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Environmental and economic assessment of urban water systems and evolution towards a sustainable model. Case study of La Vall de Boí (Lleida, Spain)

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Enginyeria de Camins, Canals i Ports

Barcelona, 22 de Setembre del 2016

Departament d'Enginyeria Civil i Ambiental

TREBALL FINAL DE MÀSTER

Environmental and economic assessment of urban water systems and evolution towards a sustainable model. Case study of La Vall de Boí (Lleida, Spain)

Anàlisi ambiental i econòmica dels sistemes urbans d'aigua i evolució cap a un model sostenible. Cas d'estudi de La Vall de Boí (Lleida, Catalunya)

Joan Muñoz i Liesa

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Department of Hydraulic and Environmental Engineering (NTNU, Norway)
Department of Civil and Environmental Engineering (UPC, Spain)

trust TRANSITIONS TO THE URBAN WATER SERVICES OF TOMORROW
SEVENTH FRAMEWORK PROGRAMME
Agència Catalana de l'Aigua
AJUNTAMENT DE LA VALL DE BOÍ
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH
NTNU Kunnskap for en bedre verden

Escola Tècnica Superior d'Enginyers de Camins, Canals i Ports de Barcelona
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Colaborators from Cadagua: Josep Pueyo.

You can only improve what you can measure
To measure is to know

Lord Kelvin

This document modestly pretends to be more than a thesis. Is pretends to defend the project and the ideas I believe in. It does not pretend to change the world but it pretends to change the little world that is surrounding me. And because I believe in people, I want to think that if everybody can change his own little world too, we will reach a better, more fair and sustainable world.

Joan Muñoz Liesa

Acknowledgements

A la meva estimada família, per haver-me-ho donat tot per arribar fins aquí. Ells són, sens dubte, les persones que més admiro en aquest món i el meu incondicional referent.

A la Marina, el meu pal de paller tants cops i que d'una altra manera, també m'ho ha donat tot.

To Rita Ugarelli and Helge Brattebø, who first very kindly accepted and believed in me and with my proposal of thesis as much as I did. They also introduced me to Industrial Ecology, risk assessment, metabolism models and new approaches as well as to the TRUST European project. Many thanks also to Sveinung Sægrov and Venkatesh Govindarajan and the entire great community of NTNU. Without them this study and my Erasmus experience would not definitely be the same.

To Alejandro Josa, who kindly accepted to supervise this work, almost at anytime and anywhere. His support and comments were essential to finish it.

To Anna, Orlane, Pierre, Till, Raquel, Klaudia, Anne-Sophie, Zoé, Emili, Simon, Xavi, Paula, Marta, Blanca, Álvaro, Lena and Lucile among many others to make my Erasmus stage in Trondheim one of the best experiences in my life that I will miss a lot.

Als meus incondicionals companys de carrera, Carlos, Clara, Jordi, Marc, Adri, Antoni, Guille i Anna. Com sempre, junts ho hem aconseguit.

A la Gemma Cervantes, qui un dia a Palamós em va introduir a l'Industrial Ecology de la NTNU i gràcies a això, vaig iniciar el curs de LCA i, mesos més tard, aquest treball.

A l'Agència Catalana de l'Aigua i, en concret, a l'Elisabet Mas, la Bernadette Catlla, en Jordi Robuste, en Marc Moliner i també a en Carlos Barbero i al personal implicat de l'ACA per la seva sempre amable atenció i predisposició, imprescindible sens dubte per dur a terme el treball.

A l'Ajuntament de La Vall de Boí, a en Chelo, cap dels tècnics de l'Ajuntament, i en especial a l'Esther Isus, per la seva amabilitat i generositat en tot moment, i per haver-me introduït a la casuística tant complexa de l'aigua de la Vall de Boí.

A les empreses col·laboradores d'aquest treball, sense les quals no hauria pogut avaluar tots els fluxos econòmics i per tant, sense les quals aquesta tesina tampoc hauria estat el mateix.

Als meus estimats avis, exemple sempre d'esforç, treball i sacrifici, gràcies als quals he tingut les oportunitats que ells no van poder tenir.

Als veïns de la Vall de Boí i la seva gent, que formen part d'aquest paradís prinenc.

Joan Muñoz i Liesa
Trondheim and Cóll, Summer 2016

Contents

Summary

The upcoming sustainability challenges in the urban water systems are driving management and planning focus towards sustainability in a more holistic and integrated view. In this work, the Dynamic Metabolism Model (DMM), based on the LCA and MFA approach, has been used to analyse the inputs and outputs from the urban water system (UWS) metabolism to give sustainability assessment. It constitutes the first step to achieve a full internalisation of costs of the UWS. This model has been carried out in a real case study in the Vall de Boí, Pyrenees, Spain. The present analysis, as well as future interventions and scenarios, are developed after consulting stakeholders involved. The impact assessment has shown that the greatest impact is the in-house and the WWTPs energy demand, so the interventions have been designed to overcome them reducing them, designing green infrastructure and using ICTs to improve the efficiency of the current assets. In this work, an integral solution has been also designed modelling water policies to understand their impacts on the UWS thanks to specific calculated KPIs. The DMM has been demonstrated as a powerful tool to comprehensively understand the impacts of specific interventions strategies that can usefully help stakeholders into the decision-making process. The results of the improvement assessment showed a reduction up to 24% of the GWP and AP impacts, and up to 49% of the EP impacts. The results also show that a sustainable urban water planning and policy, decoupled from the economic dimension can be achieved while demonstrating that can represent an opportunity to reduce costs and generate business too.

Resum

Els futurs reptes de la sostenibilitat en els sistemes urbans d'aigua estan conduint la gestió i centrant l'enfocament de la seva gestió cap a la sostenibilitat des d'un punt de vista integral i holístic. En aquest treball, el Model de Metabolsime Dinàmic (DMM), basat en la metodologia d’anàlisi de cicle de vida (ACV) i de modelització de fluxos (MFA), s'ha emprat per analitzar el metabolisme dels fluxos d'entrada i sortida del sistema urbà d'aigua per avaluar la sostenibilitat. Constitueix el primer pas per aconseguir una plena internalització dels costos dels sistems urbans d’aigua. Aquest model s'ha implementat en un cas d'estudi real a la Vall de Boí, als Pirineus catalans. L’anàlisis actual, així com les futures intervencions i escenaris, han sigut desenvolupats després de consultar els agents involucrats. L’avaluació dels impactes ambientals ha mostrat els principals impactes provenen de la demanda energètica provinent de la gestió de l’aigua a nivell domèstic i de les EDAR, de manera que les solucions proposades han estat dissenyades per mitigar els impactes que provoquen amb infrastructura verda i solucions TIC que millorin l’eficiència del sistema. En aquest treball, s’ha dissenyat també una solució integral, modelant polítiques socials d’estalvi d’aigua per entendre les repercusions d’aquestes al sistema gràcies a indicadors específics (KPIs). El DMM ha demostrat ser una útil potent eina que pot ajudar als agents implicats en la presa de futures decisions a nivell estratègic. Els resultats de l'avaluació de les millores mostren una reducció de fins al 24% dels impactes de GHG i acidificació, i fins a un 49% els impactes d’eutrofització. Els resultats també mostren que una planificació i una política urbana sostenible de l'aigua desvinculada de la dimensió econòmica pot ser aconseguida, demostrant que pot presentar una oportunitat per nous negocis tot reduint costos.

Abbreviations

ACA	Catalan Water Agency
AP	Acidification Potential
DMM	Dynamic Metabolism Model
EC	European Commission
EEA	European Environment Agency
EPA	United States Environmental Protection Agency
EU	European Union
FEP	Freshwater Eutrophication
FU	Functional Unit
GHG	Green House Gasses
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
ICT	Information and Communications Technology
KPIs	Key Performance Indicators
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
MEP	Marine Eutrophication
MFA	Model Flow Analysis
TRUST	Transitions to the Urban Water Services of Tomorrow, European research project
UWC	Urban Water Cycle (when referring the water pathways)
UWCS	Urban Water Cycle Services (when referring to the urban management services, including stakeholders operational procedures and their assets)
UWS	Urban Water Systems (when referring to the whole system, including the services and the infrastructure and assets of the system).
WFD	Water Framework Directive, European Union (2000/60/EC)
WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant

1. Introduction

Water is essential for human life, nature and economy. Urban water systems (UWS) have existed for many years in human civilisation and are responsible for several revolutions. The Romans constructed aqueducts to bring water to cities and removed wastewater with sewage systems. In the 19th century, for instance, water systems accounted for the hygienic necessities of urban areas by constructing separate systems to deliver clean drinking water and remove sewage (Hallström, 2003). At present, in the developed world, water systems have enabled people to grow crops and live outside freshwater areas, while practically have eliminated waterborne diseases (Rygaard et al., 2011). As in the Romans time or the 19th century, we are now facing a new water revolution driven by future stressors that implies taking into account different dimensions beyond the technical or economical ones, such as the environmental or social aspects of the UWS. These stressors are expected to cause important strains on the urban water systems which are in essence, securing water quality and quantity: climate change, population growth, increasing urbanisation and water scarcity are posing urgent water challenges in the urban water systems of tomorrow.

Climate change will cause more intense rainfall events (that will lead to local flooding) as well as more frequent shortfalls in water supply. Thus, it will impact on water availability in space and time, consequently it is important to secure water resources (Jenerette and Larsen, 2006; IPCC, 2007). In terms of demographic changes, the concentration of human activities intensifies local competition for all types of resources, with water amongst the most vital (Zoppou, 2001). This means an increasing difficulty to find and utilise new sources of water necessary to satisfy the growing water demand (Niemczynowicz, 1999). The EEA State of Water report an increased worrying trends of water scarcity and stress which is expected to widely spread in EU, affecting half of EU river basins in 2030. Particularly, EEA points that around 20 % of total the population of the Mediterranean region live under permanent water stress conditions and more than half (53 %) of the Mediterranean population is effected by water stress during the summer. Moreover, these changes are expected not only in Europe but elsewhere (Cheshire and Carbonaro, 1996; Skeldon, 2006). There are even more hazards for the actual urban water models, as the aged infrastructure, the lack of social policies or the non responsible use of water, in terms of the social believing that water is an infinite resource and that the actual linear water model is valid forever. For all these reasons, over the last years, new guidelines, treaties, agreements (COP21, Paris) and directives (such as Directive 2000/60/EC) have been published in order to minimise the increasing impact of human activities on the environment and also in the water ecosystems.

Innovative, integral and management tools are needed to ensure more sustainable urban water systems, studying the urban water cycle entirely – from the upstream raw water extraction to the downstream discharge of treated wastewater– to get the needed understanding of its system-wide contribution to energy efficiency and climate change (Zappone et al., 2014). The integration and optimisation of UWS models contribute to sustainable urban water planning and convert the linear urban water systems into integrated urban water cycle systems, which have been specially emphasised to reach a sustainable water management. Quantifying the whole repercussions of the urban water cycle systems enables managers to determine where the efforts must be spent, and thanks to the solutions studied, an easily comprehensive objective data can be obtained in order to prioritise future interventions. Thus, making decisions on development, production and use of technologies based on inconsistent environmental assessments can then be avoided.

In this sense, an integrated urban water cycle system represents a win-win solution that can reduce the overall consumption of resources and water flows by identifying the synergies that an integral urban water system and related industrial systems can offer. This reduction of flows has a direct impact in the economic and environmental costs, while it effectively improves human health and hygiene, as well as water independency (Lim, et al., 2010). As a result, the reduction of these impacts has to be properly quantified in order to predict the consequences of future interventions.

To also respond to the mentioned future challenges, the new urban water cycle can not be only a technological change. In addition to improving water allocation based on ecological flow, water efficiency measures from a socio-cultural change should be taken to save water and all related energy and chemical flows too (EC, Blueprint to Safeguard Europe's Water Resources), a change in the relation of the demand and offer (Folch, 2005), a hierarchical scale of values. In other words, new technologies or improvements of the existing systems have to be done together with social policies and other instruments, as it is not only about to maintain the old culture of water. Therefore, sustainability is a multi-objective problem that has to be addressed in all fields and scales. Thus, the approach taken in this work is not only to develop or choose the best technological solution between a range of alternatives, but also to design an integral solution for a more sustainable water management, given the case studied.

With a holistic view of the whole urban water systems, quantifying the economic, environmental and social impacts is the first step to internalize the externalities. In the water sector, it enables to estimate and give value to the freshwater resources, as it is a common asset that is essential to be preserved for future generations. This valuable data must be transferred to the society, including politicians, stakeholders and citizens, in order to emphasise the urgency to change to a circular sustainable model of development and the consequences if this is not done.

1.1. Justification of the case study

Urban water related issues are the focus of many studies specially due to the potential problems and stressors that are expected to come if nothing is done. Rural areas have different characteristics and consequently other problems, but they also need sustainable water policies. Several reasons emerge the necessity of assessing rural areas as it belongs this case study:

- Sustainability is a global challenge and therefore has to be approached in all its dimensions but also everywhere. Rural areas are also logically affected for these global challenges, even as far as environmental impacts concern, they are not as concentrated as in big cities and/or they become “diluted” in the environment and hence perceived somehow as not as important. As an example, the apparently (or *real*) abundance of the freshwater in some rural areas yields an inappropriate usage of the freshwater resources. This “dilution” problem affect in different ways:

    i. The lack of concern and mitigation of these impacts as the impacts have a low relative values (the low population density can lead to a false mitigation of the high absolutes values of the environmental impacts).

    ii. The lack of social perception, awareness and concern regarding these impacts, which does not help when applying mitigation policies or measures.

    iii. Also, it can happen that there are low absolute environmental impacts, not apparently visible, but that are actually causing a high relative impacts, as they are affecting a specific ecosystem specially vulnerable. Thus, it is not always perceived by the stakeholders. For instance, little water streams contaminated with untreated sewage water could cause important eutrophication problems in all the downstream areas of the river.

- The approach to solve global problems (environmental, economic and social) can be with local solutions (think global, act local). According to a European green paper[1], *many decisions influencing directly or indirectly climate change adaptation are taken at the local level. This is also where detailed knowledge on the local natural and human conditions is available. Therefore local authorities have an important role to play. Behavioural change within societies and communities depends largely on awareness of the problem. Citizens and actors may not yet be aware of the scale and magnitude of what is to come as well as their impacts on their activities.* This fact, in relation with the *diluted* environmental impacts does not help in order to let understand society the importance, for instance, of saving water. A study carried by Catalonian Sustainable Development Advisory Council[2] (CADS) during 2004 and 2005 in the Barcelona area,

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[1] Green Paper from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions - Adapting to climate change in Europe – options for EU action {SEC(2007) 849}

[2] Catalunya Estalvia Aigua (Catalonia saves water), CADS - Consell Assessor per al Desenvolupament Sostenible and Ecologistes en Acció, Goverment of Catalonia, 2006.

pointed out that more than 63% of the people surveyed did not know their own water consumption, while other authors like Domene et al. (2004) obtained a value of 44%.

- Solving environmental issues has been widely demonstrated that can also be a good opportunity to generate business too. Hence, developing multifunctional solutions in the rural areas can help to develop the territory with a fair and balanced manner without creating pressure on the cities. Thus, it also represents a way to reduce the water related problems of increased urbanisation in cities while solving the UWS' problems in rural areas.
- It is important to mitigate impacts in the upstream locations due to the high implications in all downstream water flows. Regarding the water consumption, when it occurs in upstream locations[3], it affects the whole water reach or river in the downstream from the point of extraction: it is not the same to consume water near from the sea that near from the source as it will affect much more, to the whole reach. The Ebre river, effluent of the area of the case study, is 80% used for watering crops (ACA, 2000) and thus, an excess of water consumption in the upstream locations could produce water scarcity in some downstream locations. Similarly, the water pollution in the upstream areas will affect downstream. The pathways of these contaminants are not always evident (as they can be diluted or filtered into the ground, for instance), but what is truly evident is that the water quality will not be improved in the downstream locations of the river.
- Importance of coherence with the natural environment and parks: "*In forming the hubs of a European Green Infrastructure, Natura 2000 sites provide a strategic focus for improving our natural environment and enhancing the quality of our lives. At the same time, implementing a Green Infrastructure beyond protected areas will help to strengthen the coherence of the Natura 2000 network by making the core areas more resilient, providing buffers against impacts on the sites, and offering practical real-life examples of how healthy protected ecosystems can be used in a way that provides multiple socio-economic benefits to people as well as to nature*" (Building a green infrastructure for Europe, 2014).
- The study case can be an example of the management solutions that can be applied related with the problems that are in Catalonia in terms of managing water urban infrastructure. Thus, the necessity of an integral approach can be defined in common for all the stakeholders involved: city councils, Catalan Agency of Water, Ministry of Health, and the operating companies (from a public procurement of services).
- Many studies point the necessity of achieving sustainability with public participation. Starting from rural communities can help to achieve this participation, giving example to other larger communities, with the top down approach. This means to bring ideas to

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[3] For more information regarding the water consumption impacts see the studies from Tendall et al., based on the Hanafiah et al. water impacts research.

the social communities, engaging them in the very early stages in order to achieve a more sustainable development.

- Finally, rural water systems studies can be also a way to test the performance of the actual models and decision support tools of more urbanised areas, allowing to define this way, a global decision-support model.

From a methodology perspective, this case study is also relevant because:

- The valley is geographically isolated, which facilitates the study of the urban water systems and its subsystems in a systemic thinking, controlling the inflows and outflows of each subsystem. The connections with other urban systems are also easily to identify. All in all, this allows to reduce variables of the study.
- The urban water systems of the all villages are very similar as they are managed by the same stakeholders. This facilitates the assessment carried in this work, studying all subsystems from all villages as the combination of subsystems, which form a single urban water system.

1.2. Goal and scope

The goal of the thesis is to study from an integrated, systematic and holistic view the urban water system of the La Vall de Boí in order to achieve a more sustainable model. The purpose is to model the metabolism and the economic and environmental impacts from resource flows to the different urban water systems to offer a suitable tool to examine the current status quo and the consequences of future interventions.

This will be done through:

I. Identifying, collecting and analysing the annual inputs and outputs flows of the UWS studied. This research includes the assessment of seven urban water subsystems: water supply, water distribution, water demand, wastewater demand, wastewater treatment, sludge treatment, and water recipient media subsystems.

II. Assessing the urban water system (UWS) of La Vall de Boí using the MFA - LCA approach across all subsystems to understand the share of the overall environmental impacts.

III. Proposing possible interventions and scenarios to improve the environmental performance of the system, finding out the best scenarios by comparing them with the current scenario.

IV. Taking into account the operational phase of the UWS in the MFA - LCA analysis, i.e., including the whole operational costs of the water cycle of La Vall de Boí (including also the in-house water usage). This excludes the environmental costs of the construction and end of phase of the current and the proposed infrastructure of the future interventions.

V. Considering the economic, environmental, technical and governance sustainability dimensions according to the TRUST research European project. Thus, a complete holistic and integral solution for a more sustainable water management will be given, modelling technological and governance interventions.

From this specific goals it is important to underline that only the operational phase has been considered in the LCA assessment because it has the highest contribution to the total environmental impact of the life cycle (Friedrich and Buckley, 2001; Lundie Gregory and Beavis, 2004, Raluy et al., 2006; Muñoz and Rodríguez Fernández-Alba, 2008).

The specific objectives that derive from the main scope of the thesis match with the ones well-stablished in the EPA guidelines for planning for sustainability in the water and wastewater utilities which are:

i. Reduce economic and environmental costs during the life cycle of existing or future infrastructures to operate more efficiently, using and optimising investment strategies

ii. Optimise social, environmental and economic solutions by selecting alternatives through a systematic process based on selected indicators, establishing sustainability goals

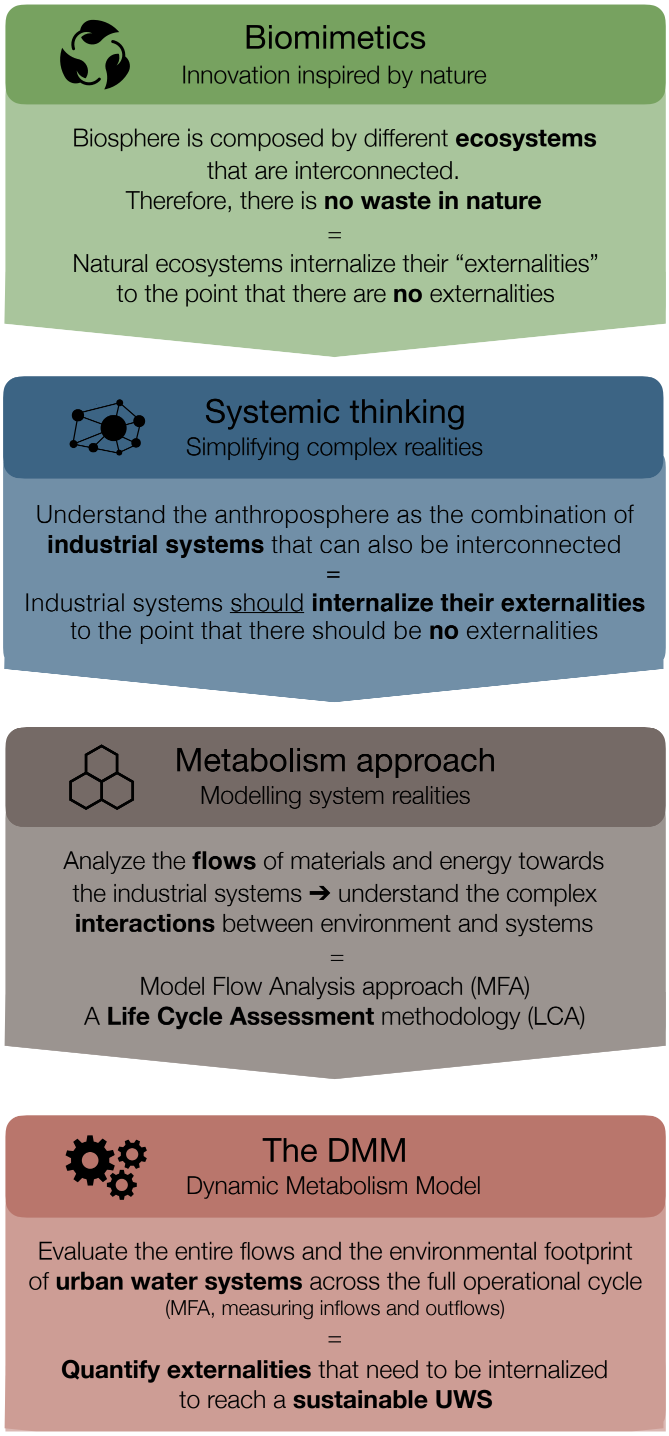
iii. Set a strategic plan for future interventions in terms of the studied scenarios and balance evaluation through the analysis of alternative solutions, traditional and non traditional, based on consistent criteria (see chapter strategies and solutions

Apart from the specific results for this case study, this work aims to generalise the obtained results to other urban water systems, demonstrating the powerfulness of the metabolism analysis through the approaches of model flow analysis (MFA) and life cycle assessment (LCA). Metabolism analysis allows to understand the implications of changing one flow in the water system, and understand the chain reactions.

The holistic approach in the study has specially taken into consideration by collecting flows from all subsystems. This is also sometimes a lack point of some UWS metabolism researches, as they are normally focused in a specific part of the UWS. The system boundaries in LCA studies are always very dependent with the availability of data, which is specially laborious when many different stakeholders are involved, as it happens in the case study. Therefore, other studies have been used, to estimate the emissions from the systems that was not possible to obtain the direct data. Even this a simplification of the analysis, it is still useful to have a wide picture of the UWS studied.

1.3. Workflow

The figure below represents the workflow of this thesis, from the basis and the core of Industrial Ecology to define the approach to reach a sustainable urban water systems. This vertical logical sequence helps the reader to understand the reasoning process of this thesis, following the same steps as the contents of the thesis, while linking them with some theoretical concepts that can be useful to keep in context the whole picture of the pathway towards sustainability of urban water systems but also, of other industrial systems too.



Biomimetics
Innovation inspired by nature

Biosphere is composed by different **ecosystems** that are interconnected.
Therefore, there is **no waste in nature**
=
Natural ecosystems internalize their “externalities” to the point that there are **no** externalities

Systemic thinking
Simplifying complex realities

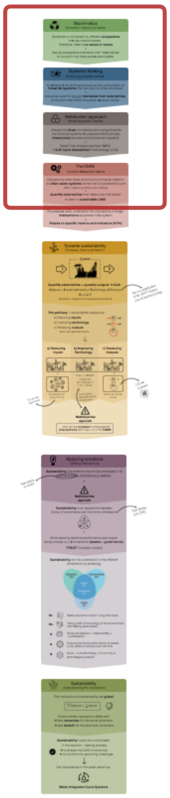
Understand the anthroposphere as the combination of **industrial systems** that can also be interconnected
=
Industrial systems <u>should</u> **internalize their externalities** to the point that there should be **no** externalities

Metabolism approach
Modelling system realities

Analyze the **flows** of materials and energy towards the industrial systems ➔ understand the complex **interactions** between environment and systems
=
Model Flow Analysis approach (MFA)
A **Life Cycle Assessment** methodology (LCA)

The DMM
Dynamic Metabolism Model

Evaluate the entire flows and the environmental footprint of **urban water systems** across the full operational cycle
(MFA, measuring inflows and outflows)
=
Quantify externalities that need to be internalized to reach a **sustainable UWS**



Quantify externalities that need to be internalized to reach a **sustainable UWS**

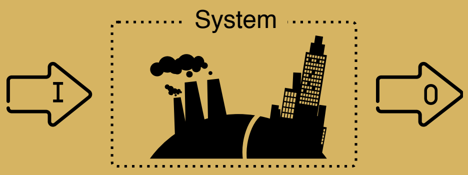
This enables us to understand the implications of single **interventions** anywhere in the system

=

Thanks to specific metrics and indicators (KPIs)

Towards sustainability

Pathways, how to achieve it?



Quantify externalities = quantify outputs ➔ LCA:

Outputs = **I**nputs (demand) x **T**echnology (efficiency)

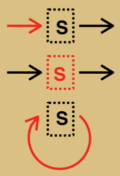
O = I x T

[Impacts = foreground x background systems]

This is a simplification of the "IPAT" formula, core of Industrial Ecology

The pathway = reducing the outputs by:

a) Reducing **inputs**
b) Improving **technology**
c) Revaluing **outputs**
➔ so we need less inputs

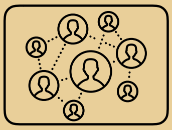


a) Reducing Inputs

b) Improving Technology

c) Revaluing Outputs

+



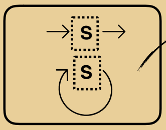
Social policies (governance)

It's not only about techs!

New / + efficient / improved technologies or infrastructures

Can be solved with multifunctional infrastructures!

+

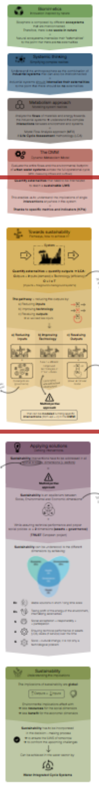


Linear ➔ Circular model

Circular economy!

Multiobjective approach

… that can be **modeled** running specific **interventions** (from a,b or c) in the **DMM!**



Applying solutions

Defining interventions

Sustainability interventions have to be addressed in all spatial scales + dimensions (+ sectors)

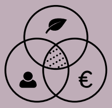
"think globally, act locally"

=

Multiobjective approach

Sustainability is an equilibrium between Social, Environmental and Economic dimensions

Triple Bottom Line (TPB)

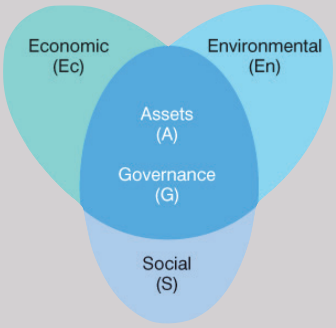


+

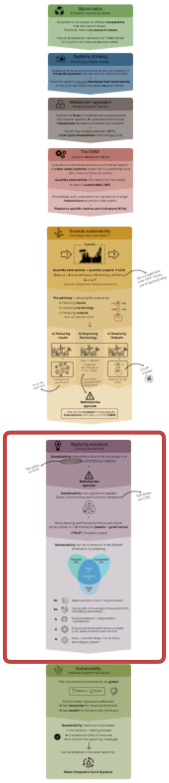
While assuring technical performance and proper social policies ⇒ **+ 2** dimensions **(assets + governance)**

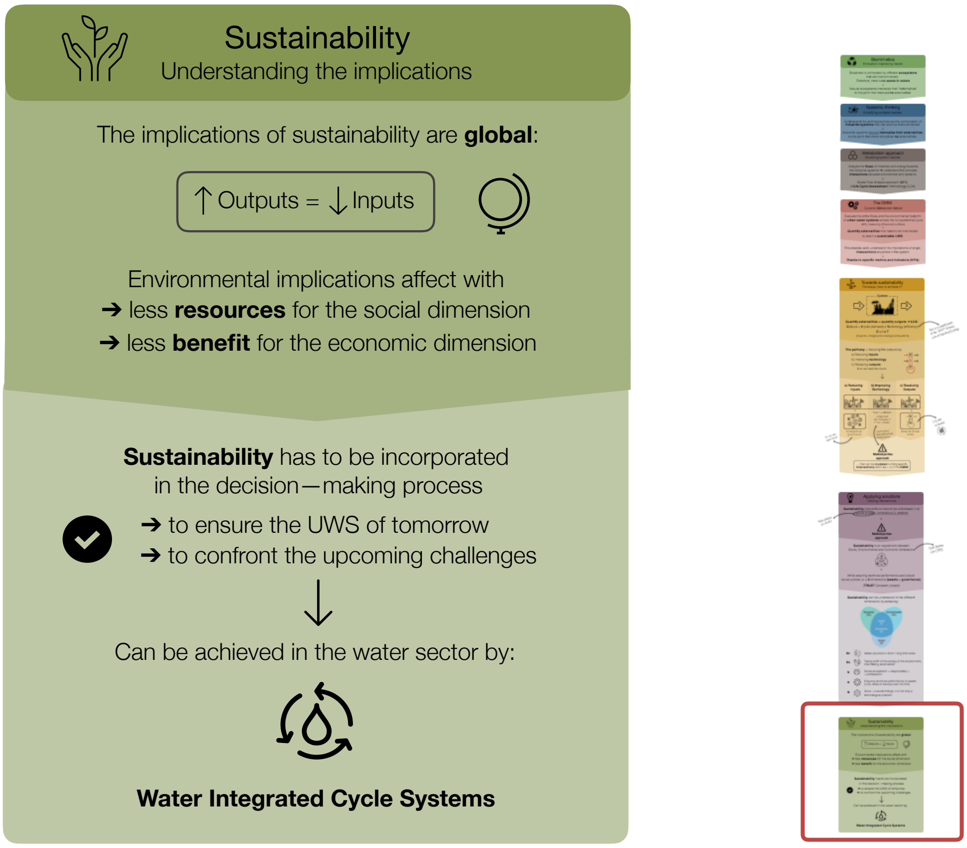
(**TRUST** European project)

Sustainability can be understood in the different dimensions by achieving:



Ec	Viable solutions in short / long time scale
En	Taking profit of the energy of the environment, Internalizing externalities
S	Social acceptation + responsibility + + participation
A	Ensuring technical performance of assets (LOS, levels of service) over the time
G	Socio—cultural change, it is not only a technological problem





Sustainability
Understanding the implications

The implications of sustainability are **global**:

↑ Outputs = ↓ Inputs

Environmental implications affect with
➔ less **resources** for the social dimension
➔ less **benefit** for the economic dimension

Sustainability has to be incorporated
in the decision—making process

✓ ➔ to ensure the UWS of tomorrow
➔ to confront the upcoming challenges

↓

Can be achieved in the water sector by:

Water Integrated Cycle Systems

Figure 1.1: Workflow of the thesis

2. Background

2.1. Sustainability into the decision-making process

Historically, urban utilities and authorities focused on primarily local and isolated issues. Thus, infrastructures were designed to solve technical aspects while trying to maximise the ratio between technical efficiency versus the economic costs. Sustainability was somehow taken into account when economic met environmental aspects in the short time scale analysis. Another frequent approach has been to copy-paste infrastructures throughout the territory when the boundary conditions of the objective area (city, village,…) were similar, Other aspects beyond the technical ones, such as social or environmental were never taken into account.

The current urban water infrastructure, management practices and social perception (or culture of water) is based on the conventional linear UWS, which aims to meet water supply demands and to convey away the wastewater and stormwater from the urban areas. This model is not sustainable anymore and this is reflected by the upcoming environmental challenges. The circular water cycle, explained in this chapter, aims to close this linearity in order to achieve a sustainable urban water system.

Biomimetics or biomimicry is the imitation of the models, systems, and elements of nature for the purpose of solving complex human problems (Vincent et al., 2006). Industrial Ecology aims to study the natural ecosystems and how they solve the natural problems as a basis for the new technologies. Biomimetics is an important source of inspiration and ables to understand sustainability concepts such as *internalizing the externalities* mentioned before. This concept exploits all its meaning if we think in the biosphere, as natural cycles internalize more than any other system does (Folch, 2005). This concept is so much built-in in the nature that there are no externalities or residues, as they are a circular loop. Sustainability thus, means internalize. The Commission of the European Communities in a Green Paper[4] points that same idea: “Sustainable use means that development and exploitation should not result in a decline in natural capital or ecosystem services. In this context, compensatory measures are important to ensure that development projects preserve the natural capital. Comprehensive cost/benefit analysis and impact assessments should gradually and systematically internalize the environmental costs of declining ecosystems”.

The systemic thinking used here aims to simplify the biosphere (which is the largest system of the Earth) as a collection of interconnected systems. Thus, environmental impacts could be understood as the sum of externalities[5] caused by all the systems that cannot be internalised by themselves or by other systems. Therefore, to internalize the externalities produced by human industrial systems, the first step is to quantify these externalities and thus, understand what impacts and how much of them has to be internalised. Therefore, this work aims to bring the studied urban water system a step towards sustainability by quantifying the actual environmental

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[4] Adapting to climate change in Europe – options for EU action {SEC(2007) 849}; Green paper from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions

[5] Externalities are understood it in this context as negative, in terms of residues or environmental impacts.

impacts and, in addition, by defining future interventions and how these will change the current situation. In other words, it intends to define how the externalities can be internalised, understanding how they will affect the metabolism of our industrial system in order to achieve sustainable goals. These goals should be at the end or ideally should internalize all these environmental impacts, at least. Hence, if all systems achieve these goals, a sustainable development will then be assured.

The approach used in this proposal is within the evaluation of the metabolism of the industrial (including urban) systems with regard to the regional and global stocks with the Dynamic Metabolism Model. The DMM stands on the MFA - LCA approach and aims to quantify several impacts in the whole life cycle assessment of the stocks flows from cradle to grave.

The growing concern of the damage or externalities that humans are causing to our ecosystems are driving new challenges. UWS and services are therefore now moving to a more regional and global nature challenges (TRUST Project)[6]. They are progressively taking care of more aspects or dimensions that are, according to Makropoulos et al. (2008), currently influenced by sustainability requirements embedded in environmental legislation in the EU (for example, Directive 2000/60/EC). The incorporation of sustainability assessment into decision—making processes is thus becoming a key task for water service providers – in the UK and elsewhere (Foxon et al., 2002). In addition, water management solutions for future urban developments should be based on sustainability issues due to implications on the social, economic and environmental aspects (Fenner et al., 2006; Makropoulos et al., 2006). These three pillars go together due to the inter-relation and interconnection: damaging the environment means less input resources of common goods that will be delivered to the social and economic system, which will also lead to less outputs from the economic system.

2.2. Water resources and climate change

Water is one of the most important systems of the biosphere, essential for human living and one of the essential goods for urban metabolism. Climate change represents a hazard for the future management of this resource. As mentioned, some of the well known related impacts are the increasing sea level, the more frequently expected floods and water scarcity. Some of these changes are very much related with the changes expected in the mean annual precipitation by the end of this century. Also, larger seasonal changes may be expected in some regions and in addition to the trend of ordinary conditions.

A Green Paper from the Commission of the European Communities[7] pointed that, according to the results of most of the climate models (EEA, 2004; Alcamo et al., 2007), northern and eastern Europe may experience an increase in annual average streamflow and water availability, whereas

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[6] Deliverable D31.1, TRUST European research project

[7] Adapting to climate change in Europe – options for EU action {SEC(2007) 849}; Green paper from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions

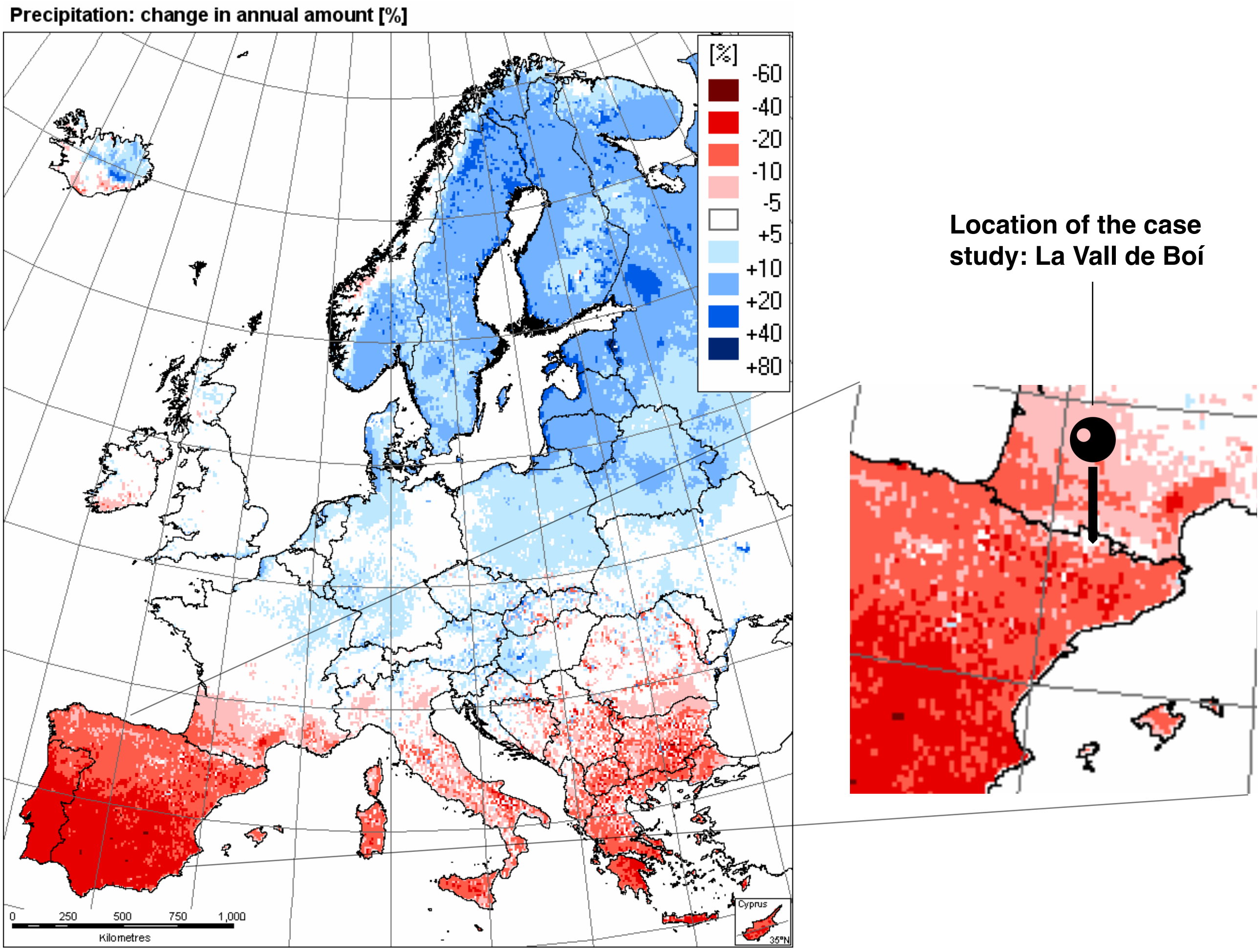

Figure 2.1: Precipitation change based on IPCC SRES scenario A2 of the SRES report. The projected climate impacts are estimated for 2071-2100 relative to 1961-1990. The maps are based on DMI/ PRUDENCE data (HadCM3 global circulation model, and HIRHAM regional climate model in 12 km resolution), and processed by JRC within the JRC funded PESETA study (http://peseta.jrc.es).

river basins in southern European, and in particular in the Mediterranean area, may see marked decreases of water availability due to increasing temperature and decreasing precipitation.

The *Adapting to climate change in Europe* Green Paper from the Commission of the European Communities pointed that, according to the results of the majority of climate models (EEA, 2004; Alcamo et al., 2007), northern and eastern Europe may experience an increase in annual average streamflow and water availability, whereas river basins in southern European, and in particular in the Mediterranean area, may see marked decreases of water availability due to increasing temperature and decreasing precipitation.

As it can be seen in figure 2.1, the location of the case study will potentially have a reduction on the mean precipitation between 10% and 20%. The map shows that the area around the case study region in the Pyrenees is considered not to have a mean precipitation variation. Nevertheless water scarcity is a wide problem in Spain and southern France and therefore, regional impacts will affect global scale impacts. Thus, considering that some downstream regions of the Ebre River basin in Catalonia (to what La Vall de Boí basin belongs) will suffer a water reduction of more than 20%, the adaptation to the climate change in these areas is also basic to meet the future global challenges.

In the mentioned Green Paper and in relation with figure 2.1 and the temperature changes, there are two important considerations that should be pointed out regarding the case study:

- The inclusion of the case study area in one of the most vulnerable areas identified in the group of *Southern Europe and the entire Mediterranean Basin*, due to the combined effect of high temperature increases and reduced precipitation in areas already coping with water scarcity.
- La Vall de Boí is also surrounded by the unique National Park of Aigüestortes, which is included in the Natura 2000 network. Therefore, it is susceptible to many European efforts and policies to safeguard and restore biodiversity and ecosystems. For instance, the 'EU Action Plan to 2010 and beyond' from the 2006 Biodiversity Communication points out the emphasis on "ensuring the integrity, coherence and connectivity of the Natura 2000 network; conserving and restoring biodiversity and ecosystem services in the wider countryside and marine environment; making regional and territorial development compatible with biodiversity".

To respond to this and according to an European Commission communication[8], in addition to improving water allocation based on ecological flow, water efficiency measures should be taken to save water and, in many cases, to save energy too.

2.3. Environmental water impacts

According to an EU Communication (A Blueprint to Safeguard Europe's Water Resources, 2012), "EU needs to focus on green growth and become more resource efficient (including water) to achieve a sustainable recovery from the current economic and environmental crisis, adapt to climate change and build resilience to disasters". This document also remarks that the principal negative human impacts to the water resources are normally interrelated. These can be several and affect to all water masses (or aquatic ecosystems). Thus, different approaches and solutions are needed in order to prevent or restore the contaminant pathways.

In general terms, the large imported potable water volumes affect the quantity of freshwater resources of the ecosystems and therefore, the quality of those waters. The impacts can be several: less water can mean more concentration of nutrients or pollutants, or a rise of the water temperature, so potentially could cause the extinction of certain species. Groundwater masses, as they are normally reachable and easily used by humans, are overexploited in many situations.

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[8] A Blueprint to Safeguard Europe's Water Resources, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM (2012) 673 final.

This means that the recharging rates are not enough for human necessities i.e., the time scale is different.

One of the well known water related problems is the already mentioned increasing urbanization that causes a modification in the land use. This significantly alters the environment and all types of ecosystems (aquatic, biodiversity loss, etc) and also has a strong influence in the stormwater quality and increased flooding, with the potential costs that this can produce. Contaminated stormwater constitutes one of the world's main transport mechanisms introducing non-point source pollutants into receiving waters (Pitt et al., 1995). Untreated stormwater discharges may also impact the receiving waters and contribute to the sediment contamination.

In terms of water quantities, it is important to understand that 69% of the global water usage is destined to agriculture, and 85% of this is consumed water i.e., that is not recovered on the hydrologic cycle. Also, 19% is used in industry and 12% corresponds to domestic usage. On the opposite, domestic water usage is mainly water withdrawal, which means water used and released back to watershed of origin after use, with a probable change in the quality.

The share of global water withdrawal also explains one of the most important pathways of water contamination, as the main sources of potential substances as phosphorous (P) and nitrogen (N) are coming from sewage flows, urban activities and fertilizers used in agriculture. The over-accumulation of these components to the aquatic ecosystems increases algae and other plants causing depletion of oxygen in the water (hypoxia).

The ecosystem's natural response of this nutrient enrichment is named eutrophication and seriously degrades aquatic ecosystems causing several problems such as toxic algal blooms, fish kills, loss of biodiversity (including species important for commerce and recreation), loss of aquatic plant beds and coral reefs, and other problems (Carpenter et al., 1998). It also affects all water usages, from the drinking water to the irrigation for agriculture, among many others.

According to the European Environment Agency (EEA), the eutrophication reduction target set in the updated EU air pollution strategy proposed by the European Commission (EC) in late 2013 will be met by 2030 if it is assumed that all maximum technically feasible reduction measures are implemented, but it will not be met by current legislation. Figure 2.2 shows the evolution of eutrophication impacts in Europe (the location of the case study is marked with a pin) from 2000 and the expected reduction of these impacts if the European Commission proposed measures are applied:

The excess of nitrogen (N) but also sulphur (S) deposition also represent the main source of acidification in natural terrestrial ecosystems. The consequences are, in essence, the increasing of acidity in water, leading to a decrease of the plants performance and biodiversity losses. It can be measured with pH or base saturation and cation exchange capacity.

According to EEA, only 4% of the EU-28 ecosystem area (3% in EEA member countries) is still projected to be in excess of acidification critical loads in 2020 if current legislation is fully implemented. These two potential impacts lead to other problems in other water masses, as ocean acidification or marine eutrophication, which is the enrichment of nutrients of marine waters

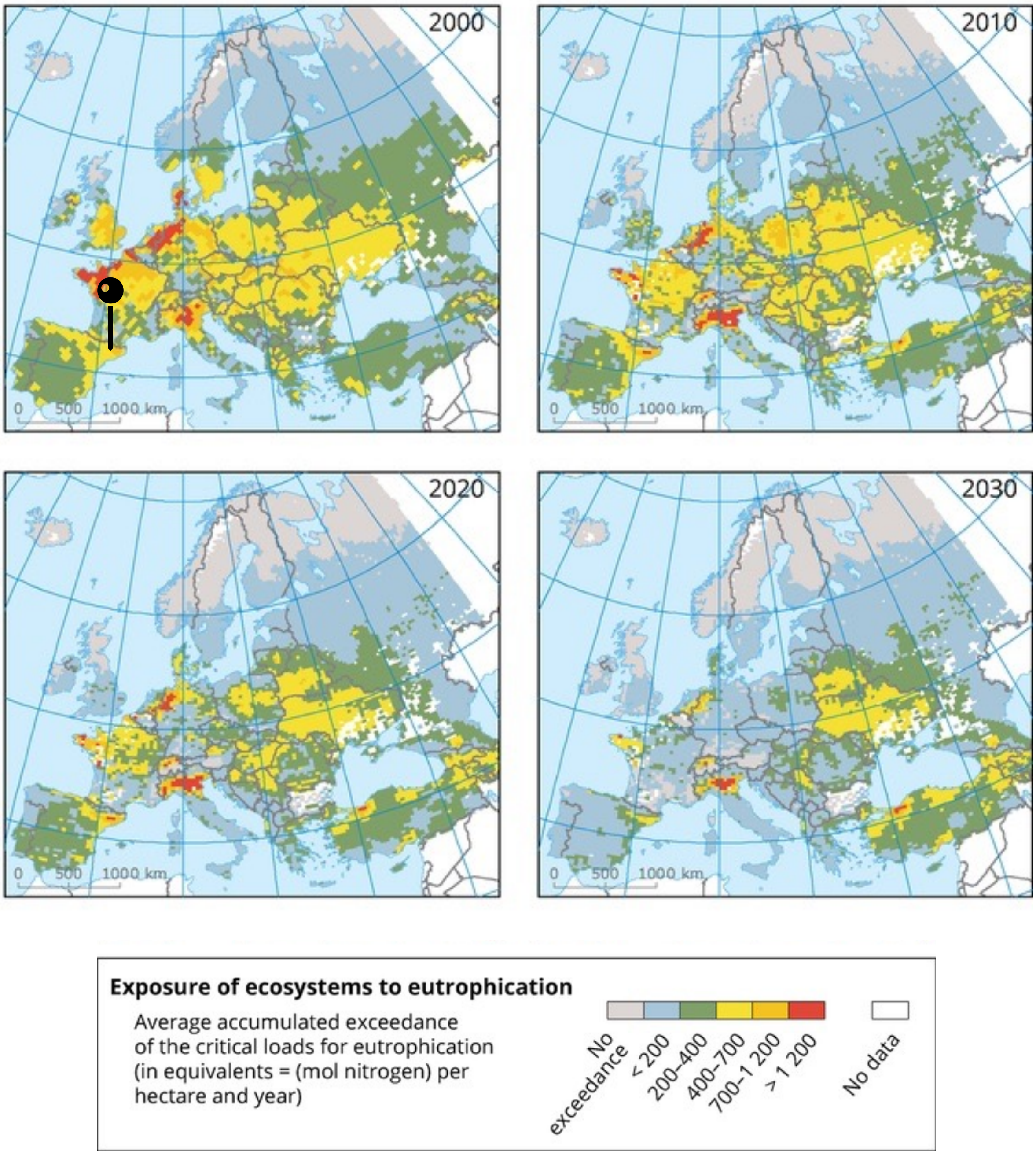

Figure 2.2: Exposure of ecosystems to eutrophication. The maps show the location of the case study (in year 2000) and the areas where critical loads for eutrophication of freshwater and terrestrial habitats are exceeded (CSI 005) by nitrogen depositions caused by emissions between 2020 and 2030. Source: CCE Database (UNECE) provided by Coordination Centre for Effects (UNECE).

promoting excessive growth of phytoplankton and macro-algae. The increasing sedimentation of organic matter consuming dissolved oxygen in water produces a decrease of the relative richness of benthic marine species as well.

The consequences or the exposure of these impacts to humans can be measured with the exposure assessment, which describes the sources, pathways, routes, and uncertainties. One of the main impacts on humans is the Bioaccumulation or the contamination of food supply. In this work, due to the important implications of acidification and eutrophication impacts in the water resources, those have been incorporated in the calculated environmental impacts, thanks to the Dynamic Metabolism Model (DMM). Moreover, quantifying these impacts is important not only for the strong relation with the UWS studied, but also as a measure of the WWTP performance. Water stressors can be several and quantified in many ways. Therefore, more impact categories related with water stressors could be studied in an ideal case expanding this way the LCA goals evaluating more than one impact. All in all the evaluation of these impacts in this work is as an example of the approach that should be done in further studies when environmental impacts are studied.

2.4. The circular water cycle: a biomimetics model

The actual linear water model is, as it has already been pointed out, economically and environmentally unsustainable. This linearity is related to the social believing that water resources are infinite and thus, sewage waters should be conveyed away, without taking into account the possibilities of recycling water for other uses.

Closing the loop in the linearity of the actual urban water systems is another example of the concept of *circular economy*. In terms of Industrial Ecology, this also meets the general scope of this field study, using the outputs of a system to become valuable inputs for another system, as nature does. The main or common goal of the circular water cycle is to use and dispose the water resources as near as possible where this resource was extracted, i.e., treating water in a very local way, reusing water once and again, retaining its full value imitating the hydrologic water cycle. Thus, the circular water cycle can be understood as another example of the said *think globally, act locally.*

Local solutions represent an effective way to close the loop from the smaller spatial scales, retaining the full value of water resources. The water circular model makes much more sense when applied to all spatial scales, as it is much more difficult to bring a complete circular model in the end of the actual linear systems because the water becomes more polluted as it travels trough the system, making these recycling schemes more and more difficult and easily as not as sustainable as local schemes. Circular models are not only good for the environment but are also economically viable and thus, constitute a great opportunity for business too, This makes this model a win win solution, reducing the overall impacts and costs of all involved stakeholders.

It is essential to treat waste flows as value flows that can be used in other systems. Makropoulos et al., (2008) pointed out in that sense within the UWOT research project, that planning and operating the urban stormwater and wastewater systems separately foregoes the potential for utilization of their flows for beneficial purposes, and disregards the fact that these systems are inter-connected and inter-related.

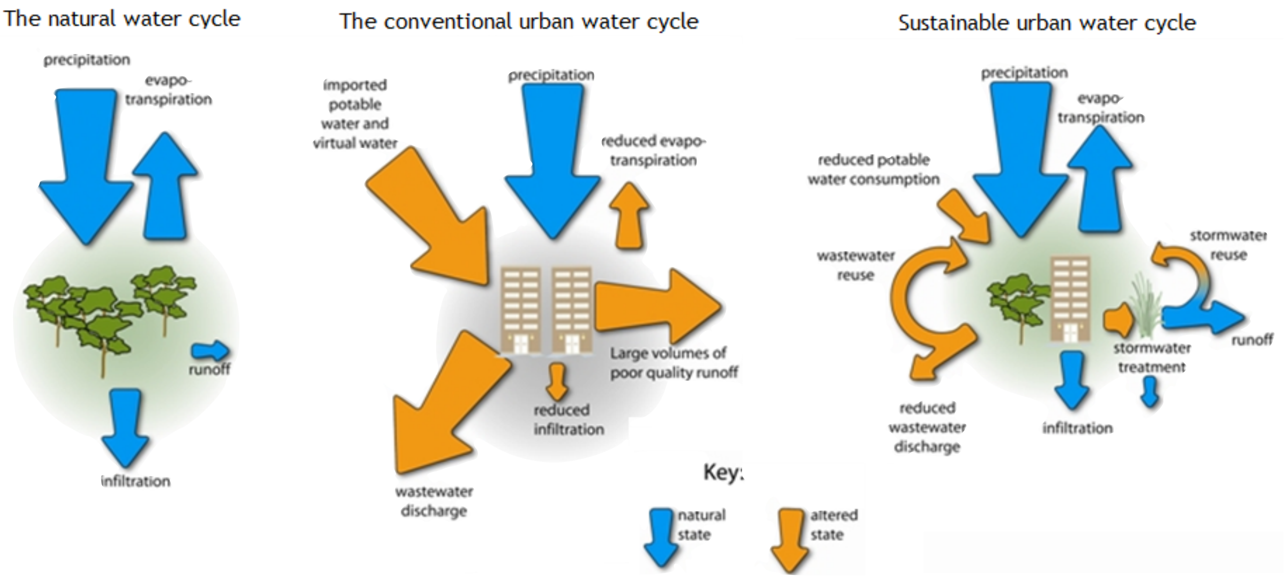

Figure 2.3: The natural water cycle, the conventional urban water cycle and the sustainable urban water cycle. Source: Healthy Waterways (2011)

The circular model makes possible to improve both poor quality and large quantities of the urban water flows, represented in figure 2.3, with the reduction of the overall wastewater by reusing it or reducing the runoff volumes and thus, the wastewater and stormwater treatment, as well as more infiltration or evapotranspiration. All in all, it is clear that the circular water cycle is necessary to reach sustainability in the urban water systems.

2.5. European and Catalan context

The growing concern of climate change, environmental impacts and the future water pressures is driving the new policies in Europe. One of the most know ones is the WFD which is the current framework of the integrated water resources management. It aims to incorporate measures regarding the climate change with economic instruments and *users pay principle* in order to reduce and optimise the water demand, as it aims this thesis. The directive actually point that the actual low costs of water in addition to a lack of proper management leads to overuse. This will be specially important due to the expected droughts in the south of Europe, for instance. On the other hand, also points the necessity to adapt to the expected increased floods, with more protection and prevention. It is worth to mention regarding to this, according to a EU green paper[9], “soft non-structural measures should be prioritised, i.e. using natural processes to the maximum to reduce flood risks e.g. working with wetlands, maximising retention capacities at source, sustainable land use and spatial planning limiting exposure and vulnerability”.

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[9] Green Paper from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions - Adapting to climate change in Europe – options for EU action {SEC(2007) 849}

Several guidelines, deliverables and research programmes in Europe are defining a common growth strategy for the coming decade as the Europe 2020. All in all, aim to incentive a proper management of the water cycle, which means bringing to the society opportunities for a green growth, in line with the priorities set by the European Commission and plans to promote a more circular economy (Roadmap for maximisation of water reuse in Europe, European Commission). Another remarkable research field proposed for the Commission is the Blueprint to Safeguard Europe's Water Resources, which has been demonstrated as way of comparing sustainability goals across many studied cities of Europe. The Blueprint aims to ensure the sustainability of all activities that impact on water, identifying obstacles and ways to overcome them.

The United Nations have defined 17 goals to reach a sustainable development. And the studies towards an integrated water cycle aims, as in this work, to deal particularly with 8 of them: clean and water sanitation, affordable and clean energy, industry, innovation and infrastructures, sustainable cities and communities, responsible consumption and production, climate action, life below water, and life on land.

Regarding the sustainability in the water sector and according to Makropoulos et al., (2008), the emerging EU environmental legislation paradigm internalises principles of integrated water management, pollution prevention and a more complete concept of sustainability which, as stated by Brunner and Starkl (2004), not only features ecological or economic aspects, but also social and institutional ones, such as the participation of stakeholders.

Examples of this more holistic approach can also be found within the SWARD project[10], which focuses on sustainability for the water industry. SWARD introduced four Sustainability Capitals to be used, namely, environmental, economic, social and technical. These additional technical aspects refer to the requirements of the water infrastructure to achieve acceptable levels of service, not overburden the existing infrastructure, while preserving at the same time the triple bottom line approach.

The water sector in Catalonia is competence of the Government of Catalonia, trough the Catalan Water Agency (except for the Ebro basin, which is also competence of the Ebro Hydrographic Confederation). Hence, regarding the catalan context, several institutions (OCCC, CADS, etc.) are also pointing to the same European policies and strategies. Among the different guidelines that have been published in the recent years, it is worth to mention the Guide to calculate the GHG from the urban water networks of Catalonia (OCCC, ACA). This guideline has been used as an example of the same approach of this work, even it calculates the GHG emissions from a general perspective and thus, with less detail. Particularly, this guide aims to continue researches in the same research direction than this thesis, by analysing a full LCA including all the phases in order to quantify all the environmental impacts related with the water consumption. Thus, this thesis covers two of the three proposed further researches of this study, and thus, providing a real case study as an example of the water sustainable approaches of tomorrow.

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[10] Sustainable Water industry Asset Resource Decisions (SWARD) project, Ashley et al., 2004. Makropoulos and colleges relate to this project as a framework for the development of the UWOT research project.

2.6. Previous studies on the urban water cycle

Support tools and models are essential to confront the new UWCS challenges and will help decision-makers to manage the water cycle with integrate tools. The UWOT decision support tool (Urban Water Optioneering Tool, Makropoulos et al., 2008) allows the selection of technological solutions trough the water balances interactions, preserving 4 dimensions and the multi-objective sustainability goals for the analyses. A mathematical model based on the Integrated Water Resources Management (IWRM) integrates and optimise the urban water infrastructures by minimising specific objective functions that describes the water volumes and contamination loads, subjected to specified mass balances and constrains.

There are few studies concerning the study of the entire urban water cycle services (UWCS). Regarding the analysis here studied within the Model Flow Analysis - Life Cycle Assessment (MFA - LCA) approach, in 2004 a study was carried out in the city of Sidney, Australia showing the implications in all dimensions of future strategies. In Oslo different studies showed the so-called energy and water nexus and the relation with the environmental impacts. These mentioned studies and others like the one performed in Alexandria (Egypt), in Tarragona (Spain) or in Turin (Italy) demonstrates that MFA and LCA analysis can offer a potential and powerful assessment tool to meet the challenges of the UWS of tomorrow.

Also, the studies show that the obtained results can vary significantly as they are very particular due to the very related site-specific factors (boundary conditions). For instance, the physical characteristics like topography of the case studies can lead to more or less pumping needs (or even as a potential source of hydropower generation), which would affect the total share of all costs, and thus, the priorities of future interventions.

2.7. The TRUST European research project

TRUST (Transitions to the Urban Water Services of Tomorrow) is an integrated research project funded by the European Union that enabled to put in common the research innovations and tools from 30 partners from eleven countries to achieve a sustainable urban water systems. The outcomes resulted from this program, i.e. study cases, models and deliverables, have been considered in this thesis as the framework and approach of the pathway towards sustainability for this case study.

One of the important outputs form the TRUST project is the definition of the sustainability dimensions in the UWCS and systems, which includes the Triple Bottom Line approach[11] accounted together with the supporting dimensions of assets and governance sustainability (the assets dimension refers to the technical aspects, as it is named in other studies). Therefore it sustains in the same idea mentioned before and scope of this work, which sustainability should be achieved by taking care of both designing the proper technology as well as proper social policies that meet the sustainability objectives.

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[11] This concept means to make decisions accounting the economic, social and environmental aspects in order to find a balance of all oh them in the solution (WCED, 1987).

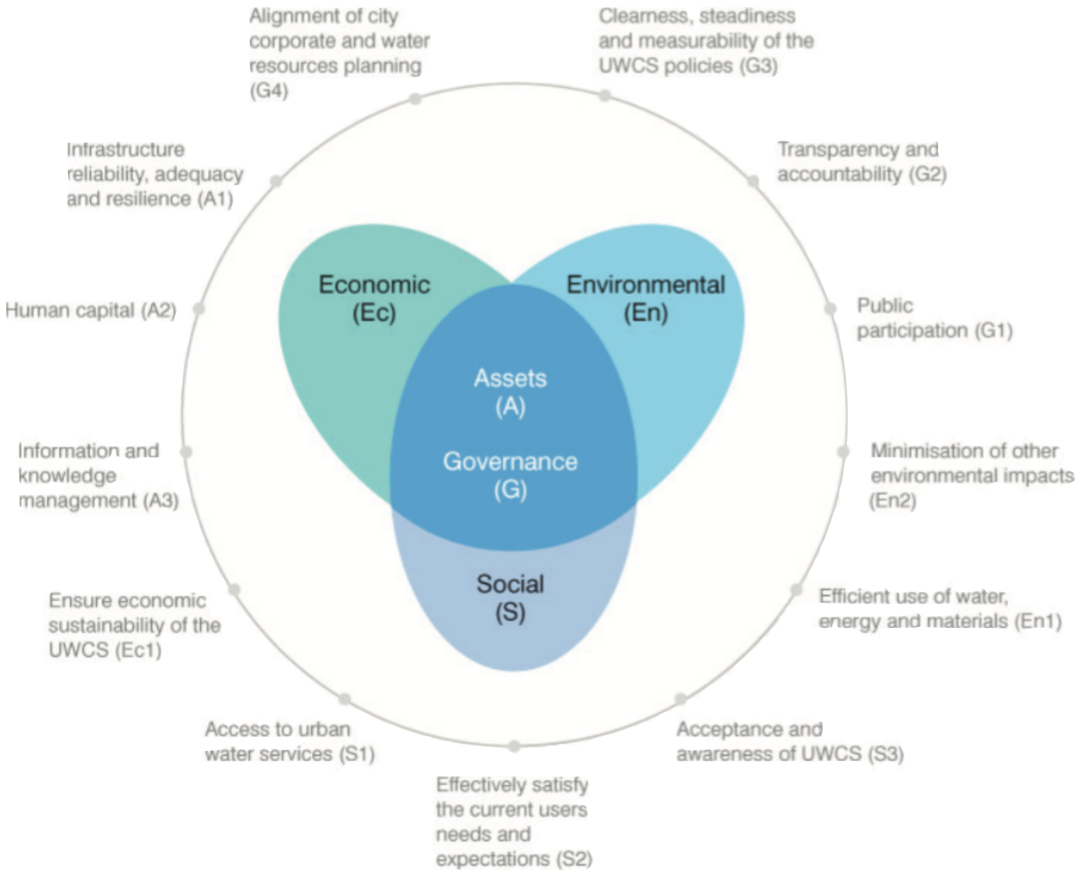

Figure 2.4: TRUST approach to sustainability assessment . The 5 dimensions of sustainability.

Expanding the borders of the objective area, beyond the technical and economical boundary conditions, leads us to take into account the opportunities and synergies that the territory or other systems can offer to the designed system[12]. It means to take profit of the energy of the environment. For instance, by using physical characteristics in order to provide energy (wind energy or hydropower thanks to the difference of altitudes) or more space to our designed system.

Moreover, taking into account the environment also means to account the social characteristics: a system that cannot be managed or maintained by local people would not be as social responsible and even as sustainable as a system that needs out-coming staff. So meeting the social aspects from the traditional Triple Bottom Line should also integrate not only the social acceptance of a specific intervention, but also to ensure local people will also take benefit of it, beyond the technical aspect that the intervention will solve. Meet this social responsibility is actually an example of regulations that can be done to meet the concept of *compact cities*[13], under the broad

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[12] Conclusions of the 2nd Rural Smart Grids Congress in Lleida (Spain), November 2013.

[13] The European Commission published the Green Paper *Towards a new culture for urban mobility* on 27 September 2007 referring to the EU strategy to combat climate change and other environmental problems. Also, European Parliament in its Resolution of 9 July 2008 called among other things for “drawing up customised sustainable mobility plans and supporting measures for regional and urban planning ('city of short distances' or 'compact cities')”.

concept of *smart growth*. Even this is a very simple and logic approach, not following it leads an excess of economic, social and environmental costs in the short and large time scale.

2.8. The Dynamic Metabolism Model (DMM), a LCA - MFA based model

The Dynamic Metabolism Model (abbreviated as DMM), according to Venkatesh et al. (2014), is "an original one developed at NTNU, as one of the outcomes of work done with Oslo VAV between years 2006 and 2010. This is a simple user-friendly model which accepts user-inputs in one single user-friendly Excel file; and using inbuilt formulas, constants, and 'intermediate' files, enables the end-user to test the impacts of changes expected / planned / imagined in the future, on sustainability indicators. The final output file presents a time-series of chosen indicators (normalised with regard to the start-year predefined by the user)".

The outputs of the DMM are specific indicators (KPIs) that can be tested with different changes that can potentially occur in the time or based on specific calculations. The KPIs are grouped under the categories: Social, Economic, Environmental, Functional and Physical, which match with the sustainability dimensions defined in the TRUST project. DMM presents 30 indicators expressed in per capita values and per unit of water volume supplied. Also, according to Venkatesh et al. (2014), "the DMM modelling principles are based on Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) methods, today widely recognised and used internationally in the fields of Industrial Ecology and Environmental Systems Analysis (Ayres & Ayres, 2002; Baccini & Brunner, 2012). This offers a mass-balance consistent quantification of resource inputs (materials, chemicals, energy carriers) and waste and emission outputs (greenhouse gases, nutrients, sewage sludge, etc.) per unit of water, wastewater and stormwater through the system, which later are used as a basis for calculating the potential life cycle environmental impacts and costs".

The DMM is also a tool sensitive to the long-term analysis, to both quantify the future investments and for instance, the increasing population or to take into account the increasing energy prices. Thus, the reduction of the emissions from urban activities with the proper lower carbon intensity solutions can be seen. TRUST tools are based the innovative use of the "metabolism model" and are assembled in a novel DSS, which allows the selection of the eligible interventions from the panel of the available technologies and procedures tested by the water companies in field applications during the project (Di Federico et al., 2014).

The goal of LCA is to compare the full range of environmental effects assignable to products and services by quantifying all inputs and outputs of material flows and assessing how these material flows have an impact on the environment (EPA, 2006)[14]. This information is used to improve processes, support policy and provide a basis for informed decisions. The LCA approach contributes to this study giving a wide and holistic view of the environmental impacts due to its foundations principles: the study of the environmental impacts in the whole life cycle of the systems studied; and the study of other environmental impacts beyond the well known green

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[14] United States Environmental Protection Agency (EPA). "Life Cycle Assessment: Principles and Practice," May 2006

house gases (GHG), which are far the most studied environmental impact and concern. Therefore, with the analysis that has been done, the whole LCA of the studied items of the system has been taken into account as well as other important environmental impacts that affects the water ecosystems such as the acidification (kg SO_2 eq.) and eutrophication (kg PO_4 eq.) impacts.

Even this more holistic view of the impacts, in further studies or improvements of the DMM, other water related impacts could be accounted in order to expand more the environmental impact boundaries. As an example, regarding the water stressors impacts, Ecotoxicity, Marine eutrophication, human toxicity, among others could be added in the analyses. Also, if sustainable interventions are taken into account, land occupation impact should be then measured, as well as resources depletion (even these impacts depend on the sustainable solutions evaluated).

3. The UWS of La Vall de Boí and methodology applied

3.1. Background

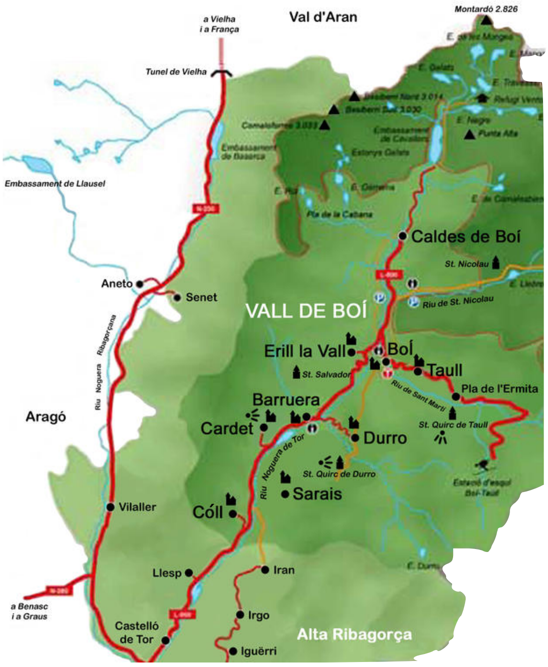

Figure 3.1 Location of La Vall de Boí

The Boí Valley is located in the North-West of Catalonia, in the central Pyrenees and in the county of L'Alta Ribagorça, which is composed by three main regions: El Pont de Suert, Vilaller and La Vall de Boí. With a total population of 3.884 habitants is has one of the lowest density population areas of Catalonia (IDESCAT, 2015). Particularly, La Vall de Boí lies in the northeastern corner of the county and has a total permanent population of 984 habitants, with a population density of 4,6 hab/km^2 specially due to the differences of relieve, as it is a very mountainous region. La Vall the Boí is composed by nine villages, from south to north: Cóll, Saraís, Durro, Cardet, Barruera, Pla de l'Ermita, Taüll, Boí and Erill la Vall. There are also two private resorts: the highest ski resort in the Pyrenees (Boí-Taüll) and the thermal spa of Caldes de Boí. The valley is known for its nine Early Romanesque churches, designated as a World Heritage Site by UNESCO. It has the densest concentration of Romanesque architecture in Europe and borders the unique National Park of Catalonia, which lies to the northeast (Aigüestortes i Estany de Sant Maurici).

The valley is composed of nine villages that have a variety of water sources, distribution systems and water treatment plants. A waste of economic and environmental resources arise from the problems that all villages have regarding the urban water management, such as the lack of wastewater treatment plants. Also, this is also consequence to the fact that La Vall de Boí has a huge amount of water as it is one of the most rainy regions of Catalonia, with an average of 1000L/m^2 per year.

3.2. Stakeholders involved

The urban water cycle services (UWCS) in Catalunya can be first separated into two main groups in order to understand the stakeholders involved. Firstly, the water supply is composed by the water supply and distribution subsystem defined in this work, and according to Catalan Water Agency (ACA) this is composed by three levels of responsibility:

1. The availability of the freshwater resources, which competence is the corresponding hydraulic administration. In the internal hydraulic basins of Catalonia (CIC, in catalan), is directly the ACA while in the hydraulic basins that belong to the Ebre river, the

administration is the Hydrographic Confederation of the Ebro (CHE, in Spanish), as it is in this case study. These administrations decide on large infrastructures or how reservoirs should be managed, for instance.

2. The production, adduction, treatment and storing drinking water, usually known as upstream supply (*abastament en alta,* in Catalan) is mostly the responsibility of municipalities, although there are several specific operators supplying high density populated areas of Catalonia, as Aigües Ter-Llobregat or Tarragona Water Consortium. In this case study, the city council of La Vall de Boí is the responsible as it is a small municipality. Water quality controls are carried by the Ministry of Health of the Government of Catalonia.

3. The distribution to users or in downstream supply (*abastament en baixa,* in Catalan), which is the responsibility of municipalities. The water quality controls are carried together with the second level of administration carried by the Ministry of Health of the Government of Catalonia.

Secondly, the other main group is the wastewater management and aquatic ecosystems quality, which includes the subsystems here studied of wastewater distribution and treatment, including the sludge treatment sub-subsystem and the hydrological cycle quality control. ACA is the competent administration that decides the infrastructures and manage the operators of the WWTPs among other responsibilities. They also the competent administration to control the water quality levels regarding the effluents returned back to the aquatic ecosystems.

In reference with the mentioned structure, the stakeholders involved in this case study are as below. In this list, are also included the companies that are supporting the main stakeholders (the city council and the WWTPs' operator) which have also been directly consulted.

- The City Council of La Vall de Boí
- The Catalan Water Agency (ACA, *Agència Catalana de l'Aigua*), under the Ministry of Territory and Sustainability of the Catalonia Government.
- The Ministry of Health of the Government of Catalonia (*Departament de Salut, Generalitat de Catalunya*).
- The operator of the WWTPs: Cadagua, which belongs to the Ferrovial company.
- The sludge post-treatment (which is transported in an external plant from the WWTPs): Grupo Griñó, (Griñó Ecologic S.A.).
- The company Laiccona SL. (*Laboratori d´anàlisis i control de la contaminació ambiental, S.L.*) as one of the habitual suppliers of the city council.

Moreover, other companies have been consulted in order to quantify the economic costs of the interventions studied such as Tecnoturbines - Powering Water; Sensotec Instruments S.A. and Damià Solar.

3.3. LCA Methodology

The approach followed in this thesis can be summarised in the following steps, which correspond to the core steps of a LCA study:

1) Scope definition of the thesis and system boundaries.
2) Preliminary impact assessment trough an overview of operational conditions, fluxes and performance of the system via personal communication and in-site data gathering with the stakeholders. Identification of the functional unit, subsystems, and types of flows.
3) Setting of the sustainability targets and definition of the first analysis of future interventions. Metrics definition trough specific Key Performance Indicators (KPIs).
4) Analysis of Life Cycle Inventory (LCI), quantifying all flows from each subsystem through Model Flow Analysis (MFA). Computation of the MFA inputs (Calibration Model) on the basis of the functional unit.
5) Calculation of suitable alternative interventions to match the sustainability targets in agreement with stakeholders expectations.
6) Computation of a Calculation Model in order to run the chosen interventions included in ten studied scenarios.
7) Impact Assessment, fine-tuning the interventions to be done in order to achieve the sustainability targets and selection of the most relevant KPIs.
8) Final computation of the results, discussion, conclusions.

3.4. Functional unit

The functional unit studied for this case study is one year of water consumption of the whole urban water system (UWS) of La Vall de Boí, including the entire study of the water cycle.

3.5. System boundaries

The physical boundaries of the case study is the entire UWCS of all the villages that belong to the municipality of the Vall de Boí (the Boí Valley) except the village of Saraís, from the catchment systems, sanitation, distribution, treatment until discharge to the aquatic environment again (see the figure 3.2). This also includes all the inputs and outputs from all these subsystems, with a LCA

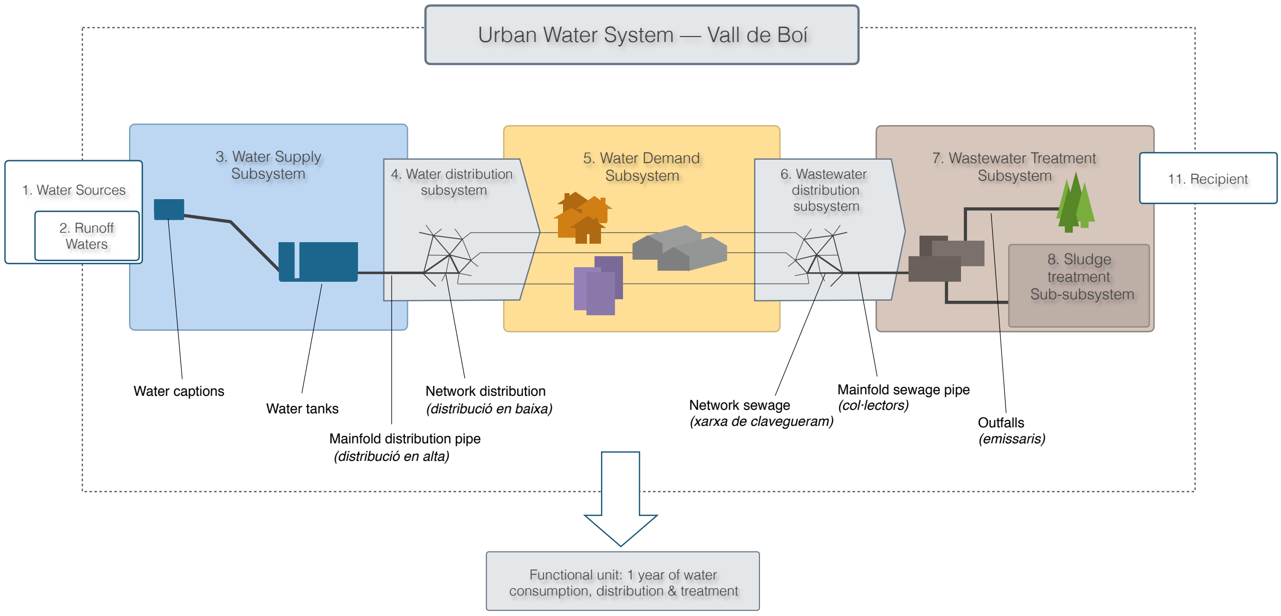

Figure 3.2: System boundaries (dot line) of the urban water system of La Vall de Boí

approach from cradle to grave of all these flows, such as energy requirements for electricity, transporting for the O&M needs or chemicals used.

Each subsystem is composed by the sum of each subsystem of each village, and therefore the results show the total amount of flows of inputs and outputs, without distinguishing how much comes from each village. For specific analysis in each village, this data could be easily extracted with the input data and calculations that have been done in the calibration model, as it will be explained in the methodology section. This aggregation of data respond basically to the fact that the same stakeholders are dealing and operating the same UWSC of each village as a whole without making distinctions. Moreover, the infrastructures used are almost the same and have similar operating systems, with only some differences regarding the three WWTPs and the specific technologies used. Particullary, three WWTPs are nowadays in operation in La Vall de Boí:

1. The WWTP of Boí: collects around 77% of the treated water flows (designed for 5240 equivalent population), as it collects the sewage from the villages of Pla de l'Ermita, Taüll, Boí, and Erill la Vall. It is the oldest and main WWTP of the UWS studied, as it also the only one that can dry the sludge coming from the rest of WWTPs.

2. The WWTP of Barruera: collects around 13% of the treated water flows coming from the village of Barruera (it was designed for 768 equivalent population). The WWTP has also a water pump for its sewage distribution subsystem. It is the most inefficient WWTP regarding the electricity inputs, 4 times as much as the WWTP of Boí.

3. The WWTP of Durro: constructed in 2006 and collects around 10% of the treated water flows (corresponding to 400 equivalent population). Is the only WWTP that does not require chemical inputs even it requires 2 times the electricity inputs of the WWTP of Boí.

4. It is worth to mention the WWTPs of Cóll and Cardet that are today missing, even they were planned to be finished for 2014. Their costs and expected operation system has been modelled in a particular scenario.

In the UWS studied two weak points in terms of lack of data have been solved in order to ensure the study of the complete subsystems, specially in terms of the annual O&M flows that the results show the relative importance of quantifying them.

- The sludge treatment sub-subsystem: the WWTPs' operator dries and pays the transportation needs of the sludge treatment. This sludge is treated in an external plant that needs electricity and diesel to compost the sludge. However, the company has no control of the specific needed inputs per unit of sludge, as it also treats sludge from other WWTPs (so allocation is therefore difficult to apply if no more data is provided). Hence, the data regarding the emissions of the processes involved in this phase was extracted from ACA historic calculations from the public compost plants and then verified with OCCC considerations[15]. Also, the results have been contrasted in a qualitative way via personal communication with the company (Grupo Griñó) in order to verify that the same processes were taken into account. The phosphorus (P) and nitrogen (N) content of the sludge have been proportioned by ACA analysis (carried out by the company Eurofins Agroambiental, S.A.) during the year 2015.
- The demand subsystem: the energy needed in-house scale was estimated according to Blokker et al. 2013 (see table 4.1), as no data was available (and specific measurements would be difficult to obtain). Even this energy can be considered beyond the system boundaries of the UWS studied and belongs to the system boundaries of in-house scale studies, one cannot neglect the relationship within this energy and the UWS trough the water flows affectations. As an example, reducing the system water pressure excess, will affect to the in-house consumption, and therefore, the hot water consumption and its necessary energy to heat it. Actually, according to Catalan Water Agency (ACA) while the energy consumption of the entire UWCS represents 0,5% of the overall annually energy consumption of Catalonia, the energy consumption in-house scale for heating water represents approximately 2%.

3.6. Assumptions and limitations

In relation with the scope of this work and the interventions proposed, the main efforts has been focussed in the quantification of the O&M flows of the actual assets of the UWCS. Therefore, there have been excluded:

- All the assets of the entire UWS, which means the WTP infrastructure and catchment systems, the water distribution networks and the WWTPs. The main reason why these

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[15] Guide to calculate the GHG from the urban water networks of Catalonia, Catalan Water Agency (ACA) and Climate Change Office of Catalonia (OCCC), (in Catalan, *Càlcul de les emissions de GEH derivades del cicle de l'aigua de les xarxes urbanes de Catalunya*).

was excluded from the system was due to the lack of data and because the scope of this work is more focused in the management and operational options instead of the assets. Also, the interventions proposed refer more to this scope and/or the rest of interventions do not take into consideration the impacts of the assets to be built. As has been already pointed out in the goal and scope section of this work, according to Friedrich and Buckley, 2001; Lundie Gregory and Beavis, 2004, Raluy et al., 2006; Muñoz and Rodríguez Fernández-Alba, 2008, the results of other studies that considerate infrastructures of the treatment plants' processes and products indicate that the environmental impact of constructing and dismantling the infrastructure materials is negligible when compared to the operation phase. However, the water pipes materials have a relative significance impacts that should be taken into account according to Amores et al., 2013, for both the water and wastewater distribution network. Again, a proper inventory of the assets (neither graphical data) of the city council makes this task much more challenging that would need future researches.

- The specific inputs to perform the water supply controls (from the Ministry of Health of Catalonia) and ACA water controls in the WWTP due to the lack of data. Only transportation needs were accounted for these services. The economic inputs considered from these analysis are just the costs of the operator of the Ministry of Health due to the in-site controls and thus, the value of time of the operator, including the transportation time requirements.

- The extra electricity needs when the current water catchments do not provide enough water. During the past, drought periods in La Vall de Boí drove to the construction of new additional infrastructure to supply the water needs of the population. Thus, with the specific data of electricity consumption per cubic meter, the related flows could then be added into the model in order to quantify these drought periods and their implications in the UWCS.

- The village of Saraís and the urban centers of Caldes de Boí and the ski resort Boí-Taüll have been excluded from the analysis due to the lack of data and because they belong to private users. Beyond that, Saraís and the ski resort do not have WWTPs, Caldes de Boí is a thermal water spa, and the ski resort is using freshwater resources to make artificial snow and for other purposes, specially regarding the differences of altitude related that could be profit for micro-turbines. Therefore, studying these systems would be also interesting with the UWS studied in this work in order to take into consideration the potential flows (water, energy, etc.) that could be profitable within the UWS.

- The transportation's needs for managing the residues from all WWTPs of the studied system. Nevertheless, as these are managed locally, they do not represent a high impact and not taking them into consideration would not change very much the overall generated impacts. Note that the overall diesel impacts are big compared with the potential diesel consumption for managing these residues.

- The transportation's needs for the chemicals consumption in the WTPs, which could not be determined due to the lack of data. Again, they can be neglected as they could probably represent, at most, 100L of diesel per year (corresponding to 1000 km per year, approximately). In contrast, the overall diesel consumption in the UWS is around 3600L, and thus 100L would represent 2,7% of the total.

3.7. Allocation methods

In this work the guidelines of ISO 14044:2006 have been followed in order to deal with the allocation problem which describes that the best procedure for allocation is to avoid it as far as possible:

1. By getting more information about the internal processes in order to avoid it.

2. By partitioning the main process in a certain way that reflects the physical relationship between them in the system.

3. Finally, if this is also not possible, a partitioning approach might be used, based in other relationships between inputs and products.

Therefore, for most of the data the procedure of allocation was avoided as the stakeholders services produce the same service that was studied or could directly provide specific inputs for the studied system. The operator of the WWTPs of La Vall de Boí is also operating other plants of the region but most of the data inputs refer to each WWTP (including the salaries of workers, for instance) and thus, allocation was not needed. Other specific data that could not be solved with procedure 1 (as described in the ISO steps above) from the information retrieved from the stakeholders had to be allocated:

- The transportation needs from the city council operators, that are checking during working days both the manual water quality controls and the rubbish management of all villages. As in this case different services are provided, it has been assumed that half of the transportation needs account for the water quality controls and half for the rubbish management.

- The operator of the Ministry of Health of the Government of Catalonia[16] is commuting to La Vall de Boí regularly for water quality checking and sometimes takes advantage of other working proposals. Therefore, as these additional works vary, no allocation method has been applied, simplifying the analysis.

- The transportation needs for the WWTPs of La Vall de Boí for chemicals and water quality controls were allocated by partitioning approach, based on the water flows

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[16] Personal communication (January 2016) with Pilar Moralejo, Health Technician from the Ministry of Health of Catalonia.

treated by the WWTPs of the studied and the rest of the WWTPs that the stakeholder provide. The partitioning variable calculated is equal to 0,47.

3.8. Impact categories

The impact categories analysed in this case study are the three impact categories calculated by the DMM. Global Warming Potential (GWP) has been added as it is, by far, the most studied environmental impact and concern of this century, whereas acidification and eutrophication are one of the most important water related impacts, justified in the environmental water impacts section (chapter 3). Thus, the three studied impact categories are:

- Global Warming Potential (kg CO_2 eq.)
- Acidification (kg SO_2 eq.)
- Eutrophication (kg PO_4 eq.)

As it can be seen, an emission metrics has been used so we can aggregate data in common units (kg eq) and emissions from different stressors can be compared. The following table includes the three characterisation factors for all impact categories, including the direct 100-year time horizon global warming potentials (GWP) relative to CO_2. This table is adapted from table 2.14 of the IPCC Fourth Assessment Report, 2007. The 4th assessment report values are the most recent (2007), but the second assessment report values (1995) are also listed. For more information, please see the IPCC website (www.ipcc.ch).

Table 3.1. Characterisation Factors (DMM)

Emission to water/air	Global warming (kg CO_2-eq/kg)	Acidification (kg SO_2-eq/kg)	Eutrophication (kgPO_4-eq/kg)
Carbon dioxide	1	0	0
Methane	25	0	0
Sulphur dioxide	0	1	0
Hydrogen sulphide	0	0	0
Ammonia	0	2,45	3,8
Nitrogen dioxide	0	0,56	0
Nitrous oxide	298	0	0
Nitrogen gas	0	0	0
Nitrate to water	0	0	4,4
Sulphur to water	0	0	0
COD to water	0	0	1
Phosphorus with effluent	0	0	1

3.9. Metrics selection: Key Performance Indicators (KPIs)

The KPIs are quantitative key values that mean to measure the specific sustainability criteria chosen for this case study. These key values offer a useful tool that allows to quickly examine and compare different scenarios (future strategies and intervention options in such systems) while preserving a holistic perspective and thus, the multi-objective of the sustainability problem. KPIs are also a way to gather and systematically measure and record data that can be easily understandable by any stakeholder. The assessment of sustainability through sustainability indicators is nowadays a common approach widely used in water studies too, including UWOT or SWARD project, as well as the 24 city blue print indicators in Europe which have been stablished in order to offer a way to quickly compare between results of studies.

In this study, specific KPIs have been chosen in order to properly examine all the improvements that the future scenarios can offer and that could better fit with the set goals of the proposed case study. Because of that, some of the KPIs used are directly obtained by the Dynamic Metabolism Model (DMM), while others have been adapted. Apart from these, specific KPIs have been added, based on the TRUST dimensions of sustainability and on the City Blue Print indicators already used as a common framework in many urban water studies around Europe. All these indicators have been grouped in different categories depending on the values which we are referring to.

4. Life Cycle Inventory of the case study

4.1. Economic and physical resources analysis

The LCIA for the studied UWS carried in this work has been done within the MFA methodology, including economic and physical resources inflows and outflows that are represented in figure 4.1. The different flows analysed are distinguished. As it can be seen, four main common flows can be identified in the subsystems: economic flows (from the different stakeholders involved), energy needs (electricity, LPG and diesel for transportation needs), chemicals and outflows.

The MFA carried out in this work has been studied according to the life cycle inventory data presented in table 4.1 for each subsystem of the UWS (see the appendices B and C for detailed values of these flows in all subsystems). Particularly, the subsystems assessed are:

- The Water Supply Subsystem (3. WSS), which is basically operated by the City Council and it is composed by the water tanks and main pipes. The Ministry of Health of the Government of Catalonia controls periodically the water tanks, but as the main controls are in the distribution subsystem, they have been considered all together in that system.
- The Water Distribution Subsystem (4. WDIS), which is operated by the City Council and controlled by the Ministry of Health.
- The Water Demand Subsystem (5. WDS), that corresponds to the users' demand of water and energy to heat the water (distinguishing electricity and LPG gas).
- The Wastewater Distribution Subsystem (6. WWDIS), composed by a single water electrical pump from the WWTP of Barruera.
- The Wastewater Treatment Subsystem (7. WWTS), composed by the main sewage distribution pipes coming from the sewage network and the wastewater treatment plants (in the villages of Barruera, Durro and Boí), managed by the company Cadagua.
- The Sludge Treatment Sub-subsystem (8. STSS), which includes the sludge transportation needs and treatment in a compost plant. Cadagua is also the manager of the sludge altogether with the company Griñó, that operates the compost plan.
- The Recipient Waters Subsystem (11. RWS), composed by the main sewage pipes that convey to the recipient water media the wastewater treated and untreated (when there is no WWTP in the village).

The 8 analysed villages have different infrastructure and thus, they do not have all the subsystems. The common ones have the same physical and O&M configuration, as they share the same stakeholders. Needless to say that this has been specially studied by each village, summing all the inputs and outputs of each subsystem type (WTS, WWTS, …) in order to properly present the overall UWS boundaries. When needed, some specific impacts have been specifically studied separately for some villages.

Among the subsystems analysed, the demand subsystem is the largest contributor of almost all inflows and outflows, as it accounts all the consumed energy for heating water in the in-house scale from the 2100 total equivalent population (TEP) of La Vall de Boí and the water flows consumed (and thus, the water costs). Therefore, the results of the flow analysis have been differentiated in some ocasions between the UWS (that implies the whole urban water system, with all subsystems) and the UWCS (which implies the urban water services that manage the urban water cycle, and thus, excluding the in-house demand subsystem) in order to see the results in their context.

4.2. Life Cycle Inventory data

The present work studies a specific UWS with a LCA approach. Due to the number of variables that determine the obtained results and with the objective to present in a clear and transparent way the methodology regarding the LCI data, table 4.1 presents the LCI data sources. It also a way to provide a proper clear context of the foreground data that has been used. In spite of the data quality rank for each component, it has to be pointed out the general variability associated with the water flows, as well as the other associated materials, chemicals, energy flows or sludge volumes. According to the stakeholders communications[17], the water volumes and specially regarding the sludge volumes from one year to another can vary significantly, as well as from month to month, according to the obtained data inputs. Because of this, the water volumes as well as other key variables of the study have been specially studied in the sensibility analysis section of this work.

In this sense, a major difficulty in this study is to deal with an urban water system that belongs to a very touristic region and therefore, is subjected to important seasonal variations. Hence, the described study of the total annual equivalent population (TEP) regarding the occupation rates of holiday houses and hotels has been done as it has been essential to quantify the needed values. This water flows variation can be seen in the water flows data inputs, with water consumptions up to 10 times higher in the holiday season months respect to off season monthly values.

As can be seen in table 4.1, almost all the data was collected from the available sources via the personal communication and data transmission from the stakeholders and site specific data gathering. When that was not possible and following this order, data was retrieved from qualitative data from stakeholders and assumptions based on this inputs, from literature data or similar studies and finally, on additional personal assumptions based on specific criteria. Also, once the LCI was done and computed in the Calibration Model (see methodology section of this work), the most important results were verified with the stakeholders in order that they approved them, modifying the assumptions when necessary.

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[17] Mainly from the City Council of La Vall de Boí (technicians, workers and current companies that maintains the water supply subsystem), the operator of the Health Ministry of Catalonia and Josep Pueyo (Cadagua's WWTPs head of operations) in La Vall de Boí during 2015 and 2016.

Table 4.1 - Characterisation of Life Cycle Inventory data

Subsystem	Life cycle component	Basis of the data	Data quality
1. Water Sources	Water volumes from source A	Water meters in the water tanks (from June 2015 to May 2016) and other calculations and assumptions (to complete the missing values, specially in the villages without water meters). Also, the WWTP volumes correlation was used to check the water balances.	High / Medium
	Water volumes from source B	Calculations and assumptions, following ACA considerations.	Medium
2. Runoff Waters	Stormwater of the catchment area	The area has been determined in the basis of the topography and maps of the villages of the City Council of La Vall de Boí and the aerial images and of the Cartography and Geologic Institute of Catalonia (ICGC). The rainfall considered is 1000L/m² according to the mean rainfall in the region (Meteo.cat, 2015) and a runoff coefficient of 0,9 (CEDEX, 2009) with a correction factor 0,9 due to the physical characteristics of the villages, as they belong to a rural area with less impervious area.	Medium
3. Water Supply Subsystem	Operating system (time, €, O&M costs inc. diesel, etc)	Site specific data and personal communication with City Council and directly with their workers	High
	Assets characteristics (pipes, infrastructure)		High
	Chlorine products	Supplier company guidelines and additional calculations	Medium
	Water quality controls	Personal communication with City Council and the Health Ministry	High
4. Water Distribution Subsystem	Operating system (time, €, O&M costs inc. diesel, etc)	Site specific data and personal communication with City Council and directly with their workers	High
	Assets characteristics (pipes, infrastructure)		High
	Leakage	Catalan Water Agency (ACA) calculations and specific assumptions to determine the leakage volume from the water sources A and B.	Medium / Low
	Pressure	Calculations based on the assets characteristics.	Medium
4. Water Distribution Subsystem	Operating system (time, €, O&M costs inc. diesel, etc)	Site specific data and personal communication with City Council and directly with their workers. The O&M costs are based on the average costs of 2014 and 2015, while the users' costs are based on the year 2015.	High
	Water bills and city council water costs	City council register of water volumes and costs by users	High

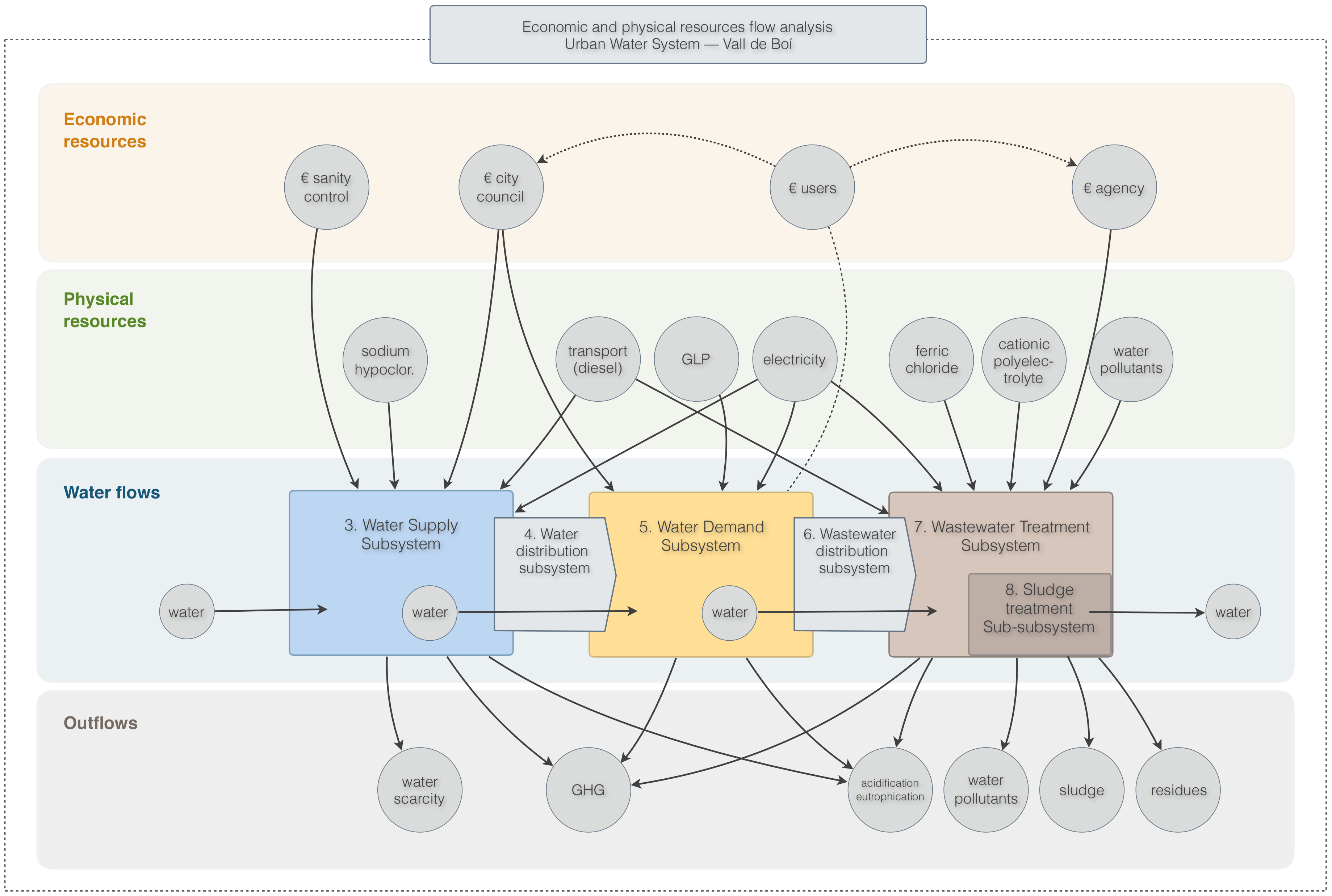

Figure 4.1: Economic and physical resources flow analysis - UWS La Vall de Boí

Subsystem	Life cycle component	Basis of the data	Data quality
	Social perception and policies	Reports and studies of the case study region and generic site data (personal perceptions and communications with citizens and the stakeholders)	Medium
5. Water Demand Subsystem	Energy needs for in-house water heating	Study from Blokker et al. 2013, from the TRUST deliverable D45.1, about the average per capita water consumption of warm and cold water, and the primary energy requirements for heating, considering 12ºC of water temperature. A correction factor has been applied (1,22) to account the difference of water consumption per capita considered (from 122,7 to 150L·p/day). The energy requirements have been adapted to the study area (as LPG gas and electricity are used) and multiplied for the TEP calculated, 2100).	High
	Water temperature chekings (to verify the applicability of the Blokker et al. study)	Water temperature measurements in Cóll and Barruera (13ºC, May 2016) and personal experience and communication with citiziens (to generalize the data, as an approximation and taking into account that during winter temperature could be less than 12ºC).	High
6. Wastewater Distribution Subsystem	Energy needs for pumping wastewater (only for the WWTP of Barruera)	Cadagua considerations in the operator's oficial report, based on the ACA calculations and historical average performance of WWTPs.	High
7. Wastewater Treatment Subsystem	Operating system (time spent, O&M flows not included in the official report like diesel)	Site specific data with the head of operations of Cadagua, Cadagua oficial report.	High
	Water volumes	Cadagua considerations in the operator's oficial report, based on the ACA calculations and historical average performance of WWTPs.	High
	Economic expenses		High
	Electricity needs		High
	Chemical products		High
	Residues and outputs		High
	Water quality (composition of BOD_5, COD, N and P).	ACA monthly operator's reports, from Cadagua real measurements during 2015.	High
	Water quality controls	Personal communication with ACA to determine the number of annual travels and kilometres to check the effluent quality, applying allocation methods to distinguish *how much* is assumed by the UWS studied.	High
8. Sludge Treatment Sub-subsystem	Operating system (time spent, O&M flows not included in the official report like diesel)	Cadagua considerations in the operator's oficial report, based on the ACA calculations and historical average performance of WWTPs.	High

Subsystem	Life cycle component	Basis of the data	Data quality
	Transportation needs	Cadagua considerations in the operator's oficial report, based on the ACA calculations and historical average performance of WWTPs. Economic costs that were not specified on the oficial report have been estimated, with the specific costs, as the 30% of the total budget of the 3 WWTPs.	Medium
	Economic expenses		High
	Sludge volumes and dryness		Medium
	Composition of N, P	Sludge analysis in 2015 of the WWTP of Boí (where all the sludge of the valley is centralized and dryed, and thus, there is no detailed information of the different analysis from the sludge from the three WWTPs). The analysis are carried by the company Eurofins Agroambiental, S.A. and proportioned by ACA.	Medium
	Sludge post treatment energy needs (electricity, diesel).	The energy requirements have been estimated according to the ACA historical data from the public compost plants. Particularly, 2,3L of diesel and 72kWh of electricity per tone of sludge with 20% of dryness has been considered. Then, it has been verified via personal communication with Griño Ecologic S.A. (the company that operates the sludge) and the Catalan Office for Climate Change (OCCC) and Catalan Water Agency (ACA) report of the GHG caused in the water systems of Catalonia, which specifies the corresponding emissions of the sludge treatment. A part, 3034 kWh/year has been calculated that are needed to dry the sludge in the WWTPs.	High / Medium
11. Recipient Waters Subsytem	N_2O and CH_4 emissions from the wastewater conveyed away to the recipient waters.	IPCC (2006), Guidelines for National Greenhouse Gas Inventories, Chapter 6: Wastewater Treatment and Discharge. No direct CO_2 emissions have been considered, as according to IPCC, are not accounted due to their biogenic origin.	High
General and background data	Total Equivalent Population (TEP).	Statistical Institute of Catalonia (IDESCAT, 2011-2015) to determine the average tourism occupancy and the number of second residences. This data has been constrasted with other informations and calculations.	High / Medium
	LCA midpoints: GWP, AP, EP	Ecoinvent 2 (DMM background data)	High
	Electricity mix impacts for GWP, AP and EP	Ecoinvent 2 (2010), CML-IA baseline, midpoint characterisation impacts for the electricity mix in Spain at grid for medium voltage (526g CO_2 eq/kWh) and low voltage (for the demand subsystem, 603g CO_2 eq/kWh).	High
	Other calculated data	DMM background data	High

4.2.1. Economic analysis

In both economical and resources flow analysis, fix and variable flows have been specially studied, as they are essential to understand which variables are modified with water consumption. For the variable flows, a linear relation with water flows affected in such systems has been considered according to the stakeholders assumptions. In the economic analysis, this differentiation has been dong it by identifying capital costs, fix costs, operational fix costs (which can vary but not in relation with the water flows), and the operational variable costs (which do vary with the water flows).

The economical assessment has been carried out for the year 2015, according to the life cycle inventory data. For the comparison of scenarios, a 20 year economic time horizon has been considered[18] with constant prices. This means that the year of study (2015) has been chosen as the base year and thus, the costs of the subsequent years are measured using the price of the base year without considering inflation, making comparisons in the future scenarios easier. However, according to the National Institute of Statistics of Spain (INE) and the Statistical Institute of Catalonia (IDESCAT), during the last 10 years, the diesel and electricity prices with respect to the annual inflation have been 1,5 and 2 points above the inflation (see table 4.2). Therefore, for the economic analysis of 2035, the diesel and electricity costs have been changed according to these values. This is specially important to take into consideration in the analysis as the expected price increasing of these energy sources will have a clear effect in the viability of the future interventions designed. Nevertheless, this is a prediction based on historical data that can be easily changed in the *calculation model* if needed in further researches.

Table 4.2 - Annual interest rates

Concept	Annual rate	Annual net rate considered (constant prices)	Source (for 2005 - 2015)
Annual inflation (IPC)	2%	0%	INE
Diesel costs	3,5%	1,5%	IDESCAT
Electricity costs	4%	2%	IDESCAT

As it will be detailed in the results section, the investment economical needs have been linearly amortised for their respective life cycle expectancy of each intervention. Modelling economic flows in a 20 year time horizon have a build-in uncertainties that are difficult to predict. Therefore, the approach of this study, in a strategic level of planning, has been to simplify these economical complex realities in a simple and understandable way with these linear amortisations. Further research would be needed in order to understand in detail this time horizon economical changes.

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[18] The DMM can analyse time horizon scenarios up to 30 years, which is more than the analysed years. In this case, 20 years of time horizon has been analysed in order to adjust better with the economic life cycle of the components and infrastructure designed in the future interventions.

4.2.2. Water flow analysis: Water balances for the Calibration Model

In the present study, a LCA and economic analysis has been done according to the water flows analysed. It is a key point of the present work that has to be carefully studied, as they determine the inputs and outputs of all subsystems. It is also important considering that a smaller proportion of the obtained results are independent form these water flows (for instance, water controls does not depend on the amount of water consumed). The water flows analysed in this system have been mainly studied through:

i) The water supply subsystem (WSS) through the existent water meters in the water tanks (monthly registered by the City Council). These determine the variable flows from the City council (as the quantity of the sodium hypochlorite).

ii) The calculations and assumptions (described as below) of the water demand subsystem. These determine the energy requirements for heating water in the in-house scale, which have been related with the WSS water flows.

iii) The downstream water flows of the wastewater treatment subsystem (WWTS), treated by the WWTPs (registered by Cadagua and controlled by ACA). These have been useful to correlate with the upstream water flows (from the demand subsystem), while also determine the Cadagua variable flows (as the variable economic needs related with the water flows).

Hence, all in all two main water flows determine the results of this work: the WSS flows and the WWTS flows. In La Vall de Boí there are three wastewater treatment plants, As mentioned, not all the villages have the same configuration of subsystems (some are inexistent or they share a common subsystem with other villages), and therefore, this correlation was not always possible to analyse for each village due the lack of data. In those cases, the data gaps where completed with the available data from other villages, giving an estimation of the calibration process.

La Vall de Boí is one of the most rainy regions of Catalonia as it is located in the Pyrenees. Water abundance and the fix price of water have lead to not controlling these water flows except in the effluents of the existent WWTPs. Fortunately, the growing concern of the City Council of La Vall de Boí, coinciding with the proposal of this work, allowed to register water flows in water tanks from June 2015 until the end of data gathering of this work in May 2016. This valuable information has been used to determine off season and seasonal consumptions for all villages and thus, differentiate two clusters of villages (mainly differentiated by the ski resort demand) to complete the needed information in the villages where not all data was available. Finally, this water balances have been studied for the whole UWS (as the sum of all water flows from all subsystems of each village).

The goal was to finally reach a calibration model within the yearly water flows of the UWS, and thus, quantify three main needed variables undetermined: the stormwater treated (assumed 11,6% of the wastewater treated[19]), the percentage of leakage of the water distribution

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[19] Note that the stormwater volume collected by the wastewater distribution subsystem is higher but is not treated by the WWTPs as it is bypassed when this peak flows occur.

subsystem (assumed 11,4% of the water supplied[20]) and the percentage of water used for watering gardens (assumed as 10%, i.e., 90% of the consumed water supply is conveyed through the wastewater distribution subsystem). Both stormwater treated and leakage were then approved in a qualitative way with the corresponding stakeholders (Cadagua and the City Council, respectively). None of these missing values could be determined in any other way due to the characteristics of the impervious surfaces (which vary significantly among villages and depending on the physical characteristics of the streets) and due to the lack and control of data (there are no mechanisms to control the leakage neither water meters in the water users). No leakage in the wastewater distribution subsystem has been assumed as no data of the assets characteristics was available nor calculations or assumptions from any stakeholder. Thus, it can be understood to be considered as a part of the water volumes considered in the water supply distribution leakage or water gardening.

The water flow analysis and the *calibration model* also abled to determine the water consumption from the demand subsystem, which were differentiated from two water sources (named A and B). The water source A comes from the water supply subsystem (3. WSS) and is modelled in the DMM, so it is related with the environmental and economic flows studied in this work. Regarding these flows, it is important to mention that the flows that are considered for heating water purposes are accounted following Blokker et al. (2013) study[21], from the TRUST deliverable D45.1. In this study, the in-house heated volume is calculated on the basis of the daily water consumption per capita, stablished in the study with a value of 122,7 L/cap·day. Instead, for the present analysis, this value has been corrected with 150 L/TEP·day and not the average water consumption per total equivalent population (TEP) of the water sources from A consumed by houses and hotels, which is 491 L/TEP·day. These two numbers can be explained according to the study “Els recursos hídrics de Catalunya”, which determined a range of water consumption between 114 and 154 L/cap·day in Catalonia depending on the region, with a mean value of 130L/cap·day for Catalonia and 145L/cap·day for Spain. Also, according to Tello (2000), there is a clear relation between the population density and the water consumption, with water consumptions over 300L/cap·day in some regions of Catalonia (Tello, 2001). This value can be even higher when private residences have gardens, as it happens in some Barcelona metropolitan areas, with water consumptions up to 400L/cap·day (Domene et al., 2004). Many studies demonstrate that gardens and private swimming pools shoot the water consumption (E.Tello, 1999 i 2001; Capellades et al, 2002; Domene i Saurí, 2003; Parés, 2004; Parés i Domene, 2004; Parés et al, 2004; Domene et al, 2004).

Due to the exposed reasons, and according to the low density of population of La Vall de Boí and the high number of gardens (as the case study belongs to a rural area), the 491L/cap·day can be

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[20] This has been calculated also following the ACA calculations and assumptions.

[21] It is worth to mention that this study considers that the water temperature is 12ºC (please see sensibility analysis section for more information). Also, considers that nearly a 60% of the in-house water volume is heated (around an average of 40ºC). The majority of the energy is used to heat water from shower (41%), followed by the heated water for the laundry (34%) and the kitchen tap (16%). LPG and electricity are considered as the primary energy source, counting a 90% and 40% of efficiency respectively. For more information, please refer to: Blokker, E.J.M., Osch, A.M.v., Hogeveen, R. and Mudde, C. (2013) Thermal energy from drinking water and cost benefit analysis for an entire city. Journal of Water and Climate Change.

justified as a high but reasonable value, while the mean value of 150L/TEP·day has been considered as the basis of the heating energy requirements of the demand subsystem. This means that the remaining 341L/TEP·day are considered to be consumed for cold water proposes, as water gardening. Hence, to adapt the Blokker and colleagues study, a dimensionless coefficient (1,2225) has been applied to proportionally adapt from the 122,7 L/cap·day considered in the study to the value of 150L/cap·day. Finally, this per capita value has been multiplied for the TEP calculated (2100). The obtained value has been expressed in terms of percentage respect to the total water supply (457 hm^3) in the DMM in order to properly model the future interventions in the *calculation model*. Thus, a reduction of flows from the demand subsystem will proportional affect the heated water flows.

The water flows from source B (which comes from other sources, also uncontrolled ones) are estimated by the ACA and not taken into consideration in the analysis as they belong to other independent subsystems. Particularly, these flows from source B go to farms, some private agricultural crops, fountains and other purposes. They are represented in figure 4.3, with the water flows represented with an arrow from the water source subsystem to the demand subsystem (98.300 m3). Is important to point that two villages (as well as other uncontrolled usages) are not treating water in the WSS and therefore, part of the non treated flows also goes to the water sources A. The demand users from source A are also graphically represented in figure 4.3 and listed in the table 4.3. The complete results of all flows of the calibration model are included in the appendix D.

Needless to say that it is important to continue registering these water flows related with each subsystem as they are strongly dependent on the results. The better level of quality inputs provided in the DMM, the more reliable and robust the obtained results will be. In further researches, if more accurate data is provided, recalculations can be easily done in order to give more accuracy to the presented results if needed.

Figure 4.2 shows all the subsystems from the UWS studied and their relationship regarding the water flows of the UWS. The black arrows represent the current water inflows / outflows, named according to which subsystem depends and goes to, while the grey arrows represent the potential water flows that could be taken into account if specific future interventions are applied. This means that subsystem number 10 (cyclic water recovery subsystem) does not exist right now and it has been represented as it is considered in some of the proposed interventions. All these flows have been quantified in table 4.3, in basis of the *calibration model*.

Table 4.3 - Annual Water Flows Quantification

Subsystem	Flow	Description	Quantity
1. Water Source	Q_{13}	Income water treated in the water tanks with chlorine for consumption.	456.992 m^3
	Q_{15}	Income water taken form other sources different from the WTP subsystem. Those are normally uncontrolled and are used for agriculture proposes, crops, farms, and other uncontrolled usage.	98.299 m^3
	$Q_{1,11}$	Income water taken form the water catchment but not treated due to the excess of water supply.	4.566.007 m^3
2. WS - Runoff waters	Q_{26+29}	Rain water collected in the streets and roofs as runoff waters.	170.746 m^3
	Q_{26}	Runoff waters which part of it is conveyed away with the combined wastewater distribution subsystem.	Calculated together with Q_{96}.
	Q_{29}	Runoff waters which part of it is conveyed away with the runoff distribution subsystem.	Undetermined, as it depends on Q_{26}.
3. Water supply	Q_{34}	Treated water is transported from the water supply system (water tanks, mainly) to the the water distribution network.	404.902 m^3
	$Q_{3,11}$	Leakage infiltrated from the water supply or distribution subsystem to the recipient.	52.090 m^3
4. Water distribution	Q_{45}	Water demand from the treated water supply subsystem.	Undetermined, as it depends on Q_{46}.
	Q_{46}	Part of the treated water used in water fountains and other sources that are partially not consumed and thus, conveyed away to the wastewater distribution system with the same quantity and quality (the part consumed is taken into account in the water flows to the demand subsystem).	Undetermined, although this flow could be considered together with Q_{45}.
5. Water demand	Q_{56}	Black and grey waters from the demand subsystem and thus, with less quantity and quality compared to the water demand.	384.657 m^3
	$Q_{5,10}$	Potential recycled water flows already used from the demand subsystem.	0 m^3
6. Wastewater distribution	Q_{67}	The combined wastewater distribution system collects the runoff directly from the drainage system in the streets (specially in old streets) and from the runoff distribution subsystem which is constructed in new streets but still not separate in all the distribution system.	Undetermined, as it depends on other undetermined flows. Without counting these, will be around 548.000 m^3.
	$Q_{6,11}$	Black water (mixted with runoff) form the sewer that is directly conveyed away to the recipient media, without any treatment in 3 of the villages of the city council + Leakage from the wastewater distribution subsystem.	16.697 m^3
7. Wastewater	Q_{78}	Water from the sludge, depending on the dryness of the wastewater treatment plant that treats them.	705 m^3

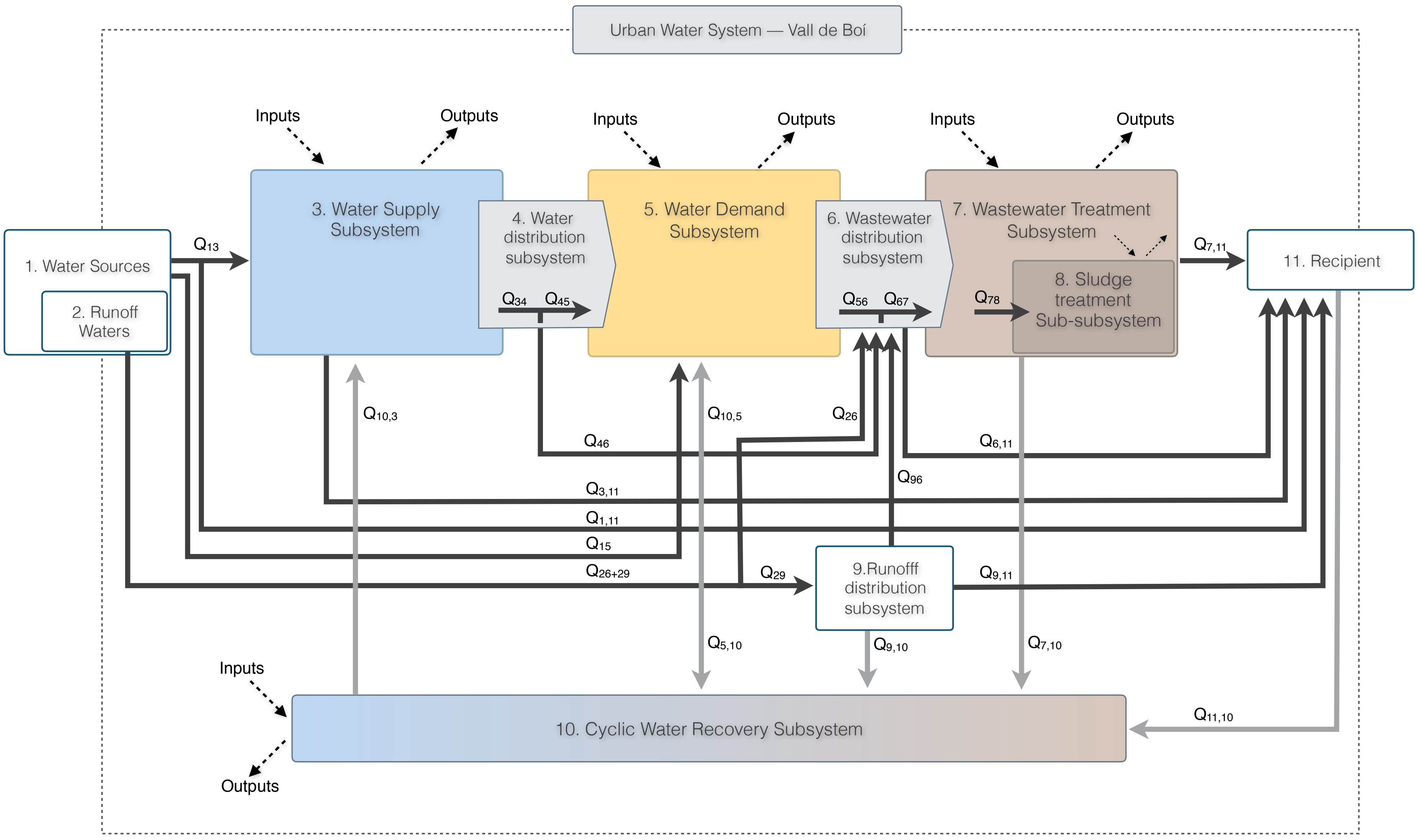

Figure 4.2 - Water flow analysis - UWS La Vall de Boí

Subsystem	Flow	Description	Quantity
plants	$Q_{7,10}$	Potential recycled water flows from the treated water in the wastewater treatment plants subsystem.	0 m^3
	$Q_{7,11}$	Effluent from the wastewater treatment plants, that complish the directives of wastewater treatment in terms of water quality.	427.050 m^3
9. Runoff distribution	Q_{96}	Rainwater streams collected in the runoff distribution system, separated from the wastewater distribution subsystem but some are still connected to it due to the lack of proper infrastructure to properly convey away the runoff waters separately to the sewage flows. When new streets are repaired, these infrastrucuture is improved and eventually, finally connected to the properly rain water distributiion subsytem	49.643 m^3
	$Q_{9,10}$	Potential recycled water flows from the runoff distribution subsystem.	0 m^3
	$Q_{9,11}$	Rainwater streams that are drained to the media thanks to the runoff distribution subsystem. Even though, the actual systems based in grey solutions, could be improved in order to achieve a more convenient way to drain these waters in terms of quantity and quality. Runoff volumes should improve the circular water model.	Undetermined, as a complete map of the area and sewage systems would be needed.
10. Cyclic water recovery	$Q_{10,3}$	Greenwater, restored from treated rainwater and treated greywater. Blackwater could be also treated but this requires more treatment to reach an acceptable standard. In the case of study, because of the dilution, the treatment could be quite simple.	0 m^3
	$Q_{10,5}$	Greenwater / recycled water, directly provided to the demand subsystem.	0 m^3
11. Recipient	$Q_{11,10}$	Potential recycled water flows from the recipient.	0 m^3

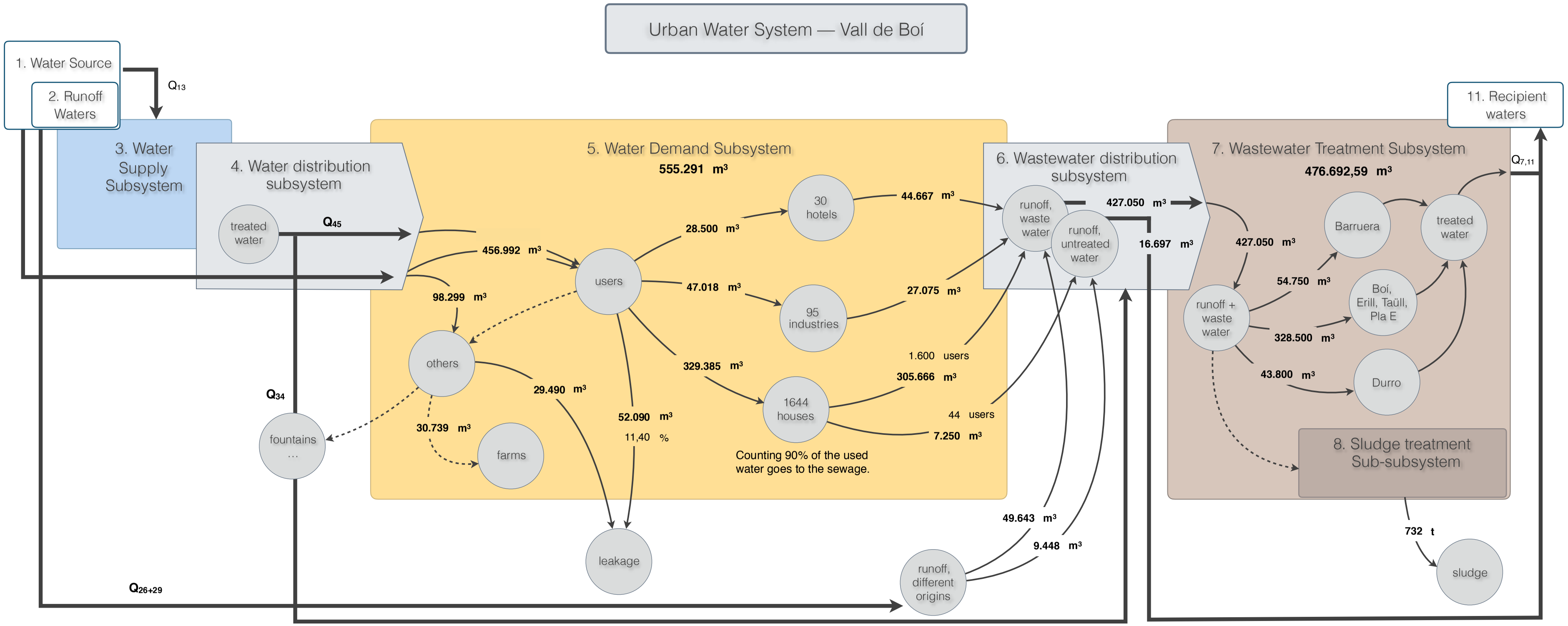

Figure 4.3 - Annual water flows quantification - UWS La Vall de Boí

4.2.3. Social analysis

In this work technical, economical and environmental assessment is carried out without considering the social dimension owing to the lack of data. This should be specifically studied in future studies in order to achieve all dimensions of sustainability. Nevertheless, social aspects have been indirectly considered in this work thanks to the stakeholders' communications and taking into account the the author's knowledge of the area.

Social aspects not only include the social acceptance of the proposed interventions, but rather the social responsibility of future interventions. This is named corporate social responsibility and promoted by United Nations in 2010, with "Mundial agreement promoting CRS". Responsibility strategies encourage actors to make a positive environmental impact and stakeholders involved in their actions. For instance, in the rural area of this case study, social responsibility could be applied developing the territory with a fair and balanced manner, fixing people to the territory without creating pressure on the cities. However, the social responsibility in infrastructures is still not considered in many studies, not even in the five sustainability dimensions of the TRUST Project (see chapter 5), and thus, should be built-in social dimension to achieve sustainability. The five dimensions of the TRUST European Project have been used as a framework of this thesis. Thus, the three sustainability dimensions considered (social, environmental and economic, named Three Bottom Line approach) have also been dealt with technical requirements of the UWS (such as performance, reliability or durability to achieve acceptable levels of service, LOS) and the governance dimension.

Accounting social aspects is essential to properly design and achieve a sustainable model in the water sector and thus, should be considered in further researches. A study[22] about the sustainable planning of the region of the study area carried by CEDRICAT among others revealed that people do not feel engaged with the decisions of the local development plans that are applied. As it is taken into consideration in the TRUST sustainable dimensions, social aspects are not only included in the social dimension (with the access, acceptance and satisfaction of UWS) but in the governance dimension as well, including for instance, public participation. This means to decide infrastructures with the population in all phases, from the designing process, to the construction, operation and maintenance, or even end of life. This is specially important as with it, we can switch from the *observers* situation of many people confronting the current environmental and social problems, to engage people with these problems, becoming *actors* instead of *observers*. People is still not aware of the common problems and it is essential to let them conscious if we want to achieve a sustainable growth.

The new water management plan in Catalonia, fully integrated with the Water Framework Directive (WFD), also points the same concept within the social participation, which should move from the current social informative tasks to the active social participation. Therefore, and as it has been already mentioned, the social dimension should be taken into consideration in further researches but also, to internalize the social values of water in a careful manner when pricing instruments for water consumption are designed.

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[22] Center of Integral Rural Development

4.2.4. Total Equivalent Population (TEP) analysis

One of the major concerns of this work has been to determine the total equivalent population (TEP) of the study area, as it is the second county (Alta Ribagorça) in Catalonia with more seasonal population. The value was specially important as it affect the results of the largest subsystem of the studied UWS. TEP consists on the annual equivalent population as the sum of the permanent population and the seasonal population linked to tourism (hotels, campings, etc) and second residences. Is expressed in % respect to the permanent population. According to IDESCAT (Statistical Institute of Catalonia), this value is for the county of Alta Ribagorça equal to 130,1% (respect to the permanent population), which includes the regions of El Pont de Suert, Vilaller and La Vall de Boí. Thus, La Vall de Boí should have 1280 TEP per year. Nevertheless, this data is not consistent as it does not cover the hotels equivalent population of the valley (440) also according to IDESCAT. This can be explained with the concentration of more permanent people in the biggest towns of the county, which are also the ones that have less tourism compared with la Vall de Boí. Both facts are translated with a lower ratio of TEP versus permanent population. For this reason, additional assumptions have been done and combined together with other IDESCAT data (number of secondary residences, average population per house and TEP of hotels and tourism resorts) in order to obtain a final result of 2100 TEP.

Other different methodologies have been used to calculate the equivalent population following ACA guidelines (estimating the water contamination per person with the BOD_5 effluent analysis) and other previous studies methodologies, giving much higher values than the ones expected while others show similar results, and thus, corroborating the chosen methodology. A sensibility analysis regarding the possible range of TEP value has been done in the discussion section of this work. They are also the basis of estimating the energy needs to heat the water demand subsystem calculated on a per capita basis. TEP has been used to give an approximate value of the energy or economic expenses per capita, which is useful when comparing with other urban water related studies, even it can not be as objective as per cubic meter basis results. A part from that, this value has been used in a qualitative way to verify the obtained data of the users and population of each village (permanent and seasonal, which has been estimated). On the other hand, these to last values have been used for both quantifying the water flows and water pollution in the villages that do not have registers of water supply flows and for those villages that do not have WWTPs (and thus, neither the quantity and quantity of wastewater can be determined).

Finally, it is important to remark that this value has not been analysed for the time horizon of the analysis, it represents the mean value according to the last data of IDESCAT, in 2014. Therefore, this value should be treated with caution if future analysis are done.

5. Status quo problems, strategies and interventions

5.1. Analysed problems

The Vall de Boí has several problems or weak points that cause a waste of environmental and economical resources, that affect the social aspect of the urban water management. Some of the listed problems cannot be defined as problems, but rather they cover the three types of possible situations: problems, potential problems and decisions. All in all, the individual managing of the different subsystems by the corresponding stakeholders of the UWS of La Vall de Boí leads an excess of the environmental and economic costs. Actually, the most challenging part of this study is to manage the UWS engaging all the stakeholders, in a collective manner, in order to find the proper solutions that could fit all the boundary conditions. These are listed as below:

1) Energy consumption:

- Energy consumption has a high economic cost, with more than 44.000€ annually spent across all WWTPs. Also, this cost is expected to increase due to the rising prices of the electricity.
- The electricity consumption is sourced from the electricity grid mix and thus, it represents a big impact. The WWTPs are the greatest consumers. The renewable sources in the electricity mix can be up to approximately 20% of the total in the Spanish grid, with 535 g CO2/kWh for mid voltage (Ecoinvent 2.2).
- There are almost no self sufficient schemes to provide or reduce the electricity needs of the UWS, taking into account the potential energy of the environment.
- The electricity source of the UWS is the mid-voltage grid, an thus, it has a high environmental impact, poor efficiency (around 35%), and generates a dependency and insecurity of the electricity source.

2) Sewage flows management:

- There is not a completely separate sewage system to treat the runoff flows. In theses rural villages, the runoff flows are a relative important part of the water treated in all of cases owing to the physical configuration of the houses and impervious surfaces.
- The current separate runoff systems are transported away with pipelines that directly flow into the recipient environment without previous treatment or retention systems.
- There are no recycling schemes that could potentially reduce the amount of flows treated or used for agriculture or industrial purposes.
- More control should be invested in some water flows that are continuously flowing and directly being conveyed to the WWTP, causing more dilution and thus, less efficiency of the WWTP treatments.

3) Water Treatment Plants (WTP):

- Chlorine is applied in water tanks that supply water to the different villages in a manual way. This causes either an excess of environmental and economic costs because of the daily maintenance and a risk of water contamination. Thanks to the good quality of the source waters, this does not represent a high risk.
- The catchment water systems are inefficient as they take more water than the needed drinking water from the water source. Nevertheless, the city council only pays for the amount of water used and not all the water subtracted from the natural source.
- Sodium hypochlorite treatment is applied in drinking water, which is not very socially accepted owing to the chlorine taste of the water.
- More security in the water quality should be done. Thus, changing the water source could be a possibility specially in the water catchments which are not coming from springs.
- Some of the water sources can be dry during drought periods, which imply to extract water from other sources. More security in water quantity and allocation should be done, also for temporally fails (to improve water security) or to increase the needed time in case of failure in the main infrastructure.

4) Sludge management in the WWTP:

- The sludge is treated by an external company —not locally— which means an increment of environmental and economic costs.
- Treating the sludge locally could benefit the local farmers, producing local jobs and economic profits due to the sludge once it is conveniently hygienized.

5) Automatisation WWTP:

- There are no technologies applied in the WWTP that could help to reduce the maintenance costs by a localized management. That could also improve the water quality of the effluent and help to prevent risks of unacceptable quality effluent returned to the environment.
- An automatisation system would improve efficiency of the plant, letting more time for the workers to spend in other purposes like improving the processes to get a dryer sludge from the plant[23].

6) Social perception of water consumption:

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[23] Personal communication with Josep Pueyo, head of technicians of the WWTPs of La Vall de Boí.

- More policies in favour of saving water consumption are needed in order to reduce the consumption per capita and stop the social perception that water resources are unlimited.
- The actual fix amount of water consumption per household does not promote the water savings or harvesting systems.

7) Precarious UWS:

- Water captions systems are very vulnerable specially in small villages, leading to risks of water contamination and distribution (interruptions) that would affect the levels of service.
- Leakage can also be caused due to precarious UWS. Fortunately, the most precarious pipes are not buried, so it is also easy to identify leakages and weak points of the water pipes.

5.2. Strategies and framework of the interventions

The IPAT (or IPCT) formula is the lettering of one of the first formulas that describes the impact of human activity on the environment. It was developed in the early 1970s by Ehrlich, Holdren and Commoner by simply identifying three factors that create an environmental impact:

$$I = P\,A\,T$$

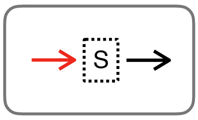
Where I is the impact, expressed as the product of (1) population, P; (2) affluence, A (or C, from the term consumption, as it refers to the average consumption of each person in the population); and (3) technology, T. Lately, this formula has been improved but their concepts are the core of the Industrial Ecology field, as they express the relationship between technology and ecology. On the one hand it examines the environmental impacts of the technological society, and, on the other, the means by which technology can be effectively channeled toward environmental benefit (Chertow, 2000). The first text book of Industrial Ecology (Graedel and Allenby 1995) defined it as its “master equation”, adopting a variant of the IPAT formula. In terms of LCA calculations, the IPAT formula is equivalent to the formula to calculate the vector of impacts, d (note that here, matrices are notated with capital letters and vectors with lowercase letters):

$$d = C\,e = C\,(S\,x)$$

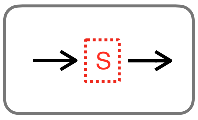
Where C is the characterisation matrix (that translates stressors into impacts, as GWP), e is the stressors vector and its equal to the product of S (matrix of stressors intensities per unit output) and x, which is the vector of outputs of a given external demand. Thus, it is clear that, despite the C term, the formula is equivalent to the IPAT formula as the population and affluence terms (P and A) are both expressed in terms of x and the term T is expressed with the term S.

These simple formulas help to explain that the main approach of this study in terms of LCA perspective is to improve both **foreground** (demand inputs) and **background** (technology, which is present in all terms presented before) systems in order to produce less environmental impacts as they result from both systems. For a reader not used to the LCA studies, we could say that the foreground system can be simplified with the x vector mentioned above, while the background can be found in the rest of the terms.

Following this definition, the approaches mentioned to reduce the environmental impacts, i.e., the outputs of industrial systems, can be summarised in these two mentioned terms, in addition to a third approach that should also be taken into consideration, which can not directly be explained by the formula:



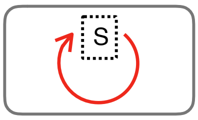
I) Reducing the inputs of the industrial systems (demand, foreground system)



II) Improving or adding new technologies (background system), by:

   i. Designing non traditional or alternative technologies / schemes, with more sustainable infrastructure, normally related with new decentralised systems.

   ii. Improving traditional technologies and infrastructure already existing, normally related with centralised schemes: designing them in a smart way, more integrated in order to be as efficient and coherent as possible. ICT technologies are a key factor in that approach: If we provide the system with ICT technologies and sensors, it will become more efficient, we will have less costs, and hence, less environmental impacts.



III) Revaluing the outputs to become valuable inputs for other industrial systems (circular economy concept, which can also turn to industrial symbiosis)

It is worth mentioning that the third approach is specially a *win-win* solution, as we “eliminate” somehow the outputs of a system while we cover the inputs of the systems that take advantage of this revalued outputs (and thus, provoking less demand of inputs for that systems). Actually, these 3 approaches match with the ones already well know in society as it is the simple 3R concept: Reduce, Reuse, and Recycle. Lately, a 4th “R” has been added to this concept which is to Revalue in energetic terms, in the same terms than the third approach described above.

This three goals or approaches have to success with specific interventions that have to be properly designed for all scales (from local to global), dimensions (economic, social and environmental) and sectors (water sector, transport sector, etc.). Because of this and the three main goals mentioned, sustainability is, as mentioned, a multi-objective problem. Therefore, an integration of all this approaches should be taken into account in a single model in order to understand the implications of single interventions anywhere in the UWS.

In the presented interventions, examples of the ones that refers to the first approach are the are the interventions I13 and I14 referring the importance and impact of consuming less water. Other examples for the second approach can be found with the recycling strategies proposed within the interventions I5 with the Green WWTP or a more rational use of the resources with the intervention number 3.4, where a separate stormwater sewage is studied. There's other solutions that can be considered in between the foreground and background improvements, such as the interventions I17, where thanks to a specific technology, the demand system is efficiently affected. Finally, the third approach can be found in the microturbines intervention (as it uses the actual water outputs from the water supply subsystem) and the sludge treatment wetland is designed, which ables to use the sludge for agricultural proposes.

5.3. Proposed interventions

The following list presents the interventions that have been proposed according to the described problems and following the mentioned strategy. These interventions have been proposed as an initial guess, preserving a wide range of the different potential alternatives that can solve the main problems of the UWS, studying all possibilities, even the ones that finally are not feasible. Hence, it ables to understand the reason why only specific interventions between this range of alternatives have been finally designed and analysed in this work. In this sense, additional comments have been also included in some of the listed interventions.

I. Energy consumption

I1 Installation of renewable energy

I1.1 Solar energy — The first calculus showed a very high costs when comparing with microturbines. Even that, can be a solution to support the microturbines.

I1.2 Installation of microturbines (runoff / supply water) — considered in the scenario 5. On the runoff waters, the solutions did not show a great result when comparing with the designed microturbines in the supply water. Only in the WWTP of Boí could be possible, with at least, 5kW of generated power. This value can be much higher if a proper analysis is done.

I1.3 Hydropower generation thanks to the connection of the sewage flows to the actual channels of the hydropower plants of the valley — This intervention was analysed for the villages of Pla de l'Ermita, Taüll, Boí, Durro and Cóll. Results show around 5 to 10 kW of generated electricity, in total. The required infrastructure (note that the sewage flows in the case of Taüll and all this group of villages would need a new WWTP or only dispose the stormwater) and the legal / bureaucracy problems make this solution not feasible, or with better alternatives (such as I1.2).

I1.4 **Biogas energy produced in the WWTP** — The 48 annual tonnes treated by the WWTP of Boí are provably not enough to consider as a feasible intervention.

I2 **Reduce the energy costs**

I2.1 **Reduce the energy consumption and power demand contracted in the WWTP thanks to the proposed interventions in this study** — With the designed scenarios (almost all of them, but specially number 9 and 3), the contracted power could be reduced. This is not trivial and needs therefore, intervention I2.2.

I2.2 **Reduce the energy power demand contracted in the WWTP by distributing in a better way the electrical machinery usage** — According to the first analysis, with a minimal investment (not more than 1000€ per each WWTP), constant monitoring of the electricity consumption can be done, in order to asses ways of reducing consumption and costs.

II. Sewage flows management

I3 **Reduce the runoff / rainwater treated in the WWTP** — All these interventions are modelled, somehow, withe the third scenario studied. Even that, there are other positive aspects that could be positive such as water retention measures, which are not accounted in the mentioned scenario.

I3.1 **Grey solutions to separate rainwater and wastewater**

I3.2 **Green solutions to manage rainwater: LIDs / SUDS.**

I3.3 **Permeable pavements**

I3.4 **Improve the actual infrastructure that separates and disposes rainwater**

I4 **Reduce the volume of water treated in the WWTP**

I4.1 **Reallocation of water needs and supply systems** — More data regarding the usage of the freshwater resources of the valley would be need it.

I4.2 **Additional green infrastructure to treat water** —Further research needs with more detailed information, this intervention could be considered, specially suitable for stormwater management.

I4.3 **Water recycling strategies** — Can be easily modelled in the UWS considering the ACA and OCCC study, in a preliminary assessment.

I4.4 **Improve the water fountains management** — Some fountains are constantly flowing water. If the water source is the treated water from the water tanks, this could be a priority to solve, in order to stop wasting chemical consumption. They are also responsible of more dilution of the WWTPs.

III. Lack of Waste Water Treatment Plants (WWTP):

I5 **Green infrastructure / solutions to treat wastewater** — It represents a great solution, specially regarding as a tertiary treatment, located besides the actual WWTPs. The results of 5% more of nutrient recovery of the treated water can be seen in the third intervention, which is remarkable. Also, can be used as a primary treatment in the villages that do not have WWTP.

I6 **Grey infrastructure /solutions to treat wastewater** — Considered in the 10th scenario, according to ACA future plans.

IV. Improving Water Treatment Plants (WTP):

I7 **Smart Water System to manage remotely the WTP** — Considered in the 4th scenario.

I8 **Water valves to prevent the water excess that is extracted from the water catchment and conveyed away again to the recipient media** — Designed and explained in the results section, but not included in any scenario as it does not represent a specially feasible solution.

I9 **Improve the water catchment systems, in order to improve water security and risk**— It represents an important intervention, stablished as a priority for ACA as it deals with risk assessment and water supply security potential problems. It has been designed and explained in the results section, but not included in any scenario as the results can not be compared with the other scenarios.

V. Sludge management: STW / STP:

I10 **Sludge treatment plant (STW) to produce natural fertiliser** — Considered in the 9th scenario.

I11 **Sludge treatment plant/s for the WWTP of the valley to produce electricity** (from the Biogas, I1.4) / distributed heating (to be used in the same WWTP) — Not feasible as explained in the intervention I1.4.

VI. WWTP automatisation:

I12 **Smart Water System to manage remotely the WWTPs** — It has been considered and predesigned, but according to Cadagua's head of operations, this intervention would improve the effluent quality control and the global performance of the operating system of the WWTPs, which is difficult to quantify. In contrast, it would not lead to any diesel savings. Therefore, this intervention was difficult to model with the available data and provably not worth to design from an LCA perspective.

VII.Policies and social perception of water consumption:

I13 **Promote reduction of water consumption by fixing variable price according to the water consumption** — Considered in the 7th scenario.

I14 **Political policies to reduce the water consumption and importance to preserve natural resources** — Considered in the 8th scenario.

I15 **Economic incentives to promote water recycling in the in-house scale, for garden use, for example** — Recycling strategies could be estimated as mentioned in the intervention I4.3. Further research would be necessary.

VIII.Demand system improvement

I16 **Pressure valves reduction in the water distribution subsystem** — Considered in the 6th scenario.

I17 **Leakage reduction** — Considered in the 3rd scenario.

I18 **Centralised water and wastewater analysis** — The actual beneficial economical costs of the government by "Diputació de Lleida" of performing centralised analysis makes this intervention not as feasible. Also, additional infrastructure would be needed (a part from the available one in the WWTP of Pont de Suert). Thus, further research needs are need it.

IX. Precarious UWS:

I19 **UWS improving to reduce infiltration and improve performance** — Further research are needed.

I20 **UWS infrastructure improving, with a proper data basis of the actual stock, more control in the water catchments and regular water meters checking in the WTPs** — As explained in the conclusion section, in order to avoid unfounded decisions of the UWS. Further research needs would be needed.

Table 5.1 - Summary of the proposed interventions

Problem	Group	ID	Description
I. Energy consumption	Renewable sources	I1.1	Solar Energy
		I1.2	Microturbines in the upstream water sources
		I1.3	Connection to the hydropower plants
		I1.4	Energy production in the WWTP
	Energy reduction	I2.1	Reduce power demand WWTP
		I2.2	Better distribution of the machinery
II. Sewage flows management	Reduce volume of runoff / rainwater treated	I3.1	Grey solutions for sewage separation
		I3.2	Green solutions: SUDs / LIDs
		I3.3	Permeable pavements
		I3.4	Improvement of the actual separation and disposal solutions of stormwater / runoff volumes
	Reduce volume of water treated WWTP	I4.1	Realocation of water sources
		I4.2	Additional green infrastructure
		I4.3	Recyling strategies
		I4.4	Improve water fountains management
III. Lack of WWTP		I5	Green solutions for water treatment
		I6	Grey solutions for water treatment
IV. Improving WTP		I7	Smart water system for the WTP
		I8	Water valves to eliminate excess water catchment
		I9	Water catchment systems improvement (fences, …)
V. Sludge managment: STW / STP		I10	STW to produce natural fertilizer
		I11	STP for electricity / heat production
VI. WWTP automatization		I12	Smart water system for the WWTPs
VII. Policies and social perception		I13	Water meters and information to reduce water usage
		I14	Policies and in-house water meters
		I15	Economic incentives to recycle water
VIII. Demand system improvement		I16	Pressure reduction
		I17	Leakage reduction
		I18	Centralised water analysis
IX. Precarious system		I19	Reduce infiltration
		I20	Improve UWS control, water catchments and meters
Total		**30**	**Integral Sustainable Solution**

5.4. Analysed interventions and scenarios

The goal of the first proposed interventions, as mentioned, was to have a whole perspective of all the potentially future interventions to improve sustainability and thus, design the best solutions and alternatives. Hence, a preliminary design of the proposed interventions was done in order to identify the best interventions, while dealing with the availability of data and the boundaries of the study. Also, stakeholders constant communications and feedbacks were taken into account to stably priorities of the interventions and thus, finally design the most suitable ones.

As expected, some of the studied solutions were not feasible or did not reflect the expectations, while others feet perfectly in the UWS and showed a very good feasibility. Other interventions calculated were analysed in detail but were finally not taken into account in any scenario as the obtained results were not worth it or not comparable with any other scenarios. Even thought, these have been also included in this work.

Each studied intervention has been represented in the figure 5.1 to understand graphically the holistic and systemic approach of them. These interventions were studied in scenarios, which are a combination of hypothesis or situations that belongs or not to one or more than one of the studied interventions. In this work, two different types of scenarios have been distinguished. Firstly, the *what if* scenarios are calculated changing the calculation model and thus, no external calculations are introduced in the model. Thus, the changes are based in assumptions and results of other studies. Secondly, the interventions based scenarios are calculated in the basis of specific future interventions designed for the UWS of the case study. Also, other assumptions, results of external studies and changes in the model have been done when needed in consonance with the intervention modelled.

Table 5.2 - Summary of the changes of the analysed scenarios

				change with water flows						
Scenario group	**nº**	**Year**	**m^3 water**	**€ UWS**	**€ users**	**electricity**	**diesel**	**sludge**	**chemicals**	**N, P removal**
What if scenarios	S0. Status quo (BAU, 2015)	2015								
	S1. Increment of energy prices	2035		electricity + diesel	electricity					
	S2. TEP growth	2035	+10,5%	✓	✓	✓	✓	✓	✓	
	S3. No leakage, runoff.	2035	-10% leak. -11% runf.							+5%
Interventions based scenarios	S4. Smart Water System	2035		✓			✓		✓	
	S5. Microturbines	2035		✓		✓				
	S6. Pressure valves reduction	2035	-7%	✓	✓	✓	✓	✓	✓	
	S7. Water meters	2035	-15%	✓	✓	✓	✓	✓	✓	
	S8. Policies + air filters	2035	-7,21%	✓	✓	✓	✓	✓	✓	
	S9. Local STWs	2035		✓		✓	✓			
	S10. New WWTP	2035	+untreated water	✓		✓	✓	✓	✓	✓

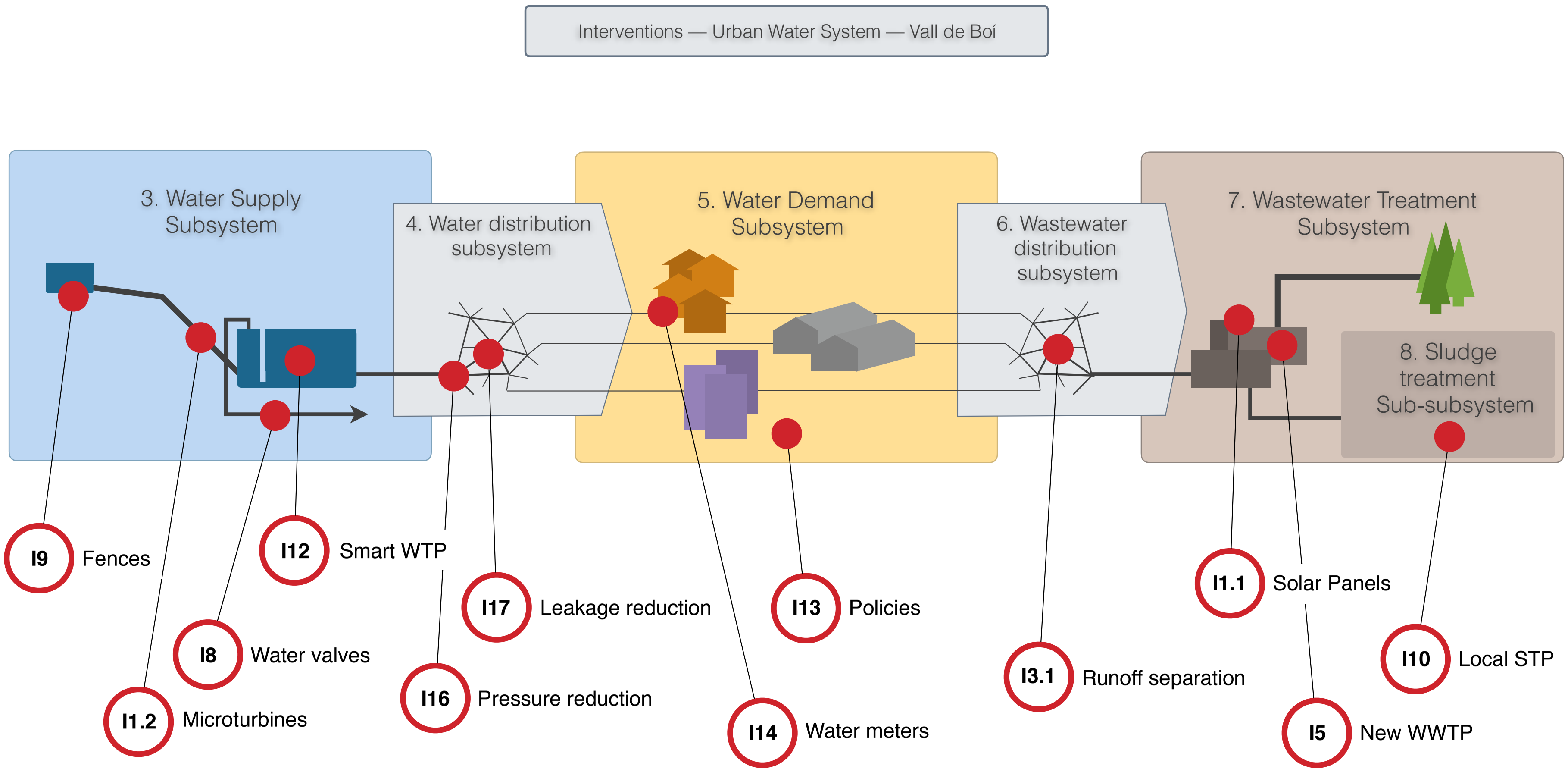


Figure 5.1 - Location of the studied interventions - UWS La Vall de Boí

The ten discrete scenarios studied in the UWS are as below. It is important to mention that the basis of all scenarios (except 0) is considered the scenario 1, corresponding to the status quo with updated energy costs for 2035. For more details regarding the scenarios calculations, please see appendix E.

5.4.1. *What if* scenarios

- **Scenario 0: Status quo / BAU scenario (2015)**

Description	This scenario corresponds to the current (or *status quo*) scenario, the so-called zero scenario where BAU (Business As Usual) conditions exists.
Justification	Analysis of the current situation in order to present the future interventions in comparison with the actual performance of the system.
Methodology, cm. changes	The results of this scenario corresponds to the status quo results presented in section 6.1 of this work.

- **Scenario 1: Status quo + increment of energy prices (2035)**

Description	Status quo scenario with updated electricity and diesel costs for the end of the period of the analysis in 2035. This scenario has been considered for the rest of scenarios (i.e., in all scenarios this price increasing is considered).
Justification	In Spain, during the last decade, the energy prices of electricity and diesel have been growing considerably (INE, 2015). This fact can not be dispensed with when renewable energy sources are taken into account in the analysis.
Methodology, calculation model changes	Following historical data of INE (2015), a annual increase of 2% and 1,5% of the electricity and diesel costs respectively until 2035. That means a total increasing at the end of the period of the analysis (2035) of 1,49 and 1,35 times respectively the 2015 prices. This increase has been calculated respect to the annual inflation, as the economic analysis has been done with constant numbers. For detailed information, please see section 4.2.1.

- **Scenario 2: Population growth / TEP growth (2035)**

Description	Population or TEP (total equivalent people) growth has been assumed in this scenario at a uniform rate of 0,5% annually (respect to previous year), which means 10,5% more in 2035. That means that the UWS will expect either an increasing permanent population or more seasonal population, i.e, occupancy of second residences and/or tourism.
Justification	La Vall de Boí is a very touristic region which is increasing its visibility and policies to increase the attractiveness as Pyrenees-tourist destination. During the recent years, this increasing has already been noticed and hence, can be also expected in the future, as well as permanent people.
Methodology, cm. changes	Increasing of 10,5% of the water flows in 2035 (considering linear relation between the water flows and the increasing of population).

- **Scenario 3: Reduction of leakage and stormwater treated in WWTPs (2035)**

Description	Modelling of 10% less of leakage in the WDIS and the overall stormwater treated in the WWTPs.
Justification	Reducing the leakage or the stormwater of a UWS is a priority for any urban water manager in order to assure a better performance of a UWS, avoiding this way, unnecessary costs and maintaining proper levels of service. Thus, it is also a priority and one of the major concerns from ACA, according to their communications during this work. Also because stormwater is treated, the wastewater is more diluted and therefore, it leads to a worst performance of the WWTPs regarding the nutrients removal.
Methodology	The interventions presented in this scenario have been considered as a *what if* scenario. This is due to the reason that is difficult to determine the economic costs and the technical interventions with the obtained knowledge of the area. For this reason, this analysis is also specially valuable, as it is a simple and quick way to understand the impacts of performing this interventions. Without the *Calculation model*, a detailed knowledge of the actual UWS stock will be needed to design specific interventions for each village (as it will happen with the runoff distribution subsystem).
Calculation model changes	A reduction of the associated water flows from the *Calculation model* has been done according to the water volumes of leakage at a rate of 0,5% annually, which means 10% less in 2035 (that means only 1,4% of leakage remaining and corresponds to the intervention ID I.3.1). Also, it has been subtracted the water volumes of stormwater, which is expected to not be treated in the WWTPs by the end of 2035 (intervention ID I.12). Because of the less dilution of water, an increasing of 5% of the nutrient removal has been also considered according to ACA considerations.

5.4.2. Interventions - based scenarios

- **Scenario 4: Smart Water System (2035)**

Description	Design of a ITC system that can control and monitor the supply water tanks that treats the water consumed, avoiding the current manual controls. Also assures to monitor the water consumptions of the water demand subsystem.
Justification	The actual water supply treatment are carried by the City Council of La Vall de Boí with sodium hypochlorite in the water treatment plants. Nowadays, the quantity of sodium hypochlorite is regulated during the labour days with a manual dispenser, checking at the same time the levels of chlorine in the water distribution subsystem in order to guarantee that these concentrations are correct in all villages (between a range of 0,2 mg/L to 0,8 mg/L). This precarious system is calling for an urgent automatisation, that will improve both the risks of water contamination due to incorrect chlorine dispensation as well as reducing the manual control needs from the City Council (i.e., diesel costs and operational costs from the workers). The smart water system

would also let the City Council and the Ministry of Health to be able to monitor the water quality and quantity by checking anytime the designed SCADA system, that will also give an alert if the system stops working properly. This intervention will also improve the social acceptance of these treatment systems, as the variability of the amount of chlorine in the water can be noticed in the water taste and odour.

Methodology

The designing process of this automatisation system is far more complex and thus, constant communications with the company Laiccona, the City Council and the approval of the Ministry of Health was needed in order to design a proper smart water system. In the cost of this intervention, it has been also countered two complete water treatments in addition to their smart system that does not exist in the villages of Cardet and Durro (and which represents more than the 50% of the total cost).

Calculation model changes

Inclusion of the calculated costs (23.700€) according to the lifetime expectancies and optimisation of the quantity of sodium hypochlorite for the water flows of the demand subsystem at a rate of 0,2 mg/L.

- **Scenario 5: Microturbines in the upstream water sources (2035)**

Description

La Vall de Boí is located in the heart of Pyrenees, in a old glacier valley. Their towns have been constructed in flat terrains, normally from glacier and river sediment disposals far below the water catchments (around 250 to 450 meters of difference of altitude). This topography has determined the operation system of the water tanks as the water pipes that distributes the water from the water catchments to the WTP. This scenario models to the microturbines intervention, taking profit of the potential of this flowing water, instead of installing a system that could stop the water flowing when the tank would be full (which has been also studied in the intervention I8 but not compared in any scenario). In other words, this scenario takes profit of the energy of the environment.

Justification

Provide to the UWS a renewable energy source that can respond to the system needs, and thus, reduce the main environmental impacts caused by electricity sourced form the Spanish electric mix. Also, this intervention allows to revalue an output from the WTPs to a valuable input for the microturbines, making it a win-win solution.

Methodology

For this scenario, a prior study of the area regarding the location and operating system of the water catchments had to be done. The design of the microturbines had to be done according to the pressure limitation on the water pipes, which are made out of PE and thus, can resist at most 160 meters of difference of altitude (the maximum pressure is 1,6 MPa). To solve this limitation, nowadays the water pipes never reach the maximum pressure by continuously flowing water to the water tanks, bypassing this way the water from the water source. This operational system is represented in figure 5.2. For this reason, the turbinated flow has been iterated to get the maximum power while never reaching a maximum of 1,5 MPa (assuming 0,94 of security coefficient). The microturbines were designed for all villages but only the three villages (where are the WWTPs: Barruera, Erill la Vall, Durro) were included in the intervention. An efficiency of 75% has been assumed according to the microturbines' manufacture and with an utilisation of approximately 1511m^3 of the annual turbinated flow, yields to a production of energy of 400.000kWh.

Calculation model changes

The electricity generated for the microturbines is assumed to be all consumed by the WWTPs and the rest is assumed to be provided to the demand system (i.e., users' electricity needs to heat the water). Note that this a simplification on the analysis as the electrical power of the microturbines is lower respect to the WWTP hired power (more information regarding the WWTP consumption would be needed). Even that, this would only affect to the destination of the produced electricity (the WDS or the WWTPs), so it does not affect to the overall avoided environmental impacts neither the economic benefits of this electricity generation. A mean price of 0,12€/kWh has been assumed due to the auto consumption benefits, which able to get better electricity rates than energy sellings (which are payed at a rate of 0,07€/kWh). These benefits have been discounted in the operational variable costs of this scenario.

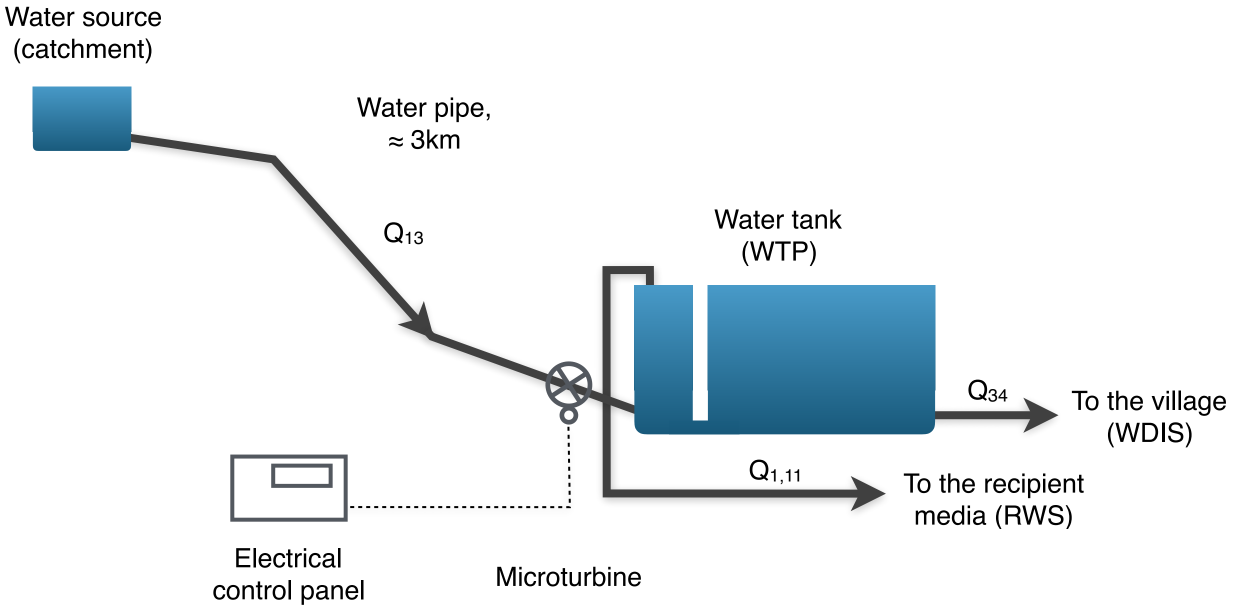


Figure 5.2 - Water catchment and water tanks operation system and location of the microturbines

- **Scenario 6: Pressure valves (2035)**

Description

The boundary conditions in terms of topography of La Vall de Boí also leads to an excess of pressure in the water pipes of distribution subsystem. Obviously, this is very dependent on the physical configuration of the water system in each village, specially regarding the altitude of the water tank and the beginning of the water pipe network. In Durro, the difference of altitude within the village, between the uphill users and downhill users can be up to 45 meters, in addition to the difference of 55 meters more to the water tank, which means a total pressure up to 100 meters of water column in some users. As an alternative to the pressure valves, a microturbine has been also considered in order to also get profit of this excess of pressure. However, the firsts economical evaluations with the microtubines' company did not show as a feasible solution (specially due to the expensive electrical control panel that needs to be installed with each turbine) and therefore it has not been considered. Another alternative to this valves could be to manually check all main water valves at the entrance of each user's house (or better install proper systems) to properly adjust the required pressure. Needless to say that this does not represent a very robust intervention even though it can be an efficient low cost measure that can be also widely sociable accepted when water pricing will be applied, helping users to save water and costs.

Justification

In La Vall de Boí, around 491L/TEP·day are consumed and the excess of water pressure in some villages is favouring this elevate water consumption. Nowadays in Barruera, for instance, some users have already installed reduction valves in the entrance of their in-house main water pipe in order to avoid the excess of pressure in their homes (which can be around 80 m).

Methodology

The water valves have been calculated to be installed in the main pipe before splits in the distribution network. This solution in not obvious and should studied carefully for each village, as the physical configuration of the system varies. Therefore, as a first attempt, a reduction of 20 meters of water column has been considered for the villages of Durro, Barruera and Cóll (which all have more than 50 meters of water column i.e., 5kg of pressure). This reduction was determined in order to assure that all users and demand systems had the minimum required pressure. The architectural technical code of Catalonia determines a minimum pressure of 10 kg of pressure for the water taps in private houses and 15 kg for heating boilers, without never reaching the maximum pressure of 50 kg. Fire hydrants also have to reach a minimum pressure of 100kg according to the actual legislation. Both conditions can be assured accounting all water losses of the distribution subsystems for the three villages. With a better knowledge of the systems and detailed analysis, this pressure reduction can be increased and thus, take all the potential of this intervention.

Calculation model changes

According to Bernoulli equation, the 20 meters of water column reduction could be equivalent to an average reduction of the 15% of the water flows of these villages. However, this is also dependent of social behaviour and needs to be properly modelled and studied. Therefore, a security rate of 7% of reduction (equivalent to subtract 6800 m^3) has been assumed in all water flows affected, also as an example of the potential of this intervention. Further research is needed in order to model this scenario precisely.

- **Scenario 7: Water meters for the demand consumption (2035)**

Description

La Vall de Boí never payed for the water consumption until some years ago, when a fix cost per year and per user was stablished. This cost corresponds to an estimation of the annual water volume payed dependent to the water user type (hotels and industries pay according to a specific formula provided by ACA to the City Council, who manage the billings). For domestic users this amount is equivalent to 9m3 per year which corresponds to 81,04€ annually. From this costs, 23,43€ goes to the City Council while ACA receives 57,61€ per domestic user, including 10% of tax. Industries and hotels pay a proportional amount respect according to their average of water consumption.

Justification

According to the guide "CBA analysis of investment projects", "*Directive 2000/60/EC recommends water-pricing policies to take account of the principle of recovery of all the costs of water services, including financial, environmental and resources costs. Water tariffs should be set in such a way as to ensure the full recovery of costs, particularly in accordance with the 'polluter pays' principle".*

Methodology

According to ACA legislation, the amount of water consumed is measured in m3, in four tranches according to consumption. There is always a minimum billing of 6 m3 per user and per month (if there are meter readings). As more water is consumed, higher are the water rates (in La Vall de Boí would be 0,49 - 1,12 - 2,8 - 4,48 €/m^3 for each tranche). Therefore, the purpose is to promote the efficient use of water and encourage the reduction of consumption higher.

Calculation model changes

To estimate the economic benefits for the water pricing, the specific pricing for La Vall de Boí has been applied by calculating the average of the monthly water supply per user (26,14 m3/monthly · user), without distinguishing the additional water volumes from hotels, that would lead to more benefits as these would be payed at a higher price (and thus, we obtain a more secure result). Additionally, according to EPA[24], studies carried in England concluded that water use by metered customers is about 10% less than non-metered customers. In Hungary, the results show even more reduction. Hence, in this scenario a descend of 15% in the water demand consumptions is expected due to the effects of water pricing.

- **Scenario 8: Policies and air filters in-house scale (2035)**

Description

Installation of the air filters in the in-house scale and policies to improve the water demand consumption.

Justification

Many studies consider (such as Ashley et al., 2004. Makropoulos et al., 2008 within the SWARD and UWOT projects) the installation of the air filters in the in-house scale as an effective cost benefit measure to improve the water demand consumption. Also, a study carried by CEDRICAT[25] pointed the importance of reducing the water consumption with air filters and policies, warning people the importance of saving water.

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[24] European Environmental Agency, Lallana, Concha., CEDEX, Niels Thyseen (2003). Indicator fact sheet: Water prices (WQ05). European Environment Agency (EEA).

[25] Center of Integral Rural Development (Centre de Desenvolupament Rural Integrat de Catalunya, Centre Tecnològic Forestal de Catalunya, 2006). "Planificació Sostenible de l'Alta Ribagorça".

Methodology

The effectiveness of these systems have been studied in Catalonia within a study carried by Catalonian Sustainable Development Advisory Council (CADS[26]), carried during 2004 and 2005 in different villages. The study is specially important for this work as for the first time, data from villages that have second residences where also included in the results. One of the most important conclusions in relation with this study was that when the air filters where completely or partially installed in the water users, the water consumptions where reduced in a range from an average of 7% to 19% for the case of secondary residences. Therefore, it concludes that secondary residences users and users with more monthly water consumption, are the ones that show better results in terms of water savings.

Calculation model changes

The study by CERDICAT calculated the costs of this intervention for the application in the study area, which have been adopted in this scenario and includes the costs of both policies and air water filters. According to the mentioned studies, a reduction of 15% of the all water flows has been considered, accounted together with the total calculated costs of this intervention, amortising linearly this costs for a 10 years of life cycle. Thus, the total costs have been multiplied by two, as it has been considered that this intervention should be carried twice during the study of the life cycle scenarios considered (20 years, until 2035).

- **Scenario 9: Local Sludge Treatment Wetlands (STWs) (2035)**

Description

In this scenario, three local sludge treatment wetlands (STW) have been considered in order to treat the sludge from the current WWTPs in Durro, Boí and Barruera, according to the results of the study of Uggetti et al., 2010.

Justification

Green infrastructure is widely considered as an alternative solution that can help on the pathway towards sustainability, specially in areas near to a Natura 2000 network, as it happens in the case study. As mentioned, according to EU: "*In forming the hubs of a European Green Infrastructure, Natura 2000 sites provide a strategic focus for improving our natural environment and enhancing the quality of our lives. At the same time, implementing a Green Infrastructure beyond protected areas will help to strengthen the coherence of the Natura 2000 network by making the core areas more resilient, providing buffers against impacts on the sites, and offering practical real-life examples of how healthy protected ecosystems can be used in a way that provides multiple socio-economic benefits to people as well as to nature*" (Building a green infrastructure for Europe, 2014).

In the same sense, Uggetti et al., 2010 points that STW are the most appropriate alternative for decentralised sludge management in small communities from an LCA perspective. Also, it is a source for nutrients that can be used as a fertiliser, since is expected that the actual mineral fertilisers will soon be in short supply. Hence, local markets can be generated too, helping these communities, by managing the local organic nutrient cycle of the future. Moreover, this solution can be considered as an alternative to the

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[26] Catalunya Estalvia Aigua (Catalonia saves water), CADS - Consell Assessor per al Desenvolupament Sostenible and Ecologistes en Acció, Goverment of Catalonia, 2006.

stormwater separation, as the dilution of the wastewater is considered as a positive aspect if the sludge is treated with STWs.

Methodology

The guidelines to design the STW for small communities including costs are provided by the mentioned of Uggetti et al., 2010. This publication also compared the O&M costs to operate a conventional sludge treatment as the ones that are in La Vall de Boí, and thus, abled to verify and compare it with the calculated ones and hence, understand if the boundary conditions match with the current study. The conclusions given by the publication derives from the study of performance of full-scale STWs constructed in Osona, in the East Pyrenees. The STWs are specially sensitive to the temperature in order to stabilise and dry the sludge, so comparing it with the case study, the mean annual temperature it is 1ºC above, while in winter can be up to 2ºC of difference. Therefore, the performance of the plants considered in the study can be assumed to be equivalent for this preliminary design, compatible with the boundary conditions of the case study. The investment needs were calculated following the equivalent people served by the WWTPs, which was rounded to match with the paper results to 500 eq. population for Durro (in reality is 400), 1000 for Barruera (in reality is 768) and 2000 for the WWTP of Boí (in reality is 5240 eq. population). For this last case, the reason why it has been considered a smaller STW is due to the fact that nowadays, the sludge produced in the WWTP is retained in a specific tank, together with the sludge of the other two plants, up to 2 months. Considering also that this WWTP will not assume the sludge that is today assuming from the WWTP of Barruera and Durro, it has been estimated that the sludge tank will have enough capacity to retain the peak season flows and thus, can be all assumed for a smaller STW. In the worst cases, this sludge can be transported to the rest of the STW or to the conventional actual system. Even that, this is a simplification that should be carefully studied in further researches. It is worth to mention that economical benefits can be obtained from the sludge produced if this can be used for agricultural proposes. The price of this sludge, according to ACA, can be around 2€/tonne of wet sludge treated, even it can vary significantly according the demand/offer relation. Also, some taxes have to be payed to treat the sludge, so all in all both concepts are assumed to be mostly the same and thus, have not been included in the analysis.

Calculation model changes

Inclusion of the STWs costs (293.600€, amortised for 25 years, also according to the authors) and the operational costs of the STW, which equal to around 45.000€/year. No diesel consumption for sludge has been considered neither the actual management costs (which have been substituted for the STWs' costs). As mentioned, no benefits have considered for the sludge production as a fertiliser.

- **Scenario 10: Conventional WWTPs (2035)**

Description

In this scenario, it has been modelled the implications of constructing the WWTPs that lack in the system and where planned to be built in Cóll and Cardet. The construction of these WWTPs were included in the "Program of Urban Wastewater Treatment, 2005 (PSARU 2005)" which is an instrument of hydrological planning developed by the Treatment Plan of Catalonia, approved by the Government on 7 November 1995, which aimed to define all actions to reduce pollution caused by the domestic use of water and achieve the objectives in terms of water quality. Note that in terms of LCA, this scenario can be compared with the others due to the exposed reasons in the methodology section described above.

Justification

The European Directive 91/271 / EEC on wastewater treatment indicates that municipalities with fewer than 2.000 equivalent population should purify their water with treatment. The mentioned program (PSARU 2005) was designed according to this same Directive 91/271 / EEC on urban wastewater treatment, and Directive 2000/60 / EC, and aimed to establish a framework for Community action in the field of water policy focused on water protection, which aimed to achieve by the year 2015 a good status of surface water bodies through the development of protection, improvement and regeneration of the water masses. Due to the economic crisis, these plants have not been constructed yet and their impacts are calling for an urgent actuation.

Methodology

The performance of this WWTPs (in terms of total energy needs, N and P removal, etc.) has been considered to be the same than the average of the rest of WWTPs of the valley. The capital costs where defined by the same program, while the operational costs have been estimated according to the WWTP of Durro (as it can be assimilable due to its operating system and dimensions), including the sludge treatment to the WWTP of Boí as it happens in Durro. Note that only operational phase is also considered in this scenario in terms of environmental costs and that can be comparable due to in the other scenarios because the impact of untreated wastewater is also considered in the rest of scenarios. Hence, the function of the system then, in terms of an LCA perspective, is still the same.

Calculation model changes

Inclusion of the WWTP costs according to PSARU 2005 (307.500€ for both WWTPs, linearly amortised for 30 years, even this is low but secure value). Changes of the electricity and diesel needs have been included according to the mentioned operating system of Durro, as an approximation.

6. Results

6.1. *Status quo* assessment: LCI and LCIA results of the current scenario

In this section, the results referring to the life cycle inventory (LCI) analysis (economic and energy flows) and the life cycle impact assessment (LCIA, i.e., environmental impacts evaluation) are presented.

The economic and physical resources flow analysis showed that the inflows going to the demand subsystem were the largest ones respect to the rest of flows. Hence, the economic and environmental associated flows are also much larger in the demand subsystem (WDS) than in any other subsystem. Because of this, the results presented in this chapter have distinguished between the UWS (including all the urban water cycle, i.e., UWS = UWCS + WDS) and the UWCS (referring the urban water cycle services, excluding the demand system) when needed in order to properly understand the results within its context. Hence, note that almost all graphs are presented with a logarithmic scale due to properly show the results of all subsystems.

6.1.1. KPIs results

Table 6.1 shows the KPIs results for the current scenario, expressed per year. From these, specific chosen KPIs will be the basis of the proposed scenarios. Additionally, some KPIs based on the City Blue Print indicators have been also added, in order to be able to compare the results with other urban water studies. In the table, the results have been distinguished with the mentioned UWS and UWCS, but also the WDS as it is by far the most important subsystem. Also, the rate per cubic meter and per TEP has been added. Even that, the KPIs results / TEP should be treated with caution, due to the high seasonal occupation of the valley that can vary significantly as explained in the TEP analysis section. Therefore, these values are considered to be not as representative as the cubic meter basis, which is a more objective value. In this sense, a sensibility analysis of the TEP value has been done in the discussion section.

These values will be explained in detail in each section. From a global perspective, and as mentioned, it has to be pointed the relative importance of the WDS respect to the total UWS (which is the sum of UWCS + WDS).

Table 6.1 - Summary of the results

KPIs (per year basis)	Scenario 0	KPI/m^3	KPI/TEP
Total UWS costs	719.800 €	1,58	342,76
Total UWCS costs	177.300 €	0,39	84,43
Fix operational + capital costs (€)	131.800 €	0,29	62,76
Operational variable costs (€)	45.500 €	0,10	21,67

KPIs (per year basis)	Scenario 0	KPI/m^3	KPI/TEP
Economic water benefits (€)	-144.300 €	-0,32	-68,71
WDS costs (€)	542.500 €	1,19	258,33
GWP (kg CO_2 eq)	1.746.100 kg	3,82	831,48
AP (kg SO_2 eq)	11.100 kg	0,02	5,29
EP (kg PO_4 eq)	24.300 kg	0,05	11,57
GWP UWCS (kg CO_2 eq)	210.200 kg	0,46	100,10
AP UWCS (kg SO_2 eq)	1.400 kg	0,00	0,67
EP UWCS (kg PO_4 eq)	22.400 kg	0,05	10,67
GWP WDS (kg CO_2 eq)	1.535.900 kg	3,36	731,38
AP WDS (kg SO_2 eq)	9.700 kg	0,02	4,62
EP WDS (kg PO_4 eq)	1.900 kg	0,00	0,90
Electricity (kWh)	1.714.100 kWh	3,75	816,24
Diesel (kWh)	38.700 kWh	0,08	18,43
LPG gas (kWh)	2.356.900 kWh	5,16	1122,33
Total Energy UWS (kWh)	4.109.800 kWh	8,99	1957,05
Total Energy UWCS (kWh)	292.600 kWh	0,64	139,33
Total Energy WDS (kWh)	3.817.100 kWh	8,35	1817,67
Chemicals (kg)	3.400 kg	0,01	1,62
Sludge (kg)	732.100 kg	1,60	348,62
Residues (kg)	9.600 kg	0,02	4,57
Nutrient recovery (% wastewater)	98,12%	-	-
Water system leakages (%)	11,40%	-	-
Water safe sanitation (% pop.)	97,51%	-	-
Water footpirnt (m^3)	457.000	-	-
Water scarcity (%)	0,00%	-	-
Water consumption (L/cap·day)	491	-	-

*The m^3 basis corresponds to the total water consumption, i.e., 456.992 m^3

**The TEP basis corresponds to the total equivalent population, 2100 TEP.

6.1.2. LCI - Economic costs

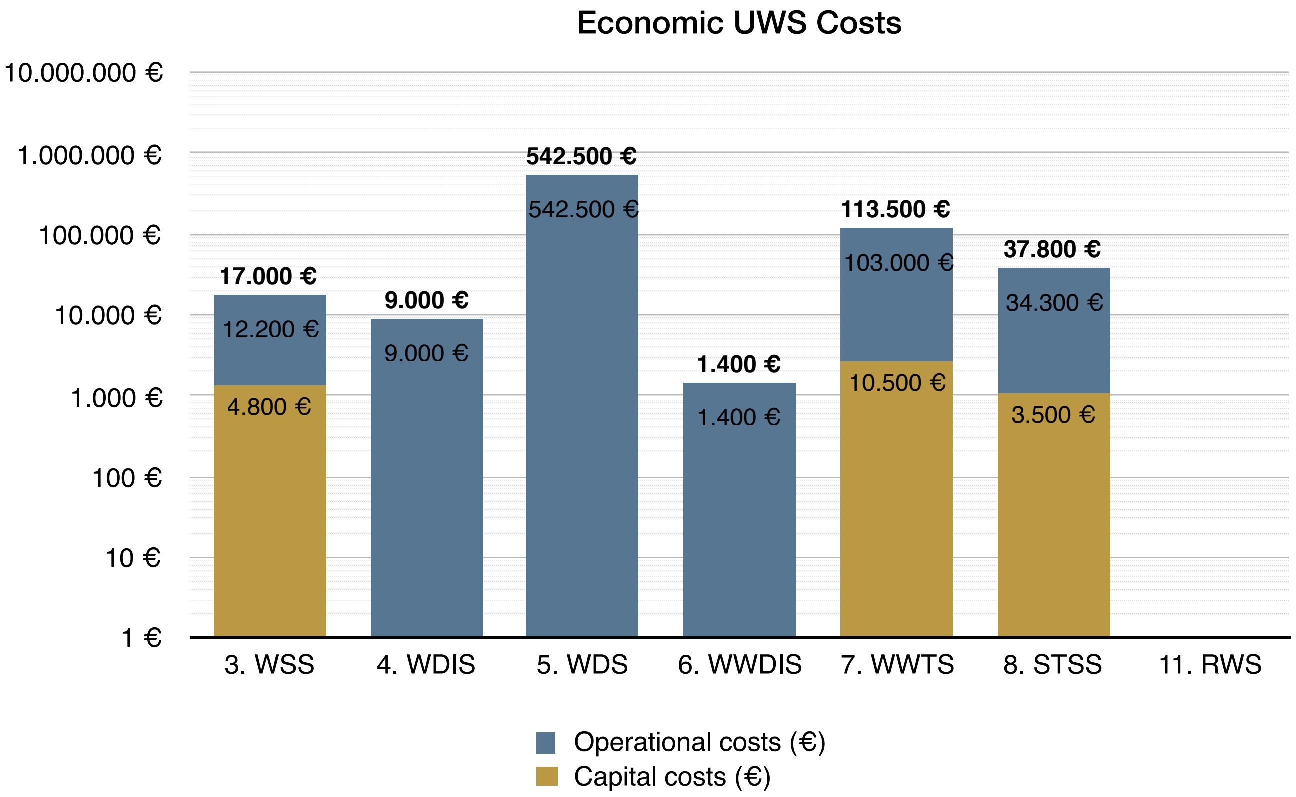

Figure 6.1: Economic UWS costs, total, operational and capital costs, in absolute values.

Figure 6.1 shows the total economic costs (which includes capital and operational) that the water distribution subsystem (5. WDS) is the largest economic costs in the UWS. The WDS includes the water consumption costs (159.000€) and the electricity and LPG costs for heating the water (from 2100 TEP). These costs are seven times larger than the waste water distribution subsystem (7. WWTS), and 15 times larger than the sludge treatment sub-subsystem. The costs of the supply subsystem represent only 9% of the UWCS total costs, whereas the distribution subsystems (4. WDIS and 6. WWDIS) represent only 6%. In contrast, no economic flows are affected (i.e, electricity, etc.) when effluent water is conveyed to the recipient water subsystem (11. RWS). It is also worth mentioning that in the UWCS, the fix costs (including capital and operation fix costs) represent around 132.000€ while the operational variable costs are around 45.000€ (25,6% of the total). In contrast, the overall UWS fix costs are much higher (429.000€) compared to the variable ones (291.000€).

In order to facilitate the comparison among different subsystems, the ratio between the costs per cubic meter (€/m^3) is shown in table 6.2. This ratio is comparable to the economic relevance of the absolute costs even the cubic meter basis is different, while it can be useful to compare with analogous indicators of the respective subsystems of other areas. Note that the overall ratio of the UWS is 1,925 €/m^3, whereas the UWCS costs are 0,391 €/m^3 (85€/TEP) five times less as the UWS costs as happens in the absolute results.

Table 6.2 - Ratio €/m3 for each subsystem

	3. WSS	4. WDIS	5. WDS	6. WWDIS	7. WWTS	8. STSS	11. RWS	Total UWS	Total UWCS
€/m^3	0,04	0,02	1,86	0,00	0,25	0,11	0,00	**1,93**	**0,39**

From the stakeholders perspective, the operator of the WWTP represents the greatest contributor in the UWCS costs with 86% of the total, followed by the City Council (10%) and the Ministry of Health (4%).

6.1.3. LCI - Energy requirements

Energy requirements are very much related with the economic costs and the environmental impacts of the whole UWS (energy-carbon nexus) as they represent one of the main flows. Figure 6.2 illustrates the energy requirements by each subsystem in absolute values, which follow the same order of importance as the economic costs of each water subsystem. LPG is the main energy source in the UWS (2356,9 GWh, in 5. WDS) followed by electricity (1714 GWh for the UWS; 254 GWh for the UWCS) and diesel, which is essentially used for the transportation needs (33,5 GWh).

The ratios between electricity (kWh) per cubic meter (m^3) and for each subsystem are summarised in table 6.3. For the same exposed reasons, again the WDS has the highest ratio of electricity consumption of the system. Note that the ratio of electricity consumption of the WWDIS is considerable high as the cubic meter basis is not the same for all subsystems (in this case, only covers the volume treated of the WWTP of Barruera, where the electrical pump is required).

It has to be pointed that, in relation with other urban water studies, the kWh of electricity per cubic meter is higher than the obtained value for the UWCS. This is because the UWCS studied belong to a little villages when compared with bigger cities, which leads to less efficiency of the system and specially regarding the WWTP. In this sense, even the value is not showed in this table, the electrical efficiency (kWh/m^3) between the WWTP of Boí (5400 eq. pop.) is four times the efficiency of the WWTP of Barruera (768 eq. pop.), even is not that far from the WWTP of Durro, as it is provided with newer technologies.

Table 6.3 Energy ratios for each subsystem

	3. WSS	4. WDIS	5. WDS	6. WWDIS	7. WWTS	8. STSS	11. RWS	Total UWS	Total UWCS
Electricity (kWh)/m^3	0,00	0,00	3,88	0,08	0,57	0,02	0,00	**3,75**	**0,56**
Fossil fuels (kWh)/m^3	0,02	0,01	6,26	0,00	0,05	0,01	0,00	**5,24**	**0,08**

	3. WSS	4. WDIS	5. WDS	6. WWDIS	7. WWTS	8. STSS	11. RWS	Total UWS	Total UWCS
Energy (kWh)/m^3	0,02	0,01	10,14	0,08	0,62	0,03	0,00	**8,99**	**0,64**

6.1.4. LCIA - Environmental impacts

The Water Demand Subsystem accounts for the major bulk (88%) of global warming potential (GWP) of the UWS as it can be seen in figure 6.3. The Wastewater Treatment Subsystem (7. WWTS) contributes an 8% and the remaining 5% corresponds to the rest of subsystems, which can be better seen in the UWCS share. Hence, regarding the UWCS, the represents WWTS 64% of the total share, followed by the wastewater emissions caused by CH_4 and N_2O from both treated and untreated wastewater (i.e., the Recipient Waters Subsystems, 11. RWS). Finally, the Water Supply Subsystem (WSS) covers 7% of the impact, while the sludge only represents 3% of the overall impacts.

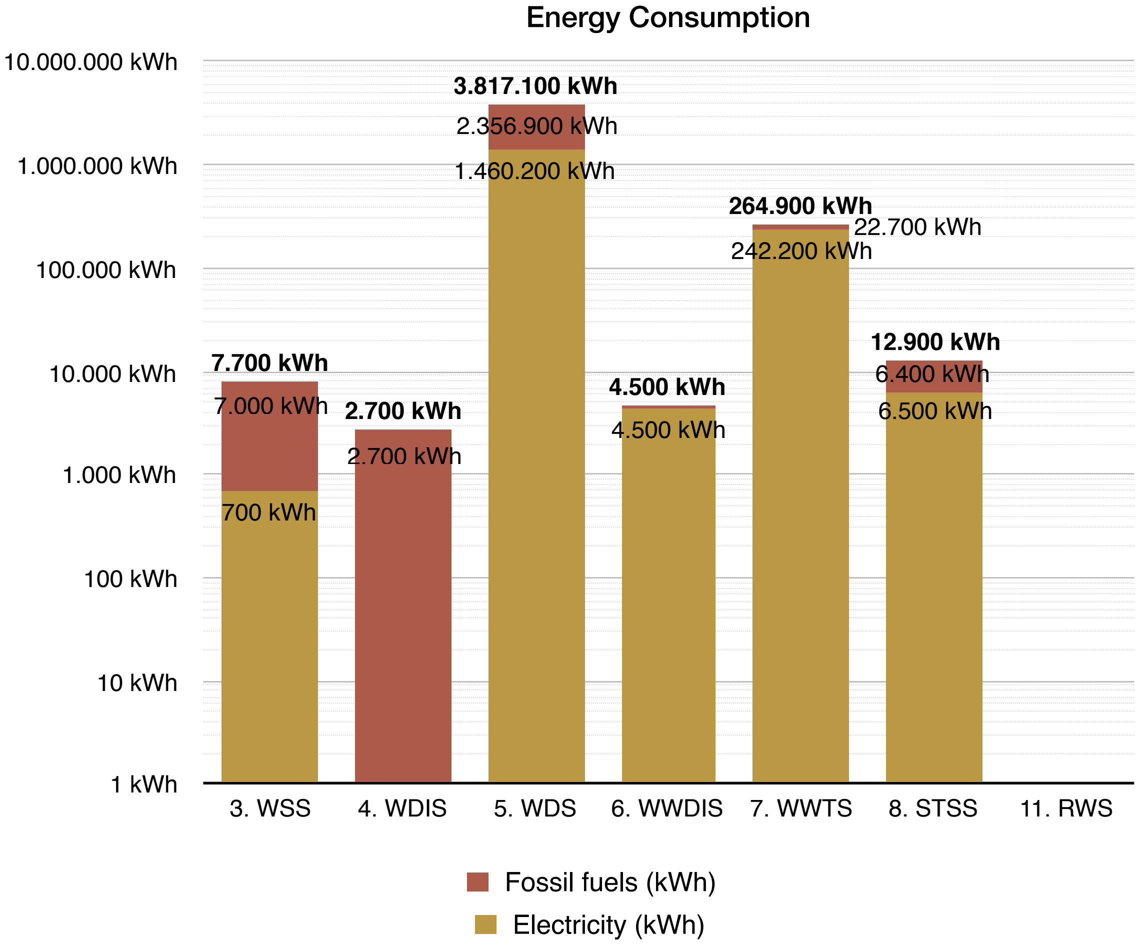

Figure 6.2 Energy consumption by energy source (kWh) for each subsystem

Figure 6.4 shows the share of GWP impacts by each product consumed in the UWS and respect to figure 6.4, both are very similar due to the energy—carbon nexus. Hence, the rates of electricity, LPG and wastewater remains the same value. From this las figure, it is important to underline that CO_2 equivalent emissions of the overall diesel consumption within all subsystems is comparable to the emissions caused by the annual chemical consumption in WTPs and WWTPs, even these impacts are not as visible, which remarks the necessity of quantifying these impacts.
The ratio of GWP emissions per cubic meter (kg CO_2/m^3) for each subsystem is presented in table 6.4. In the same way, the WDS is the largest ratio with 4,08 kg CO_2 eq/m^3, followed by the WWTP with a ratio of 0,32 kg CO_2 eq./m^3 and the recipient waters subsystem with 0,12 kg CO_2 eq./m^3. The overall ratio of the UWCS is 0,26 kg CO_2 eq./m^3 (note that direct comparisons can not be done as the cubic meter basis is different from each subsystem considered).

Table 6.4 Ratio kg CO2 eq/m3 for each subsystem

	3. WSS	4. WDIS	5. WDS	6. WWDIS	7. WWTS	8. STSS	11. RWS	Total UWS	Total UWCS
kg CO_2 eq/m^3	0,03	0,00	4,08	0,04	0,32	0,01	0,12	**0,26**	**2,17**

Figures 6.5, 6.6 and 6.7 show the absolute environmental impacts across the different subsystems in absolute values (note the logarithmic scale of the graphs). As in the previous cases, the subsystems with the largest impacts in terms of GWP are the WDS, followed by the WWTS (10 times less than the WDS). In contrast, it is followed by the RWS due to methane and nitrogen oxide emissions of the wastewater.

Regarding the acidification impacts, expressed in kg of SO_2 equivalents, the ranking of results within the different subsystems follow the same pattern as the GWP. Recipient water subsystem i.e., polluted wastewater (treated or untreated), does not lead to acidification impacts. In contrast, it is responsible of the greatest impact regarding the eutrophication potential. Moreover, it is important to remark that the contribution of eutrophication impacts for the wastewater untreated is around 27%, whereas it only represents 1,88% of the wastewater (treated and untreated) of the UWS. Hence, the ratio of kg PO_4 eq/m^3 is significantly high in the untreated wastewater compared to treated wastewater.

These impacts should be treated in the context of the studied case, as they can vary significantly depending on the affected region. This is called in LCA terms, regionalisation[27]. Regionalisation

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[27] As an example, groundwater extraction impacts are not the same if they are caused in the Netherlands (were the groundwater level is near the ground surface, so more plants will be affected after water extractions because the water table will be lower so the roots of the plants will not reach it) than in Australia, where the groundwater level is 45 meters down the surface (so almost no vegetation will be affected).

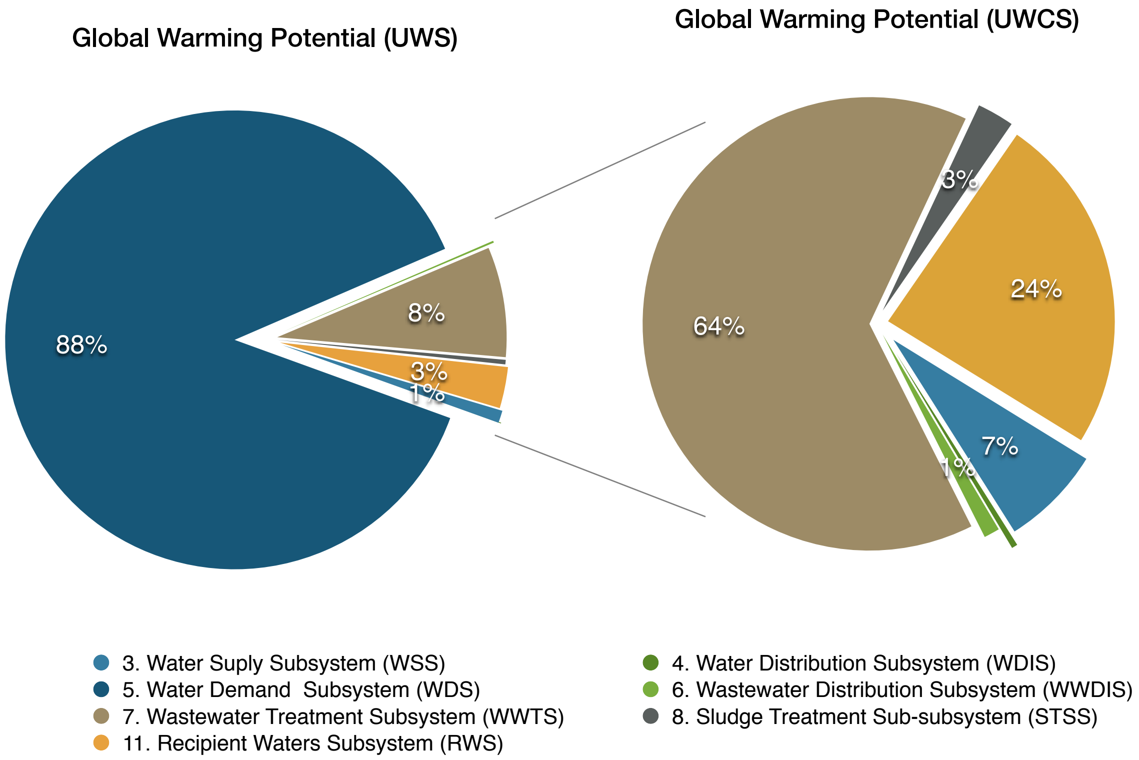

Figure 6.3. Global Warming potential (%) by each subsystem

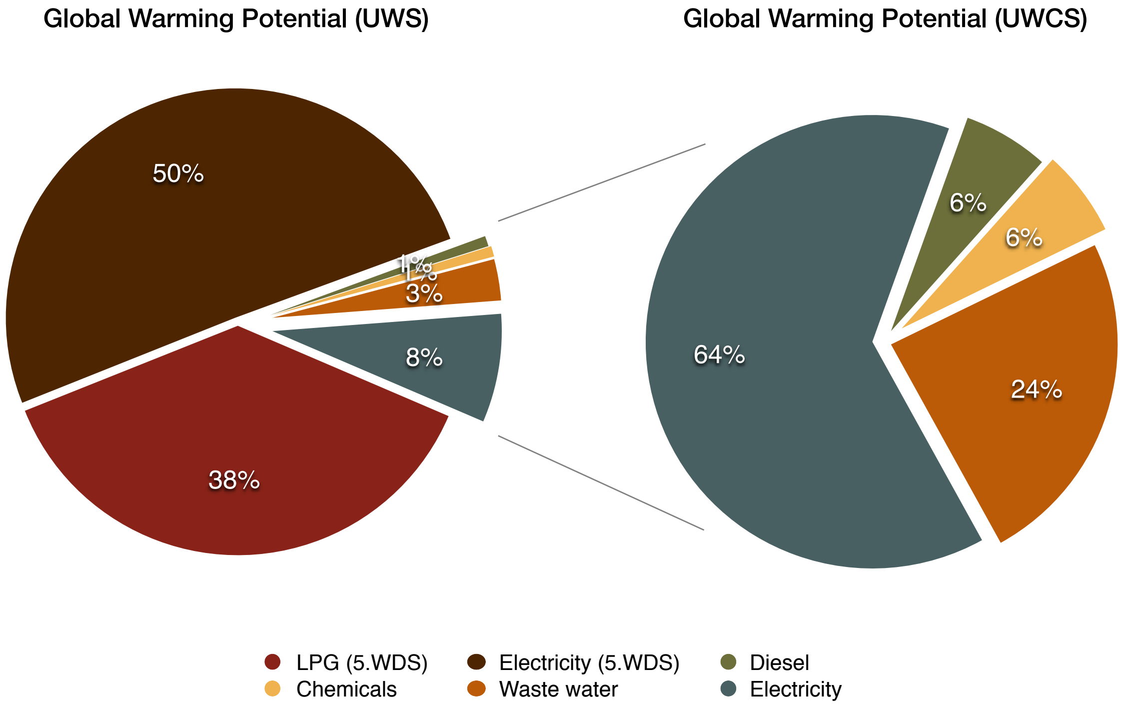

Figure 6.4. Global Warming potential (%) by each product

today is actually, one of the problems designing a LCIA data basis[28] for a global scale.

In the studied case, the consequences of the eutrophication impacts are not the same due to the concentrations of these contaminants in freshwater resources. Non treating the water discharged in large rivers such as the *Noguera de Tor* River (which is the receptor of the effluent from the WWTP of Barruera, with an average flow of 8,1 m^3/s and up to more than 15 m^3/s)[29] would probably cause less damage than non treating the waste water discharged in the *Fenero* Stream in Cóll with flow rates around 50L/s or even less[30]. Moreover, downstream of this discharge effluent in Cóll, a farm is catching this water to feed their cattle, with the subsequent potential problems that this could cause. Therefore, this arises the need of further studies in order to determine the potential of this regional impacts as the eutrophication impacts could cause.

6.2. Improvement assessment: results of the studied interventions

In this section, the results of the studied interventions are evaluated following the same methodology (trough the calculation model) and compared with the status quo scenario, modelling the specific needed changes of inputs and outputs in the subsystems of the whole UWS.

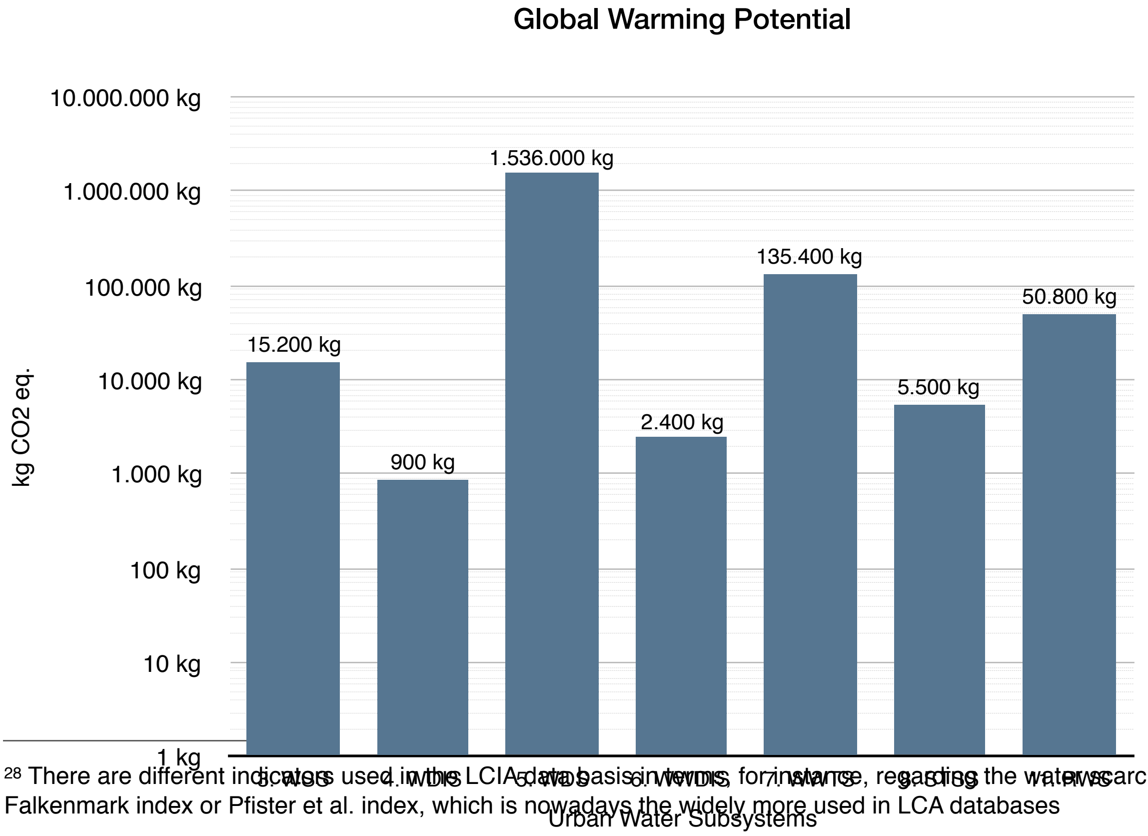

Figure 6.5. Global Warming potential (kg CO_2 eq) by each subsystem

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[28] There are different indicators used in the LCIA data basis in terms, for instance, regarding the water scarcity: the Falkenmark index or Pfister et al. index, which is nowadays the widely more used in LCA databases

[29] CHE, Hydrographic Confederation of the Ebro river.

[30] Site specific qualitative data, in Cóll, La Vall de Boí, February 2016.

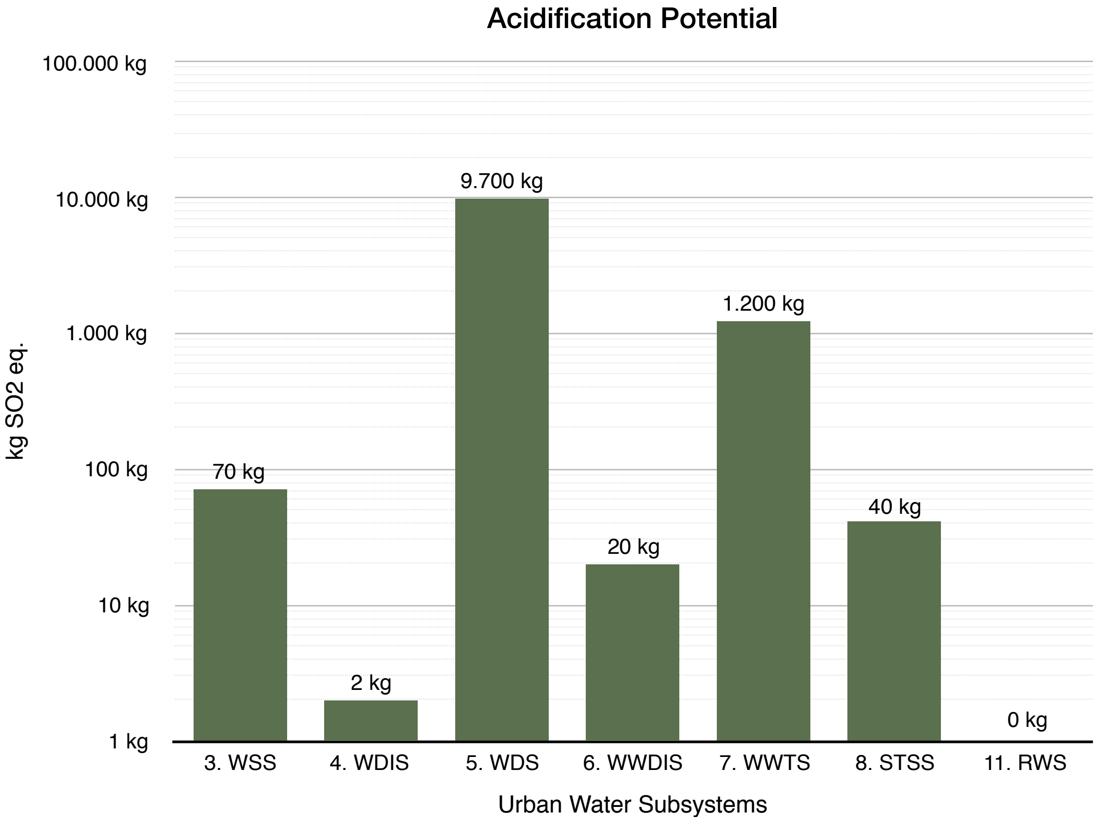

Figure 6.6. Acidification potential (kg SO_2 eq) by each subsystem

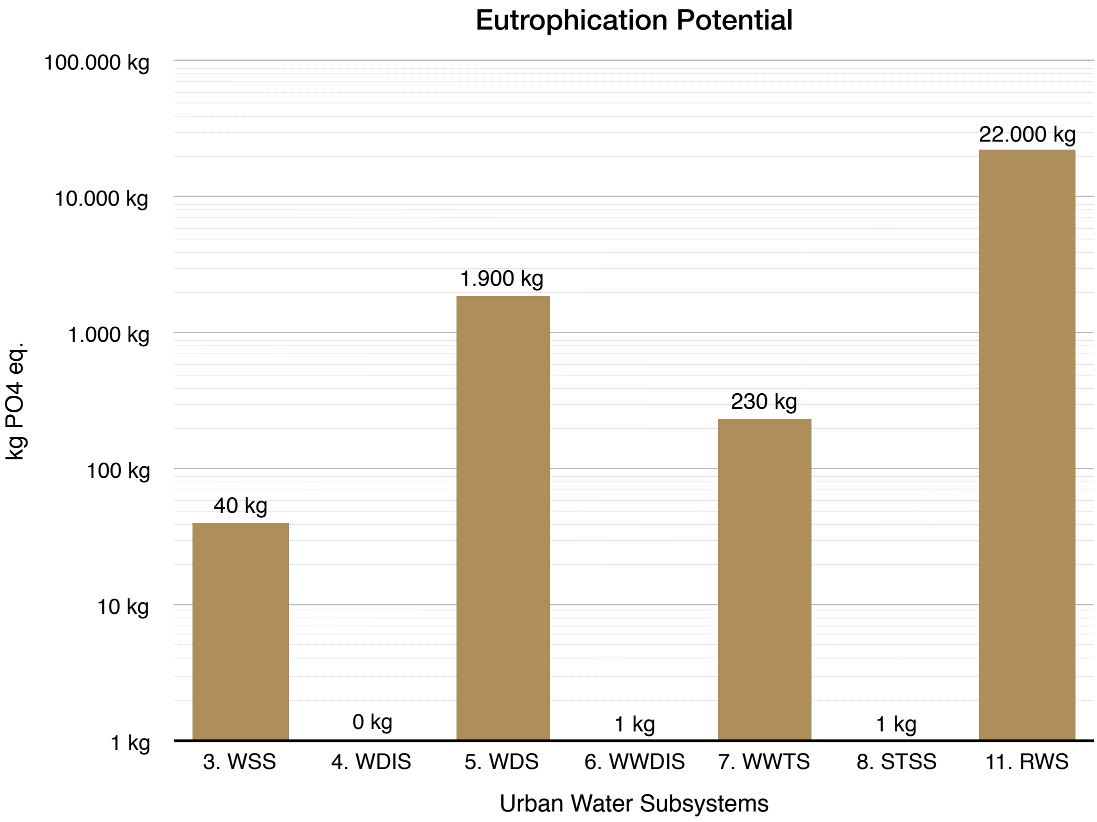

Figure 6.7. Eutrophication potential (kg PO_4 eq) by each subsystem

As mentioned before, the economic assessment has been carried for a 20 years time horizon with constant prices i.e., with no annual inflation considered except for diesel and electricity, as the last 10 years according to INE and IDESCAT, have been 1,5 and 2% respectively above the inflation. To study the economic costs in the different scenarios, several local companies have been consulted and even discussed together the proposed technologies and infrastructures needed while also taking into account the stakeholders involved. The capital costs required by each intervention have been linearly amortised during the economic life cycle that has been considered by the companies. The residual values when the life time of the analysis did not coincide with the economic lifetime has been also considered when this amortisation was done.

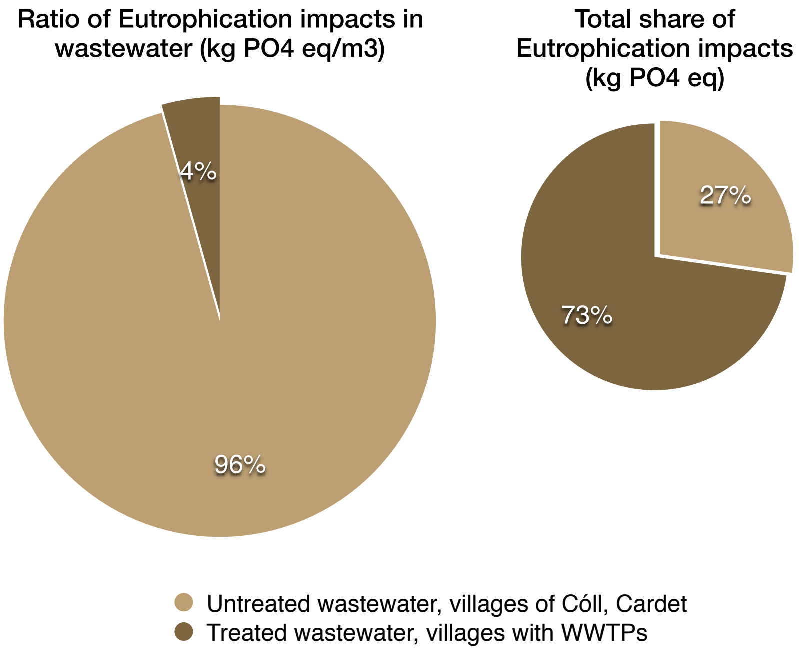

Figure 6.8. Eutrophication potential ratio and share of the wastewater

Operational and maintenance costs have been also obtained from the manufactures' companies and in case that was not possible, it has been estimated as a general rule, considering an annual rate of 2% of the corresponding capital costs.

Three additional scenarios have been considered and calculated but have been not included in the KPIs comparison as no relevant data was extracted. For the obtained results and more details, please see appendix E.

- **Intervention I.9: Fences in the water catchment**

  In this intervention, fences in 4 villages that nowadays have no security in the water catchments were designed. The intervention was calculated assuming that the city council could perform this intervention with their technicians. The result was an investment of around 3.100€ for a fence of 5x5 square meters. The benefits would be a risk improvement in terms of water quality security, which could save much more impacts. As no KPIs are related with this risk improvement, it has not been accounted in the comparison.

- **Intervention I.8: Water valves to eliminate excess of water catchment**

  In order to not by pass the water from the water catchments, a remote controlled valve has been calculated to be closed when no more water is needed. This would eliminate the excess of water catchment but it is incompatible with intervention I1.2 (microturbines) and also does not represent a major improvement (it is also not quantifiable in any of the KPIs). Therefore, it has been also excluded from the analysis.

- **Intervention I.1.1: Solar panels**

  Solar panels where designed to produce energy for the WWTPs, but the costs where much higher (around 1M€) to equal the same production of energy of the microturbines. Therefore, the investment would not have much sense and thus, has been also excluded from the analysis.

Table 6.5 Analysed scenarios

Group	nº	Year	Name	Implementation form
What if scenarios	Sc 0	2015	Status quo	No changes in the UWS are considered.
	Sc 1	2035	Increment of diesel & electricity prices	No changes in the UWS are considered. Electricity and diesel costs have been updated to 2035.
	Sc 2	2035	Total Equivalent People (TEP) growth.	0,5% more annually, 10,5% more at the end of 2035, due to more occupancy from tourism and population growth.
	Sc 3	2035	No leakage, No stormwater treated (I3.1 + I12)	0,5% less annually, during 20 years. As wastewater is less diluted, an increasion of 5% in the N and P removal in the WWTPs is assumed.
Interventions based scenarios	Sc 4	2035	Smart water system (I12)	Investment during 2016. Economic life cycle expectancy of 20 years.
	Sc 5	2035	Microturbines in the upstream (I1.2)	Investment during 2016 for the villages of Barruera, Durro and Erill la Vall. Economic life cycle expectancy of 25 years.
	Sc 6	2035	I16: Pressure valves in the villages of Cóll, Cardet, Barruera, Durro.	Investment during 2016. Economic life cycle expectancy of 25 years.
	Sc 7	2035	I14: Water meters for the demand consumption.	Investment during 2016. Economic life cycle expectancy of 20 years.
	Sc 8	2035	I13: Policies and air filters in-house scale	Investment during 2016, simplification of the analysis assuming an economic life cycle expectancy of 20 years. Assuming 15% of performance for the affected flows in hotels and houses, which correspond to 7,21% less from the total of extracted water.
	Sc 9	2035	I10: Local STWs	Investment during 2016. Economic life cycle expectancy of 20 years.
	Sc 10	2035	I5: WWTPs construction	Investment according to ACA for the construction of the WWTPs of Cóll and Cardet, with the corespondent increasing of linear costs (electricity, diesel and O&M costs). The ratio of water pollution removal has been considered thefor the untreated wastewater
Water supply subsystem improvement			Scenario combination 1	Scenario 4 + 5
Water savings improvement			Scenario combination 2	Scenario 6 + 7 + 8
Performance impovement			Scenario combination 3	Scenario 3 + 9 + 10

6.2.1. Discrete scenarios

Table 6.6 summarises the selected KPIs results (please see appendix C for the absolute obtained values) for the different studied scenarios (evaluated in 2035), normalised respect to the status quo or BAU scenario in 2015. Hence, these values can be also understood as a percentage. The red and orange values indicate the worst results (>1) respect to the baseline scenario, whereas the dark and light green indicators denote progressively better performance (<1). However, for the *water safe sanitation (% of population)* and *nutrient recovery (% of wastewater)* KPIs, the highest values are better than values below 1 and vice-versa. Following this definition, all economic indicators show worse performance due to the increase of the energy prices expected by 2035. Note that according to this, if the first three economic KPIs values of any scenario are below 1.128, 1.049 and 1.357 respectively, this means better performance with respect to scenario 1 which corresponds to the BAU scenario with the increased energy prices. This is due to the fact that all scenarios are also evaluated in 2035.

Respect to the environmental impacts, the three analysed impact categories are evaluated both in the UWS and the UWCS, because in the UWCS the demand subsystem has been excluded as it is by far the greatest environmental. Environmental impacts are mostly variable, in contrast, fix environmental impacts are not so significative. This is specially remarkable in the UWS, as variable impacts are higher compared to fix ones. In this case, the fix impact mostly corresponds to the diesel consumption needed to control and maintain the UWS, which is independent from the water consumed. Because of that, when water flows are affected, all the related KPIs vary almost at the same proportion. The same conclusions can be obtained in relation to the energy consumption due to the energy-carbon nexus, as well as in relation to the chemicals consumption and sludge production (both are assumed linear respect to the water flows, according to ACA and Cadagua considerations).

In general terms, the best scenario is the seventh one corresponding to the water meters effect (when water pricing instruments are applied with a variable price instead of the low fix amount payed nowadays by the users). As a 15% of reduction of all water flows is expected, a similar reduction is also expected in terms of environmental costs, as well as energy, chemicals and sludge production. Even in this scenario a significant capital expenditure is required (and the annual O&M related costs), the reduction of water flows implies a reduction of the overall costs (around 5% less respect to the BAU scenario in 2035), including users' costs. Similar results are obtained when water filters are applied in the in-house scale, which means an overall reduction of 7,21% of the water flows. This is also a low cost measure that also shows the best performance in terms of total economic costs for 2035.

Regarding the total economic impact, the third scenario represents a reduction of the costs, where 10% of the reduction of leakage is assumed and no stormwater is treated in the WWTPs (which represents 11,4% of the total wastewater treated). As it is a what if scenario it only shows the economic savings by achieving this scenario in 2035, which would represent around 7000€ annually from that year on. With these saved costs, it is not very feasible to do this improvement in economic terms, although it certainly is from the environmental point of view specially due to the nutrients efficiency removal of the WWTPs. It is assumed that the removal of nutrients efficiency will be increased around 5% because of the lesser dilution of the wastewater. This affects the eutrophication impacts at a higher proportion.

Regarding the global warming potential impacts, number 5 scenario, where microturbines are installed in the upstream water resources, is the best one. All the generated electricity is assumed to be used in the WWTPs and the rest for the demand system, which implies a reduction of emissions up to 63,2% in the UWCS (0.366)[31]. This intervention not only improves significantly the CO2 emissions but it is also economically worth it due to the electricity saved costs, making this scenario one of the best future interventions. This is also specially beneficial owing to the expected increase of energy prices, while it assures a constant renewable energy source, independent from the grid. Microturbines are also the best solution regarding the acidification potential, with a reduction up to 0.077 and 0.810 in the UWCS and the UWS respectively, as it is caused mainly by energy consumption.

Regarding the eutrophication potential impacts, the best scenario is again number 3, thanks to the minor dilution of the wastewater. In the same terms, scenario 10 where new WWTPs are modelled according to ACA plans, a significant reduction of eutrophication impacts is achieved thanks to the N and P removal (assumed equal to the average of the rest of WWTPs, i.e., 67 and 68% respectively). In this case, a value of 0.789 is obtained, while the AP grows up to 1.004 and the GWP remains almost the same thanks to the saved N_2O and CH_4 emissions of the treated wastewater. In contrast, the operational costs are considerably increased, giving a total economic value of 1.322 (almost 20% more than the BAU scenario in 2035) because only 25 years of life cycle has been considered, according to the followed study. This scenario is also useful to understand the consequences that additional green treatments (after the WWTPs) would produce regarding the environmental impacts, which should be studied in further researches.

A local sludge treatment wetland (STW) is implemented in the current villages that have a WWTP in scenario 9. This also represents a good intervention in economic and environmental costs, as the total costs could be reduced up to 13.000€ annually, corresponding to the 0.074 of difference between the baseline scenario in 2035. In this scenario, the agricultural usage of the sludge[32] is also modelled, accounting for the avoided impacts of the saved fertilisers that would be needed to produce if this sludge was not used. These avoided impacts represent one third of the total saved CO2 of this scenario and with more proportion for the EP and AP impacts. Moreover, this intervention also reduces the management risks of transporting the sludge in a centralised sludge treatment plant. Neither the GWP nor AP show a great reduction but, considering that the diesel corresponds to 5% of both impacts in the UWCS, a 2% of reduction (3% in total) in both cases is quite remarkable. Similar results in terms of GWP and AP impacts are shown in scenario 4. In this case, thanks to the ICT technologies in the water supply subsystem, a reduction of more than 3%

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[31] Note that the rest of CO_2 emissions are consequence of the N_2O and CH_4 emissions of wastewater, chemicals, etc. As mentioned, no environmental costs are assumed in the operational phase, and even this work does not count the emissions from the construction and demolition of the system's assets, can be almost neglected in this case (in microturbines LCA studies show values less than 5g CO_2 eq/kWh, without producing greater impacts like land occupation due to a dump reservoir).

[32] Direct land application is considered mainly due to the domestic origin of the sludge (and thus, no other treatments would be needed). No emissions have been also accounted in the process of land application is considered.

Table 6.6 - Summary of the KPIs results

Scenarios evaluated in 2035	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario com. 1	Scenario com. 2	Scenario com. 3
Key Performance Indicator	**+ Energy prices**	**+ TEP**	**– Runoff – Leakage**	**Smart water sys.**	**Micro turbines**	**Pressure reduction**	**Water meters**	**Policies**	**Local STW**	**New WWTP**	**En. + water supply im.**	**Water demand im.**	**Perfromance im.**
Total UWS costs (€)	**1,128**	**1,165**	**1,088**	**1,105**	**1,059**	**1,127**	**1,180**	**1,113**	**1,057**	**1,322**	1,036	**1,163**	**1,210**
Capital + Opex fix costs (€)	1,049	1,049	1,049	**1,064**	**1,092**	**1,053**	**1,156**	**1,063**	**1,139**	**1,129**	**1,106**	**1,174**	**1,218**
Operational variable costs (€)	**1,357**	**1,500**	**1,200**	**1,227**	0,964	**1,341**	**1,247**	**1,260**	**0,819**	**1,882**	**0,833**	**1,133**	**1,187**
Economic water costs (€)	1,000	1,000	1,000	1,000	1,000	1,000	**8,685**	1,000	1,000	1,000	1,000	**8,685**	1,000
Users' costs (€)	**1,170**	**1,262**	**1,153**	**1,170**	**1,170**	**1,157**	1,038	**1,107**	**1,170**	**1,170**	**1,170**	0,962	**1,153**
GWP (kg CO_2 eq)	1,000	**1,104**	**0,927**	0,996	**0,872**	0,985	**0,851**	**0,928**	0,995	0,999	**0,868**	**0,764**	**0,920**
AP (kg SO_2 eq)	1,000	**1,105**	**0,802**	0,997	**0,810**	0,985	**0,850**	**0,928**	0,994	1,004	**0,807**	**0,764**	**0,800**
EP (kg PO_4 eq)	1,000	**1,105**	**0,689**	0,999	0,983	0,984	**0,850**	**0,928**	0,999	**0,789**	0,982	**0,762**	**0,477**
GWP UWCS (kg CO_2 eq)	1,000	**1,101**	**0,863**	0,963	**0,366**	0,985	**0,856**	**0,931**	0,955	0,989	**0,330**	**0,771**	**0,807**
AP UWCS (kg SO_2 eq)	1,000	**1,102**	**0,887**	0,972	**0,077**	0,984	**0,854**	**0,930**	0,954	1,036	**0,049**	**0,768**	**0,878**
EP UWCS (kg PO_4 eq)	1,000	**1,105**	**0,732**	0,999	0,989	0,984	**0,850**	**0,928**	0,999	**0,772**	0,988	**0,762**	**0,502**
Total Energy UWS (kWh)	1,000	**1,104**	0,993	0,999	1,000	0,985	**0,851**	**0,928**	0,998	1,004	0,999	**0,765**	0,994
Energy UWCS (kWh)	1,000	**1,093**	**0,897**	0,983	1,000	0,986	**0,867**	**0,936**	0,968	**1,058**	0,983	**0,789**	**0,922**
Chemicals (kg)	1,000	**1,105**	**0,894**	**0,598**	1,000	0,985	**0,850**	**0,928**	1,000	1,014	**0,598**	**0,763**	**0,908**
Residues & Sludge (kg)	1,000	**1,105**	**0,884**	1,000	1,000	0,984	**0,850**	**0,928**	1,000	1,039	1,000	**0,762**	**0,923**
Water footpirnt (m3)	1,000	**1,105**	**0,900**	1,000	1,000	0,985	**0,850**	**0,928**	1,000	1,000	1,000	**0,763**	**0,900**
Water system leakages (%)	1,000	1,000	**0,123**	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	**0,123**
Water safe sanitation (% pop.)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,026	1,000	1,000	1,000
Nutrient recovery (% wastewater)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,019	1,000	1,000	1,000

corresponding also to diesel consumption can be achieved. Again, this is also remarkable when comparing it with the total diesel environmental impact. This scenario is also positive in economic terms, which can be reduced mainly thanks to the savings from the personal costs of the City Council of La Vall de Boí and the water quality controls of the Ministry of Health. This scenario particularly demonstrates that green infrastructure can be competitive in comparison with traditional solutions, demonstrating that economic growth can be decoupled from the environmental impacts.

On the other hand, scenario 6 (water pressure valves) only represents a reduction of 0.015 of the environmental impacts, even though water volumes decrease at the same proportion while no economic costs are almost affected. This is caused by the very low rate of water flows decreasing that have been considered (only a secure value of 7% of the water flows from Barruera, Cóll, Cardet and Durro). Further research is needed regarding this scenario to properly model more accurately the implications that this reduction pressure valves could cause, as it is expected to reduce more than the secure value modelled. Research and examples based on real study cases are needed, as the results not only depend on the technical issues, but also, on the social behaviour in terms of water usage. Barruera can also be studied as a first pilot case as it is clear that a reduction pressure valve would be needed. As expected, scenario number two is the worst scenario as an increasing of 10,5% of TEP is considered. As mentioned, the environmental and energy KPIs related vary according to this percentage in the UWS and similarly with less linearity in the UWCS.

Finally, in order to give guidelines to the stakeholder of the present study, green cells have been represented in table 6.6 which indicates the best three values per each obtained KPI. Hence, for instance, if the ACA wants to reduce the overall GWP impacts of the UWS, they should prioritise first scenarios 3, 5 and 7. The relation of kg CO_2 eq. saved / euros invested can be also useful.

As mentioned, some of the results show little benefit with respect to the current situation and thus arises the need of applying more than one intervention at the same time, everywhere in the system and at all spatial scales (from the in-house scale to a global scale). This justifies the importance of the wide holistic approach adopted in this work in both the analysis and in the interventions design process to achieve a sustainable UWS. Also because of this, the combination of scenarios has been described in the following section. Moreover, even some interventions deal with solving low relative impacts (such as all interventions that aims to reduce the diesel costs), the proposed solutions are also needed because provably there is no other way to mitigate them. In these specific cases, only electrical cars could be a feasible solution.

In other words, it demonstrates in a quantitative way the multi-objective problem of sustainability. Even when better results are obtained in a single intervention, it also points out the necessity of this multi-dimension approach in the application of interventions. This is because there is no sense of investing big amounts of money in one intervention without doing it in the social dimension to also reduce the water flows (which will require much less investment while it will also potentially impact positively). This means that sustainability cannot be achieved only with a technological change, but also with a social change. Therefore, switching to a sustainable water management is not only to try to find the way to keep the old culture of water.

6.2.2. Combination of scenarios

A combination of scenarios has been considered as all of them are compatible and can be implemented together. Hence, the following spider diagrams represent the results of this combination of scenarios in comparison with the baseline scenario (status quo in 2015), represented with a dot line in these diagrams. As can be seen in these figures and in the KPIs' table, all combinations show a significant reduction of all KPIs, generally above 10%, which mean a multiobjective solutions.

The combination of scenarios derive from the assessment of the status quo, where the energy requirements and their corresponding GWP and AP impacts have been identified as the largest environmental impacts. Therefore, interventions have been focused on solving this aspect. Also, special focus has been done to reduce the EP impacts by treating wastewater. In respond to this two main causes, while keeping always feasible solutions that could not significantly compromise the economical dimension, 3 main approaches have been considered:

1. **Implementing ICT and renewable energy sources ➔ Energy and water supply improvement scenario:**
   Is the best combination to improve GWP and AP impacts of the UWCS and hence, UWS impacts too. It also improves the consumption of chemicals while reducing the overall costs mainly thanks to the microturbines.

2. **Reducing the water demand ➔ The water demand improvement scenario:**
   It reduces significantly the overall flows thanks to the reduction of water demand. This scenario is specially remarkable as it shows the potential of social policies and other non-infrastructure instruments that can also achieve a more sustainable system. It also provides funds to improve the system through water pricing and thus, internalising the economic flows of the system.

3. **Installing green and grey technologies lacking in the system ➔ The system performance improvement scenario:**
   It shows the impacts of implementing the actual missing infrastructure (WWTPs) and a more reasonable sludge treatment system. It improves the leakage and the stormwater treated as well. All environmental impacts are significantly reduced and specially the eutrophication impacts, which are reduced by 50% in the UWCS. In contrast, as expected, this scenario needs more investment than any other one with more than 14.000€ annually (respect to the current costs of 177.000€).

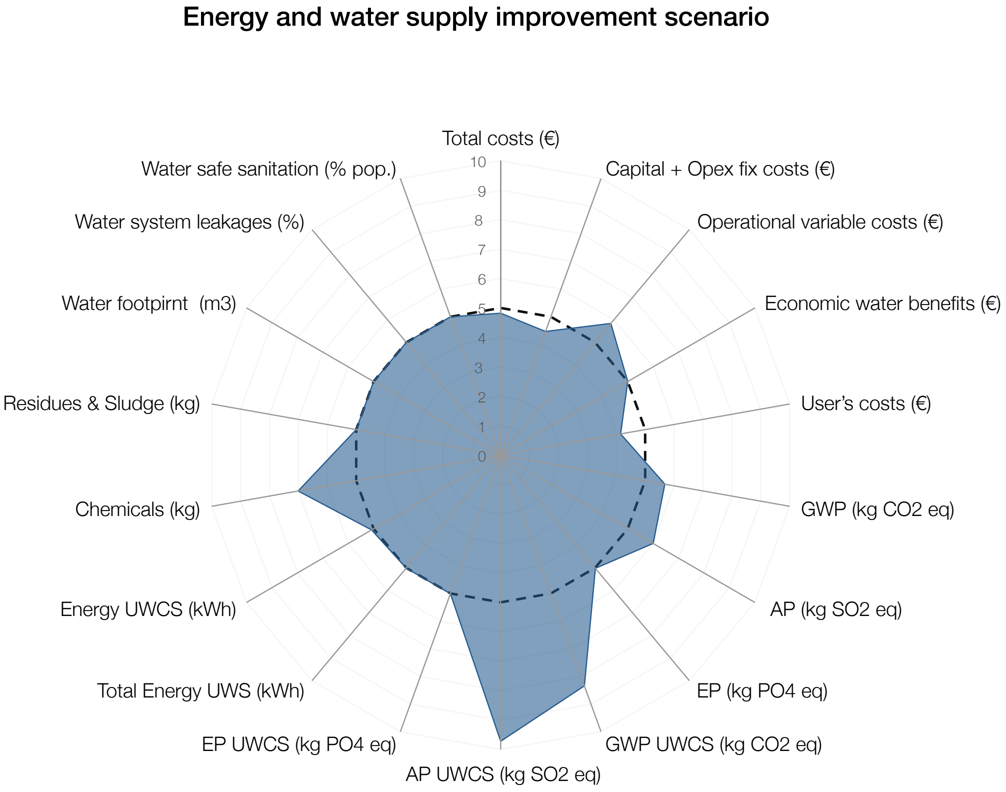

Figure 6.9. Results of the first combination of scenarios

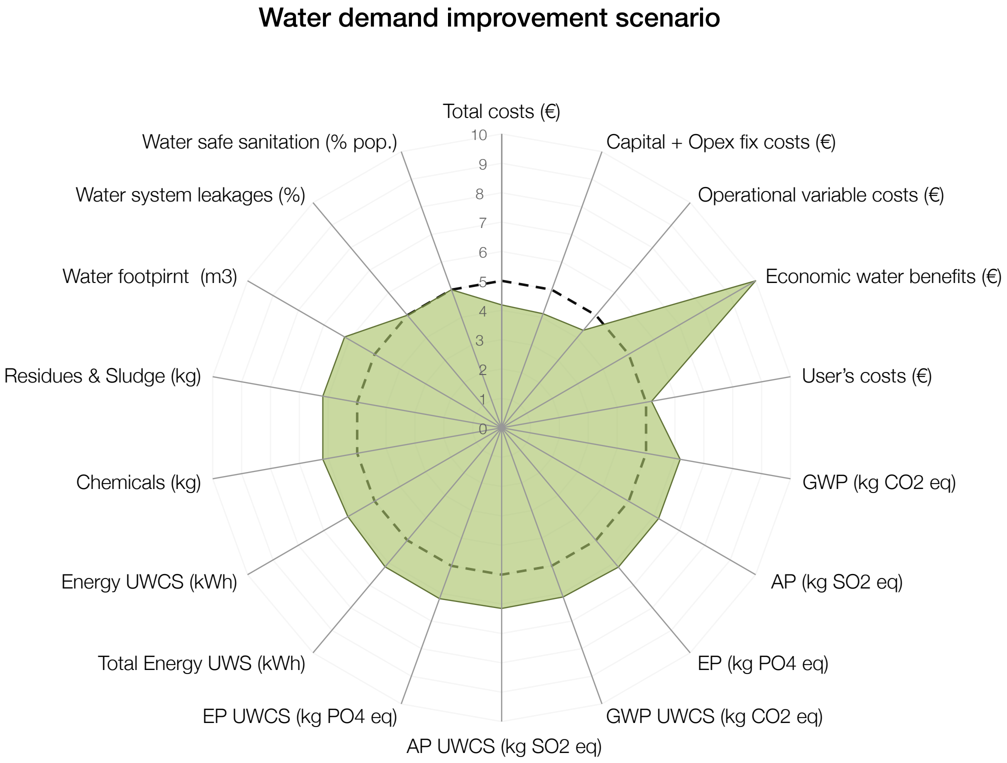

Figure 6.10. Results of the second combination of scenarios

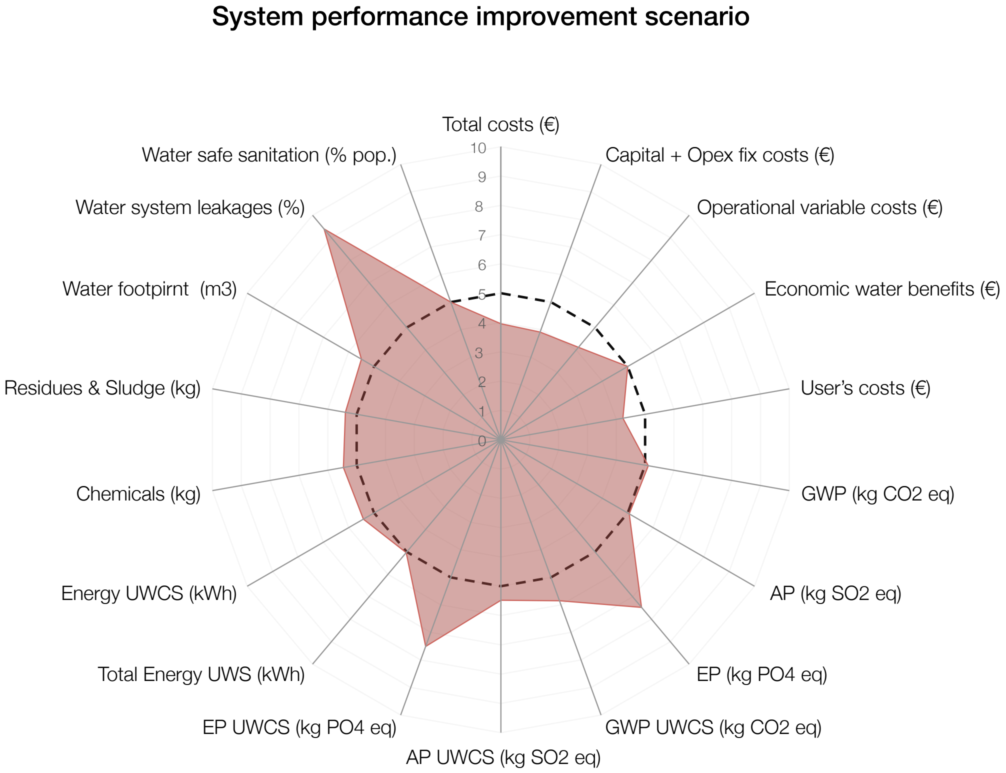

Figure 6.11. Results of the third combination of scenarios

7. Discussion

7.1. Comparison of the results

The economic results of this study can be contextualised by following the study of the Barcelona Chamber of Commerce[33], where the unitary costs of water resources are divided in Catalonia in two groups: upstream costs (from catchment to demand systems) and downstream costs (from demand to disposal systems). This costs can be seen in the following table, comparing the case of Catalonia (for the years 2009 and 2015) with the obtained results of this study (mid 2015/16)

Table 7.1 - Comparison of the urban water cycle costs of Catalonia - La Vall de Boí

Urban water cycle costs	**Catalonia**			**La Vall de Boí**	
Monetary costs in €/m^3	**Real income in 2009 (€/m^3)**	**Real costs in 2009 (€/m^3)**	**Estimation of costs in 2015 (€/m^3)**	**Real income in 2015 (€/m^3)**	**Direct costs in 2015/16 (€/m^3)**
Guarantee of supply (upstream O&M costs)	1,15	1,23	1,49	0,11	0,06
Guarantee of treatment (downstream O&M costs)	0,60	1,34	1,52	0,23	0,36

According to the calculations done in the status quo scenario, the economic flows received (which do not coincide with the user's payed amounts, as these include 10% of taxes) to the competent authority are in overall are 0,3442€/m^3 (0,3787€/m^3 for the users). From this income, 0,1125€/m^3 is received for the upstream costs while 0,2317€/m^3 is received to cover the downstream costs. This costs are far from the Catalonia estimated upstream and downstream O&M costs for 2015, that were expected to be 1,49 and 1,52 €/m^3 respectively. This difference can be explained provably for two reasons: i) because only direct costs are accounted in the present study (so does not account the indirect costs such as other municipality's costs or the ACA costs, only water expenses marginal costs); ii) because of the simplicity of the UWS studied when compared to the complexity of UWSs in bigger cities.

Even this significant difference, within the UWS of La Vall de Boí, the difference is not that much between income and outcome costs. Actually, the actual users' payments could eventually cover the municipality's costs but not the treatment costs. This situation of La Vall de Boí is also similar to the catalan problem regarding the difference between costs and investments, with a 44,8% of the costs covered in 2009, similar to the 63,9% of coverage in La Vall de Boí. All in all, this numbers put in context again, the non internalisation of the UWS' costs and the urgent necessity to establish water pricing in order to at least, internalize the economic dimension of the studied UWS.

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[33] *Els recursos hídircs de Catalunya,* Cambra de Comerç de Barcelona, which made the data provided based on the report "*Pla de Gestió i del Programa de Mesures".*

7.2. Life cycle costing

In this study, the depreciation has been also take into consideration according to the available data basis of ACA's and the city council's infrastructure. However, it has not been presented in the chosen KPI values as it does not change within the studied scenarios.

Table 7.2 summarises the obtained data, without including the water pipes from the distribution system due to the lack of data. The direct costs of the PE water pipes have been estimated form the WSS have been calculated with the length of the pipes multiplied with the price per meter (ITEC, 2015). The rest of costs are provided by the stakeholders and other additional calculations. The economic life cycle has been assumed with 50 years in order to calculate the annual depreciation, assumed linear over the years. Hence, from a LCC perspective, the depreciation results (around 60.000€/year) show a relative importance when comparing with the UWCS operational costs (177.300€/year), which mean 1/3 of the operational costs and 1/4 of the operational and depreciation costs. As it is evident, when comparing with the UWS costs, the relative importance of depreciation costs is not that high (719.800€)/year). This is remarkable, as in contrast, from a LCA perspective, the construction and demolition phases are not as important as the operational phase according to many studies (Friedrich and Buckley, 2001; Lundie Gregory and Beavis, 2004, Raluy et al., 2006; Muñoz and Rodríguez Fernández-Alba, 2008).

Table 7.2 - UWS Assets La Vall de Boí

Subsytem	Infrastructure	Location	Value	Subsystem Depreciation
3. Water Supply Subsystem	PE Ø90 mm water pipes of water catchments	All villages	166.841,07 €	16.017,03 €
	WTP	All villages	634.010,40 €	
4. Water distribution subsystem	PE Ø110 mm water distribution pipes	All villages	unknown	
6. Wastewater distribution subsystem	PVC Ø300 mm wastewater pipes	All villages	unknown	
7. Wastewater treatment subsystem	Main folds sewage pipes	All villages	unknown	
	WWTP	WWTP Boí	1.262.130,00 €	43.515,24 €
		WWTP Barruera	564.950,00 €	
		WWTP Durro	348.682,13 €	
Lifetime expected	50	years	2.976.613,60 €	59.532,27 €/year

7.3. Economic - environmental relation assessment

From the specific environmental and economic results of the *status quo* assessment, other conclusions can be obtained. Figure 7.1 shows the relations between the economic and environmental costs per unit of the different studied resources in the UWS (grey arrows). With this information, a third relation between the environmental costs and the economic costs (green arrow) can be easily obtained (€/kg impact), which is represented in Figure 7.2.

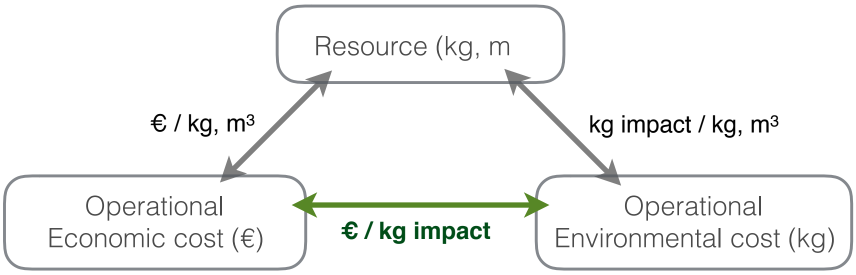

Figure 7.1. Relation between the studied variables

This means that per each euro spent in electricity, 3,28 kg of CO_2 eq. will be generated. With water consumption, two values should be remarked: in the one hand, the UWS environmental costs of the water consumption, including the impacts of heating water divided by the total costs of the energy consumption and the water consumption give a value of 2,49 kg of CO_2 eq. per euro spend. But social behaviour is also important to take into consideration, as when water is a cheap resource, people would also consume warm water without taking into account that much the cost of energy, but rather could also consume it due to the cheap water price. That is why, in the other hand, a 11,00 kg of CO_2 eq. is obtained when dividing the total environmental UWS costs for the water price only. Needless to say that to model this behaviour is a difficult task that it is more

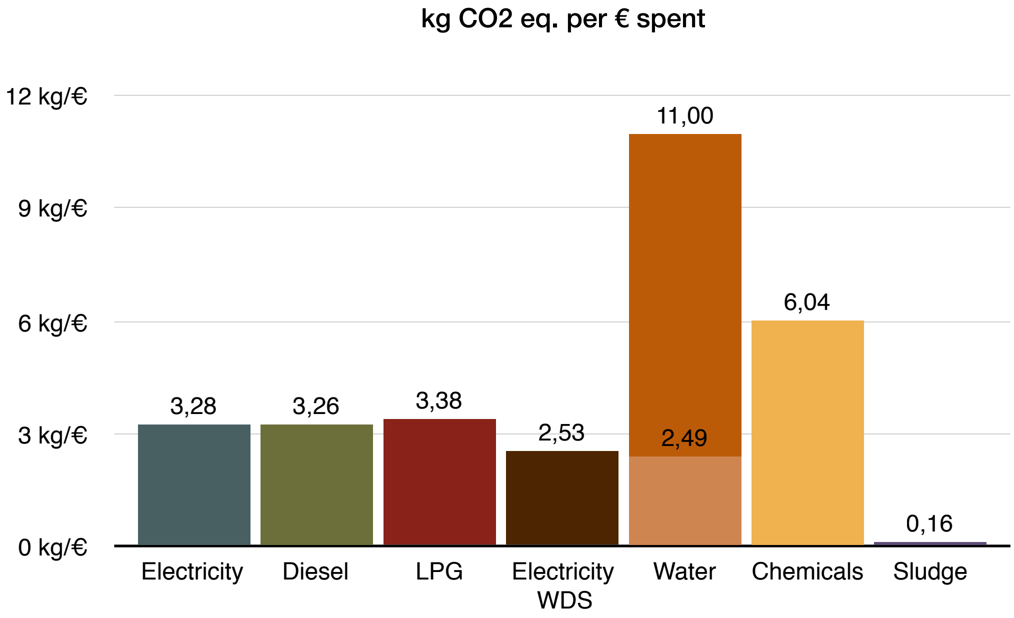

Figure 7.2. Relation between the kg of CO_2 produced per euro of the different UWS' resources

complex than giving these two values, but give a first quantification attempt. Hence, if a mean value is considered, understanding that social behaviour can be in half way of the two described, a 6,75 kg of CO_2 eq. is obtained, which is still a higher value compared with the others.

Chemical products also generate a high value of 6,04 kg of CO_2 eq. per euro spent. Particularly, sodium hypochlorite has a higher value, as it generates 9,85 kg of CO_2 eq/€. For this reason, when the intervention I.12 was designed, from a economic perspective there was no willingness to improve the sodium hypochlorite consumption, as it costs annually around 1.300€ and thus, it does not lead to important savings. In contrast, from a environmental perspective it makes much more sense (note that chemicals contribute with 6% of the overall GWP), and thus, policies are needed in these cases to incentive an efficient consumption.

All in all, this relationship analysed in the proper context highlights where environmental impacts are easy to generate as the lower price of the products is leading nowadays to an excess of environmental impacts (independently from the subsystems or stakeholders that is assuming the economic cost). Hence, it shows up where efforts should be spent in taxes or policies. To put this numbers in the proper context, it is worth to mention that the overall annual impacts of energy consumption for a normal user (3700kWh, IDAE) produces 810 kg CO_2 eq while according to this results, water consumption in La Vall de Boí generates, in average and per user, 2850 kg CO_2 eq. All in all, the relationship here explained represents a simple way to compare product prices and environmental impacts, understanding where externalities should be *more* internalised.

7.4. Sensibility analysis

The results of a LCA study are never unique or unequivocally as are normally very dependent on many variables. For this reason, special emphasis has been done in this work in order to present the results and methodology in a transparent and consistent way. As a result, the life cycle inventory data has been pointed out in this work, for the same reason this sensibility analysis is needed in order to understand the variability of the presented results. Hence, the main assumed variables in the study has been changed to establish, this way, a range of results, giving orders of magnitudes of the results.

In the following lines, four key variables are identified, showing the results of the assumed variations and then compared with the obtained results at the end of this section. Finally, the calculation of the PE pipes of the WSS have been also presented to also understand the magnitude of the produced impacts.

7.4.1. Analysis of the key variables of the case study

- **Water temperature of the demand subsystem**

The LCI and LCIA results showed that the demand system (i.e., the energy required for heating water in the in-house scale) is by far, the largest contributor regarding the main economic and environmental impacts. Therefore, it is important to analyse what are the effects of changing one degree in the water temperature. As it has been already mentioned, two water checking were done for this study in May 2016 in Barruera and Cóll, with a result of 13ºC, while the considered study is calculated with a water temperature of 12ºC. Even this 1ºC of variation, it has been assumed as a valid approximation, as many variables can easily turn the water temperature to 12ºC or even less in winter periods. Because of this lack of a more consistent data (in all villages and monitored during one year, at least), this sensibility analysis has been considered in order to understand what are the range of possible results.

The heating energy, as it is obvious, is linearly dependent on the temperature changes. This way, by simply multiplying the results of 1ºC by the degrees of difference and summing or subtracting them to the results of 12ºC, a range of results can be obtained. For this analysis, a maximum difference of ±3ºC of the mean annual temperature has been assumed due to, for instance, the difference on the water temperature during the summer and winter periods. Thus, respect to the 12ºC considered in the case study, the range of results from 9 to 15ºC are as shown in table 7.3.

Table 7.3 - Results of the WDS according to the demand water temperature

Energy ratio	+1ºC	15ºC water demand	9ºC water demand
LPG (kWh)	5.388 kWh	1.444.059 kWh	1.476.387 kWh
Electricity (kWh)	4.789 kWh	2.342.552 kWh	2.371.288 kWh
Total energy (kWh)	10.177 kWh	3.786.611 kWh	3.847.675 kWh
Users' costs (€)	1.094 €	380.469 €	387.036 €
GWP (kg CO_2 eq)	4.165 kg	1.523.381 kg	1.548.371 kg
Acidification (kg SO_2 eq)	29 kg	9.644 kg	9.820 kg
Eutrophication (kg PO_4 eq)	5 kg	1.840 kg	1.872 kg

- **Total Equivalent Population**

For the same reasons exposed regarding the water demand temperature, the total equivalent population (TEP) is also a key factor as the demand subsystem inflows/outflows are the result of multiplying the energy requirements per capita by the TEP value. In the study, a 2100 has been considered according to the Statistical Institute of Catalonia (IDESCAT). Even that, other results have been obtained but have not included in the analysis as they were considered as not as optimal as the calculated one.

Hence, according to the results of other assumptions of IDESCAT, a 1900 TEP can be obtained (please see TEP analysis section for more information). In contrast, 2400 TEP can be obtained by considering the water flows and the permanent and expected seasonal users (and thus, population by multiplying by an average of 2 people/user according to the average of the valley).

Table 7.4 - Results of the WDS according to the TEP considered

Total Equivalent Population	2100 (from the calculus)	1900	2400
LPG (kWh)	1.460.223 kWh	1.321.154 kWh	1.668.826 kWh
Electricity (kWh)	2.356.920 kWh	2.132.451 kWh	2.693.623 kWh
Total energy (kWh)	3.817.143 kWh	3.453.606 kWh	4.362.449 kWh
Users' costs (€)	383.753 €	347.205 kWh	438.575 kWh
GWP (kg CO_2 eq)	1.535.876 kg	1.389.602 kWh	1.755.287 kWh
Acidification (kg SO_2 eq)	9.732 kg	8.805 kWh	11.122 kWh
Eutrophication (kg PO_4 eq)	1.856 kg	1.679 kWh	2.121 kWh

- **Annual water volumes of the UWS**

As presented in the water flow analysis section, the WSS and the WWTS water flows of the UWS determine the obtained results of this work (the WDS flows are calculated as a percentage of the WSS flows). Also, considering that the economic and physical resource inflows and outflows principally vary with the water flows, determining them precisely is a key factor. Despite of this, there is a build-in variability of this UWS water flows, specially due to the tourism affectation of the case study.

In this study, the water flows considered in the WSS are 457 hm^3 and 427 hm^3 for the WWTS (note the 93,45% of difference between inflows and outflows). However, considering the historic data for the last 5 years and the ACA calculations of the WWTS flows, a range of flows can be obtained from 402 hm^3 (in 2011) to 484 hm^3 (in 2015, from January to December). Regarding the WDS water flows, no historical data is available because, as mentioned, the only registers available started in June 2015 until the end of this work in May 2016. In response to this lack of data, the same relation of inflows and outflows can be assumed in order to perform this sensibility analysis. Summarising, the range of water flows considered are as follows:

Table 7.5 - Variability of the annual water flows in the UWS of La Vall de Boí-1

Subsystem	Considered in the calculus (hm^3)	Minimum (2011, hm^3)	Maximum (2015, hm^3)
Water Treatment Subsystem	457	430	518
Wastewater Treatment Subsystem	427	402	484

It is worth to mention that the results are not only affected by the volume of water flows, but also, regarding the WWTS, the share of these flows among the three WWTPs, as they have different operating systems, and therefore, different inputs and outputs too. Studying the share of the treated water volumes in 2011 and 2015 compared with the present analysis, it has been concluded that this share is almost constant, with 77% of the water flows treated in the WWTP of Boí, 14% in the WWTP of Barruera and 9% in the WWTP of Durro. Therefore, the variations of water flows considered in this sensibility analysis can be modelled with the *calculation model* build for this work as they represent a realistic results.

- **LCA background data**

In this work, the background data of the LCA carried has been provided by the DMM, which refer to the Ecoinvent 2. To adapt the DMM to the case study, the provided electricity impacts have been changed for the electricity mix in Spain for low and medium voltage production at grid. The data basis chosen for these impacts is also the Ecoinvent 2 with CML-IA baseline to match with the DMM background data version. For this sensibility analysis, a newer version of Ecoinvent (version 3) with CML-IA baseline has been considered, as it is notably different form the previous version. In contrast, the Ecoinvent 2.2 version have similar results: regarding the GWP, for instance, the impacts are 615 and 536 g CO_2 eq./kWh for low and medium voltage compared to 603 and 526 g CO_2 eq./kWh respectively for version 2.

As can be seen in table 7.6, the differences between versions 2 and 3 of Ecoinvent are significant when comparing GWP and Acidification impacts, while are almost negligible regarding the Eutrophication impacts. Particularly, acidification impacts are almost doubling in the newer version respect to version 2, while the differences are fewer in GWP for medium voltage. In contrast, for low voltage the differences are much bigger. This is also an important issue because, as it has been already pointed out, the main impacts derive from the demand subsystem, i.e., in part due to low voltage electricity consumption. Hence, for the results obtained in the current work, the GWP are significantly higher due the higher values of version 2, but also, due to the even more difference between medium and low voltage.

Table 7.6 - Impacts per kWh of electricity sourced from the Spanish grid-1

	Medium voltage		Low voltage	
Impact category	**Ecoinvent 2**	**Ecoinvent 3**	**Ecoinvent 2**	**Ecoinvent 3**
GWP (kg CO_2 eq)	0,526	0,481	0,603	0,492
Acidification (kg SO_2 eq)	4,950E-03	2,840E-03	5,720E-03	2,900E-03
Eutrophication (kg PO_4 eq)	9,460E-04	1,070E-03	1,170E-03	1,100E-03

- **UWS assets: PE water pipes**

This thesis has been focused in the operational phase of the UWS in La Vall de Boí, as it is the most important phase in terms of LCA impacts (Friedrich and Buckley, 2001; Lundie Gregory and Beavis, 2004, Raluy et al., 2006; Muñoz and Rodríguez Fernández-Alba, 2008). The study of the assets and their impacts is a common approach in UWS studies. Brattebø, Venkatesh, Ugarelli and colleagues assessed Oslo's UWS while Petit-Boix and colleagues estimated the environmental impacts of the Spanish sewage pipes.

However, as mentioned, the water pipes materials have a relative significance impacts that should be taken into account according to Amores et al., 2013, for both the water and wastewater distribution network. Due to the lack of data and a proper inventory of the pipes from the city council, this task is much more challenging that would need future researches. Despite of this fact, the length of the PE water pipes was determined for the WSS (which belong to the water catchment subsubsystem) in order to design the microturbines intervention. Knowing the diameter (90 mm) and the weight per meter according to the PE fabricants (3,16kg/m) and for 1,6MPa of maximum pressure, the environmental impacts of the construction phase can be determined thanks also to the DMM. To put this numbers into a proper context, dividing the impacts per the expected lifetime of a PE pipe (which is normally assumed to be 50 years, even studies show that this value can be significantly higher with normal operational conditions) and then comparing with the overall environmental impacts, the results of table 7.7 can be obtained.

This results show a low relative impacts compared to the UWS and UWCS results, in contrast with the mentioned authors. This is provably because the calculated impacts only corresponds to the PE pipes of the WSS as well as does not consider the whole life cycle perspective of the impacts. The values only covers the impacts from the pipes fabrication, excluding the construction phase which can not be neglected. For more and detailed information, please see publications of the mentioned authors. All in all, the presented results pretends to simple evaluate the relative impacts of water pipes respect to the obtained values of this work. Further researches should be done in order to properly take into account these impacts.

Table 7.7 - Impacts of the PE water pipes of the WSS

	Length (m)	Weight (kg)	GWP (CO_2 eq)	AP (SO_2 eq)	EP (PO_4 eq)
WSS PE pipes	18.337	57.945	135.591 kg	37 kg	494 kg
for 50 years of lifetime			2.712 kg	1 kg	10 kg
% respect to the UWS			0,16%	0,01%	0,04%
% respect to the UWCS			1,29%	0,05%	0,04%

7.4.2. Comparison of results of the sensibility analysis

Once the key variables of the sensibility analysis are presented, the following table summarises with the most relevant KPIs, the results of this analysis. The results have been normalised respect to the current calculus (presented numerically in the first column), and marked with bold the most different ones.

As a conclusion, according to the results, the water temperature does not influence that much on the results (±1%), while the TEP considered can vary the results with ±10% despite the energy consumption that can vary up to 20% more. Water flows show similar variations (-6%, +13%) and Ecoinvent newest data basis affect principally to the acidification impacts. As mentioned, these impacts are almost half of the obtained results due to the impact category for electricity mix, which is also half of the value of Ecoinvent 2 considered in the analysis. GWP, in this case, is 10% reduced.

Table 7.8. - Sensibility analysis results

	Current calculus	15ºC water	9ºC water	1900 TEP	2400 TEP	Water 2011	Water 2015	Ecoinvent 3
Capital + Operational fix costs (€)	131.700	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Operational variable costs (€)	45.500	1,00	1,00	1,00	1,00	0,94	1,13	1,00
User's costs (€)	542.500	0,99	1,01	0,93	1,10	0,96	1,09	1,00
GWP (kg CO_2 eq)	1.746.000	0,99	1,01	0,92	1,13	0,94	1,13	**0,90**
AP (kg SO_2 eq)	11.100	0,99	1,01	0,92	1,13	0,94	1,13	**0,58**
EP (kg PO_4 eq)	24.300	1,00	1,00	0,99	1,01	0,94	1,13	1,00
Electricity (kWh)	1.714.200	0,99	1,01	**0,87**	**1,20**	0,94	1,13	1,00
Fossil fuels (kWh)	2.395.600	0,99	1,01	0,94	1,09	0,94	1,13	1,00
Total Energy (kWh)	4.109.800	0,99	1,01	**0,91**	1,13	0,94	1,13	1,00
Chemicals (kg)	3.400	1,00	1,00	1,00	1,00	0,94	1,13	1,00
Residues & Sludge (kg)	741.800	1,00	1,00	1,00	1,00	0,94	1,13	1,00
Water footpirnt (m^3)	457.000	1,00	1,00	1,00	1,00	0,94	1,13	1,00
Water consumption (L·cap/day)	491	1,00	1,00	1,00	1,00	0,94	1,13	1,00

7.5. Final remarks

- There are different limits regarding the sustainability improvement: There is a limit regarding the social habits and water consumption (i.e., at least one person needs to cover his basic needs spending 100L/day, according to WHO in 2003). Also, there is a physical limit regarding the technological improvements (i.e., technologies can be very efficient but until a limit value). Finally, there is an economical rational limit (which can coincide or not with the physical limits of the assets). It means that a system can be improved until a limit, where it would not have sense to invest that amount of money: from a logical or coherent perspective it would have more sense to improve other aspects of sustainability. In other words, we can spend much more money building expensive infrastructure to cover all the actual social needs, but from a certain point it will be much worth to spend this money in changing these socials needs. This demonstrates again the importance of dealing sustainability with a holistic approach and with multiobjective solutions.

- More policies should be done in order to promote more water saving, reallocating the economic investments and benefits across the urban water subsystems. Actually this is the reason why today some of the modelled scenarios have not been already made. This means that political policies are essential to redistribute the benefits of this model, as the reduction of one flow implicates reduction of the overall costs, which also affects to more than one stakeholder. For instance, the city council will provably not invest in a water saving campaign, as the benefits of this campaign will not almost affect them, but it will to Cadagua or ACA. In this sense, the ACA has a fundamental role to play. For instance, the city council will provably not invest in a water saving campaign, as the benefits of this campaign will not almost affect them, but it will to Cadagua or ACA.

- More efforts in the reduction of the water consumption have to be done beyond the urban water demand. Two thirds of the total water consumed in Catalonia belong to the Catalan basins of the Ebro, while in contrast, only 8% of population lives in these basins. This is because more than 80% of water consumption from the Ebro basins goes to the agricultural sector (ACA, 2000). In addition, the agricultural prices for water consumption are extremely low, much more than the north of Europe, where water scarcity problems are not as important. Thus, sustainable policies and improvements are also needed in the rural sector, showing up again the multi-objective approach of sustainability. The metabolism analysis approach of this work can help, as it is an awareness tool for society, letting us understand what are the impacts of the activities.

- The work presented here has been done within the limitations of availability of data (lack of data, sensitive and confidential data, etc.) and thus, has relied on additional considerations. However, limitations as well as the strong points of the results are clearly exposed in the Life Cycle Inventory Data sources, making it clear enough for further research. Also, beyond these limitations, this work has effectively shown the potential of the DMM and the metabolism concept as a powerful methodology to asses environmental and economic of UWS.

8. Conclusions and further research

This study has carried out a metabolism analysis through a MFA - LCA approach of the UWS at La Vall de Boí in order to assess the economic and environmental impacts of the current situation (status quo) and to model future interventions through ten discrete scenarios. From the assessment of the current situation, the following conclusions can be drawn:

- The greatest environmental impact of the UWS of La Vall de Boí is, by far, the water demand subsystem with 88% of the total share of the GWP. This is consequence of the energy requirements from 2100 TEP to heat the water (i.e., electricity and LPG) in the in-house scale. Hence, from an environmental and economic point of view, the impacts are much related with the water sewage flows rather than the demand flows.

- The second contributor of the GWP impacts is the WWTS and particularly the WWTPs with a 8% of share due to the electricity consumption. It is also the greatest environmental impact of the UWCS (in which the demand subsystem is excluded) with a 64% of the total share. Also, inside the UWCS, the second largest impact (24%) is the recipient waters subsystem caused by the NO_2 and CH_4 generated in the treated and untreated wastewater. In contrast, there are almost no impacts from the other subsystems. This is also caused by the fact that there is no need to pump the water supplied thanks to the topography of the valley.

- The share of the assessment water subsystems across the analysed impacts (GWP, AP and EP) is not the same. In the UWCS, the GWP is mainly caused by the already mentioned WWTS and the RWS. In contrast, for the AP impacts, the energy from the wastewater treatment plants contributes with more than 90% of the total share. Conversely, the RWS is causing 99,66% of the total eutrophication impacts.

- Energy consumption is responsible for the overall GWP and AP impacts, with a 96% of share in the UWS and 70% in the UWCS. Particularly, electricity has been identified as the major source of these impacts (with 58% and 64% of share respectively). Transportation needs represent 1% and 6% of share in the UWS/UWCS, in spite of the isolation of the valley with respect to other urban industrial systems. It must be stressed that chemicals consumption impacts are comparable with diesel consumption (also with the same share) although they are not so visible. Therefore, efforts are needed to eliminate them or to improve the efficiency of the current technology.

- The low price of water does not internalise neither the economic dimension nor the environmental or social aspects of the UWS studied, which represent other forms of economy. This low price also leads to an excess of water consumption and a bad usage of freshwater resources with approximately 500L/TEP·day. Also, the lack of control of the volume of water supplied does not help, as only a few water tanks have water meters. Controlling water flows is essential to monitor the demand of the water subsystem, to detect leakages or unexpected water consumptions and to control illegal consumptions. The City council has just started this control which must be continued in a more exhaustive and thorough way. In this sense ICT could help.

From the current assessment of the studied UWS, a set of scenarios has been analysed and the following conclusions regarding the range of studied interventions can be drawn:

- From the assessment of the status quo, the energy requirements are the largest environmental impact regarding the GWP and AP, and therefore, interventions have been focused on solving this aspect. Also, special focus has been done to reduce the EP impacts by treating wastewater. In respond to this two main causes, while keeping always feasible solutions that could not significantly compromise the economical dimension, 3 main approaches have been considered:
    - (i) **Implementing ICT and renewable energy sources**: renewable solutions (microturbines) and new technologies (ICT, with a smart water supply system) have been modelled together in the first combination of scenarios and have shown a reduction of 67% and 13% of the GWP impacts of UWCS and UWS respectively. They also achieved a reduction of the AP impacts of 95% and 20% respectively. These interventions reduce the total costs more than 8% thanks specially to electricity generation.
    - (ii) **Reducing the water demand** and thus, the energy demand of the whole UWS: as the environmental costs are very linearly dependent on the water consumption, the results of these scenarios show one of the best performances. This has been doing modelled with water pricing, the air filters installed in the in-house scale and the water pressure reducing valves. These three conditions have been modelled together in the second combination of scenarios and have shown a reduction of around 76% of the overall energy, chemicals, sludge and environmental impacts. Despite the additional costs that this would mean, the total costs are increased by 3,2% with respect to the BAU conditions in 2035.
    - (iii) **Installing green and grey technologies lacking in the system,** the local and green solutions (with a sludge treatment wetland), stormwater separation and the construction of a WWTPs allowed a 50% of reduction of the EP impacts in both the UWCS and the UWS in the first combination of scenarios. In this case almost no EP impact was produced. Moreover, a reduction of around 10% of the total energy needs, chemical consumption and the GWP and AP impacts in the UWCS could also be achieved.
- In contrast with the first combination of scenarios where almost no EP impact was achieved, thanks to the local and green solutions (with a sludge treatment wetland), the stormwater separation and with the construction of the WWTPs that lacks on the system, a 50% of reduction of the EP impacts could be achieved in both the UWCS and the UWS. Moreover, a reduction of around 10% of the total energy needs, the chemical consumption and the GWP and AP impacts in the UWCS can also be achieved.
- In all scenarios, the users' costs have been also taken into account in order to let the whole community understand that the proposed interventions are also beneficial for them too, as in all scenarios the users' costs have been equal or reduced (except for the water pricing, scenario 7).
- The most efficient interventions proposed are those that take advantage of the energy of the environment such as microturbines. Their use would lead to an internalisation of most of the externalities of the studied UWS.

- Some of the interventions did not show a significantly change on the overall environmental impacts. However, it must be pointed out that some of these problems provably have no other alternatives if we want to mitigate these impacts and if a sustainable UWS wants be achieved. Hence, as there is no other way to reduce these costs, these solutions are also important and can not be dispensed with.

Finally, final remarks can be also extracted:

- The DMM is demonstrated as an efficient decision—making tool that can easily show the implications of future intervention analysis anywhere in the system at different phases of strategic planning. The model is also useful for future changes in the boundary conditions of the system (population growth or increasing prices of oil and electricity) and for long term future interventions. KPIs results have shown as an easy way where interventions are worth to apply and show a specially good performance, preserving a wide picture of the changes. It provides an aid to political decision-makers, helping them to decide when and where efforts should be spent in order to efficiently manage the economic flows to improve sustainability of urban water systems.

- The provided results of the status quo scenario and the future scenarios can be used as an awareness tool of the implications that has the consumption of water in the specific studied UWS. We all should understand what are the impacts of our activities as well as the future stressors and challenges. According to EU, behaviour change of societies is very dependent of this awareness. We all must have in mind that environmental impacts will turn to the society (water scarcity, pollution, etc.) and thus, will also affect the economic growth.

The proposed range of interventions proposed will lead stakeholders of the system to understand the environmental and economical implications of the specific technological and socio-political interventions anywhere in the system and at all spatial scales. Thus, this work gives guidelines in the strategic planning level to design sustainable water management systems with a preliminary design of the technological and socio-political solutions proposed for a sustainable water management system.

Last but not least, two important issues should be remarked: all scenarios are well studied and agreed with all stakeholders involved. They are based on real results that can be achieved according to the boundary conditions, feasible and without overdoing the complexity of the UWS. Furthermore, all the scenarios are compatible and could be implemented together forming an integral sustainable solution that could significantly reduce the environmental impacts of the actual UWS without compromising the economic dimension. The proposed future scenarios can revalue the UWS, offering local jobs and reducing some of the actual risks. This constitutes a win - win solutions for the entire community.

The future research could be continued with the guidelines provided as follows:

- Improve the lack of registered data nor control of the current assets of the UWS, specially regarding the water pipes. This is remarkable important, as decisions and interventions are therefore difficult to establish and may lead to unfounded decisions of the future strategies as well as potential problems in the future.

- Improving the foreground data of the WWTPs, with input data from an average of more years, in order to have a more representative data. This is specially important in this case study as the WWTPs represent the biggest environmental and economical impact of the UWS.

- Involve the Hydrographic Confederation of the Ebro in this case study as a stakeholder, in order to take into account their feedback of the actual operating system of the UWS, with their identified weak points, problems and performance. Also, their participation should be take into account when defining future interventions and strategies, as some of them will require they acceptance.

- Model other future scenarios as: green WWTP for wastewater treatment according (and hence, compare it with the grey WWTP modelled in the scenario 10) and as a substitution or combination with the actual systems to remove more nutrients once the effluent is treated (specially with the obtained results and the important contribution of GWP impacts of the N and P content of wastewater). Also, electric vehicles could also be modelled in order to confront the diesel consumption (which could be charged with the microturbines during the nights), centralised recycling schemes (with the average energy needs per cubic meter according to ACA and OCCC) or any other scenarios interesting for the involved stakeholders.

- Eutrophication impacts should be properly treated specially in the small rivers and streams and moreover in the villages of Cóll and Cardet, which does not have WWTPs.

- The regionalised environmental impacts should be treated specifically to understand the consequences of all impacts across the subsystems and the villages.

- Recycling strategies regarding the inflows of materials used in the system should be studied in order to minimise those impacts. This should be done specially when the assets (water pipes) could be taken into the study in further researches.

- Water recycling and water saving schemes analysis should be done in this specific case study for all sectors: domestic, industrial and agricultural. Understanding where are geographically the water demands is essential to design recycling schemes. This could lead to understand if recycling schemes are worth it or not (enabling to compare, for instance, the impact of GHG emissions by providing these recycling schemes in the upstream compared to the emissions or impacts in the downstream if this is not done).

- Social aspects should be more taken into account, beyond the in site generic social perception perceived by the author during the consultation of the range of possible alternatives that could be done. Social responsibility should also be accounted in that sense to achieve an integral sustainability solution.

- As mentioned, in further studies or improvements of the DMM, other water related impacts could be accounted in order to expand more the environmental impact boundaries. As an example, regarding the water stressors impacts, Ecotoxicity, Marine eutrophication, human toxicity, among others could be added in the analyses. Also, if sustainable interventions are taken into account, land occupation impact should be then measured, as well as resources depletion (even these impacts depend on the sustainable solutions evaluated). An example of the motivation of these work can be explained with the diesel consumption in the studied UWS: the share of the produced GWP impacts is not that important but it would cover the majority of the particle matter formation impacts (kg PM2,5 or 10) if these impacts would be included in the analysis.

- Assets of the UWS could be taken into account, even this would represent rather a fix environmental impact considering the relative simplicity of the UWS studied. As mentioned, the operational phase it is more relevant.

- Extra pumping needs when there is water scarcity should be taken into account in a specific scenario. All water catchments of La Vall de Boí have an alternative water source that should be measured specially in terms of electricity when dry seasons affect the actual water sources.

- Understand implications of this water consumption in the downstream of the river *Noguera Ribargorçana* and others, to quantify how this excess of water consumption in La Vall de Boí affects to other water systems, including urban and natural ones. Hence, pricing policies and governance decisions regarding the water consumption could be evaluated by understanding the impacts that would cause the lack of freshwater resources in the downstream. Thus, the costs of water consumption can be compared, for instance, if recycling schemes are planned to be applied (i.e., model the changes of flows of downstream's UWS and doing the same in this studied UWS, in order to compare how are both affectations and compare which one is better).

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Appendices

A. Key advantages of the circular level in decreasing to the linear model

In the section of this work referring to the water cycle, in chapter 1, some of the main advantages has been already pointed, but as this model is the core of almost all interventions proposed in this work, some other implications and advantages haven been summarised below:

- The reduction of the total consumption of water resources, which means a reduction of the discharge volume of treated wastewater into waters as well as electricity, reducing overall environmental impacts. The treated wastewater can be used for other water demand systems using industrial, agricultural, and environmental waters after being diluted with freshwater to meet their water quality requirements.

- The reduction of the consumption of potable waters. Treating water to potable standards is an expensive and energy consuming process. However, only a small proportion (approximately 15–20%) of in-house water demand is actually used for purposes requiring drinking water quality (incl. water used for drinking, cooking and cleaning dishes). On the other hand, grey waters represents up to 50% of the total domestic consumption.

- By reusing water, we can also recover nutrients in wastewater and a wide variety of substances from water, reducing both waste and costs. Moreover, value can be obtained from this substances, as a value inputs for other systems that we once considered as unwanted outputs. The recently advances with membrane-based treatments as well as other technologies would help in this recovery process.

- From the environmental point of view, reusing wastewater has less impact than using water form other sources such as the sea water. The reason is because the desalination process has important impacts due to the amount of energy used and the impacts associated with the extraction of water and disposal of the non treated water.

- Another advantage of reusing greywater is that the supply is regular and not dependent on external phenomena (such as rain). As a result, comparing with the rain water tanks and treatment systems, the storage space required could be much smaller.

- Designing and planning urban water supply can also solve the water resource allocation (from the water supply goals). Thus, the water system can be improved using and treating the local water resources, which means a system optimisation in order to increase the water quality and reduce the electricity costs and environmental impacts.

- With a proper management, the average concentrations of the influents supplied for drinking water can also be reduced, which can improve human health and hygiene.

- The human consumption and usage of water resources have a significant impacts on aquatic ecosystems, with a negative effects on water quantity and quality. Therefore, by decreasing this consumption, the human impact in the aquatic ecosystems will be also improved. This can also contribute to the restoration of estuaries of the river because the integrated system decreased the diversion of the river to different water basins (Flannery et al., 2002).

Status quo assessment

Subsystem / acronym	3. Water Suply Subsystem	4. Water Distribution Subsystem	5. Water Demand Subsystem	6. Wastewater Distribution Subsystem	7. Wastewater Treatment Subsystem	8. Sludge Treatment Sub-subsystem	11. Recipient Waters Subsystem	Total UWS	Total UWCS
Concept	**3. WSS**	**4. WDIS**	**5. WDS**	**6. WWDIS**	**7. WWTS**	**8. STSS**	**11. RWS**	**UWS**	**UWCS**
UWS costs (€)	**1,70E+04**	**8,95E+03**	**5,42E+05**	**1,36E+03**	**1,14E+05**	**3,78E+04**	**0,00E+00**	**7,21E+05**	**1,79E+05**
Capital costs (€)	**4,77E+03**	**0,00E+00**	**0,00E+00**	**0,00E+00**	**1,05E+04**	**3,49E+03**	**0,00E+00**	**1,87E+04**	**1,87E+04**
Depreciation (€)	1,60E+04	0,00E+00	0,00E+00	0,00E+00	4,35E+04	0,00E+00	0,00E+00	5,95E+04	5,95E+04
Operational costs (€)	**1,22E+04**	**8,95E+03**	**5,42E+05**	**1,36E+03**	**1,03E+05**	**3,43E+04**	**0,00E+00**	**7,02E+05**	**1,60E+05**
Salaries (€)	8,80E+03	1,16E+03	0,00E+00	0,00E+00	4,46E+04	1,91E+04	0,00E+00	7,37E+04	7,37E+04
Energy (€)	8,08E+02	2,72E+02	3,84E+05	1,36E+03	4,08E+04	4,82E+03	0,00E+00	4,32E+05	4,81E+04
Chemicals (€)	1,27E+03	0,00E+00	0,00E+00	0,00E+00	8,81E+02	0,00E+00	0,00E+00	2,15E+03	2,15E+03
Outputs (€)	0,00E+00	0,00E+00	0,00E+00	0,00E+00	4,20E+03	5,50E+03	0,00E+00	9,70E+03	9,70E+03
O&M (€)	1,30E+03	7,51E+03	0,00E+00	0,00E+00	1,25E+04	4,89E+03	0,00E+00	2,62E+04	2,62E+04
Electricity (kWh)	7,36E+02	0,00E+00	1,46E+06	4,49E+03	2,42E+05	6,50E+03	0,00E+00	1,71E+06	2,54E+05
Fossil fuels (kWh)	6,97E+03	2,67E+03	2,36E+06	0,00E+00	2,27E+04	6,40E+03	0,00E+00	2,40E+06	3,87E+04
Energy UWS (kWh)	7,71E+03	2,67E+03	3,82E+06	4,49E+03	2,65E+05	1,29E+04	0,00E+00	4,11E+06	2,93E+05
Chemicals (kg)	2,22E+03	0,00E+00	0,00E+00	0,00E+00	1,19E+03	0,00E+00	0,00E+00	3,41E+03	3,41E+03
Outputs (kg)	0,00E+00	0,00E+00	0,00E+00	0,00E+00	7,42E+05	0,00E+00	0,00E+00	7,42E+05	7,42E+05
GWP (kg CO2 eq)	1,52E+04	8,86E+02	1,54E+06	2,36E+03	1,35E+05	5,55E+03	5,08E+04	1,75E+06	2,10E+05
Acidification (kg SO_2 eq)	7,13E+01	2,36E+00	9,73E+03	2,22E+01	1,22E+03	3,78E+01	0,00E+00	1,11E+04	1,36E+03
Eutrophication (kg PO_4 eq)	3,97E+01	2,19E-01	1,86E+03	4,24E+00	2,34E+02	6,67E+00	2,21E+04	2,43E+04	2,24E+04
Water flows related (m^3)	4,57E+05	4,57E+05	3,76E+05	5,48E+04	4,27E+05	4,27E+05	4,34E+05	4,57E+05	4,57E+05

•Renewable water resources such as surface water need to be appropriated for human demand, rather than non-renewable ones such as ground water from aquifers with long mean residential time (Oki and Kanae, 2006; Twin Cities Metropolitan Council, 2007).

- As it was mentioned in some of the reasons exposed, electricity consumption for transferring water resources could be then reduced. This is specially important because is the greatest impact environmental impact in the water supply from the life cycle perspective (Stokes and Horvath, 2006; Lim and Park 2007, 2008). Thus, it also produces a high economic cost. Long distance transportation of water resources or pumping water from wells instead of using surface water are examples.
- The sustainable water system will also reduce the life cycle cost for urban water infrastructures and thus, improve the economic aspect of sustainability (Kim et al., 2006).
- Recycling water also means a better water security, which is also an important factor in generating the integrated urban water cycle system to stably supply water. This will also mean a less water resource dependency on other regions, improving regional water security. The importance could be increased in the future due to the climate change impacts.

B. Foreground data: LCI data sources details

C. Specific results of the KPIs for the studied scenarios (2035)

KPIs' absolute results of the studied scenarios

Scenarios evaluated in 2035	**Scenario 0**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Key Performance Indicator	BAU conditions	+ Energy prices	+ TEP	— Runoff — Leakage	Smart water sys.	Micro turbines	Pressure reduction
Total costs	**1,773E+05**	**2,000E+05**	**2,065E+05**	**1,929E+05**	**1,960E+05**	**1,878E+05**	**1,998E+05**
Capital costs (€)	**1,874E+04**	**1,874E+04**	**1,874E+04**	**1,874E+04**	**2,061E+04**	**2,438E+04**	**1,924E+04**
Operational costs (€)	**1,585E+05**	**1,813E+05**	**1,878E+05**	**1,741E+05**	**1,754E+05**	**1,634E+05**	**1,806E+05**
Operational fix costs (€)	1,318E+05	1,383E+05	1,383E+05	1,383E+05	1,401E+05	1,439E+05	1,388E+05
Operational variable costs (€)	4,550E+04	6,177E+04	6,825E+04	5,461E+04	5,582E+04	4,385E+04	6,104E+04
Economic water benefits (€)	-1,443E+05	-1,443E+05	-1,443E+05	-1,443E+05	-1,443E+05	-1,443E+05	-1,443E+05
User's costs (€)	5,425E+05	6,347E+05	6,847E+05	6,255E+05	6,347E+05	6,347E+05	6,276E+05
GWP (kg CO_2 eq)	1,746E+06	1,746E+06	1,928E+06	1,619E+06	1,738E+06	1,523E+06	1,720E+06
AP (kg SO_2 eq)	1,109E+04	1,109E+04	1,225E+04	8,888E+03	1,105E+04	8,984E+03	1,092E+04
EP (kg PO_4 eq)	2,428E+04	2,428E+04	2,683E+04	1,673E+04	2,426E+04	2,387E+04	2,391E+04
GWP UWCS (kg CO_2 eq)	2,102E+05	2,102E+05	2,314E+05	1,815E+05	2,025E+05	7,704E+04	2,070E+05
AP UWCS (kg SO_2 eq)	1,357E+03	1,357E+03	1,496E+03	1,204E+03	1,319E+03	1,047E+02	1,336E+03
EP UWCS (kg PO_4 eq)	2,243E+04	2,243E+04	2,478E+04	1,641E+04	2,240E+04	2,219E+04	2,208E+04
Total Energy UWS (kWh)	4,110E+06	4,110E+06	4,537E+06	4,080E+06	4,105E+06	4,110E+06	4,049E+06
Energy UWCS (kWh)	2,926E+05	2,926E+05	3,198E+05	2,624E+05	2,877E+05	2,926E+05	2,885E+05
Chemicals (kg)	3,408E+03	3,408E+03	3,766E+03	3,048E+03	2,037E+03	3,408E+03	3,356E+03
Residues & Sludge (kg)	7,418E+05	7,418E+05	8,196E+05	6,556E+05	7,418E+05	7,418E+05	7,300E+05
Nutrient recovery (% wastewater)	98,12%	98,12%	98,12%	98,12%	98,12%	98,12%	98,12%
Water system leakages (%)	11,40%	11,40%	11,40%	1,40%	11,40%	11,40%	11,40%
Water safe sanitation (% pop.)	97,51%	97,51%	97,51%	97,51%	97,51%	97,51%	97,51%
Water footpirnt (m³)	4,570E+05	4,570E+05	5,049E+05	4,113E+05	4,570E+05	4,570E+05	4,502E+05
Water scarcity (%)	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Water consumption (L·cap/day)	491,07	491,07	542,58	441,96	491,07	491,07	483,75

KPIs’ absolute results of the studied scenarios.

Scenarios evaluated in 2035	**Scenario 7**	**Scenario 8**	**Scenario 9**	**Scenario 10**	**Scenario com. 1**	**Scenario com. 2**	**Scenario com. 3**
Key Performance Indicator	Water meters	Policies	Local STW	New WWTP	Water supply im.	Water demand im.	Perfromance im.
Total costs	**2,091E+05**	**1,974E+05**	**1,873E+05**	**2,344E+05**	**1,837E+05**	**2,062E+05**	**2,145E+05**
Capital costs (€)	**3,284E+04**	**2,054E+04**	**3,048E+04**	**2,923E+04**	**2,625E+04**	**3,515E+04**	**4,097E+04**
Operational costs (€)	**1,763E+05**	**1,768E+05**	**1,568E+05**	**2,052E+05**	**1,574E+05**	**1,711E+05**	**1,735E+05**
Operational fix costs (€)	1,524E+05	1,401E+05	1,500E+05	1,488E+05	1,458E+05	1,547E+05	1,605E+05
Operational variable costs (€)	5,673E+04	5,731E+04	3,728E+04	8,565E+04	3,791E+04	5,155E+04	5,401E+04
Economic water benefits (€)	-1,253E+06	-1,443E+05	-1,443E+05	-1,443E+05	-1,443E+05	-1,253E+06	-1,443E+05
User’s costs (€)	5,633E+05	6,004E+05	6,347E+05	6,347E+05	6,347E+05	5,219E+05	6,255E+05
GWP (kg CO_2 eq)	1,485E+06	1,621E+06	1,737E+06	1,744E+06	1,515E+06	1,334E+06	1,607E+06
AP (kg SO_2 eq)	9,430E+03	1,029E+04	1,103E+04	1,114E+04	8,946E+03	8,467E+03	8,875E+03
EP (kg PO_4 eq)	2,064E+04	2,253E+04	2,426E+04	1,917E+04	2,385E+04	1,851E+04	1,158E+04
GWP UWCS (kg CO_2 eq)	1,799E+05	1,956E+05	2,007E+05	2,079E+05	6,932E+04	1,621E+05	1,697E+05
AP UWCS (kg SO_2 eq)	1,158E+03	1,261E+03	1,294E+03	1,406E+03	6,673E+01	1,041E+03	1,191E+03
EP UWCS (kg PO_4 eq)	1,906E+04	2,081E+04	2,240E+04	1,731E+04	2,216E+04	1,710E+04	1,126E+04
Total Energy UWS (kWh)	3,498E+06	3,816E+06	4,100E+06	4,127E+06	4,105E+06	3,143E+06	4,087E+06
Energy UWCS (kWh)	2,537E+05	2,739E+05	2,831E+05	3,096E+05	2,877E+05	2,308E+05	2,699E+05
Chemicals (kg)	2,897E+03	3,162E+03	3,408E+03	3,455E+03	2,037E+03	2,599E+03	3,094E+03
Residues & Sludge (kg)	6,305E+05	6,883E+05	7,418E+05	7,708E+05	7,418E+05	5,652E+05	6,846E+05
Nutrient recovery (% wastewater)	98,12%	98,12%	98,12%	100,00%	98,12%	98,12%	98,12%
Water system leakages (%)	11,40%	11,40%	11,40%	11,40%	11,40%	11,40%	1,40%
Water safe sanitation (% pop.)	97,51%	97,51%	97,51%	100,00%	97,51%	97,51%	97,51%
Water footpirnt (m³)	3,884E+05	4,240E+05	4,570E+05	4,570E+05	4,570E+05	3,487E+05	4,113E+05
Water scarcity (%)	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Water consumption (L·cap/day)	417,41	455,66	491,07	491,07	491,07	374,69	441,96

D. Detailed annual water flows of the Calibration Model

Summary of the annual water volumes - Calibration model

Concept	Value	Unit	%	Basis %
Subtracted water	4.712.873	m^3		
Non used water	4.255.881	m^3		
Water demand supplied, including leakage	555.291	m^3		
Water supplied WTP (source A)	**456.992**	m^3	100,00%	
Houses (1644)	329.385	m^3	72,08%	
Hotels (30)	47.018	m^3	10,29%	
Industries (95)	28.500	m^3	6,24%	
Leakage	52.090	m^3	11,40%	
Other supplies, ACA (source B)	**98.299**	m^3	100,00%	
Others	38.070	m^3	38,73%	
Farms	30.739	m^3	31,27%	
Leakage	29.490	m^3	30,00%	source B
Total outflows wastewater subsystem	**443.747**	m^3		
Black waters	384.657	m^3		
Runoff waters	59.090	m^3		
Wastewater treated WWTP	**427.050**	m^3	100,00%	WWTP
Black waters	377.407	m^3	88,38%	WWTP
Runoff waters	49.643	m^3	11,62%	WWTP
Wastewater untreated	**16.697**	m^3		
Black waters	7.250	m^3	1,59%	WTP
Runoff waters	9.448	m^3	5,53%	Total Runoff
Runoff, following approximate calculations	170.746	m^3	29,07%	
Untreated runoff	121.103	m^3	70,93%	Total Runoff
Bypassed	96.883	m^3	80%	
Separete sewage	19.377	m^3	20%	
Total leakage	81.580	m^3	14,69%	

E. Specific results of the interventions

In this section, the specific results of the calculations of the studied scenarios are listed in the following tables. Note that only the scenarios that were needed to calculate are presented below.

I7 - Smart water system for the WTP

Intervention	Smart water system for the WTP		
Intervention refrence	I7		
Subsystem	Subsystem 3: Water Supply Subsystem		
Intervention Description	Aims to solve the 4th group of problems related with the WTP		
Problems solved	• 6 villages with a non-optimized chlorine dosing pumps and remote control + 2 villages without chlorine system (Durro, Cardet). • The sanity quality controls of the water supplied for human consumption. • The city council quality controls to adjust the chlorine concentration, checked now a days manually and dairy for each village.		
Additional improvements	• Risk in the water quality supply • SCADA connectivity protocol • SINAC (Nation Information System of the Consumed Waters, in Spanish SINAC) transmission of data (even the information can not be automatically uploaded, the system can provide the standardized data requirements automatically)		
Stakeholders consulted	• City council Vall de Boí (operator and owner of the WTP) • Ministry of Sanity (Govern of Catalonia) • Laiccona (company that normally provides to the city council material and maintenance of the WTP subsystem) • Sensotec (company that supplies hydraulic components)		
Material / equipment / technology requirements	**Nº of units and component**	**€ / unit**	**Total €**
	6 units of various needed material to connect the actual chlorine dosing pumps to the chlorine meters. Transmission of the data in the data transmission unit.	293,02 €	1.758,13 €
	6 water meters and transmission of the data in the data transmission unit.	181,50 €	1.089,00 €
	6 units of GPRS data transmission (to provide internet connection).	484,00 €	2.904,00 €
	6 units of software installation and coding.	302,50 €	1.815,00 €

	6 units of installation of the equipment and calibration.	242,00 €	1.452,00 €
	Subtotal (6 WTP automatization system)		**9.018,13 €**
	1 receptor of the data transmitted, for all WTP stations.	544,50 €	544,50 €
	1 server, to store the data transmitted, for all WTP stations.	726,00 €	726,00 €
	Subtotal (1 data transmission system)		**1.270,50 €**
	2 units of chlorine dosing pumps and meters.	4.235,00 €	8.470,00 €
	2 units of mechanic and electrical installation of the equipment.	968,00 €	1.936,00 €
	2 units of all the compsnents described above to automatize the WTP and transmit the data via internet.	1.503,02 €	3.006,04 €
	Subtotal (2 WTP chlorine system, automatized and with data transmission system)		**13.412,04 €**
	TOTAL cost of intervention (tax inc., 21%)		**23.700,67 €**
Additional requirements	Representative study of the concentration of chlorine in the water distribution subsystem in order to determine that the measurements in the WTP are similar or representative for all the distribution network. That means, specially, to compare the levels of chlorine in the furthest points of the network from the WTP, and determine if the chlorine level is enough (i.e, not lower than 0,2mg of chlorine per L). This requirement is set for the department of sanity (March 2016, by oral communication), as a possible way to reduce the actual costs of the daily manually water controls checking. This assumption can be done as the water distribution networks are in general little enough to not have big differences between the concentrations of chlorine measured in the network compared to the measurements in the WTP.		

Further interventions	1. Chlorine meters could be installed in the network, and thus, control much better the water quality. 2. Turbidimeters could also be installed in order to eliminate completely the actual daily manually checking costs by the city council. Both of these meters have not been considered for the high price that will suppose, which would not compensate the actual costs (3500€ + 2000€ + 2000€ + taxes, counting both meters and the installation costs and connection to the remote systems). 3. A chlorine - free treatment will be ideal from the social perspective, as it's not sociable accepted. Even that, the efforts in this intervention, optimizing and minimizing the chlorine levels, will affect positive in the social acceptance, as now a days chlorine levels are some times too high (so can be noticed in the taste) because of the uncontrolled chlorine dosing pumps.	
Total investment		
Fix	According the materials and equipment needed described above.	23.700,67 €
Variable	Needed to matin the servers and the SCADA system, as well as to provide internet connection for all stations (50€/month, approximately) + 0,5% of the inital investment.	863,7 €/year
Total savings (per year)		**6.447,52 €/year**
Economic	City council operator costs: the time spent by the worker (that is now controlling the water quality) 3 days out of 5 days per week could be saved, according to the sanity department. At least, 2 days out of 5 per week the worker should check the color and taste of the water and register these data. More over, a chlorine measurement could be done (or should be done at least 2 times per month) to check that the measurements of the chlorine WTP are representative enough compared to the water distribution network.	4.054,98 €/year
	Controller costs, from the sanity department: thanks to the WTP automatization system, the responsible worker can be informed remotely and periodically of the results measured in the WTP. Therefore, at least, half of the time spend it now a days could be earned.	1.106,22 €/year
	Sodium hypoclorite economic savings.	783,68 €/year

Energy	City council operator costs: the entire of diesel savings are counted even the workers have to travel to all the villages every day to also check the bins and trash around each village. Only some days (when the workers could consider to not check the trash), this half travel distance could be saved, even its consider negligible for calculus. Therefore, additional efforts in other fields should be done in the city council (in this case, with the rubbish management) to take more advantages of this intervention.	333,45 L
	Controller costs, from the sanity department: it's considered in the same way as in the economic expenses, that half of the travels could be saved.	123,5 L
Chemicals	Sodium hypoclorite can be optimized to a concentration of 0,3mg/L (instead of 0,5mg/L, as an average) thanks to the smart water system.	1.370,98 kg
Water flows	No water flows are affected	0 m3
Others	Social acceptance, due less chlorine taste in the water.	

I9 - Water catchment systems improvement

Intervention	Water catchment systems improvement		
Intervention refrence	I9		
Subsystem	Subsystem 3: Water Supply Subsystem		
Intervention Description			
Problems solved	• Not all of the actual water catchments are properly fenced in order to ensure no risk of external contamination, even this is mandatory by law and seen it as a priority for the Water Catalan Agency (ACA).		
Additional improvements	• Reduction of the operational and maintenance costs as a result of a more conditioned water catchments (for instance, due leakage of undesired solids that could clog out the water pipes).		
Stakeholders consulted	• City council Vall de Boí (operator and owner of the WTP and catchments) • Catalan Water Agency (ACA, controller of the water catchments)		
Material / equipment / technology requirements	**Nº of units and component**	**€ / unit**	**Total €**

	4h of 2 workers to transport all material from the city council to the location of the water catchments, with 4x4 car to the closest point.	33,44 €	133,74 €
	5x5 m^2 of cleared field with less than 0.6 m of vegetation, with mechanical tools and mechanical load on truck.	0,95 €	23,75 €
	5x5 m^2 of excavation and finished smooth slope with mechanical means	1,61 €	40,25 €
	20 meters of fence height 1.5 m steel wire mesh with simple torsion galvanized finish, 50 mm diameter mesh step 2.7 and 2.7 mm, poles galvanized tube diameter 50 mm col 3 m each positioned anchored to the work and proportion of posts for singular points. This component implies:	27,82 €/meter of fence	556,46 €
	0,37 h of 1st official worker	8,61 €	172,12 €
	0,37 h of assistant worker	7,40 €	147,93 €
	4,18 kg of polymer cement mortar with synthetic resins and fibers.	3,39 €	67,72 €
	1,50 m^2 of fabric metallic simple torsion galvanized wire mesh passing 50 mm and 2,7 mm of diameter.	3,27 €	65,40 €
	0,34 u of intermediate poles of galvanized steel, diameter 50 mm and 1,8m height.	2,66 €	53,24 €
	0,07 u of poles for to ends, tensile or singular points of galvanized steel tube, diameter 50 mm and 1,8m height.	1,92 €	38,40 €
	0,04 h of drilling machine to drill holes cooled water for 5 to 20 cm maximum.	0,34 €	6,85 €
	2,00 % of auxiliary expenses on labor costs.	0,24 €	4,80 €
	Subtotal, 1 mounted fence for 1 water catchment, 5 x 5 meters of dimensions or equivalent, with transport, labour and tax costs included.	1	**754,21 €**

	Total costs, for 4 mounted fences for the villages: Cóll, Cardet, Boí, Taüll - Pla de l'Ermita.	4	3.016,83 €
	TOTAL cost of intervention		**3.016,83 €**
Additional requirements	Prior checking of the water catchment site should be done provably, in order to better define the materials and other needs. Instead or in addition, oral communication with the workers of the city council could help to define the intervention for each village, in that sense.		
Further interventions	1. The additional / secondary water catchments used in case of water scarcity (when the main water catchments can not be used to provide enough water for the users) should also be checked properly in terms of water quality and contamination risk. 2. The water catchments could also be reallocated, in order to prioritize ground water catchments instead of the surface waters (rivers and other types) that are now a days providing supply water to some of the villages. The ones that should be prioritize are the shared water catchments from Boí, Taüll and Pla de l'Ermita, that are now coming from rivers and other surface waters.		
Total investment 1st year			
Fix			3.016,83 €
Variable			0
Total savings (per year)			**0 €/year**
Economic	No economic savings are affected, as the investment it provides an improvement in the water contamination risk. Even that, as a result of the improvement of the water catchments, less O&M works could be saved even can not be quantified.		0 €/year
Energy	No energy savings are affected		0 L
Water flows	No water flows are affected		0 m3
Outputs	Environmental impact, measured within the total amount needed for each of the components of the fence (concrete, steel, energy usage and needed for the LCA of these materials, even it's not complete LCA analysis and only focus in the CO_2 emissions). The calculus is based on the data basis of the Catalonia Institute of Construction Technology - ITeC.		66,76 Kg CO2
Others	Risk of water supply contamination savings, with the impact that this could cause, even the quality of the income waters in general is very good itself.		

I8 - Water valves to eliminate excess water catchment

Intervention	Water valves to eliminate excess water catchment
Intervention refrence	I8
Subsystem	Subsystem 3: Water Supply Subsystem
Intervention Description	
Problems solved	• All of the actual water catchments are delivering water to the WTP continuously, independently from the water consumption. These water volume depends on the water inflows from the catchment points, even normally there is a more or less permanent water table in the little deposits in the water catchments. That means that the water pipes are almost always submerged so it's possible to approximate the annual water volume subtracted, knowing as well the characteristics of the WTP where this water pipes ends. • Environmental impacts of subtracting / bypassing water more than 3 km in almost all the villages of the origin rivers / streams.
Additional improvements	• Eliminate / reduce the potential of acidification and eutrophication or other environmental impacts that could cause even the disappearance of the rivers / streams where the water catchments are placed. Special attention should be done in the water bodies with small volumes of water, which are potentially to have more impact (such as Cóll and Cardet).
Stakeholders consulted	• City council Vall de Boí (operator and owner of the WTP and catchments) • Catalan Water Agency (ACA, controller of the water catchments) • Sensotec (company that supplies hydraulic components)

Material / equipment / technology requirements	**Nº of units and component**	**€ / unit**	**Total €**
	1 Level transmitter, stainless steel body, ceramic membrane and gasket in Viton. Range 0 to 10.00 mc.a. cable 12 meters with internal vent tube. IP68. Type Sensotec LMK307. Powered from the PID regulator.	366,63 €	366,63 €
	1 Digital PID controller box. With manual and automatic control. Double dial, one for the value of the instantaneous level and the other for the value of the desired setpoint. 4-20mA. 4-20mA control output or three points to the valve. 230 VAC power. 96x48mm format, to be mounted in a panel.	356,95 €	356,95 €

	1 unit of GPRS data transmission to provide internet connection to the water valve and the digital controller, which will remotely control the valve respect to the level transmitter.	484,00 €	484,00 €
	1 Linear valve modulating 2-way fluid at room temperature. Metal seat DN50 flanged PN16. Steel body material. Stainless steel shaft. kvs = 37m3 / h. Electric actuator to 230Vc.a. Linear regulation with RC 3 points. Model: MV521165	2.093,30 €	2.093,30 €
	3 Butterfly valves wafer type to mount the bypass installation. Suitable for mounting between flanges DN80 PN10 / 16. For application water at room temperature. Aluminum body. Inox disc and EPDM gaskets. With manual control with lever positioning, having several attachment points on its route.	118,58 €	355,74 €
	1 Bifunctional air valve for DN80 PN10 / 16. Gray cast iron body material, type GG15. Float polyurethane, rubber sealing gasket. Gray cover EN-GJL-250 cast. 6,8 mm steel screws.	310,00 €	310,00 €
	1 Forged flat flange, DIN 2576 PN 10/16, diameter DN80.	21,18 €	21,18 €
	1 Y type filter, flange connection DN80 PN16. Body Material GG15 gray cast iron.	117,37 €	117,37 €
	Subtotal, 1 mounted water valve for 1 WTP.	1	**4.105,17 €**
	8 water valves, even it depends on which village a micro turbine can be installed instead.	8	32.841,32 €
	TOTAL cost of intervention		**32.841,32 €**

Additional requirements	It's important to underline that the water valve should not be installed below **100/160 meters** of altitude (depending on the case) respect to the water catchment, as the water pipes are not designed to resist more water pressure. Provably the best place to install the valve could be just next to the water catchment, if there is internet connectivity trough GPRS. Therefore, prior checking of the water catchment site and the water pipes should be done, in order to check how this intervention could fit in each case. The optimal place to install the water valve can be different depending the case in order to better fit with the physical constrains. In that sense and in addition, oral communication with the workers of the city council could help to define the intervention for each village.	
Further interventions	1. The additional / secondary water catchments used in case of water scarcity (when the main water catchments can not be used to provide enough water for the users) should also be checked properly in terms of water quality and contamination risk. 2. The water catchments could also be reallocated, in order to prioritize ground water catchments instead of the surface waters (rivers and other types) that are now a days providing supply water to some of the villages. The ones that should be prioritize are the shared water catchments from Boí, Taüll and Pla de l'Ermita, that are now coming from rivers and other surface waters.	
Total investment 1st year		
Fix		32.841,32 €
Variable		0
Total savings (per year)		**0 €/year**
Economic	No economic savings are affected, as the investment it provides an improvement in the water contamination risk. Even that, as a result of the improvement of the water catchments, less O&M works could be saved even can not be quantified.	0 €/year
Energy	No energy savings are affected	0 L
Water flows	No water flows are affected	0 m3
Outputs	Environmental impact of the life cycle of all the products and materials needed, not quantified due lack of information.	
Others	None	

I10 - STW to produce natural fertilizer

Intervention	STW to produce natural fertilizer		
Intervention refrence	I10		
Subsystem	Subsystem 7: Wastewater Treatment Subsystem		
Intervention Description			
Problems solved	• Sludge problems with managing the sludge in the WWTP, which implies internal transport and external transport. The internal transport is necessary to transport the sludge form the WWTP of Barruera and Durro to Boí, where the dewatering processes is carried out. The external transport is needed to transport the dry sludge to the STP in Tàrrega, a village 176km away. • The costly and high energy demanding technologies to dewater the sludge, that are normally not feasible in small WWTP. • Low energy requirements, reduced operation and maintenance costs and low environmental impact.		
Additional improvements	• Eliminate / reduce the chemicals fertilizers demands for the crops that are		
Stakeholders consulted	• Cadagua (the operator of the WWTP) • Catalan Water Agency (owner of the WWTP)		
Material / equipment / technology requirements	**Nº of units and component**	**€ / unit**	**Total €**
	1 STW of 500 PE for the village of Durro (400 PE).	50.563 €	50.563 €
	1 STW of 1000 PE for the village of Barruera (700 PE).	83.606 €	83.606 €
	1 STW of 2000 PE for the village of Boí, Taüll, Erill and Pla de l'Ermita (5420 PE).	159.442 €	159.442 €
	TOTAL cost of intervention		**293.611 €**
Additional requirements			
Further interventions			
Total investment 1st year			
Fix			293.611 €

Variable	Durro	3.372 €
	Barruera	6.099 €
	Boí	11.092 €
Total savings (per year)		**45.179,89 €/year**
Economic	Direct sludge post treatment costs, from the three WWTPs.	5.503,48 €
	Electricity costs, due the dryning processes of the sludge, estimating the time operation of the centrifugal machine, the average power consumption and the electricity costs. Also, the potential reduction of the contracted power is accounted, (53€/kW, as an average).	4.245,02 €
	Other indirect and O&M direct costs, accounted as the 30% of the total operational costs (Uggetti et al., 2010) of the three WWTP, substracting the accounted detailed costs (post treatment and electricity).	35.431,39 €
Energy	Environmental impact of the life cycle of all the products and materials needed, not quantified due lack of information.	
Others	None	

I17 - Pressure reduction

Intervention	Pressure reduction
Intervention refrence	I17
Subsystem	Subsystem 5: Water Demand Subsystem
Intervention Description	
Problems solved	• Excess of water consumption by the demand system due the fix amount payed by the 1769 users. The residential users pay a fix water volume of 9m^3 per month while industries and hotels have different fix water volume payed in terms of their characteristics. All in all, as users are not paying as a function of the real water consumption, this doesn't promote water reduction measures in-house scale and doesn't internalize UWS costs and externalities.
Additional improvements	• Internalize externalities caused by the consumption of freshwater resources in the entire UWS.

Stakeholders consulted	• City council Vall de Boí (operator and owner of the WTP and catchments) • Catalan Water Agency (owner of the WWTP) • Sensotec (company that supplies hydraulic components)		
Material / equipment / technology requirements	**Nº of units and component**	**€ / unit**	**Total €**
	Pressure reducing valve PN16 DN-80. P3100 series. Hydraulically operated with piston. Cavitation Control V-PORT system. For a pressure jump form 8 to 2 bar.	2.093,30 €	2.093,30 €
	Valve assembly in the urban water system distribution network.	1.046,65 €	1.046,65 €
	Subtotal, 4 villages (at least, 1 per each distribution network)	4	3.139,95 €
	TOTAL cost of intervention		**12.559,80 €**
Additional requirements	The water meters characteristics and price are very dependent on the range flow that can measure, as well as the diameter of the pipe, maximum pressure reachable, or type of connection. Thus, an average cost has been calculated for a standard water meter that could fit the characteristics of the majority of the users.		
Further interventions	1. Additional data transmission system could be added in order to provide real data to the Catalan Water Agency of the consumed water volumes.		
Total investment 1st year			
Fix			12.559,80 €
Variable (2%)			251,20 €
Total savings (per year)			Automatically calculated with the DMM
Economic	Economic savings on the UWS mainly due less needs on the WWTP.		0 €/year
Energy	Energy savings on the UWS mainly due less needs on the WWTP.		0 L
Water flows	7% reduction of the affected water flows		6.806,15 m3
Outputs	Environmental impacts savings on the UWS due the reduction of the needed water flows.		
Others	Improved water scarcity		

I14 - In-house water meters

Intervention	In-house water meters		
Intervention refrence	I14		
Subsystem	Subsystem 5: Water Demand Subsystem		
Intervention Description			
Problems solved	• Excess of water consumption by the demand system due the fix amount payed by the 1769 users. The residential users pay a fix water volume of $9m^3$ per month while industries and hotels have different fix water volume payed in terms of their characteristics. All in all, as users are not paying as a function of the real water consumption, this doesn't promote water reduction measures in-house scale and doesn't internalize UWS costs and externalities.		
Additional improvements	• Internalize externalities caused by the consumption of freshwater resources in the entire UWS.		
Stakeholders consulted	• City council Vall de Boí (operator and owner of the WTP and catchments) • Catalan Water Agency (owner of the WWTP) • Sensotec (company that supplies hydraulic components)		
Material / equipment / technology requirements	**Nº of units and component**	**€ / unit**	**Total €**
	1 water meter in-house scale, for flows up to 1-120L/min. DN32 G1-1 / 2 " 1.25 with LCD Display.	148,85 €	148,85 €
	Installation of the water meter in the user's main water pipe.	81,87 €	81,87 €
	Technical report of the current situation, and design and application of the specific solution.		15.000,00 €
	Subtotal, 1769 users	1769	423.150,77 €
	TOTAL cost of intervention		**423.150,77 €**
Additional requirements	The water meters characteristics and price are very dependent on the range flow that can measure, as well as the diameter of the pipe, maximum pressure reachable, or type of connection. Thus, an average cost has been calculated for a standard water meter that could fit the characteristics of the majority of the users.		
Further interventions	1. Additional data transmission system could be added in order to provide real data to the Catalan Water Agency of the consumed water volumes.		

Total investment 1st year		**423.150,77 €**
Fix		423.150,77 €
Variable		depending on the data collection system
Total savings (per year)	Calculated supposing 15% of reduction of the water consumption	**1.137.017,79 €/yea**
Economic	Economic savings on the UWS mainly due less needs on the WWTP.	2.242,65 €/year
	Economic savings on the in-house user's system, due the less consumption of water in the UWS.	25.940,32 €/year
	Economic benefits from the water consumption payment, calculated following ACA prices for the municipality, considering that all users (1769) pay the same amount, i.e., 26,16 m^3/user with 7% less of the total water consumption.	1.108.834,83 €/yea
Energy	Energy savings on the UWS mainly due less needs on the WWTP.	12.485,74 kWh
Water flows	15% reduction of all water flows	62.876,58 m3
Outputs	Environmental impacts savings on the UWS due the reduction of the needed water flows.	
Others	Improved water scarcity and security.	

I1.2 - Microturbines

Intervention	Micro turbines to produce energy		
Intervention refrence	I1.2		
Subsystem	Subsystem 7: Wastewater Treatment Subsystem		
Intervention Description	Aims to solve the 1st group of problems related with the energy consumption and its environmental impact in the WWTP		
Problems solved	• The non renewable electricity source and therefore, the environmental impact that represent. Now a days, the electricity is coming from the grid mix (renewable sources can be up to 20% of the electricity sources). • Reduction of the largest environmental impact of the UWS of la Vall de Boí. • Reduction of the economic costs in electricity in the long term approach.		
Additional improvements	• Electricity independence and security, diversifying the electricity sources. • Real internalization of the externalities caused by the UWS.		
Stakeholders consulted	• Cadagua (the operator of the WWTP) • Catalan Water Agency (owner of the WWTP) • Tecnoturbines (company that supplies micro turbines as well as all the electrical components and additional technologies)		
Material / equipment / technology requirements	**Nº of units and component**	**€ / unit**	**Total €**
	Hydraulic vertical axis turbine model 15N11. With inlet / outlet DN50 flanged, nominal pressure PN40, cast base, shaft, impellers and cover surface made out of stainless steel. Three-phase electric generator, protection class IP55.	13.125,39 €	39.376,16 €
	Electrical control panel for injection monophase electricity grid with power 20-40 kW, with voltage range of 180-264 VAC, maximum current of 10.5 A and a frequency range of 47-63 Hz The system includes: plate assembly, electrical protection, rectifier, inverter display for parameter display, wiring and communications with wifi antenna for remote access via the web.	10.291,81 €	30.875,43 €

	Displacement in supervision of installation and commissioning of the installation of 2 technicians of Tecnoturbines.	5.050,00 €	15.150,00 €
	Installation of additional the microturbines and other additional electrical installation requirements.	2.846,72 €	8.540,16 €
	Subtotal (3 microturbines for the villages of Barruera, Durro and Erill La Vall)		**93.941,75 €**
	TOTAL cost of intervention		**93.941,75 €**
Additional requirements			
Further interventions			
Total investment			**95.820,585**
Fix			93.941,75 €
Variable			1.878,84 €/year
Total savings (per year)	Automatically calculated with the DMM		