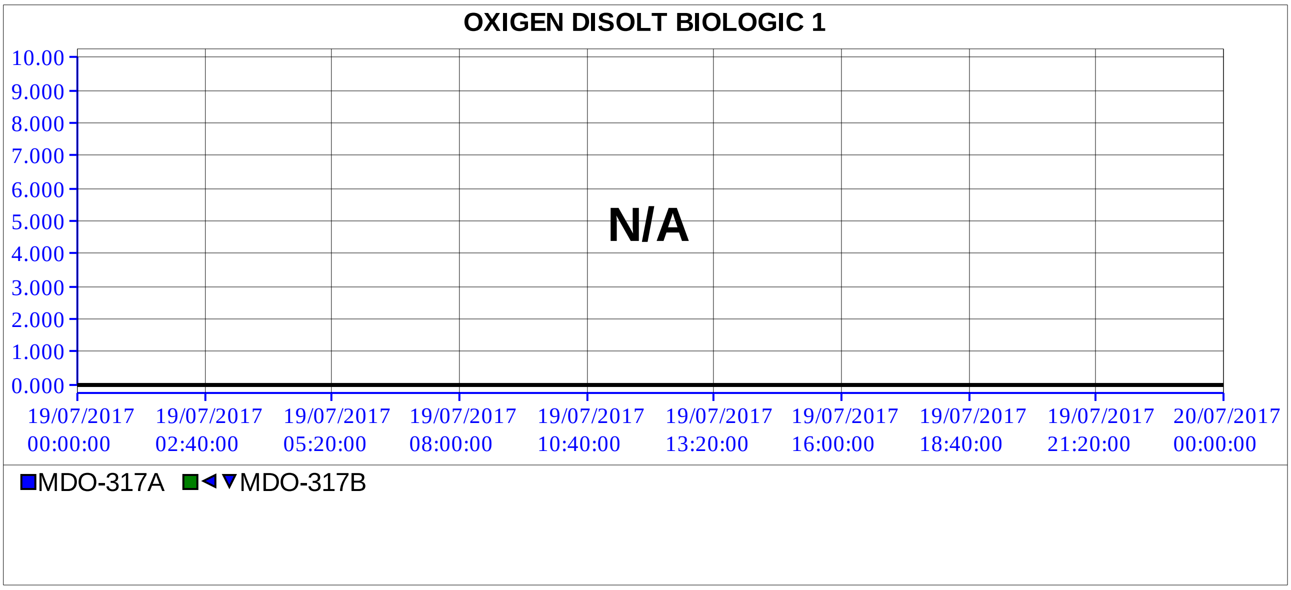


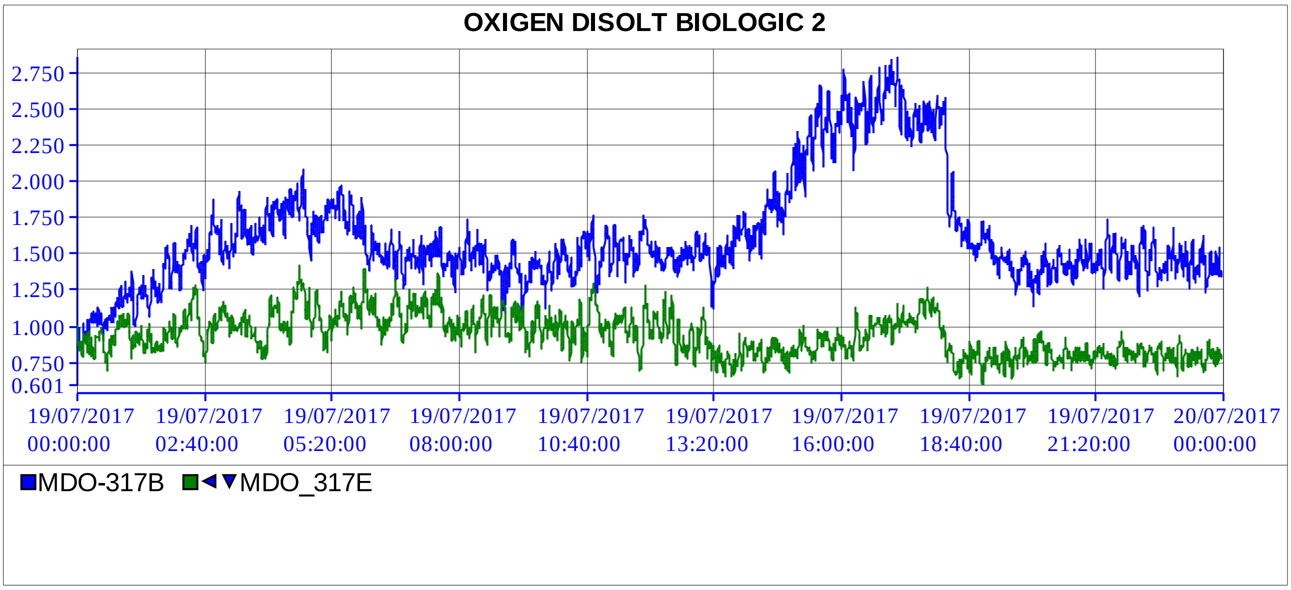
Valor Maxim	778 m3/h	**Hora** 19/07/2017 08:02:40	**Valor Mig**	691 m3/h
Valor Mínim	601 m3/h	**Hora** 19/07/2017 19:01:20		
Valor Maxim	756 m3/h	**Hora** 19/07/2017 10:46:00	**Valor Mig**	699 m3/h
Valor Mínim	631 m3/h	**Hora** 19/07/2017 19:01:20		
Valor Maxim	715 m3/h	**Hora** 19/07/2017 10:31:10	**Valor Mig**	697 m3/h
Valor Mínim	662 m3/h	**Hora** 19/07/2017 00:15:30		

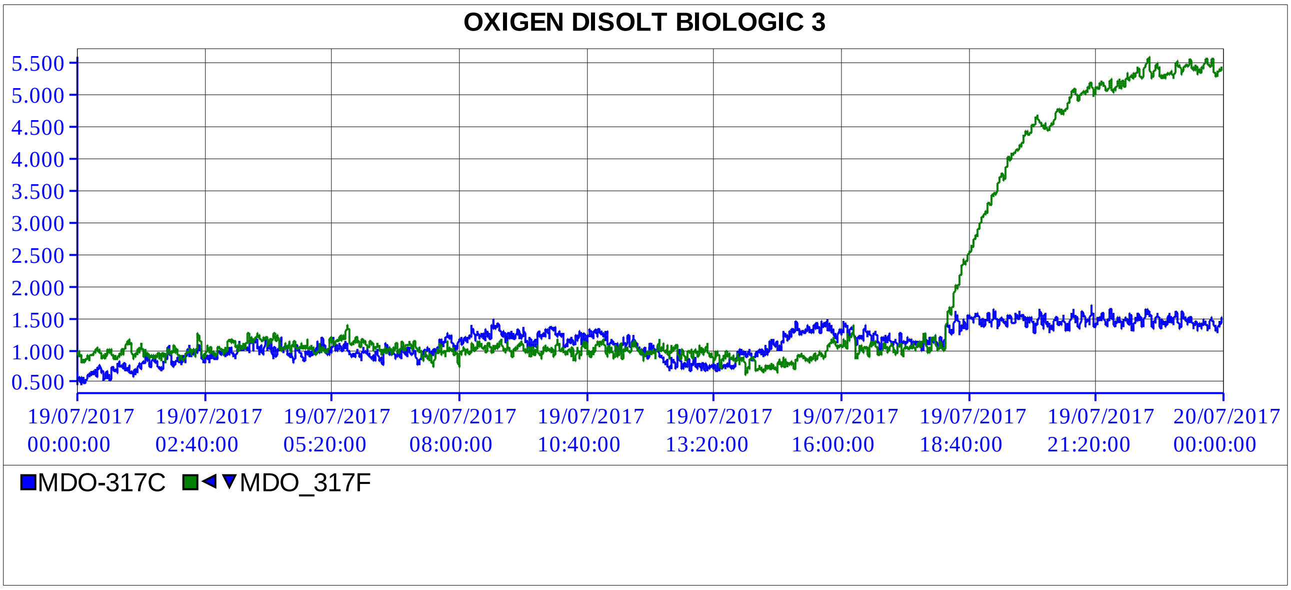
BOMBES RECIRCULACIO EXTERNA


SOPLANTS


VALVULES PROPORCIONALS


OXIGEN DISOLT BIOLOGIC 1
10.00
9.000
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
N/A
19/07/2017 00:00:00
19/07/2017 02:40:00
19/07/2017 05:20:00
19/07/2017 08:00:00
19/07/2017 10:40:00
19/07/2017 13:20:00
19/07/2017 16:00:00
19/07/2017 18:40:00
19/07/2017 21:20:00
20/07/2017 00:00:00
🟦MDO-317A 🟩◀▼MDO-317B

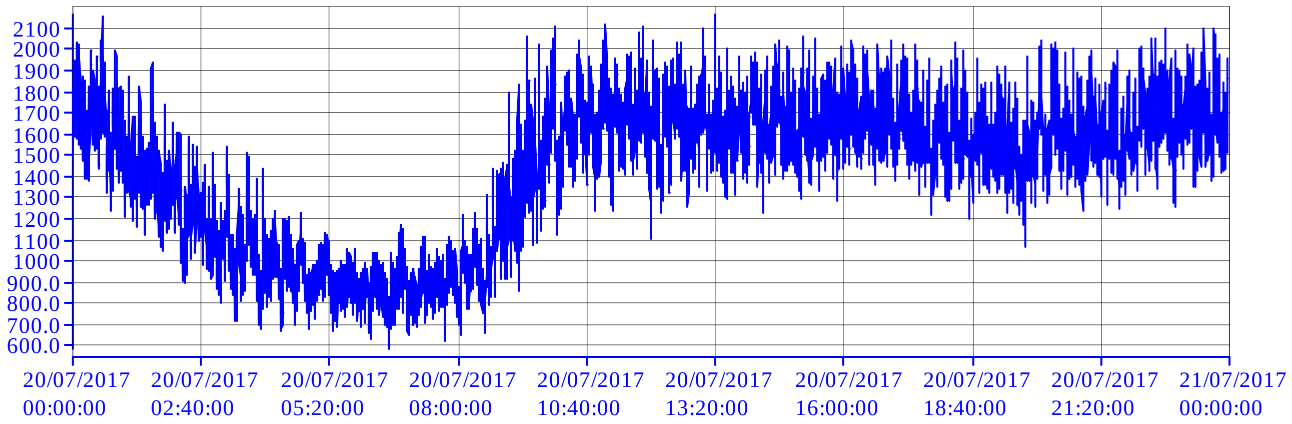

OXIGEN DISOLT BIOLOGIC 2
2.750
2.500
2.250
2.000
1.750
1.500
1.250
1.000
0.750
0.601
19/07/2017 00:00:00
19/07/2017 02:40:00
19/07/2017 05:20:00
19/07/2017 08:00:00
19/07/2017 10:40:00
19/07/2017 13:20:00
19/07/2017 16:00:00
19/07/2017 18:40:00
19/07/2017 21:20:00
20/07/2017 00:00:00
🟦MDO-317B 🟩◀▼MDO_317E


OXIGEN DISOLT BIOLOGIC 3
5.500
5.000
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
19/07/2017 00:00:00
19/07/2017 02:40:00
19/07/2017 05:20:00
19/07/2017 08:00:00
19/07/2017 10:40:00
19/07/2017 13:20:00
19/07/2017 16:00:00
19/07/2017 18:40:00
19/07/2017 21:20:00
20/07/2017 00:00:00
🟦MDO-317C 🟩◀▼MDO_317F

Data inici	20/07/2017 00:00:00
Data final	20/07/2017 23:59:59

BIOLOGIC

CAUDAL ENTRADA BIOLOGIC

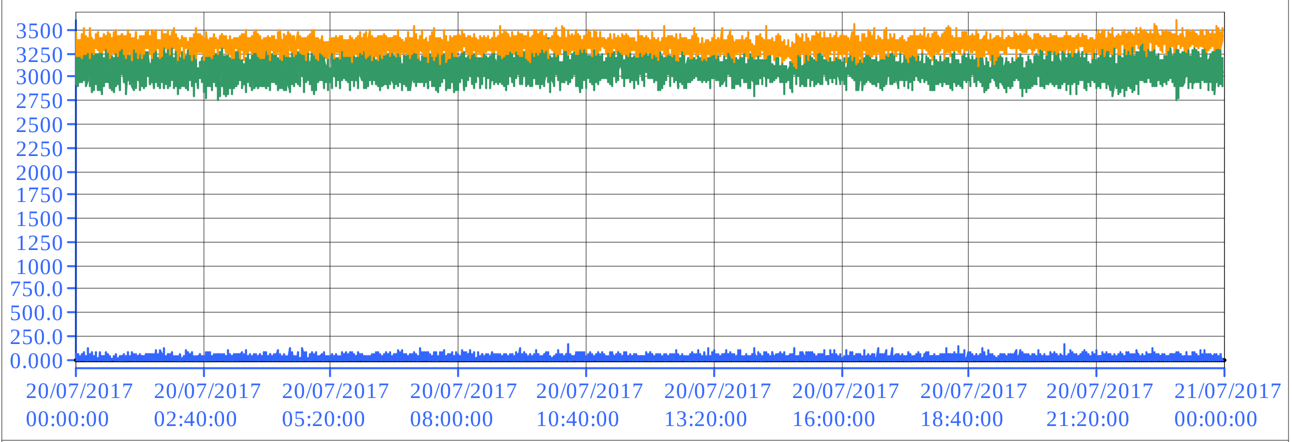


■MDC-339B

Valor Maxim	2162 m3/h	**Hora**	20/07/2017 13:21:10	**Valor Mig**	1434 m3/h
Valor Mínim	589 m3/h	**Hora**	20/07/2017 06:34:10		

Contador Inici m3	Contador final m3	Caudal Diari m3
81318664	81358792	40128

RECIRCULACIO INTERNA

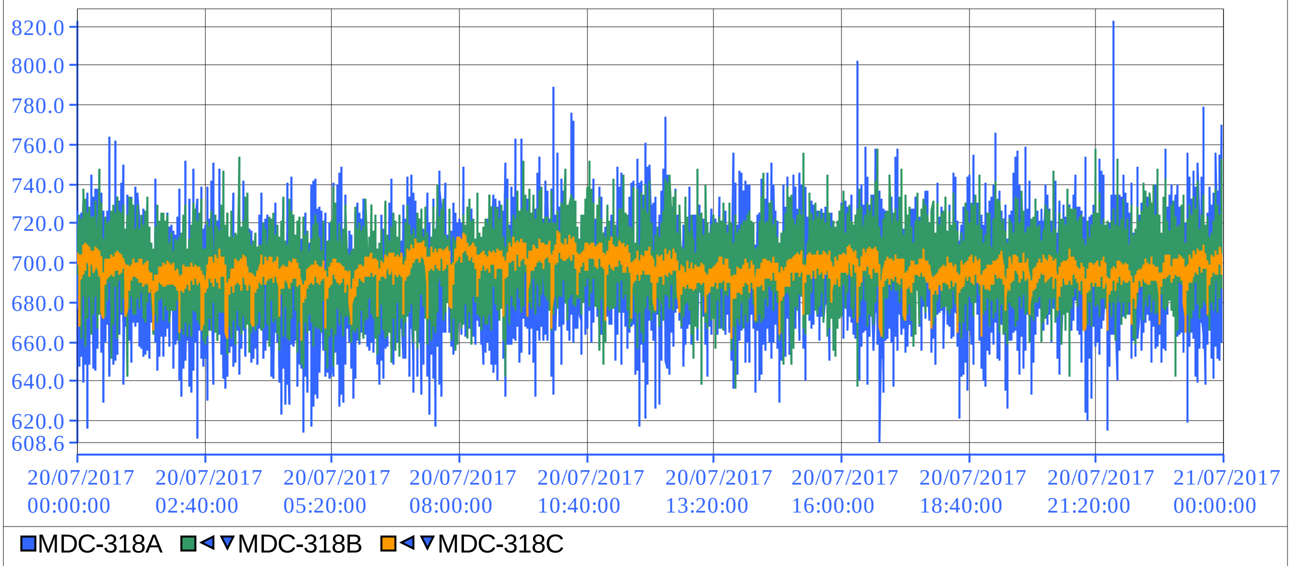


■MDN-315A ■◄▼MDN-315B ■◄▼MDN-315C

Valor Maxim	166 m3/h	**Hora** 20/07/2017 10:18:00	**Valor Mig**	19 m3/h
Valor Mínim	0 m3/h	**Hora** 20/07/2017 00:00:10		
Valor Maxim	3426 m3/h	**Hora** 20/07/2017 18:54:20	**Valor Mig**	3079 m3/h
Valor Mínim	2755 m3/h	**Hora** 20/07/2017 00:00:10		
Valor Maxim	3594 m3/h	**Hora** 20/07/2017 23:03:00	**Valor Mig**	3345 m3/h
Valor Mínim	3100 m3/h	**Hora** 20/07/2017 15:04:50		

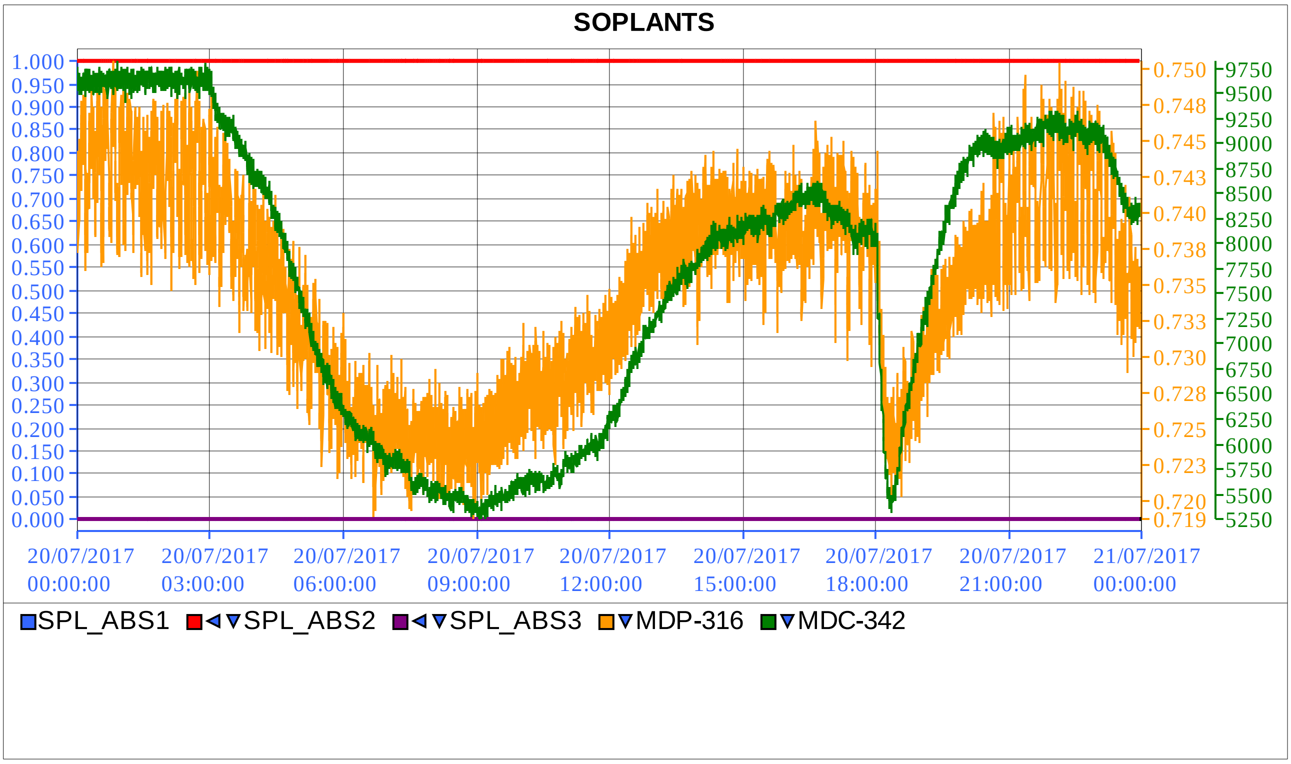
Data inici 20/07/2017 00:00:00
Data final 20/07/2017 23:59:59

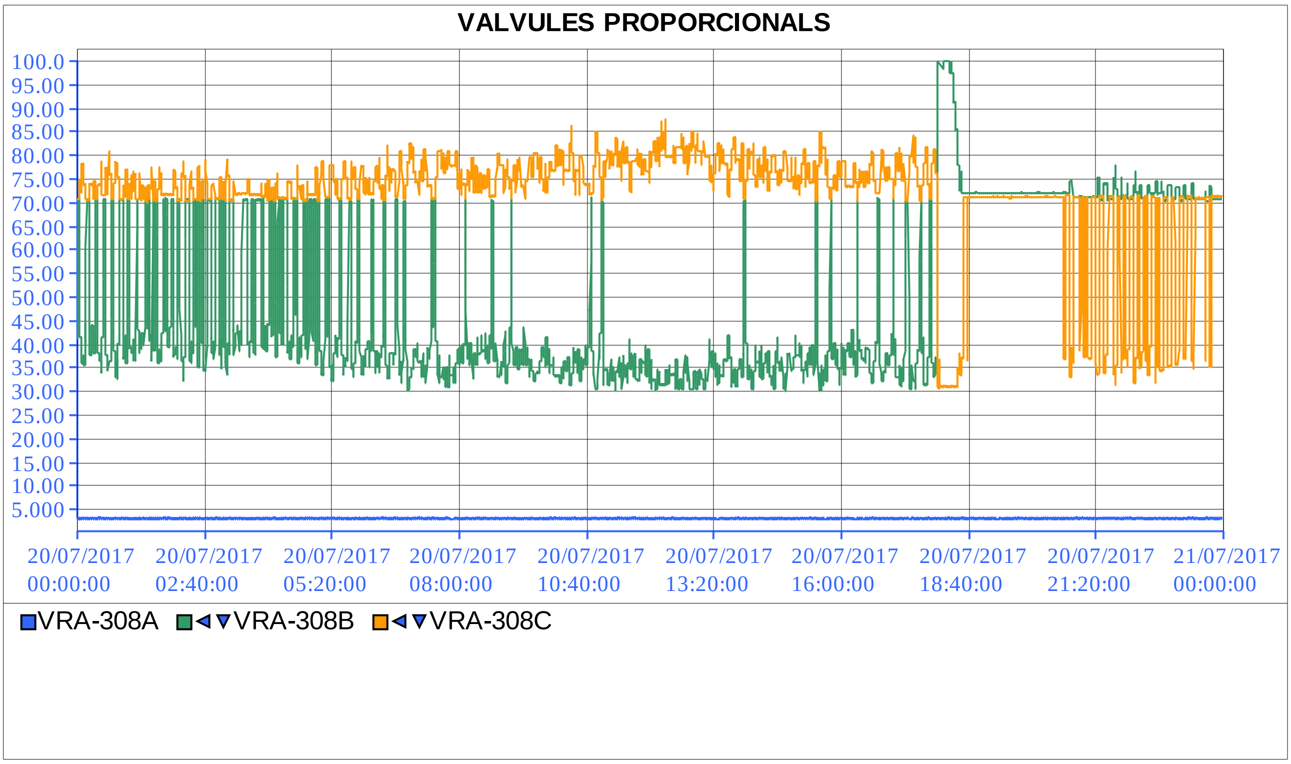
CABAL RECIRCULACIO EXTERNA



Valor Maxim	823 m3/h	**Hora**	20/07/2017 21:44:30	**Valor Mig**	693 m3/h
Valor Mínim	609 m3/h	**Hora**	20/07/2017 16:50:50		
Valor Maxim	758 m3/h	**Hora**	20/07/2017 16:46:50	**Valor Mig**	699 m3/h
Valor Mínim	636 m3/h	**Hora**	20/07/2017 16:50:50		
Valor Maxim	716 m3/h	**Hora**	20/07/2017 10:03:20	**Valor Mig**	696 m3/h
Valor Mínim	661 m3/h	**Hora**	20/07/2017 04:42:10		

BOMBES RECIRCULACIO EXTERNA


SOPLANTS
1.000
0.950
0.900
0.850
0.800
0.750
0.700
0.650
0.600
0.550
0.500
0.450
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
0.750
0.748
0.745
0.743
0.740
0.738
0.735
0.733
0.730
0.728
0.725
0.723
0.720
0.719
9750
9500
9250
9000
8750
8500
8250
8000
7750
7500
7250
7000
6750
6500
6250
6000
5750
5500
5250
20/07/2017 00:00:00
20/07/2017 03:00:00
20/07/2017 06:00:00
20/07/2017 09:00:00
20/07/2017 12:00:00
20/07/2017 15:00:00
20/07/2017 18:00:00
20/07/2017 21:00:00
21/07/2017 00:00:00
SPL_ABS1
SPL_ABS2
SPL_ABS3
MDP-316
MDC-342


VALVULES PROPORCIONALS
100.0
95.00
90.00
85.00
80.00
75.00
70.00
65.00
60.00
55.00
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.000
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20/07/2017 08:00:00
20/07/2017 10:40:00
20/07/2017 13:20:00
20/07/2017 16:00:00
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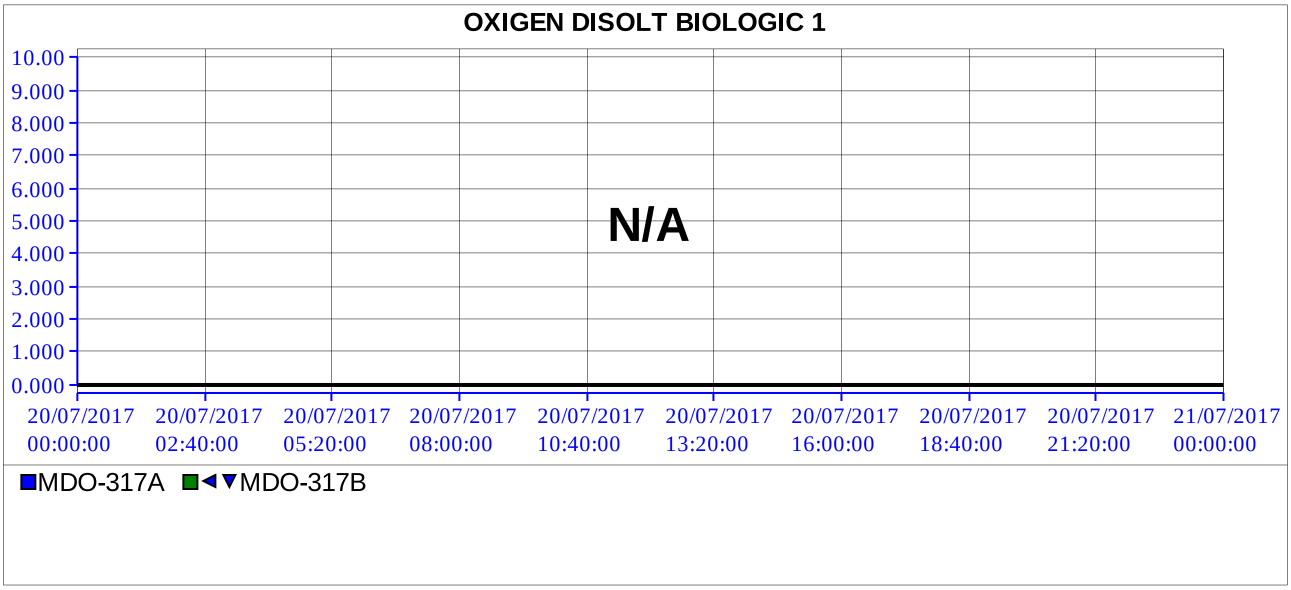
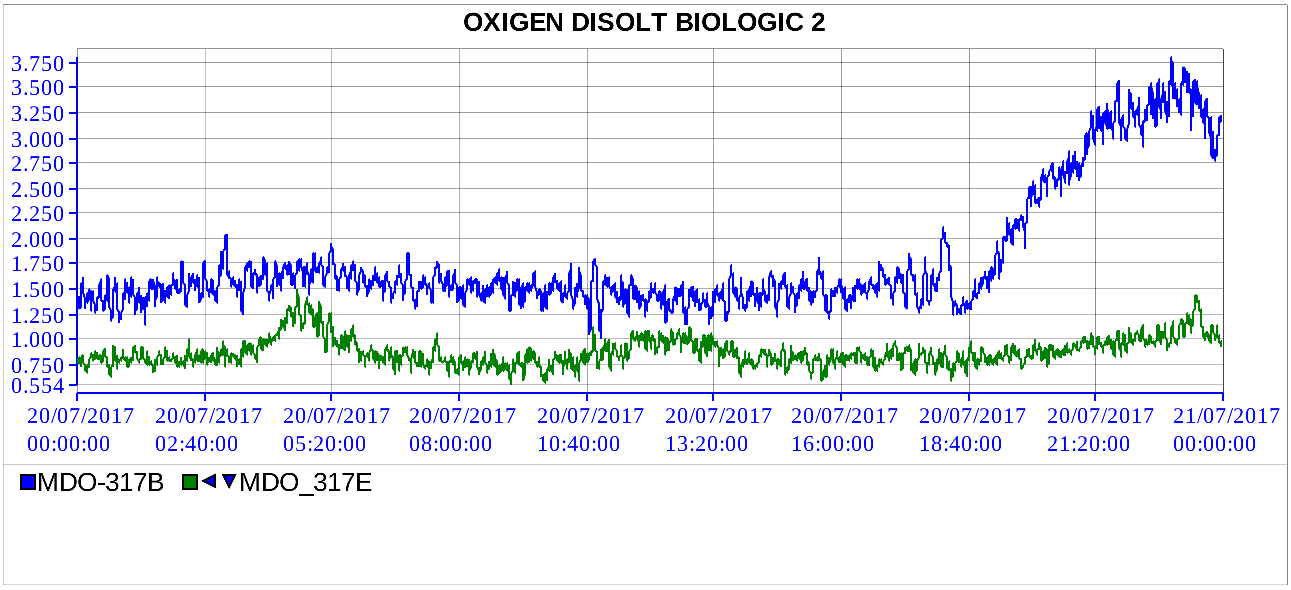
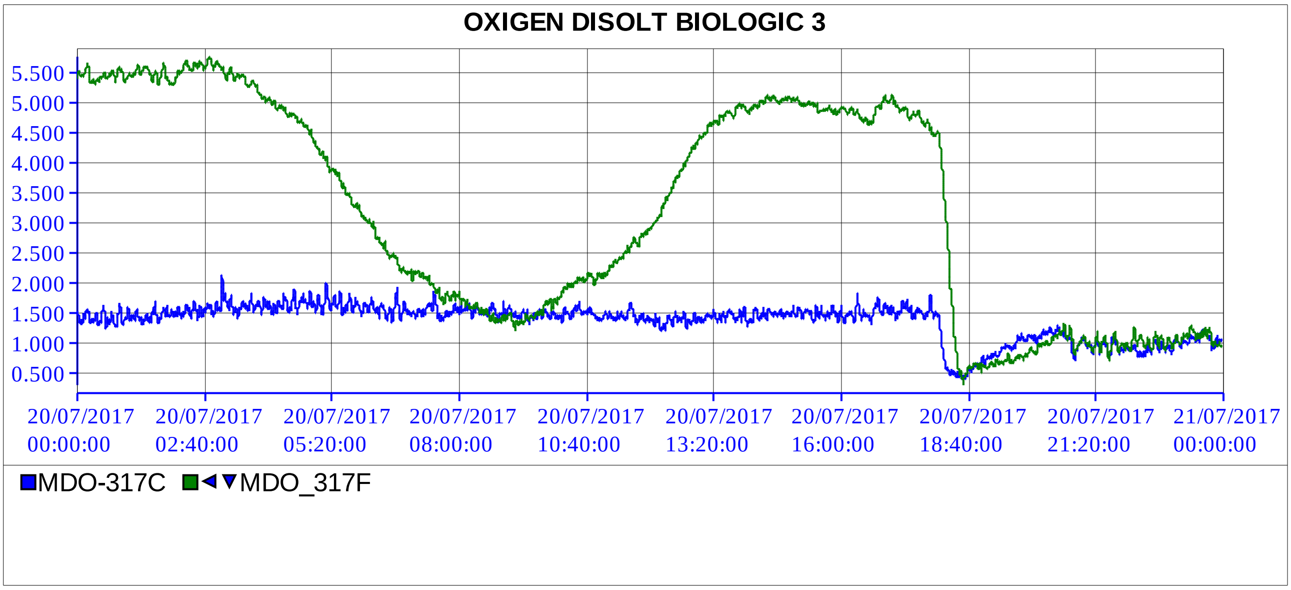
21/07/2017 00:00:00
VRA-308A
VRA-308B
VRA-308C


OXIGEN DISOLT BIOLOGIC 1
10.00
9.000
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
N/A
20/07/2017 00:00:00
20/07/2017 02:40:00
20/07/2017 05:20:00
20/07/2017 08:00:00
20/07/2017 10:40:00
20/07/2017 13:20:00
20/07/2017 16:00:00
20/07/2017 18:40:00
20/07/2017 21:20:00
21/07/2017 00:00:00
■MDO-317A
■◄▼MDO-317B


OXIGEN DISOLT BIOLOGIC 2
3.750
3.500
3.250
3.000
2.750
2.500
2.250
2.000
1.750
1.500
1.250
1.000
0.750
0.554
20/07/2017 00:00:00
20/07/2017 02:40:00
20/07/2017 05:20:00
20/07/2017 08:00:00
20/07/2017 10:40:00
20/07/2017 13:20:00
20/07/2017 16:00:00
20/07/2017 18:40:00
20/07/2017 21:20:00
21/07/2017 00:00:00
■MDO-317B
■◄▼MDO_317E


OXIGEN DISOLT BIOLOGIC 3
5.500
5.000
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
20/07/2017 00:00:00
20/07/2017 02:40:00
20/07/2017 05:20:00
20/07/2017 08:00:00
20/07/2017 10:40:00
20/07/2017 13:20:00
20/07/2017 16:00:00
20/07/2017 18:40:00
20/07/2017 21:20:00
21/07/2017 00:00:00
■MDO-317C
■◄▼MDO_317F

B

AUTOMATING SIMBA#

B.1 SCRIPT TO PREPARE A SIMBA# INFLUENT FILE

In appendix A.3 on page 119, the data from the sampling campaigns was organized in a systematic way. In this section, part of that data and the grab samples obtained from ICRA's lab will be used to produce an `.xlsx` ready to be used for SIMBA#. The use of Python to automate the creation of the influent allows to test different re-sampling techniques. By using a script rather than a spreadsheet it is possible to reproduce the creation process from scratch, and ensures that we use a routine that never needs to modify the original data.

The next python script creates a dataframe named influent, then fills it with the necessary data in a step by step manner: *i)* time and flow, *ii)* Alkalinity and ISS, *iii)* Nutrients. The nutrient values are correlated with the in-house WRRF lab measurements. Similarly, a dataframe is created from the SCADA system data that contains flow values. All the data is plotted and checked, the necessary unit changes applied, and finally the *dataframes* are exported as `.csv`, already with the right column names and structure to be used.

The script used is available in GitHub as `InfluentGeneration.py`.

B.2 SIMBA# SCRIPTING

SIMBA# was initially created on MATLAB , a mathematical-oriented programming language with a Graphical User Interface (GUI) oriented to graphical system design (Simulink). Standalone SIMBA# is coded in the programming language C Sharp , it offers a GUI that focuses on WRRF process modelling, and adds a number of capabilities oriented towards that end.

The scripting capabilities are still available through the so called "*green blocks*". These blocks allow the user to write its own scripts in C sharp using SIMBA#'s Application Programming Interface (API). Conversely, very much like in any programming language, a series of global variables and local variables (associated to the functions in *green blocks*) are created during a simulation. This is instrumental to automate simulation tasks such as: *i)* Batch simulations, *ii)* Data exporting, *iii)* Scenario analysis and *iv)* Sensitivity analysis. The following scripts have been used to automate SIMBA$^{\#}$ in various simulations:

B.2.1 *Batch simulations*

This script shows how to run a model during 200 days in steady state, save the final state of the model, and then use it in a dynamic simulation of 2 days. Using this basic structure and various *green blocks* it is possible to concatenate several simulations of different scenarios.

SIMBA_Batch

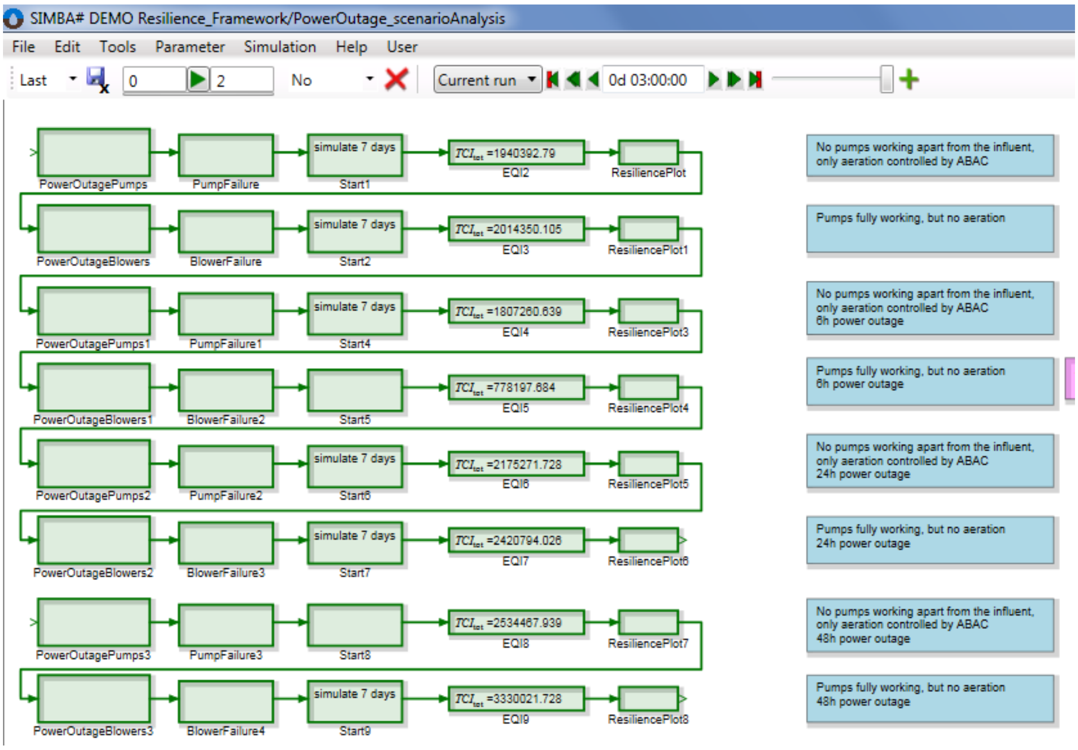
```
public override void userCodeAsync(sisiAPIint api) {
   sb.mainText="Batch";

   api.con.clear();

   string av=api.dia_getParam("FromXLS1","average");
   api.con.writeLn(av);
   api.dia_setParam("FromXLS1","average","1");
   //api.setParam("temperature","Constant_0","18");
   api.createModel();
   api.prepareSim(0.0, 200.0);
   while(true) {
     if (api.step()) break;
     api.updateGui();
   }
   // user stop!
   if (api.isSimError()) return;

   api.closeSim();
   api.con.writeLn("Done.");
   api.saveState("test.ssi");

   // and 2 days dynamic
   api.dia_setParam("FromXLS1","average","0");
   api.loadState("test.ssi");
   api.createModel();
   api.prepareSim(0.0, 2.0);
   while(true) {
      if (api.step()) break;
      api.updateGui();
   }
   api.con.writeLn("Done.");
}
public override void userCode(sisiAPIint api) {
}
```



No pumps working apart from the influent,
only aeration controlled by ABAC

Pumps fully working, but no aeration

No pumps working apart from the influent,
only aeration controlled by ABAC
6h power outage

Pumps fully working, but no aeration
6h power outage

No pumps working apart from the influent,
only aeration controlled by ABAC
24h power outage

Pumps fully working, but no aeration
24h power outage

No pumps working apart from the influent,
only aeration controlled by ABAC
48h power outage

Pumps fully working, but no aeration
48h power outage

FIGURE 38. SIMBA$^{\#}$ layout for Scenario analysis

B.2.2 *Scenario analysis*

By setting several *green blocks* in series, and adjusting the local variables in those blocks, it is possible to build a complex net of scenarios. Figure 38 shows as an example the SIMBA$^{\#}$ layout used to simulate the various scenarios of power outage studied in chapter 6 on page 81. The first block sets variables related to plant set-up, the second those related to stressors models, the third one starts the batch simulation, the fourth provides instant feedback by calculating an resilience and effluent quality index and the fifth extracts the simulation results in the desired format.

B.2.3 *Export data from simulations*

Although SIMBA$^{\#}$ can perform most calculations and plot simulation data, it is very useful, particularly in case of scenario and sensitivity analysis, to compare data directly against other simulations. To export data systematically from the simulations into an excel spreadsheet a script can be used. There are various ways of doing this, but I find the most convenient to be exporting data directly from plots. The following script uses the `api.ex_exportPlotToExcel()` command for this. This function takes 6 arguments:

1. Name of plot to be exported
2. Default variable x
3. Name of sheet in excel file to export the data
4. cell numbers in coordinates (x coordinate)
5. cell numbers in coordinates (y coordinate)
6. Boolean to write over existing data (True/False)

Plots

```
public override void userCode(sisiAPIint api) {
   //
   Stopwatch tick=new Stopwatch();
   tick.Reset(); tick.Start();

   xlsx x = new xlsx();
   x.openFile("calibration_results.xlsx");

   string sheet = "calibration";

   api.ex_exportPlotToExcel("BlowerAir", x, "Airflow",
      1, 1, false);
   api.ex_exportPlotToExcel("BlowerCapacity", x,
      "Capacity", 1, 1, false);
   api.ex_exportPlotToExcel("BlowerkWh", x, "kWh", 1,
      1, false);
   api.ex_exportPlotToExcel("DOreactors1", x,
      "DOlane1", 1, 1, false);
   api.ex_exportPlotToExcel("DOreactors2", x,
      "DOlane2", 1, 1, false);

   x.saveFile();
   x.close();

   //matrix
   tick.Stop();
   api.con.writeLn("tick=" +
      tick.ElapsedMilliseconds.ToString() + " ms.");
   api.con.writeLn("base case results saved");

}
```

Another useful export function is that of diagrams:

Diagrams

```
public override void userCode(sisiAPIint api) {
   sb.mainText="Export Diagrams";
```

```
   xlsx x = new xlsx();          // create an excel
      object
   x.openFile("diagrams.xlsx"); // open an excel file
      for writing

   api.ex_exportExcel_ProjectDiagrammsPng(x,"Draw", 1,
      1, true); // create bitmaps (PNG) from all
      diagramms
        // and copy these in sheet Draw

   x.saveFile();     // save the excel workbook
   x.close();        // close the file

}
```

B.2.4 *Sensitivity analysis*

In order to carry a sensitivity analysis, a series of batch simulations must be executed in order, while varying the parameter under analysis. To do this using the GUI we must use a layout like the one in fig. 39 on the following page.

The general idea is to set a counter and use a `while` loop inside another, as illustrated in the following pseudocode:

```
set counter1 = 10
Parameter1 = default1
while counter1 > 0 :
        set counter2 = 8
        Parameter1 = Parameter1 + increment
        counter1 = counter1 - 1
        Parameter2 = default2
        while counter2 > 0 :
                Run simulation
                Save results
                Parameter2 = Parameter2 + increment
                counter2 = counter2 - 1
```

The inner loop runs simulations while increasing the value of the desired parameter (i.e. RAS). Once the simulations finish, the outer loop increases the secondary parameter of the sensitivity analysis (i.e. SVI), and restarts the inner loop.

This type of analysis is likely to produce hundreds of simulations, which translates in a great amount of data. To export data in orderly manner, the script that writes to an excel spreadsheet needs to be aware of the simulation runs. The following script accesses the value of the SVI and RAS global variables, and uses it to decide the name of the excel file and sheet in which the simulation results will be created

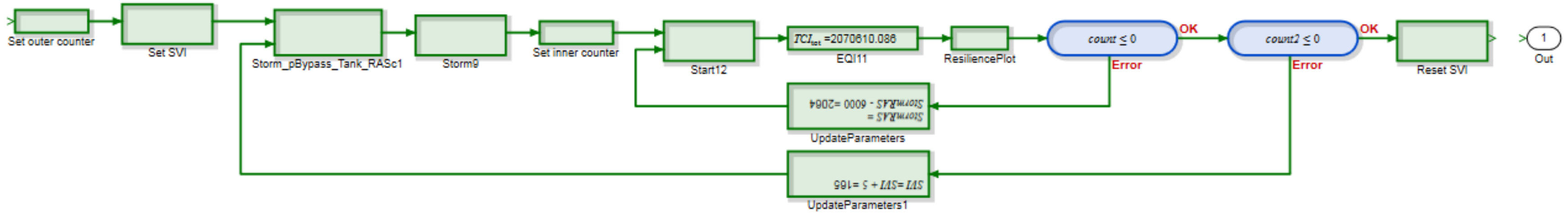


FIGURE 39. SIMBA# layout for double sensitivity analysis

respectively. In this manner, each excel file contains several sheets with the results of one RAS sensitivity analysis. In appendix C on page 143 an example is shown on how to use a Python script to handle such amount of data.

```
public override void userCode(sisiAPIint api) {
   //
   Stopwatch tick=new Stopwatch();
   tick.Reset(); tick.Start();

   string excelName = vars["SVI"].val.ToString();

   xlsx x = new xlsx();
   x.openFile("ResultsResilienceStorm" + excelName
      +".xlsx");

   string sheet = "RAS_" +
      vars["StormRAS"].val.ToString();

   api.ex_exportPlotToExcel("EffluentPlant", x, sheet,
      1, 1, false);
   api.ex_exportPlotToExcel("ResiliencePlot", x,
      sheet, 1, 11, false);
   api.ex_exportPlotToExcel("SludgeBlanket", x, sheet,
      1, 21, false);
   api.ex_exportPlotToExcel("MLSS", x, sheet, 1, 43,
      false);
//   api.ex_gb_exportGreenBlockVars("S_PlotToExcel1",
    x, sheet, 1, 1, false);

   x.saveFile();
   x.close();

   //matrix
   tick.Stop();
   api.con.writeLn("tick=" +
      tick.ElapsedMilliseconds.ToString() + " ms.");
   api.con.writeLn("base case results saved");

}
```

B.2.5 *Excel Manipulation*

A very interesting feature of SIMBA# is the ability to use spreadsheet-based models in combination with the WRRF model. It is possible to manipulate excel files by means of *green blocks*, using data from the simulation output or user input. The results of the spreadsheet can then be fed into the model using the input-from-excel blocks -such as the ones used for influents, centrifuge flow or stressors such as spills. The following script shows how to make use of this capability:

Coupling SIMBA# with a spreadsheet-based model

```
public override void userCode(sisiAPIint api) {
xlsx x = new xlsx();
   x.openFile("DynTG_inCTRL.xlsx");

   // Select sheet Main
   x.activate_sheet("Main");
   // PE   B10
   x.setData0(new object[,] { {localvars["PE"].val} },
      10, 2);

   // Qm B16
   x.setData0(new object[,] { {vars["Q_inf_AA"].val}
      }, 16, 2);

   // COD; TKN; P   B19..B23
   x.setData0(new object[,] { {vars["COD_inf_AA"].val},
                              {vars["TKN_inf_AA"].val},
                              {vars["TP_inf_AA"].val},
                              {vars["ISS_inf_AA"].val},
                              {vars["Alk_inf_AA"].val}
                            }, 19, 2);

   x.saveFile();
   x.close();

   oleXls.doCalcTG("DynTG_inCTRL.xlsx",vars["Q_inf_AA"].val);
}
```

C

DATA ANALYSIS WITH PYTHON

C.1 SCRIPT TO ANALYZE SIMULATION RESULTS: EXAMPLE WITH STORMWATER RESILIENCE

In appendix D on page 145 we explained how to use scripts to automate SIMBA# simulations and extract data from a double sensitivity analysis. The results of such simulation are various excel files with various sheets containing results of each simulation. To work with SIMBA# output `.csv` files and reconciliate the results of various simulations, a Python script has been written that traverses the files and joins the data in a systematic way. All the figures created in this script correspond to those used in the stormwater resilience scenario in section 6.5 on page 91.

The following script makes use of Python dataframes from the *pandas* library, and the enhanced version of the dictionary built-in data structure: *default dictionary*, from the *collections* library. A list with all important modules would be:

OS This module provides a portable way of using operating system dependent functionality

PANDAS An open source, BSD-licensed library providing high performance, easy-to-use data structures and data analysis tools for the Python programming language

NUMPY NumPy is the fundamental package for scientific computing with Python

SCIPY Python-based ecosystem of open-source software for mathematics, science, and engineering

MATPLOTLIB Matplotlib is a Python 2D plotting library which produces publication quality figures in a variety of hardcopy formats and interactive environments across platforms

SEABORN Seaborn is a Python visualization library based on matplotlib. It provides a high-level interface for drawing attractive statistical graphics

RE This module provides regular expression matching operations

GLOB The glob module finds all the pathnames matching a specified pattern according to the rules used by the Unix shell

COLLECTIONS This module implements specialized container datatypes providing alternatives to Python's general purpose built-in containers

The script used to carry out the data analysis of SIMBA$^{\#}$'s outputs is available in GitHub as *`ResultsResilienceStorm.py`*.

D

CALIBRATION AND MODEL SET-UP

D.1 SIMBA# MODEL

The SIMBA# model used to carry out the resilience assessment has been made available in GitHub as:

`ResilienceOfWRRF_modelBasedAssessment_SIMBAmodel.zip`

The model can be run downloading a free copy of SIMBA# from the website https://www.inctrl.ca/software/download/.

D.2 FULL REPORT

A `Full_report.xlsx`file is also available in GitHub, containing the layout and sub-model specifications of the SIMBA# model. These include:

- Integrator algorithm and settings
- Diagrams of the model layout and sub-models
- Sludge mass balance
- Excel input files
- Version of sub-models used
- Version of converter models used (e.g. influent fractionation)

D.3 ON THE STORY AND FUTURE OF MODELING

The development of models for solving complex problems has been increasingly adopted by many fields of science. Those modellers are often reminded that models are an *inaccurate* representation of reality, and thus the conclusions we may extract from them need to be taken carefully. A deep understanding of the model, and also the field being studied, is necessary to ask the right questions and interpret the results correctly. This premise is well summarized by a famous quote from George E. P. Box:

This quote is commonly simplified to: "Essentially, all model are wrong, but some are useful"

> "Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful."
> Box and Draper, 1987

In his book, Complexity Science (Downey, 2012), Allan Downey tries to demonstrate how computational models do useful work, including prediction, explanation, and design. There has been a gradual shift in the criteria models are judged by, and in the kinds of models that are considered acceptable. Complex models are steadily being more accepted, and they are often appropriate for certain purposes and interpretations (Downey, 2012).

WRRF are complex non-linear systems. Most commonly used models are both based on physical laws, expressed in the form of equations, and solved by mathematical analysis (as in classical models), but also based on simple rules, such as the monod equation to relate microbial growth rates in an aqueous environment to the concentration of a limiting nutrient: eq. (11), and implemented as computations.

$$\mu = \mu_{max} \frac{S}{K_s + S} \tag{11}$$

Activated sludge modelling is becoming common for all sorts of studies, i.e. design, optimisation, learning, prediction and automation (Hauduc *et al.*, 2009). These models are commonly packed in specialised software which incorporates the biokinetic models with the group of sub-models that enable the simulation of a complete treatment plant. An overview of the most important sub-models is:

- Bio-kinetic model
- Hydraulic and transport model
- Sensor model
- Settler model
- Input/Influent model
- Pump model
- Controller model
- Aeration model
- Output model

A review of activated sludge modelling since the first ASM1 model (Henze *et al.*, 1987), can be found in Gernaey, Van Loosdrecht, *et al.* (2004), and more recently in H. Hauduc, L. Rieger, *et al.* (2013). Guidelines for the standardization in the use of modelling for wastewater treatment are developed in Rieger, Gillot, *et al.* (2012). Efforts to achieve standardization in benchmarking modelling studies were made by the benchmark simulation models (BSM) (U. Jeppsson *et al.*, 2013).

Chapter 6 on page 81 shows a model calibration and validation in which the plant has been stressed to test the ability of the model to represent the plant's response against sudden changes.

Modelling stressors adds a new challenge to the modelling paradigm. Whereas in most studies a process of calibration and validation is carried out to verify that the model is able to represent the plant response accurately, it is hard for a common study to gather enough data that can be used to calibrate a stressor. This is especially true for strong storms, power outages and flooding events, which would incapacitate the data collection equipment. Furthermore, for unobserved stressors, it is impossible to validate the ability of the model to represent the behaviour of the plant under the stressor.

Therefore, although the model still has to be calibrated and validated, and it is possible to collect data on sudden changes, when using a model to test the plant against unknown situations, special precaution are required when reaching conclusions. Three changes of paradigm need to be taken into account:

Chapter 6 on page 81 includes three cases of resilience assessment aiming to understand the plant's behaviour against a stressor and design a resilient strategy

PREDICTIVE → EXPLANATORY Rather than expecting the model to provide a plant-specific answer, such as the breaking point of a settler in a storm, the model tries to study the effect of different storms under different strategies, and *understand* the cause-effect of such circumstances. Understanding the *behaviour* of the plant through the model allows us to compare between different cases, and find rules to design resilient strategies. Following the example of a settler breaking point, it is possible to monitor the evolution of the sludge blanket in the clarifier, as well as the N_2 gas production, as an indicator of risk of clarifier breakdown.

REALISM → INSTRUMENTALISM Instrumentalism is the view that models can be useful even if the entities they postulate don't exist. In a WRRF model for example, the nature of some plant sub-models can be instrumentalist. Bio-kinetic models are based on chemical reactions and mass balances, with kinetics modelled using the monod equation, resulting in a predictive model. Settling models on the other hand are based on empirical data on particulate settling, and are not predictive. However, models are used because they are useful to predict or explain the behaviour of a system particularly well.

Table 7 on page 57 shows a view of the sub-models landscape and their level of detail

ANALYSIS → COMPUTATION In classical engineering, the space of feasible designs is limited by our capability for analysis. The ability to automate a WRRF design by simulating different scenarios and varying model parameters enables the development and implementation of probabilistic design procedures (Belia *et al.*, 2009). For example, assigning uncertainty distributions rather than using a blanket safety factor approach will enable design engineers to make better informed decisions leading to designs that take the inherent uncertainties into account. This will lead to more resilient water resource recovery facilities.

BIBLIOGRAPHY

100RC (2013). Tech. rep. Rockefeller Foundation. URL: http://www.%20100resilientcities.org/resilience#/-_/%20[Accessed%2023%20September%202016].

Alex, J (2011). “A simple three-layer clarifier model”. In: *Watermatex*. San Sebastian, pp. 264–271.

Alex, J, L Benedetti, J Copp, K V Gernaey, U Jeppsson, I Nopens, M Pons, L Rieger, C Rosen, J P Steyer, P Vanrolleghem, and S Winkler (2008). *Industrial Electrical Engineering and Automation Benchmark Simulation Model no . 1 (BSM1)*. Vol. 1. 1. Sweden: Dept. of Industrial Electrical Engineering and Automation. Lund University.

Alex, Jens, Leiv Rieger, and Oliver Schraa (2016). “Comparison of Advanced Fine-Bubble Aeration Control Concepts with Respect to Energy Efficiency and Robustness”. In: *WEFTEC*. New Orleans, pp. 136–147.

Amand, L, G Olsson, and B Carlsson (2013). “Aeration control - A review”. In: *Water Science and Technology* 67.11, pp. 2374–2398. ISSN: 02731223. DOI: 10.2166/wst.2013.139.

Amaral, Andreia, Giacomo Bellandi, Usman Rehman, Ramiro Neves, Youri Amerlinck, and Ingmar Nopens (2018). “Towards improved accuracy in modeling aeration efficiency through understanding bubble size distribution dynamics”. In: *Water Research* 131, pp. 346–355. ISSN: 18792448. DOI: 10.1016/j.watres.2017.10.062. URL: https://doi.org/10.1016/j.watres.2017.10.062.

Amaral, Andreia, Oliver Schraa, Leiv Rieger, Sylvie Gillot, Yannick Fayolle, Giacomo Bellandi, Youri Amerlinck, Séverine T.F.C. Mortier, Riccardo Gori, Ramiro Neves, and Ingmar Nopens (2017). “Towards advanced aeration modelling: From blower to bubbles to bulk”. In: *Water Science and Technology* 75.3, pp. 507–517. ISSN: 02731223. DOI: 10.2166/wst.2016.365.

Amerlinck, Y., W. De Keyser, G. Urchegui, and I. Nopens (2016). “A realistic dynamic blower energy consumption model for wastewater applications”. In: *Water Science and Technology* 74.7, pp. 1561–1576. ISSN: 02731223. DOI: 10.2166/wst.2016.360.

APHA (1999). *Standard Methods for the Examination of Water and Wastewater*. 21st Editi. Washington DC: American Public Health Association, American Water Works Association. URL: https://www.mwa.co.th/download/file_upload/SMWW_1000-3000.pdf.

Belia, E., Y. Amerlinck, L. Benedetti, B. Johnson, G. Sin, P. a. Vanrolleghem, K. V. Gernaey, S. Gillot, M. B. Neumann, L. Rieger, a. Shaw, and K. Villez (2009). “Wastewater treatment modelling: Dealing with uncertainties”. In: *Water Science and Technology* 60.8, pp. 1929–1941. ISSN: 02731223. DOI: 10.2166/wst.2009.225.

Benedetti, Lorenzo (2016). “An empirical settler model for fast simulation including wet-weather conditions”. In: 4, p. 44272.

Box, George. E. P. and N. R. Draper (1987). *Empirical Model Building and Response Surfaces*. New York, NY: John Wiley and Sons.

Bürger, Raimund, Stefan Diehl, Sebastian Farås, Ingmar Nopens, and Elena Torfs (2013). “A consistent modelling methodology for secondary settling tanks: A reliable numerical method”. In: *Water Science and Technology* 68.1, pp. 192–208. ISSN: 02731223. DOI: 10.2166/wst.2013.239.

Butler, D, R Farmani, G Fu, S Ward, K Diao, and M Astaraie-Imani (2014). “A New Approach to Urban Water Management: Safe and Sure”. In: *Procedia Engineering* 89.C, pp. 347–354. ISSN: 18777058. DOI: 10.1016/j.proeng.2014.11.198. URL: http://www.scopus.com/inward/record.url?eid=2-s2.0-84923080192%7B%5C&%7DpartnerID=tZOtx3y1.

Butler, D, Sarah Ward, Chris Sweetapple, Maryam Astaraie-Imani, Kegong Diao, Raziyeh Farmani, and Guangtao Fu (2016). “Reliable, resilient and sustainable water management: the Safe & SuRe approach”. In: *Global Challenges* September. ISSN: 20566646. DOI: 10.1002/gch2.1010. URL: http://doi.wiley.com/10.1002/gch2.1010.

Campbell, D (2017). “Sustainability and Infrastructure. Are you prepared for an unknown future?” In: *INFLUENTS*, (12) 42–43. URL: http://www.kelmanonline.com/httpdocs/files/WEAO/influentswinter2017/index.html%7B%5C#%7D%20[Accessed%201%20May%202018].

Campos, Luiza C and Geoff Darch (2015a). *A climate change report card for Infrastructure Working Technical Paper Wastewater infrastructure : collection , treatment and disposal*. Tech. rep., pp. 1–48.

– (2015b). *Adaptation of UK wastewater infrastructure to climate change*. Tech. rep. 3. Infrastructure Asset Management.

Conroy, P and S De Rosa (2013). *Resilience planning: good practice guide*. Tech. rep. 13.

Conroy, P, P Von Lany, and S De Rosa (2013). “RESILIENCE: MAKING A BUSINESS CASE FOR PR14 Report Ref. No. 13/RG/06/3”. In: 13.

Corominas, Luis (2006). “Control and optimization of an SBR for nitrogen removal : from calibration to plant operation”. PhD thesis, p. 187. ISBN: 8469002414.

Cuppens, a., I. Smets, and G. Wyseure (2012). “Definition of realistic disturbances as a crucial step during the assessment of resilience of natural wastewater treatment systems”. In: *Water Science and Technology* 65.8, pp. 1506–1513. ISSN: 02731223. DOI: 10.2166/wst.2012.040.

Currie, J., N. Wragg, C. Roberts, J. Tattersall, and G. Leslied (2014). “Transforming ‘value engineering’ from an art form into a science

– process resilience modelling". In: *Water Practice & Technology* 9.1, pp. 104–114. ISSN: 1751231X. DOI: 10.2166/wpt.2014.012. URL: http://www.iwaponline.com/wpt/009/wpt0090012.htm.

Derlon, Nicolas, Christian Thürlimann, David Dürrenmatt, and Kris Villez (2017). "Batch settling curve registration via image data modeling". In: *Water Research* 114, pp. 327–337. ISSN: 18792448. DOI: 10.1016/j.watres.2017.01.049. URL: http://dx.doi.org/10.1016/j.watres.2017.01.049.

Dominguez, Damian (2008). "Handling Future Uncertainty: Strategic Planning for the Infrastructure Sector". PhD thesis. ETH ZURICH, p. 87. URL: http://en.scientificcommons.org/43961676.

Downey, Allen B. (2012). *Think Complexity*. Second edition. Green Tea Press. URL: http://greenteapress.com/complexity/.

Enerwater (2015). *Deliverable 2.1. Study of published energy data. H2020-EE-2014-3-MarketUptake [ONLINE] Available at http://www.enerwater.eu/download-documentation/ [Accessed 15 May 2017]*. Tech. rep.

Fernández-Arévalo, Tamara, Bikram S. Sabherwal, Steve Arant, Evangelia Belia, Pau Juan-García, Oliver Schraa, Leiv Rieger, Lluís Corominas, and Eduardo Ayesa (2018). "Experiences in the application of mathematical models in full scale WWTPs: the modelling from the perspective of applied research". In: *Proceedings of the 6th IWA international conference on Water Resource Recovery Modelling*. Quebec, Canada.

Fernández-arévalo, Tamara, Bikram S Sabherwal, Evangelia Belia, Pau Juan-garcía, Oliver Schraa, Leiv Rieger, Lluís Corominas, and Eduardo Ayesa (Submitted). "Experiences in the application of mathematical models in full scale WWTPs: the modelling from the perspective of applied research". In: *Water Science and Technology*.

Folke, Carl (2006). "Resilience: The emergence of a perspective for social–ecological systems analyses". In: *Global Environmental Change* 16.3, pp. 253–267. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2006.04.002. URL: http://www.sciencedirect.com/science/article/pii/S0959378006000379.

Francis, Royce and Behailu Bekera (2014). "A metric and frameworks for resilience analysis of engineered and infrastructure systems". In: *Reliability Engineering & System Safety* 121, pp. 90–103. ISSN: 09518320. DOI: 10.1016/j.ress.2013.07.004. URL: http://linkinghub.elsevier.com/retrieve/pii/S0951832013002147.

Ganin, Alexander A., Emanuele Massaro, Alexander Gutfraind, Nicolas Steen, Jeffrey M. Keisler, Alexander Kott, Rami Mangoubi, and Igor Linkov (2016). "Operational resilience: Concepts, design and analysis". In: *Scientific Reports* 6, pp. 1–12. ISSN: 20452322. DOI: 10.1038/srep19540. arXiv: 1508.01230. URL: http://dx.doi.org/10.1038/srep19540.

Gay, Leon F. and Sunil K. Sinha (2013). *Water Infrastructure Asset Management Primer (WERF report)*. Tech. rep. Water Environment Research Foundation; IWA Publishing, pp. 1–56.

Gernaey, Krist V., Ulf Jeppsson, Peter A. Vanrolleghem, and John B. Copp (2014). *Benchmarking of Control Strategies for Wastewater Treatment Plants. IWA Scientific and Technical Report No. 23.* London: IWA Publishing, p. 120. ISBN: 9781843391463.

Gernaey, Krist V., Mark C M Van Loosdrecht, Mogens Henze, Morten Lind, and Sten B. Jørgensen (2004). "Activated sludge wastewater treatment plant modelling and simulation: State of the art". In: *Environmental Modelling and Software* 19.9, pp. 763–783. ISSN: 13648152. DOI: 10.1016/j.envsoft.2003.03.005.

Gersonius, Berry, Richard Ashley, Assela Pathirana, and Chris Zevenbergen (2013). "Climate change uncertainty: Building flexibility into water and flood risk infrastructure". In: *Climatic Change* 116.2, pp. 411–423. ISSN: 01650009. DOI: 10.1007/s10584-012-0494-5.

Goldbloom-Helzner, David, Jodie Opie, Brian Pickard, and McFeely Mikko (2015). "Flood Resilience : A Basic Guide for Water and Wastewater Utilities". In: WEFTEC proceedings, Sept. 26–30, 2015, pp. 2029–2032.

Hauduc, H., L. Rieger, a. Oehmen, M. C M van Loosdrecht, Y. Comeau, a. Héduit, P. a. Vanrolleghem, and S. Gillot (2013). "Critical review of activated sludge modeling: State of process knowledge, modeling concepts, and limitations". In: *Biotechnology and Bioengineering* 110.1, pp. 24–46. ISSN: 00063592. DOI: 10.1002/bit.24624.

Hauduc, H., I. Takacs, S. Smith, A. Szabo, S. Murthy, G. T. Daigger, and M. Sperandio (2015). "A dynamic physicochemical model for chemical phosphorus removal". In: *Water Research* 73, pp. 157–170. ISSN: 18792448. DOI: 10.1016/j.watres.2014.12.053.

Hauduc, H, S Gillot, L Rieger, T Ohtsuki, a Shaw, I Takács, and S Winkler (2009). "Activated sludge modelling in practice: an international survey." In: *Water science and technology : a journal of the International Association on Water Pollution Research* 60.8, pp. 1943–1951. ISSN: 0273-1223. DOI: 10.2166/wst.2009.223.

Henze, M, C P Leslie Grady Jr, W Gujer, G V R Marais, and T Matsuo (1987). "A general model for single-sludge wastewater treatment systems." In: *Water Research* 21.5, pp. 505–515. ISSN: 00431354. DOI: http://dx.doi.org/10.1016/0043-1354(87)90058-3.

Hering, Janet G., T. David Waite, Richard G. Luthy, J??rg E. Drewes, and David L. Sedlak (2013). "A changing framework for urban water systems". In: *Environmental Science and Technology* 47.19, pp. 10721–10726. ISSN: 0013936X. DOI: 10.1021/es4007096.

Holling, C S (1973). "Resilience and Stability of Ecological Systems". In: *Annual Review of Ecology and Systematics* 4.1, pp. 1–23. ISSN: 0066-4162. DOI: 10.1146/annurev.es.04.110173.000245. arXiv: arXiv:

1011.1669v3. URL: http://www.annualreviews.org/doi/abs/10.1146/annurev.es.04.110173.000245.

– (1996). "Engineering resilience versus ecological resilience". In: *Engineering within ecological constraints* 1996, pp. 31–43.

Hopkins, L. N., P. a. Lant, and R. B. Newell (2001). "Operating space diagrams: A tool for designers of wastewater treatment plants". In: *Water Science and Technology* 44.2-3, pp. 69–76. ISSN: 02731223.

Hosseini, Seyedmohsen, Kash Barker, and Jose E. Ramirez-Marquez (2016). "A review of definitions and measures of system resilience". In: *Reliability Engineering and System Safety* 145, pp. 47–61. ISSN: 09518320. DOI: 10.1016/j.ress.2015.08.006.

Hunter, J. D. (2007). "Matplotlib: A 2D graphics environment". In: *Computing In Science & Engineering* 9.3, pp. 90–95. DOI: 10.1109/MCSE.2007.55.

Hwang, H., a. Forrester, and K. Lansey (2014). "Decentralized water reuse: Regional water supply system resilience benefits". In: *Procedia Engineering* 70, pp. 853–856. ISSN: 18777058. DOI: 10.1016/j.proeng.2014.02.093. URL: http://dx.doi.org/10.1016/j.proeng.2014.02.093.

Ifak (2015). *Institut für Automation und Kommunikation [ONLINE] Available at https://simba.ifak.eu/ [Accessed 11 May 2017]*. Tech. rep.

IWA (2017). *Principles for Water Wise Cities*. Tech. rep. London: International Water Association, p. 6. URL: www.iwa-network.org/.../2016/08/IWA%7B%5C_%7DPrinciples%7B%5C_%7DWater%7B%5C_%7DWise%7B%5C_%7DCities.pdf.

Jeppsson, U., J. Alex, D. J. Batstone, L. Benedetti, J. Comas, J. B. Copp, L. Corominas, X. Flores-Alsina, K. V. Gernaey, I. Nopens, M. N. Pons, I. Rodríguez-Roda, C. Rosen, J. P. Steyer, P. a. Vanrolleghem, E. I P Volcke, and D. Vrecko (2013). "Benchmark simulation models, quo vadis?" In: *Water Science and Technology* 68.1, pp. 1–15. ISSN: 02731223. DOI: 10.2166/wst.2013.246.

Juan-García, P., D. Butler, J. Comas, G. Darch, C. Sweetapple, A. Thornton, and Ll Corominas (2017). "Resilience theory incorporated into urban wastewater systems management. State of the art". In: *Water Research* 115, pp. 149–161. ISSN: 18792448. DOI: 10.1016/j.watres.2017.02.047. URL: http://dx.doi.org/10.1016/j.watres.2017.02.047.

Juan-García, P., Mehlika A Kiser, O. Schraa, L. Rieger, and Lluís Corominas (2017). "Exploring the potential of dynamic air supply models to evaluate control strategies: the experience at the Girona WRRF". In: *Instrumentation, Control and Automation 2017*. Quebec, pp. 303–316.

Juan-García, P, Mehlika A Kiser, Oliver Schraa, Leiv Rieger, and Lluís Corominas (2018). "Dynamic air supply models add realism to the evaluation of control strategies in water resource recovery facilities". In: *Water Science & Technology* in-press.September, pp. 1–11. DOI: 10.2166/wst.2018.356.

Juan-garcía, Pau, Leiv Rieger, Geoff Darch, Oliver Schraa, and Lluís Corominas (In preparation). "Resilience of Water Resource Recovery Facilities: A Framework for Model-based Assessment". In: *Water Research*.

Latif, Muhammad A., Chirag M. Mehta, and Damien J. Batstone (2015). "Low pH anaerobic digestion of waste activated sludge for enhanced phosphorous release". In: *Water Research* 81, pp. 288–293. ISSN: 18792448. DOI: 10.1016/j.watres.2015.05.062. URL: http://dx.doi.org/10.1016/j.watres.2015.05.062.

Lempert, Robert J, David G Groves, Steven W Popper, Steve C Bankes, J Lempert, G Groves, Steven W Popper, and Steve C Bankes (2015). "A General , Analytic Strategies for Generating and Narrative Scenarios Method Robust". In: 52.4, pp. 514–528. DOI: 10.1287/mnsc.1050.0472.

Mabrouk, Nabil, Jean Denis Mathias, and Guillaume Deffuant (2010). "Computing the resilience of a wastewater treatment bioreactor". In: *Proceedings - 5th International Multi-Conference on Computing in the Global Information Technology, ICCGI 2010*, pp. 185–188. DOI: 10.1109/ICCGI.2010.60.

Martin, Cristina and Peter A. Vanrolleghem (2014). "Analysing, completing, and generating influent data for WWTP modelling: A critical review". In: *Environmental Modelling and Software* 60, pp. 188–201. ISSN: 13648152. DOI: 10.1016/j.envsoft.2014.05.008. URL: http://dx.doi.org/10.1016/j.envsoft.2014.05.008.

Meng, Fanlin, Guangtao Fu, and David Butler (2017). "Cost-E ff ective River Water Quality Management using Integrated Real-Time Control Technology". In: DOI: 10.1021/acs.est.7b01727.

Milly, P C D, Julio Betancourt, Malin Falkenmark, Robert M Hirsch, Zbigniew W Kundzewicz, Dennis P Lettenmaier, and Ronald J Stouffer (2008). "Climate change. Stationarity is dead: whither water management?" In: *Science (New York, N.Y.)* 319.5863, pp. 573–574. ISSN: 0036-8075. DOI: 10.1126/science.1151915. arXiv: science.1151915 [10.1126].

Moddemeyer, Steve (2015). "Sustainability is dead: long live sustainability". In: *Water 21* April, pp. 12–14.

Mugume, S, Diego E Gomez, Guangtao Fu, Raziyeh Farmani, and David Butler (2015). "A global analysis approach for investigating structural resilience in urban drainage systems". In: *Water Research*. ISSN: 00431354. DOI: 10.1016/j.watres.2015.05.030. URL: http://linkinghub.elsevier.com/retrieve/pii/S0043135415300142.

Mugume, Seith, Diego Gomez, and David Butler (2014). "Quantifying the Resilience of Urban Drainage Systems Using a Hydraulic Performance Assessment Approach". In: *13th International Conference on Urban Drainage*. September. Sarawak, Malaysia.

Ning, Xiong, Yi Liu, Jining Chen, Xin Dong, Wangfeng Li, and Bin Liang (2013). "Sustainability of urban drainage management: A perspective on infrastructure resilience and thresholds". In: *Frontiers of Environmental Science and Engineering* 7.5, pp. 658–668. ISSN: 20952201. DOI: 10.1007/s11783-013-0546-8.

Nopens, Ingmar, Marina Arnaldos, Evangelina Belia, Ulf Jeppsson, Dave Kinnear, Paul Lessard, Sudhir Murthy, Maureen O'Shaughnessy, Leiv Rieger, Peter Vanrolleghem, and Stefan Weijers (Oct. 2014). "Maximising the benefits of activated sludge modelling". In: *Water 21*, pp. 31–33.

Nopens, Ingmar, Elena Torfs, Joel Ducoste, Peter a. Vanrolleghem, and Krist V. Gernaey (2015). "Population balance models: a useful complementary modelling framework for future WWTP modelling". In: *Water Science & Technology* 71.2, p. 159. ISSN: 0273-1223. DOI: 10.2166/wst.2014.500. URL: http://www.iwaponline.com/wst/07102/wst071020159.htm.

NYC Mayor's Office of Recovery & Resiliency (2013). *A Stronger More Resilient New-York*. Tech. rep. New York City: NYC Mayor's Office of Recovery & Resiliency, p. 445.

Odriozola, Juan, Sergio Beltrán, Montse Dalmau, Luis Sancho, Joaquim Comas, Ignasi Rodríguez-Roda, and Eduardo Ayesa (2017). "Model-based methodology for the design of optimal control strategies in MBR plants". In: *Water Science and Technology* 75.11, pp. 2546–2553. ISSN: 02731223. DOI: 10.2166/wst.2017.135.

Ofwat (2015a). *Resilience Task & Finish Group 1*. Tech. rep. England and Wales: Ofwat.

– (2015b). *Towards resilience : how we will embed resilience in our work*. Tech. rep. December. Ofwat.

– (2015c). *Towards resilience : how we will embed resilience in our work*. Tech. rep. December. Ofwat.

Olsson, L., A. Jerneck, H. Thoren, J. Persson, and D. O'Byrne (2015). "Why resilience is unappealing to social science: Theoretical and empirical investigations of the scientific use of resilience". In: *Science Advances* 1.4, e1400217–e1400217. ISSN: 2375-2548. DOI: 10.1126/sciadv.1400217. URL: http://advances.sciencemag.org/content/1/4/e1400217.abstract.

OREDA (2009). "OREDA Project Participants, SINTEF Industrial Management 2009 OREDA Reliability Data Handbook, Norway." In:

Pandit, A. and J.C. Crittenden (2015). "Resilient Urban Systems: Where We Stand Now and Where We Need to Go". In: *Solutions*, Vol 6, (1), 74–81.

Pons, Marie-Noëlle (2007). "Implementation of toxic inhibition in wastewater treatment benchmark siimulation models". In: *IFAC Proceedings Volumes* 40.4, pp. 49–54. ISSN: 14746670. DOI: 10.3182/20070604-3-MX-2914.00077. URL: http://linkinghub.elsevier.com/retrieve/pii/S1474667016328452.

Regmi, Pusker, Heather Stewart, Youri Amerlinck, Magnus Arnell, Pau Juan-Garcia, Bruce Johnson, Thomas Maere, Ivan Miletic, Mark Miller, Leiv Rieger, Randal Samstag, Domenico Santoro, Oliver Schraa, Spencer Snowling, Imre Takacs, Elena Torfs, Mark C.M. van Loosdrecht, Peter A. Vanrolleghem, Kris Villez, Eveline I.P. Volcke, Stefan Weijers, Paloma Grau, Jose Jimenez, and Diego Rosso (Submitted). "The Future of WRRF modelling – Outlook and challenges". In: *Water Science and Technology*.

Rehman, Usman, Chaim De Mulder, Youri Amerlinck, Marina Arnaldos, and Stefan R Weijers (2016). "Towards better models for describing mixing using compartmental modelling : a full-scale case demonstration". In: p. 2015.

Rieger, L, J Alex, and O Schraa (2016). *Model-Supported Design, Testing, and Implementation of Process Control Strategies.* London, UK.: In Ingildsen, P. and Olsson, G. (ed.) Smart Water Utilities: Complexity Made Simple. IWA Publishing.

Rieger, L, S Gillot, G Langergraber, T Ohtsuki, A Shaw, I Takacs, and S Winkler (2012). *Guidelines for Using Activated Sludge Models: IWA Task Group on Good Modelling Practice. Scientific and Technical Report No. 22*. Vol. 9781843391. ISBN: 9781843391746.

Rieger, L, Richard M Jones, Peter L Dold, and Charles B Bott (2014). "Ammonia-Based Feedforward and Feedback Aeration Control in Activated Sludge Processes". In: *Water Environment Research* 86.1, pp. 63–73. ISSN: 10614303. DOI: 10.2175/106143013X13596524516987.

Rieger, L, I Takacs, and H Siegrist (2012). "Improving Nutrient Removal While Reducing Energy Use at Three Swiss WWTPs Using Advanced Control". In: *Water Environment Research* 84.2, pp. 170–188. ISSN: 10614303. DOI: 10.2175/106143011X13233670703684.

Rieger, Leiv, J. Alex, S. Winkler, M. Boehler, M. Thomann, and H. Siegrist (2003). "Progress in sensor technology - Progress in process control? Part I: Sensor property investigation and classification". In: *Water Science and Technology* 47.2, pp. 103–112. ISSN: 02731223.

Rosen, C., D. Aguado, J. Comas, J. Alex, J. B. Copp, K. Gernaey, U. V., Jeppsson, M.-N. Pons, J.-P. Steyer, and P. Vanrolleghem, A (2008). "A Inhibition and toxicity modelling with the long term control benchmark model (BSM1_LT) framework". In: *IWA World Water Congress*. Vienna, Austria, Sept. 7-12.

Rosen, Christian, L. Rieger, U. Jeppsson, and P. a. Vanrolleghem (2008). "Adding realism to simulated sensors and actuators". In: *Water Science and Technology* 57.3, pp. 337–344. ISSN: 02731223. DOI: 10.2166/wst.2008.130.

Rosso, D, Judy A. Libra, Wolfgang Wiehe, and Michael K. Stenstrom (2005). "Membrane properties change in fine-pore aeration diffusers: Full-scale variations of transfer efficiency and headloss". In: *Water Research* 42.10-11, pp. 2640–2648. ISSN: 00431354. DOI: 10.1016/j.watres.2008.01.014.

Rosso, Diego, Judy A. Libra, Wolfgang Wiehe, and Michael K. Stenstrom (2008). "Membrane properties change in fine-pore aeration diffusers: Full-scale variations of transfer efficiency and headloss". In: *Water Research* 42.10-11, pp. 2640–2648. ISSN: 00431354. DOI: 10.1016/j.watres.2008.01.014.

Schellekens, Eric and David Ballard (2014). "Resilience Pathway 2 . 0 ; a promising pathway for cities to accelerate climate adaptation while unlocking private money flows and raising capacity levels". In: September 2013.

Schoen, Mary, Troy Hawkins, Xiaobo Xue, Cissy Ma, Jay Garland, and Nicholas J. Ashbolt (2015). "Technologic resilience assessment of coastal community water and wastewater service options". In: *Sustainability of Water Quality and Ecology* 6, pp. 1–13. ISSN: 22126139. DOI: 10.1016/j.swaqe.2015.05.001. URL: http://linkinghub.elsevier.com/retrieve/pii/S2212613915000276.

Schraa, O and M. Gray (2017). "Process Control Systems at Water Resource Recovery Facilities: Use of Process Simulation to Assist with Controller Design and Tuning." In: *ISA Water/Wastewater and Automatic Controls Symposium. Aug 8-10,* Wyndham Lake Buena Vista Disney Springs Resort Area, Orlando, Florida, USA. URL: www.isawwsymposium.com.

Schraa, O, L Rieger, and J Alex (2015). "A Comprehensive Aeration System Model for WRRF Design and Control". In: *Proceedings of WEFTEC.15*. Chicago, Illinois, USA, pp. 5091–5120.

– (2017). "Development of a Model for Activated Sludge Aeration Systems: Linking Air Supply, Distribution, and Demand". In: *Water Science and Technology*, pp. 1–10. ISSN: 0273-1223. DOI: 10.2166/wst.2016.481.

Scott, Christopher a., Christopher J. Bailey, Ralph P. Marra, Gwendolyn J. Woods, Kerri Jean Ormerod, and Kevin Lansey (2012). "Scenario planning to address critical uncertainties for robust and resilient water-wastewater infrastructures under conditions of water scarcity and rapid development". In: *Water (Switzerland)* 4.4, pp. 848–868. ISSN: 20734441. DOI: 10.3390/w4040848.

Silvert, William (2000). "Modelling As a Discipline". In: *International Journal of General Systems* 30.3, pp. 261–282. ISSN: 0308-1079. DOI: 10.1080/03081070108960709. URL: http://www.tandfonline.com/doi/abs/10.1080/03081070108960709.

Solon, Kimberly, Xavier Flores-Alsina, Krist V. Gernaey, and Ulf Jeppsson (2015). "Effects of influent fractionation, kinetics, stoichiometry and mass transfer on CH4, H2 and CO2 production for (plant-wide) modeling of anaerobic digesters". In: *Water Science and Technology* 71.6, pp. 870–877. ISSN: 02731223. DOI: 10.2166/wst.2015.029.

Swamee, P and A Jain (1976). "Explicit equations for pipe-flow properties". In: *Journal of the Hydraulics Division (ASCE)* 102.5, pp. 657–664.

Sweetapple, Chris, Guangtao Fu, and David Butler (2016). "Reliable , Robust , and Resilient System Design Framework with Application to Wastewater-Treatment Plant Control". In: *American Society of Civil Engineers*, pp. 1–10. DOI: 10.1061/(ASCE)EE.1943-7870.0001171..

Takacs, I., G. G. Patry, and D. Nolasco (1991). "A dynamic model of the clarification-thickening process". In: *Water Research* 25.10, pp. 1263–1271. ISSN: 00431354. DOI: 10.1016/0043-1354(91)90066-Y.

Talebizadeh, Mansour, Evangelia Belia, and Peter A. Vanrolleghem (2016). "Influent generator for probabilistic modeling of nutrient removal wastewater treatment plants". In: *Environmental Modelling & Software* 77.February, pp. 32–49. ISSN: 13648152. DOI: 10.1016/j.envsoft.2015.11.005. URL: http://www.sciencedirect.com/science/article/pii/S1364815215300967.

Thornton, A., N. Sunner, and M. Haeck (2010). "Real time control for reduced aeration and chemical consumption: A full scale study". In: *Water Science and Technology* 61.9, pp. 2169–2175. ISSN: 02731223. DOI: 10.2166/wst.2010.971.

Torfs, Elena, Sophie Balemans, Florent Locatelli, Stefan Diehl, Raimund Bürger, Julien Laurent, Pierre François, and Ingmar Nopens (2017). "On constitutive functions for hindered settling velocity in 1-D settler models: Selection of appropriate model structure". In: *Water Research* 110, pp. 38–47. ISSN: 18792448. DOI: 10.1016/j.watres.2016.11.067. URL: http://dx.doi.org/10.1016/j.watres.2016.11.067.

Tran, Huy T, Michael Balchanos, Jean Charles Domerçant, and Dimitri N Mavris (2017). "A framework for the quantitative assessment of performance-based system resilience". In: *Reliability Engineering and System Safety* 158.February 2016, pp. 73–84. ISSN: 0951-8320. DOI: 10.1016/j.ress.2016.10.014. URL: http://dx.doi.org/10.1016/j.ress.2016.10.014.

UKWIR (2017). *RESILIENCE - PERFORMANCE MEASURES, COSTS AND STAKEHOLDER COMMUNICATION*. Tech. rep. London: UKWIR. DOI: 1840578335.

Vannecke, Thomas P. W., Nicolas Bernet, Mari K. H. Winkler, Gaelle Santa-Catalina, Jean-Philippe Steyer, and Eveline I. P. Volcke (2016). "Influence of process dynamics on the microbial diversity in a nitrifying biofilm reactor: Correlation analysis and simulation study". In: *Biotechnology and Bioengineering* 113.9, n/a–n/a. ISSN: 00063592. DOI: 10.1002/bit.25952. URL: http://doi.wiley.com/10.1002/bit.25952%7B%5C%%7D5Cnhttp://onlinelibrary.wiley.com/doi/10.1002/bit.25952/full.

Walker, Brian, C. S. Holling, Stephen R. Carpenter, and Ann Kinzig (2004). "Resilience, adaptability and transformability in social-ecological systems". In: *Ecology and Society* 9.2. ISSN: 17083087.

Weirich, Scott R., JoAnn Silverstein, and Balaji Rajagopalan (2015). "Resilience of Secondary Wastewater Treatment Plants: Prior Performance

Is Predictive of Future Process Failure and Recovery Time". In: *Environmental Engineering Science* 32.3, pp. 222–231. ISSN: 1092-8758. DOI: 10.1089/ees.2014.0406. URL: http://online.liebertpub.com/doi/10.1089/ees.2014.0406.

Wood, David M, Anna Roche, Mira Chokshi, and Kris May (2015). "Preparing the San Francisco Sewer System for the Looming Compound Challenge of Climate Change Induced Rainfall , Extreme Tides , and Sea Level Rise". In: pp. 6399–6415.

Woods, David (2010). *Urban Wastewater Management. An Introductory Guide. An FWR Guide*. Tech. rep. FR/G0008. U.K: Foundation for Water Research. URL: www.fwr.org.

Xue, Xiaobo, Mary E. Schoen, Xin (Cissy) Ma, Troy R. Hawkins, Nicholas J. Ashbolt, Jennifer Cashdollar, and Jay Garland (2015). "Critical insights for a sustainability framework to address integrated community water services: Technical metrics and approaches". In: *Water Research* 77, pp. 155–169. ISSN: 00431354. DOI: 10.1016/j.watres.2015.03.017. URL: http://linkinghub.elsevier.com/retrieve/pii/S0043135415001992.

Yazdani, A., R. Appiah Otoo, and P. Jeffrey (2011). "Resilience enhancing expansion strategies for water distribution systems: A network theory approach". In: *Environmental Modelling and Software* 26.12, pp. 1574–1582. ISSN: 13648152. DOI: 10.1016/j.envsoft.2011.07.016. URL: http://dx.doi.org/10.1016/j.envsoft.2011.07.016.

Zhu, Jun Jie and Paul R. Anderson (2017). "Effect of long-term successive storm flows on water reclamation plant resilience". In: *Water Research* 111, pp. 1–9. ISSN: 18792448. DOI: 10.1016/j.watres.2016.12.026. URL: http://dx.doi.org/10.1016/j.watres.2016.12.026.

INDEX

COLOPHON

This thesis was created with LaTeX. TeX is an open source high-quality typesetting system designed and mostly written by Donald Knuth in 1978. It was designed to allow anybody to produce high-quality books. LaTeX builds on TeX and includes features designed for the production of technical and scientific documentation. It was written in the early 1980s by Leslie Lamport at SRI International.

The document style is a combination of the *classicthesis* style, developed by André Miede and Ivo Pletikosić [1] and "Masters doctoral thesis", originally created by Steve R. Gunn and modified into a template by Sunil Patel [2]. Bibliography was processed by Biblatex.

The thesis has been typeset with the Palatino font, and the beautiful AMS Euler fonts, an upright cursive typeface, commissioned by the American Mathematical Society (AMS), designed and created by Hermann Zapf with the assistance of Donald Knuth. Code has been typeset using the great `Bera Mono` font.

Palatino is the name of an old-style serif typeface designed by Hermann Zapf, initially released in 1949

The Euler font tries to emulate a mathematician's style of handwriting mathematical entities on a blackboard, which is upright rather than italic

The artwork has been produced using the *matplotlib* Python library (Hunter, 2007). Matplotlib is a 2D graphics package used for Python for application development, interactive scripting, and publication-quality image generation across user interfaces and operating systems.

Resilience of water resource recovery facilities

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[1] https://bitbucket.org/amiede/classicthesis/
[2] https://www.latextemplates.com/template/masters-doctoral-thesis