

A close-up photograph of water flowing from a heavily rusted metal pipe. The water is clear and cascades down the left side of the frame. The pipe is dark brown and textured with rust, featuring a circular hole on the right side. The background is blurred, showing a greyish-brown wall.

Decisions on urban water systems: some support

Manel Poch
Ulises Cortés
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Ignasi Rodríguez-Roda
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Presentation



“Water is a scarce resource and its management has to be as effective as possible”

Most of us would certainly agree with this fine sounding phrase. But developing it and putting it into practice is not easy.

Firstly, because we are already having problems identifying the meaning or interpretation we give to some words. For example, water as a resource. Water is not just a natural resource, it is the basis of the industrial sector, a generator of cultural heritage and a linchpin of society. And we sometimes use the term *scarce* when referring to a problem of distribution or overexploitation. In any case, this means that water management is very complex. This is because there are different agents involved and all of them have different interests; these interests are often contradictory and can lead to conflict. Everyone understands the concept of efficient management differently. Efficient: why and for whom?

At the same time, we have to make decisions. Decisions that involve a way of managing the resource. For example, authorising (or not) a withdrawal from a water course, building (and how) a treatment plant or defining (what and in which range) the quality parameters guaranteeing its drinkability... These examples, and many more that we could cite, are some of the aspects on which a group of people are responsible for acting, deciding and getting the decisions implemented.

The hypothesis presented in this book is that to achieve this efficient management there are no simple formulas or universal solutions. However, this does not mean that all solutions are equally correct. Experience shows us that some are better than others.

Achieving effective water management affects us all. But to reflect on and assess the decisions made is a task that must be delimited so it can be dealt with in a book such as the one the reader has in their hands. In this context, the authors have already made two decisions.

The first makes reference to the size. In

this book, we are not going to discuss the whole water cycle, just the part that relates to urban water system. This is understood as the set of decisions concerning the collection of wastewater, transporting it, treating it and returning it to the environment or reusing it. Bearing in mind that there are already excellent manuals available providing design and calculation criteria for plants, this book wants to go a step further. Its aim is to analyse the decisions that have to be made at every stage. And to be able to do it in a comprehensive way so as to identify the questions that need to be asked in each case. Which decisions need to be made and what impact can they have. Nor is the aim to give a comprehensive view of each case; that would take a whole encyclopedia. In any case, we hope to interest the reader enough so that they go to the references indicated at the end of the book to obtain a more exhaustive analysis of each of the cases presented.

The second decision is to make it clear that the book offers its own point of view. This is our view and our proposal obtained from almost twenty years of experience. That is why an intimate style has been used throughout. We discuss cases we have experienced, some of which have already been implemented with success, some are under development, others remain a possibility, others are sleeping like a baby ... but all the cases relate to real problems with all their constraints and possibilities. From an initial analysis of the findings, we are going to discuss the ones that are, in our opinion, the problems that must be addressed for urban water management and how this leads to different decision levels. In each of them, we will try to discuss, giving practical examples, a way to overcome these problems. It is not necessarily the only way or the best way. But we hope the reader can draw their own conclusions.

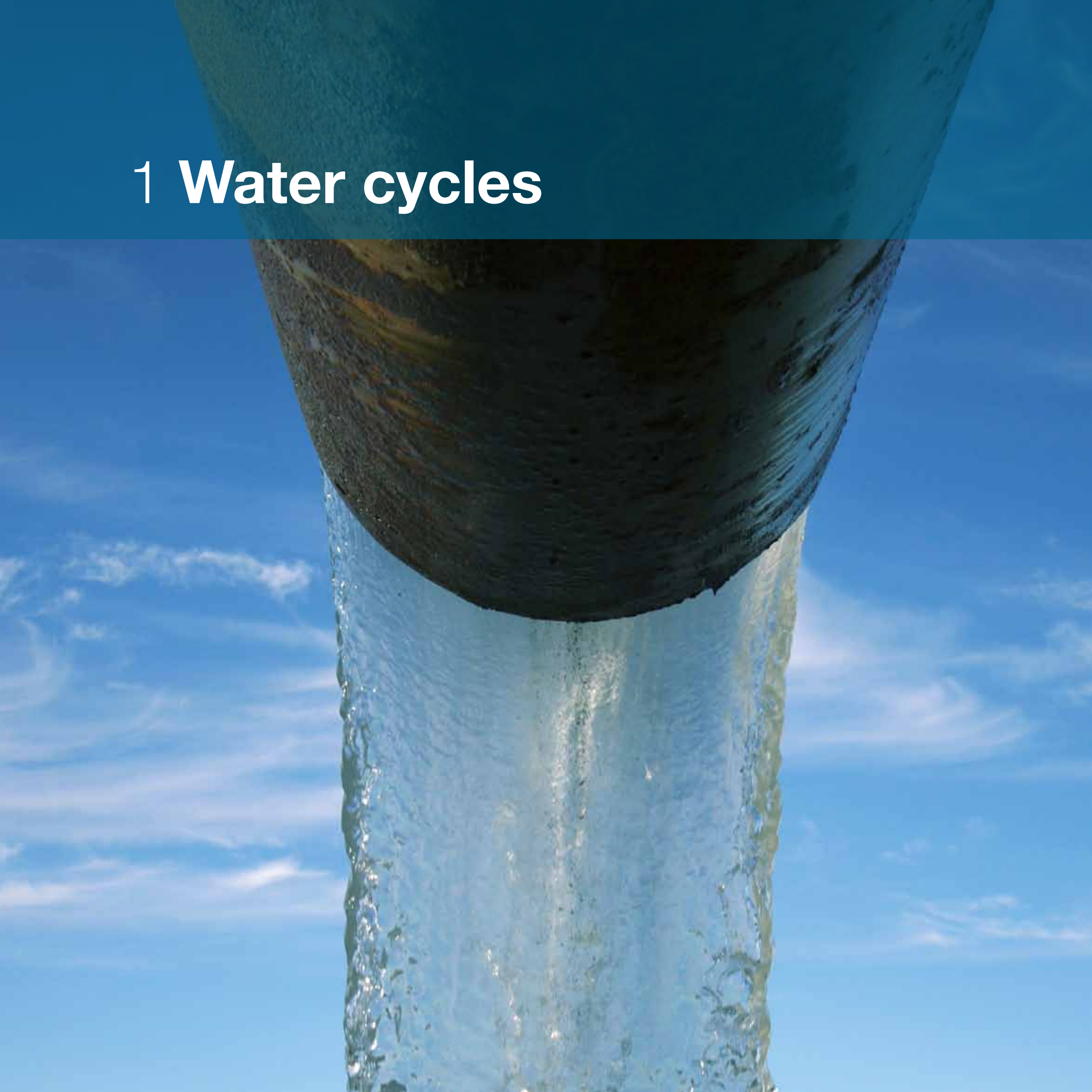
For all these reasons this book is for peo-

ple who are, in some way, involved in water management and treatment, and who are involved in making decisions about this. People who are already making decisions and want to know the thoughts of others working in this field. People who are not currently working in this field, but are interested in it and want to know what type of decisions that they will have to face and analyse proposals made by people already working in the field. And finally, people affected by the issue and wanting to broaden their knowledge.

We do not want to end this introduction without thanking all the people and institutions involved in the development of some of the systems presented in this book for their help. THANK YOU to all of them.

We can only hope that the work presented here will be helpful to the reader. We can guarantee though, that the experience of contributing to better management of the water resource is absolutely fascinating.

1 Water cycles



This chapter starts by providing a general presentation of the natural water cycle, to show how this cycle has been altered by anthropogenic use, which has resulted in an urban water cycle. This new cycle, which is currently almost always an open cycle, means that water is used and returned to the environment. From this principle, an analysis has been made on the evolution of how water is treated before it returns to the natural environment, and how this evolution is not just temporal but spatial as well, since it corresponds to different levels of treatment on the planet. From here, we will discuss the current trends in urban treatment systems and whether we are looking at a new paradigm involving a change in mentality to solve the problem. In order to overcome these new challenges and the decisions involved in them, it is important to have decision support tools available. The following chapters discuss the authors' experience in the design and building of environmental decision support systems and how they can contribute to better management of urban water systems.

1.1 The natural water cycle

Water is distributed on the planet in solid, liquid and gaseous forms, and can also be found forming part of living beings. The estimate of the overall amount of water varies according to sources, but the total volume of water on our planet is around 1,400 million km³. Of this volume, the majority (97%) is found in seas and oceans and only a small amount (approx. 3%) is fresh water, the majority of which is frozen (approx. 70%). In the coming years, we will see how the system evolves and how much of this fresh water

But our planet's water is not still; it moves through the water cycle. When you search for a diagram of the water cycle on Google, one of the first images that comes up is from the United States Geological Service. A naturalistic image that presents the concept of the water cycle in which, curiously, there is no human activity footprint.

Each year, some 577,000 km³ of water moves around the Earth. 502,800 km³ evaporates from the oceans and 65,200 km³ from the land, representing a fall in sea level of over one metre per year. At the same time, an equivalent amount of water falls in the form of precipitation, of which 458,000 km³ falls over the ocean and 110,000 km³ falls over the land, adding around one metre to the sea level, but not in the same place. The difference between evaporation and precipitation over the ocean largely controls the general currents that maintain the balance. On the other hand, the difference between precipitation and evaporation over land represents the total amount of water added to the 42,600 km³/year that flows down rivers and 2,200 km³/year of

groundwater discharged directly into the ocean.

Taking into account the large amount of water that circulates in the atmosphere and the small amount of water present in this section, its residence time is just a few days, the same as in the rivers and biosphere. Soil moisture is recycled every few months, whilst the lakes and aquifers do this over weeks and years, and the glaciers take decades and centuries to renew.

... the water on our planet is not stagnant, it moves around forming the water cycle

becomes part of the salt water masses. Around 30% is in the form of groundwater in aquifers, some of which is difficult to access and only 0.3% of which is on the surface, meaning it is directly useable for human consumption.

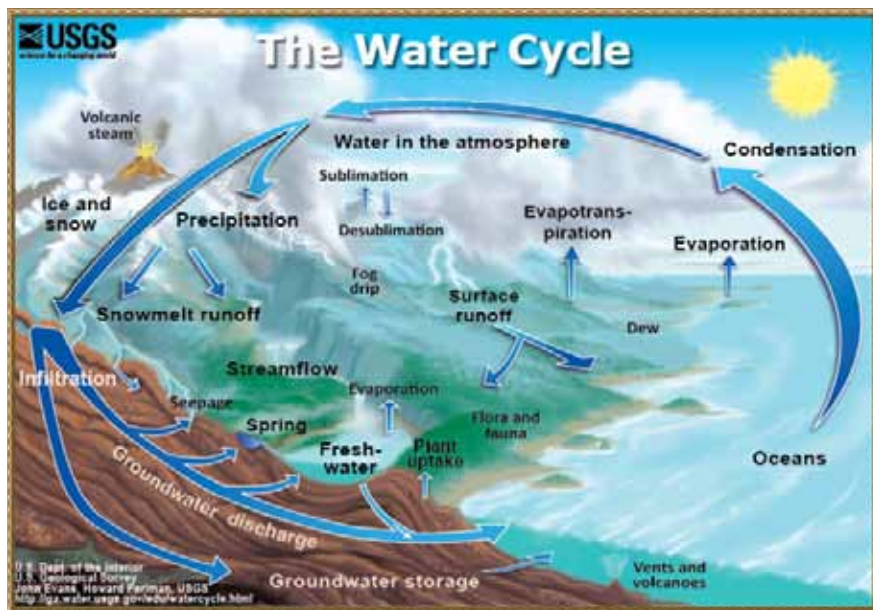


Fig. 1.1.1. Distribution of water on the planet

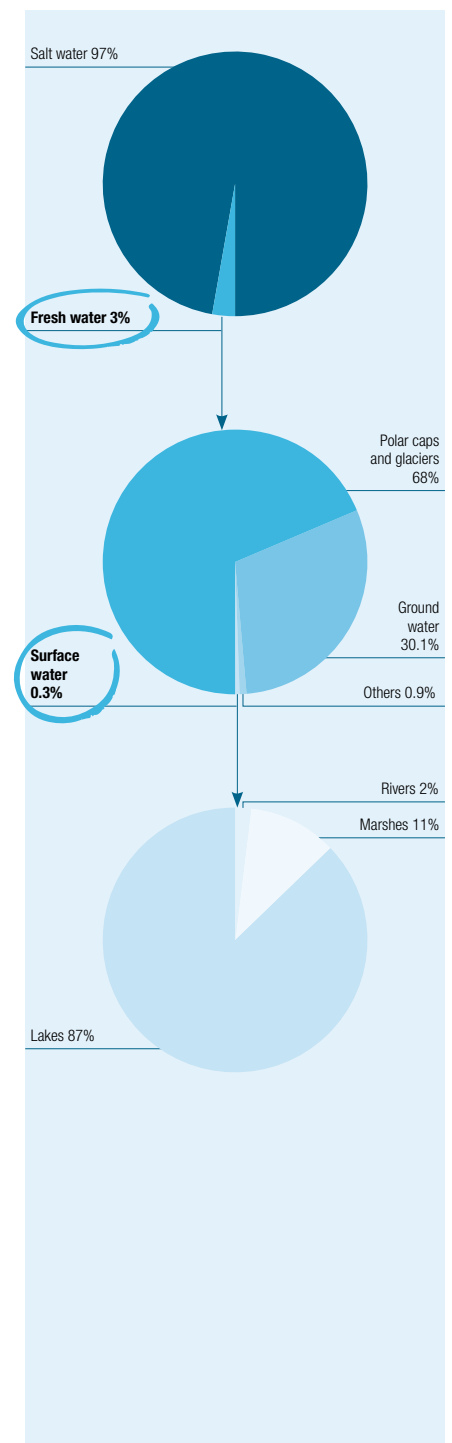
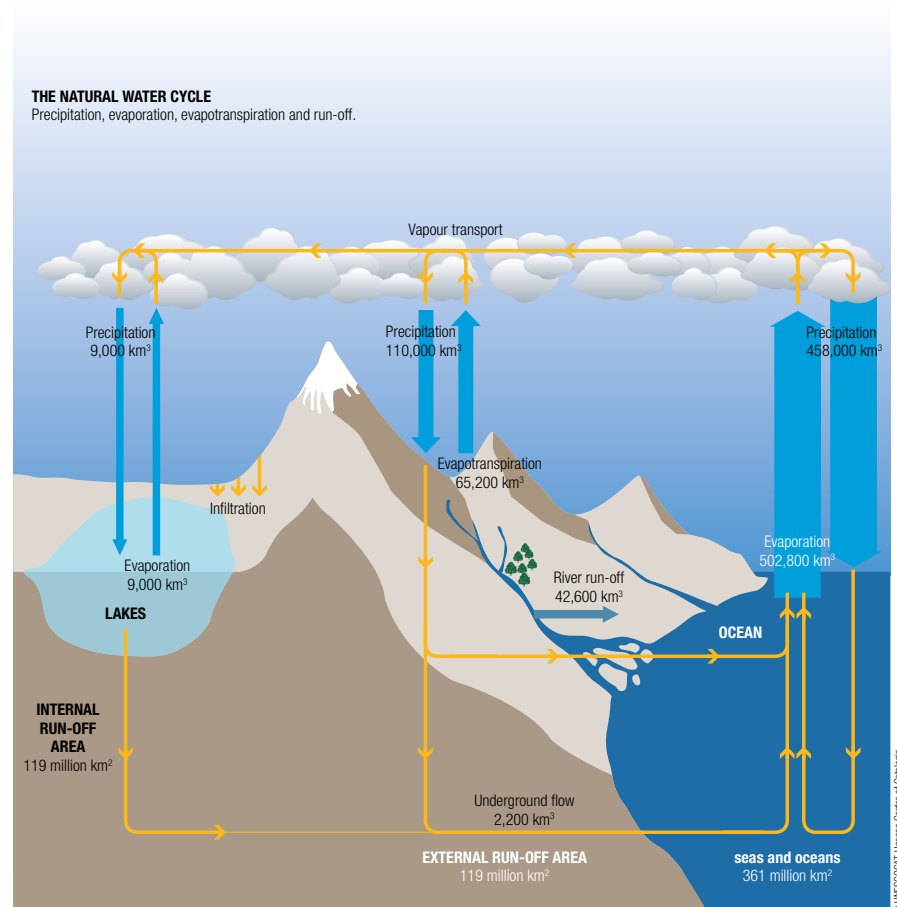


Fig. 1.1.2. Diagram of the water cycle provided by the United States Geological Service and at the top of the rankings on Google

Fig. 1.1.3.
Quantification of the flows between the different sections into which the planet's water cycle can be grouped.



Water is a special molecule

Jaume Alemany, Catalan Institut for Water Research ICRA

The water molecule is composed of an oxygen atom combined with two hydrogen atoms (H₂O) forming a 108° angle. The oxygen's high electronegativity and the molecule's geometry give rise to its polarisation, which enables the formation of so-called "hydrogen bond links" with itself and with molecules from other polar substances. This structure gives it its unique properties that

allow it to exist as we know it:

- 1) A liquid in a wide temperature range (0-100°C). Other similar molecules such as ammonia or hydrogen sulphide are gases at room temperature.
- 2) In its solid state it is less dense than when it is a liquid, unlike most compounds, which increase in density when in a solid state. The fact that ice floats, thermally insulates the lower layers and allows the existence of bodies of water where life can continue despite low temperatures.
- 3) The specific heat or amount of energy required to increase the temperature by one degree and the vaporisation heat or energy required to change it from a liquid or gaseous state are greater than those for other equivalent substances. This means that heating (or cooling) a body of water requires a greater exchange of energy than expected, which gives bodies of water high thermal inertia (e.g. rivers, lakes and seas). This explains the oceans' ability to moderate land temperature. In addition, it provides protection against thermal fluctuations for life in and out of water, and
- 4) its solvent characteristics (universal solvent), means it can be used as a method of transporting nutrients and excretory substances.

These properties are also related to the water cycle. The driving force behind this cycle is solar energy, which evaporates the water from seas and oceans. To do this it consumes a portion of the energy that the planet receives from the sun. Once condensed (rain) or solidified (snow or hail), the force of gravity brings the water down to the surface of the Earth where it circulates on the surface and underground until it reaches the sea, starting a new cycle.

Although the determination of the energy flow values in the Earth's system is an ongoing area of research and there are various estimates with some degree of uncertainty, it is an interesting exercise to estimate the energy magnitudes associated with the water cycle. The heat required to evaporate the 577,000 km³ of water/year that mobilises the water cycle –taking a water vapourisation enthalpy of 2,253 kJ/kg into account– gives 1,299.981 · 10³ PJ (PJ= petajoule =10¹⁵ J), which can be estimated at almost 50% of the solar energy that arrives on the Earth's surface. Therefore, there is no doubt that the water cycle is important to the Earth's energy balance.

However, according to the International Energy Agency, in 2008, globally, we produced, and consumed, energy equivalent to 513.611 · 10³ PJ, which amounts to almost 40% of the energy that moves the water cycle. Human activity magnitudes (and therefore their impact) are significant with respect to natural magnitudes.

1.2 The urban water cycle

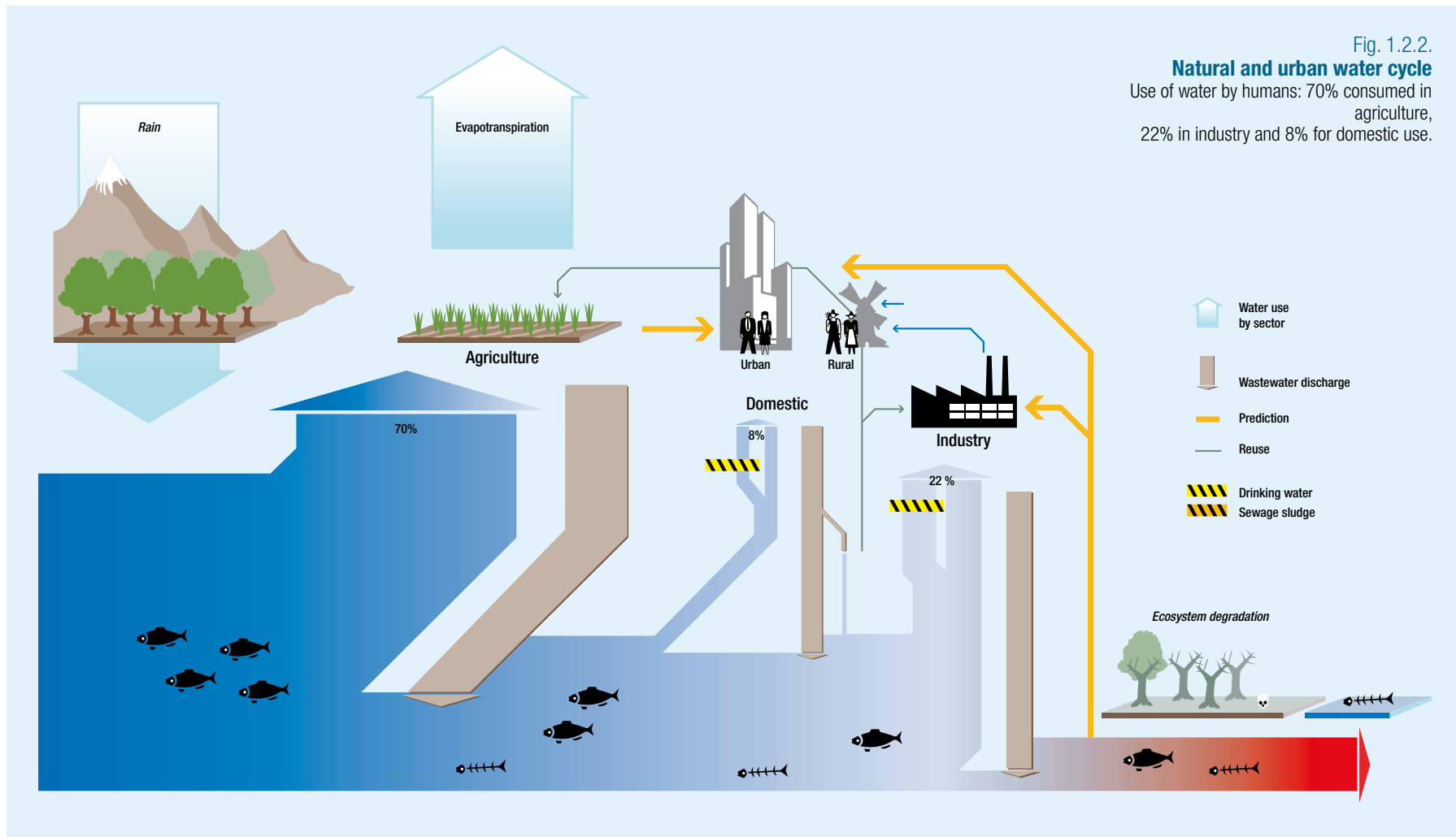
Water is not just present in the general water cycle; it also forms part of other cycles. In this book, we are interested in the modification of the natural cycle by human activity and, in particular, the cycles associated with water management that are being developed. The current paradigm of urban use of water implies: that it is removed from the natural cycle, either from a surface water course, an underground environment or through the use of reservoirs as an environmental regulator; transported to plants where it will be treated to achieve quality levels that allow for its distribution; used for human consumption; collected again and transported in the sewer system;

and treated in wastewater treatment plants until it reaches a level that allows its reuse or its return to the environment.



▼ Figure 1.2.1. A diagram of the urban water cycle, proposed by la the Catalan Water Agency.





The water footprint

Anna Monistrol Térmens – Environmental consultant

Have you ever thought about how much water it takes to make a cup of coffee? The answer is 140 litres. This surprising figure is due to the fact that this coffee has been grown in a field in a distant country, mostly irrigated with rainwater, harvested, washed, sorted, dried and husked to obtain a clean grain and, finally, roasted to achieve a perfect roasted coffee. The water consumed in this process is calculated at 21,000 litres per kg of coffee. As a result, to prepare a 7-gram cup, 140 litres are required.

These and other questions are intended to measure the water footprint, an indicator of the volume of water used to produce goods and services directly and indirectly for the consumer, producer and retailer. This is the water consumed, evaporated and/or polluted per unit of time and usually calculated for a consumer group (individual, family, city, country) or producers (public organisations, economic sectors, private companies). In the water footprint, we distinguish between blue water (fresh natural water that circulates on the surface of the land or through aquifers), green water (rainwater on the surface) and grey water (polluted water associated with manufacturing). According to data from Water Footprint Network:

- Growing a banana requires 70 litres of water, 1 cup of coffee 140 litres, 1kg of rice 3,400 litres and 1kg of beef 15,500 litres.
- The global water footprint average is 1,240 m³ per inhabitant/year. 74% is green water, 11% is blue water and the remaining 15% is grey water. Agricultural production contributes to 92% of this total.
- The Spanish water footprint is 2.325 m³ per inhabitant/year and around 36% of this is originates from outside Spain. It is a water importing country.
- The sum of the virtual water flows between countries relative to the sale of coffee is 80,000 million m³/year, which represents approximately 6% of the international virtual water flows worldwide.

The water footprint is an explicit indicator from a geographical point of view, since it does not just show volumes of water used and its pollution, it also shows the places it comes from. Many countries have significantly externalised their water footprint to import goods requiring a high water content for their production from other places. This puts significant pressure on water resources in the exporting regions, often without the proper mechanisms to control and conserve this properly. In fact, many of these problems are closely linked to the global economic structure. Being aware of water consumption data can help governments, companies, consumers and society in general to rationalise the management of the planet's water resources.

1.3 A little bit of history...

Although human beings have generated wastewater since the beginning of time, it is probably not until human concentrations reach a certain size, like the problems associated with this (and the activities performed at the same time) that the issue becomes a concern. So perhaps it is no surprise that the bibliography on the history of water treatment is much smaller than that for obtaining and managing the water resource in general.

The first sanitation system design was to take wastewater out from the population centres

It seems clear that the main objective was to distance the population from that which was offensive to both sight and smell, an option that resulted in the improvement of sanitation for its inhabitants.

Although archeological remains have been found in places like Mesopotamia, Egypt and Ancient Greece, it would not be much of an exaggeration to say that, in the West, the history of sanitation systems does not differ much from the history of civilisation, and like in many other aspects relative to the Romans, although they were not the inventors of wastewater management systems, with their advances in engineering and urban architecture, they demonstrate a before and after.

This should not surprise us. In Ancient Rome, water was an important part of their culture and social organisation. So much so that their engineers excelled in

constructions to collect it, transport it, distribute it and even evacuate it. The Cloaca Maxima, which still feeds out into the river Tiber near the Rotto and Palatino bridge, is a magnificent example of well thought-out construction for evacuation, in the same way as the Segovia aqueduct or the baths in Bath helped with transport or use.

...in the history of sanitation, the Middle Ages lasted until the 19th century

The Middle Ages are usually considered as the period from the fall of Rome until that of Constantinople in 1453, but perhaps it would be more accurate to say that, in terms of the history of sanitation, the Middle Ages lasted until the 19th century. Much of the progress made during Roman civilisation, and a large part of the constructions that supported it, fell, in this period, into disrepair and were forgotten. Until the middle of the 18th century, washing "ignored" the body, except the visible parts like the face and hands. In addition, water was considered to be unhealthy and hygiene even sinful. This perception limited the development of management techniques. We now know that in Europe, wastewater flowed through the streets, which added to the increase in the population density, contributed to the epidemics that the continent suffered in the Middle Ages. If we consider that this was the general situation, we should also point out that there are exceptions such as the *Statuti delle Strade e dell'acquae del contado di Milano* (1346), which focused on the problems of cesspools, the edict of Villers-Cotterets (1539) or the "gongfermor" profession in London, which had its own regulations.

An important part of this picture is represented by Spain and the territories occupied by the Muslims, since in Islamic cul-

ture, as in the case of Rome, water had special importance, particularly from a religious point of view, since it formed part of the treatment ritual before prayers. Islam, a system of social organisation originating from desert areas, created a legislative corpus relative to the use and ownership of water, particularly for irrigation and drinking (for both people and animals), but also for the evacuation of wastewater. The relevance of the issue is demonstrated by the existence of professional associations specialised in urban systems for distribution and drainage. In Fez, one of these corporations still existed until the first half of the 20th century. It appears that, in this context, the wastewater evacuation system is based on the separation of water to be collected into rainwater and wastewater. Each type corresponded to different piping.

The survival of the organisational system after the conquest can be seen, for example, in the preparation of the Granada Water Laws in 1501. Like other laws at the time, the main focus was on the use of water for irrigation, and therefore led to the establishment of a series of rules and institutions, some of which, like the Valencia Water Tribunal, still exist today, additionally taking the removal of wastewater into consideration.

The increase in population began in the second half of the 18th century and gathered pace in the second half of the 19th century, during which Europe grew from 170 million inhabitants in 1800 to 300 million in 1870, increasingly concentrated in the cities, which, accompanied by the growth in industry, resulted in the saturation of the existing wastewater evacuation systems, rendering them obsolete. The cholera and typhus epidemics that ravaged Europe repeatedly between 1830 and 1870, with a key time being the *Great Stink* of 1858 in London, led to the inevitable revision of the wastewater management system. There was a move from a decentralised collection and treatment system to a centralised one.

Constructed in 600 B.C., there is data on the maintenance and operation of the Cloaca Maxima until after the fall of the Western Roman Empire, a fact that traditionally marks the start of the Middle Ages.



In this context, the city of London was one of the pioneers in the search for governmental solutions to public health problems derived from sewage. But it was not just seen as a public health problem, but as a cost problem. E. Chadwick, a member of the Metropolitan Commission of London Sewers, firmly believed that public health needed to be improved to save. His report, *The Sanitary Condition of the Labouring Population* (1842), marked a turning point in thinking on public health, and its findings highlighted the need to seek help from engineers, not just from doctors. This "new" trend culminated in the design of new sewage systems in Europe and the United States. Examples of this were seen in Hamburg in 1843, Chicago in 1850, Paris in 1853 and London in 1858.

However, once again, it was an Englishman who was the first to formulate a consistent theory on the mode of transmission of certain diseases. In 1849, Dr. Snow published, for the first time, his work *On the mode of Communication of Cholera* (reissued in 1855, improved through fieldwork carried out after the cholera outbreak in 1854). In this work, Dr. Snow proved that there was a correlation between people falling ill and the place where they had drunk water.

The construction of the sewage systems was implicit in another debate: the use of a unitary system in which rainwater and wastewater uses the same pipes, or that of a separate system, in which different pipes are used for the collection of rainwater and wastewater. This debate had supporters and detractors of both options and, in our opinion, is still relevant. Probably because it is a debate in which there are positive and negative factors relative to both options, which will evolve over time, in line with aspects such as environmental sensitivity, the costs of the different options and the interrelation with other aspects of society, such as the type of town being developed.



▲ *"In terms of the deaths in the area, in 61 cases I was informed that the deceased drank water from the pump in Broad Street regularly or sporadically... The outcome of the investigation concluded that there was no cholera outbreak in this part of London with the exception of people who regularly drank from the aforementioned pump. I had a meeting with the parish authorities for St. James on the afternoon of 7th September, and presented the aforementioned circumstances to them. As a result of said meeting, the pump's handle was removed the following day."*

John Snow, letter to the editor *Medical Times and Gazette*

An interesting example can be seen in the United States where, at the end of the 19th century, the majority of systems in place were unitary systems until the start of the 20th century when there was a re-evaluation of the separate type. This change was, in large part, brought about by the population growth and the increased urbanisation of some areas, which, again, rendered the sewage systems used until that point obsolete as they were insufficient to absorb the quantities of wastewater dumped. To put it simply, the unitary system was transporting public health problems and risks from urban areas to other areas.

But the construction of drinking water and wastewater treatment systems was expensive and few municipalities

could cover the costs. The debate on the profitability of constructing both types of plants or just the first, assuming this was sufficient to guarantee the quality of the drinking water, was attacked and had different supporters and detractors, until this was clearly chosen due to the need to construct both types of plants, not just from a public health point of view but due to the presence of a new agent in the system, the environment. We can consider that a new phase in sanitation systems began with the development of a series of treatment technologies; those that have survived to this day.

The desire to protect drinking water from possible contamination through the wastewater collection systems started to be the quality aspect of water that had the most impact in the late 19th century and the early 20th century

1.4 Analysis of the evolution

From the initial concept of sanitation
–to reduce the amount of disease
producing agents–
to that of treatment
–with the appearance of a new agent,
the environment–

The finding that the public water supply was only part of the sanitary problem causing thousands of deaths every year, and that it would also require work relative to the development of treatment systems, became a growing clamour in England. A clamour that did not just have a bearing on the most underprivileged social sectors that were affected but which started to affect the ruling classes, who saw it as a constraint to economic prosperity. As is happening now, decisions made within the social sphere conditioned sanitation systems. Therefore, investments in this area began to increase, so that in the late 19th century, according to Caldecott, a quarter of local government debt was caused by costs related to water and sanitation. At a social level, this investment represented a fall in infant mortality and a rise in life expectancy.



At a technical level, these strategic decisions involved the development of new treatment technologies, which materialised in 1914 with the appearance of the activated sludge system that became the standard treatment system from this moment, with different modifications and variations that are still in existence today.

In essence, treatment with activated sludge involves putting residual water into contact with a multispecific population of microorganisms that use the organic matter to transform it into new biomass, and into energy for maintenance. Therefore, oxygen is required; this is usually provided by mechanical aeration equipment and this reduces the amount of organic matter present in the water, and thus a reduction in the impact in the receiving environment. This contact may occur through suspended micro-organisms, which require separation at a later stage, establishing the recirculation of the decanted micro-organisms, some of which are purged from the system. The excess biomass generated and purged from the system requires specific treatment involving thickening, conditioning, stabilisation and drying, as processes carried out in the treatment plant itself, whilst the final drying processes usually take place in specific plants.

The bibliography on the collection and treatment of wastewater is extensive. Here we just want to highlight how these technologies have been developed in a process at the same time as the con-

cerns that have motivated their evolution and the indicators used to assess their performance.

Therefore, an initial concern about sanitary aspects (from which the name sanitation is derived) has evolved into environmental aspects, and sanitation facilities have become wastewater treatment plants, which not only concern the oxygen but also the compounds that can consume oxygen due to spillage. A second evolution occurred relative to the environmental impact of the nutrients, oxygen-consuming elements, but, above all, potential causes of other environmental problems such as eutrophication.

This involved the evolution of the initial activated sludge systems, which were modified to reduce the concentrations of these compounds. It is not just to provide oxygen to oxidise the organic matter but today it is to establish anoxic areas to achieve nitrification and denitrification. An interesting point is that this process took place throughout the 20th century and that there are testimonials (like the one from Willy Gujer) from people who followed this evolution throughout their professional careers.

But these changes are being modified by a new leap, motivated by a new concern that involved some new indicators and involves the application of new technologies as well as a new generation of professionals. A concern motivated by the evolution in the quality of life achieved in industrialised societies, where the use of synthetic chemical products for health care, or simply as an addition to hygiene, has meant the appearance of emerging pollutants, new compounds that are not easily broken down by the activated sludge processes developed in the early 20th century. We need new technologies, with new biological processes or with the use of membranes, that are capable of providing higher performance, but still with

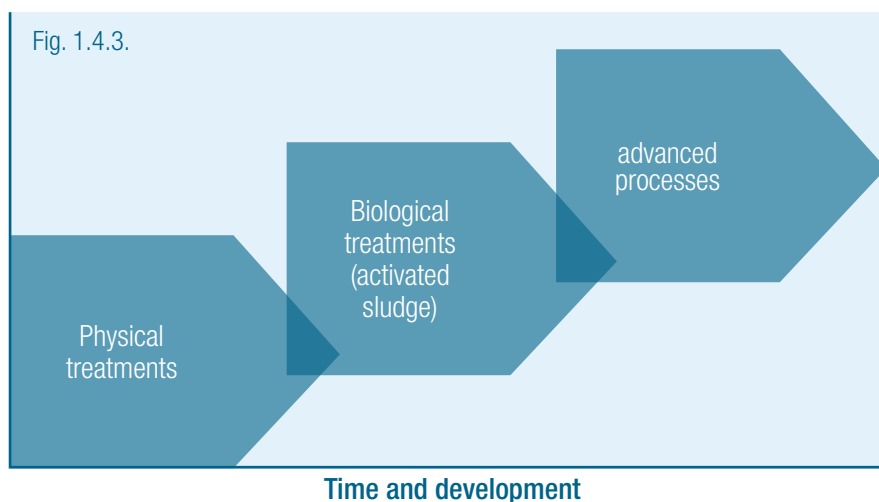
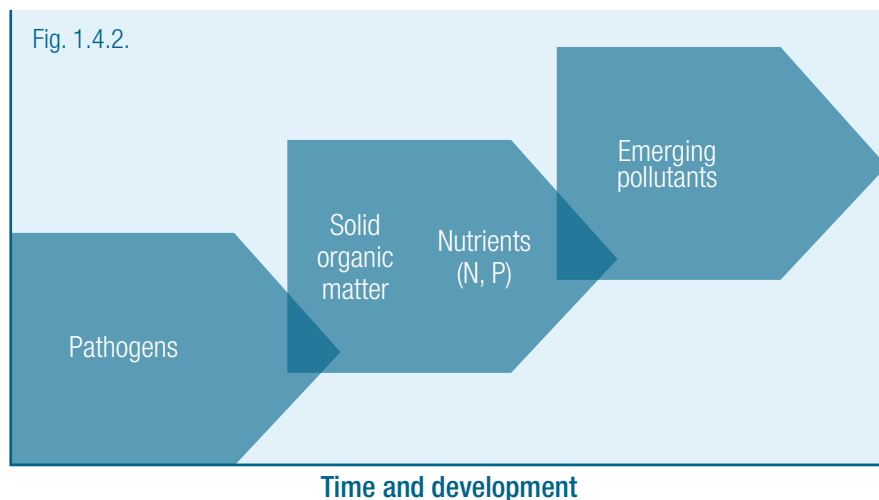
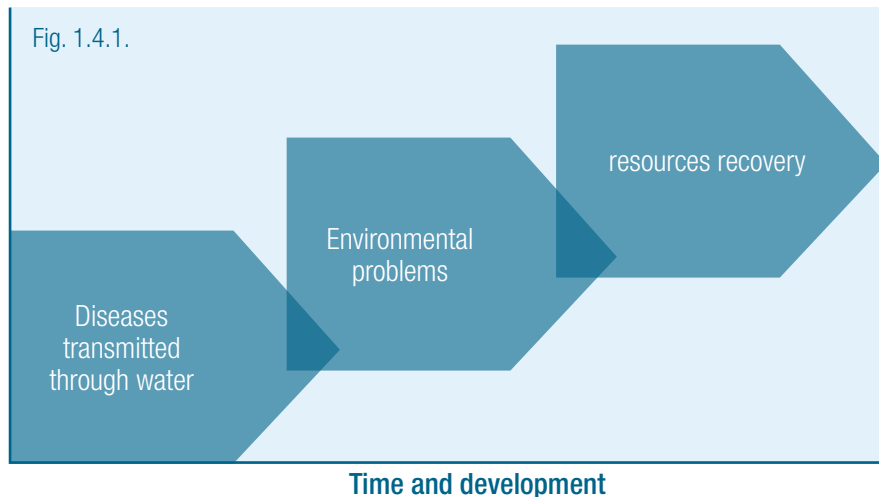
more complex side effects and greater energy costs.

The bases for a new paradigm are fulfilled

►
Fig. 1.4.1.
**Evolution of the problems
faced in wastewater treatment**

Fig. 1.4.2
**Evolution of the elements
to be treated**

Fig. 1.4.3
Evolution of the technologies



Miquel Rigola Lapeña, University of Girona

As we have seen in the historical review, in former times, the richest societies, based in densely populated cities, organised sanitation systems designed to alleviate the problem of excrement that would have otherwise flowed through the streets.

After the fall of Rome, society's progress regressed, drinking water wells were contaminated, and the city streets became receptors for all types of filthy waste and sources of disease transmission. Only the rural areas benefitted from the excrement by applying it to the crop fields to recover the nutrients and enrich the soils.

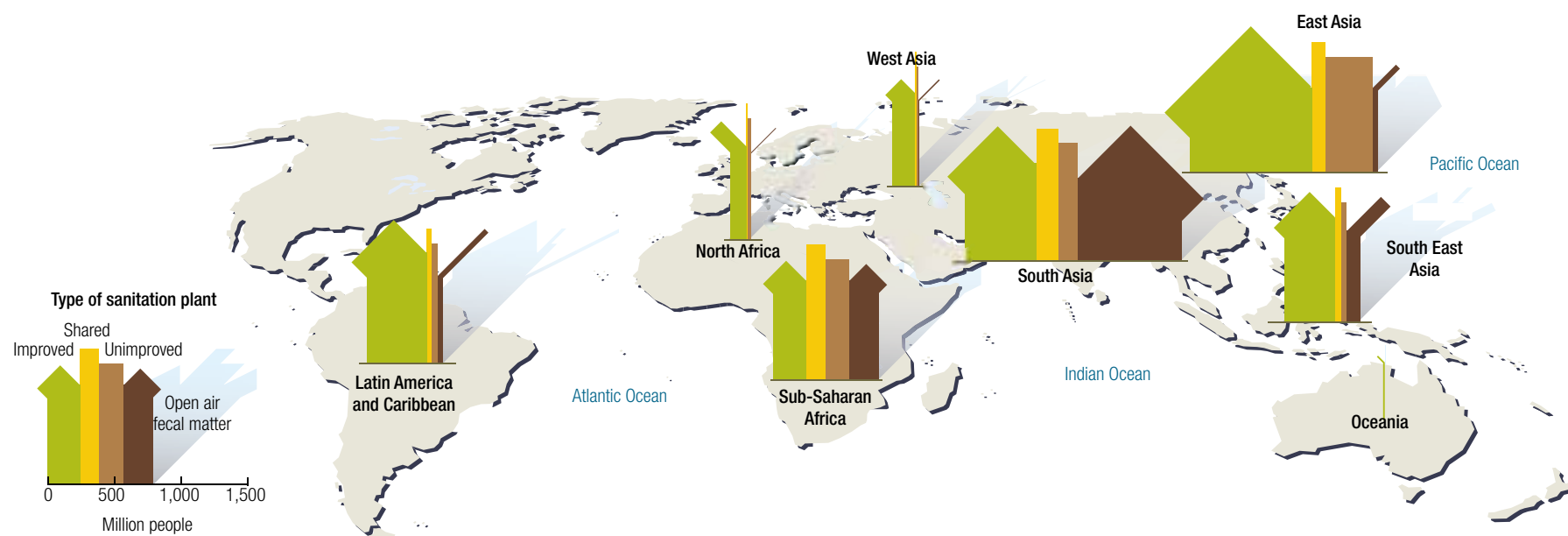
In this context, we can place the 19th century at the start of the current wastewater sanitation paradigm, with the microbiological discoveries that saw the appearance of hygiene as the basis for a healthier life. Urban sewers were part of the solution, but when blackwater flowed into the rivers, they became masses of dirty water; this situation was particularly worrying since they were the sources of drinking water. This saw the start of the process of purifying drinking water, but the problem is too serious to fail to understand that the problems must be solved at source.

This resulted in the birth of a wastewater treatment plant industry, where the activity was initially focused on sanitation, with the main aim being to remove pathogenic organisms and reduce soluble organic matter to a minimum. This saw the rise in activated sludge systems. Rural societies were initially opposed to a process that deprived them of their source of nutrients to fertilise their land.

Secondly, after the problem of the transmission of microbial diseases was controlled, it was obvious that the residual nutrients, mainly those derived from nitrogen and phosphorous, caused other pathological problems for humans and many other environmental problems, which were not solved by the activated sludge processes. In addition, industrial development is able to supply synthetic nutrients to agriculture and anthropic nutrients were not deemed necessary. A new cultural element led to the destruction of these nutrients in wastewater treatment systems, but it will soon become apparent that their recovery is important in a society faced with the depletion of its natural resources.

The 20th century saw the proliferation of the health and hygiene industries. Their products, on their own or their metabolites, contribute increasingly larger amounts to the effluent receiving waters. As a result, there was the need to find more efficient methods and technologies to remove emerging pollutants, pending the organisation of preventive measures. The accumulation of corrective measures means the system is a significant consumer of resources, which makes it difficult to view it as a great result of rationality and requires significant research efforts to be able to close the water cycle. These thoughts concern the planning of a new sanitation paradigm.

1.5 Sanitation today



Not every country has the same level of sanitation at the same time

There are currently, simultaneously, three situations on our planet.

- There are countries whose main problem is still preventing waterborne diseases in poor conditions. We have to take into account the fact that there are currently 900 million people without access to adequate drinking water, and that 2,600 million (approximately half of the third world population) do not have access to sanitation systems. Every year, at least 1.8 million children under five die from water related diseases, approximately 17% of deaths at this age. Each year, 2.2 million people die from diarrhoea problems, of which it is calculated that 88% are due to water quality problems.

- Other countries are currently making great efforts to treat their wastewater by removing organic matter first. An example of this is the construction of the Atotonilco plant in Mexico, in the state of Hidalgo, which should be the biggest in the world, with the capacity to treat 23 m³/s and an additional 12 m³/s in rainy conditions. It will remove the organic matter whilst maintaining the nutrients in the water.
- The third situation concerns countries (the European Union, the United States and Australia for example) that have already solved, in a large part, their problems of access to wastewater treatment systems for the majority of their inhabitants. Organic matter, and in many cases nutrients, are

removed from the wastewater. These countries are simultaneously studying the behaviour of these processes to remove emerging pollutants, and making significant research efforts to develop new processes that may satisfactorily combat this new type of contamination.



Fig. 1.5.1.

Access to sanitation systems worldwide

Improved: plants that guarantee the separation of sewage from human contact. This includes the connection to a drainage system, septic tanks or latrines.

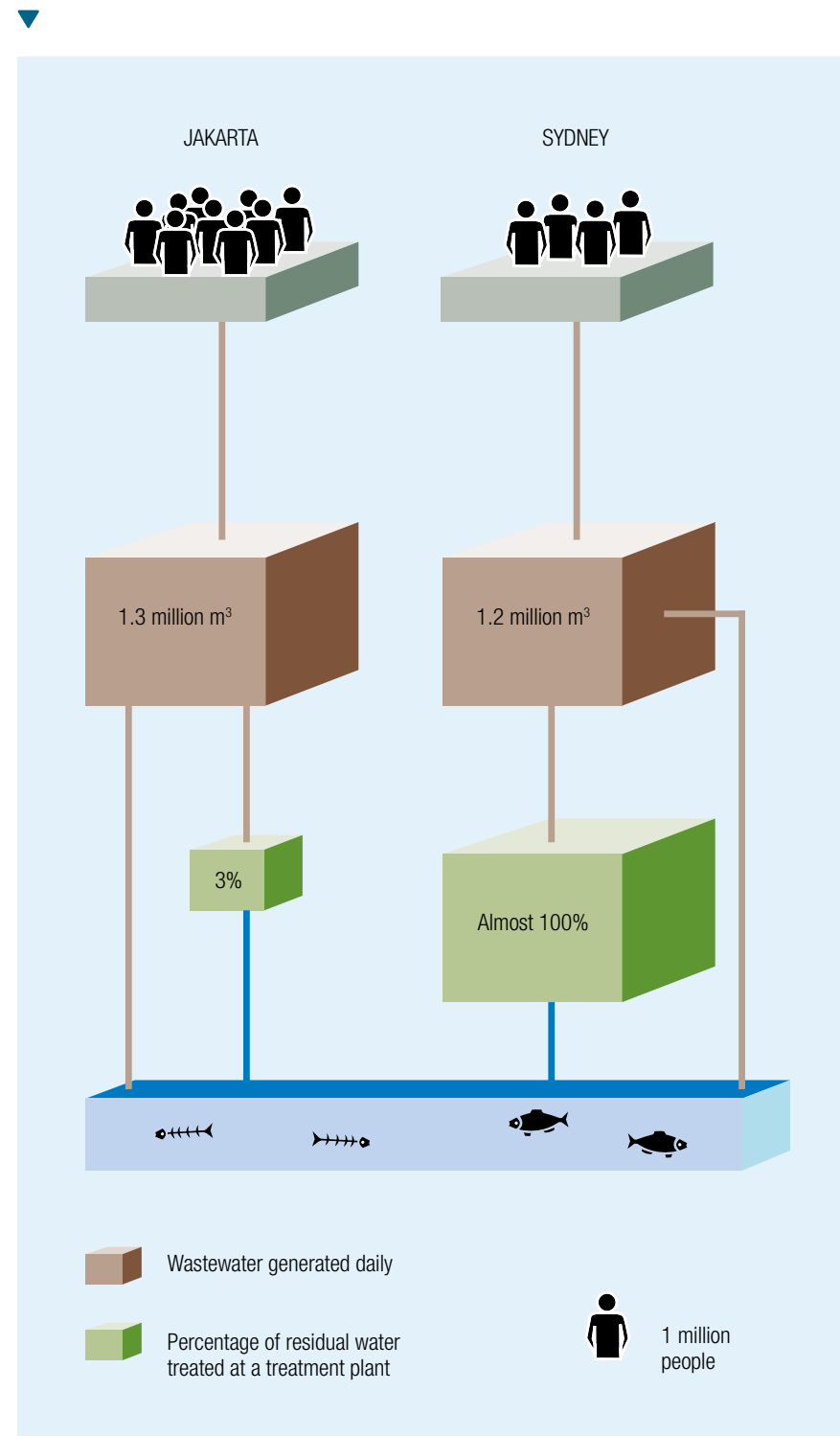
Shared: any type of sanitation services accepted and shared between two or more households.

Unimproved: plants that do not guarantee the hygienic separation of sewage from human contact.

Open air faecal matter: in fields, forests, water courses or other open spaces, discharged as solid residue.

Currently, there are three types of situations occurring simultaneously on our planet

Fig. 1.5.2. An example of the difference in sanitation levels can be seen if we compare Jakarta and Sydney



Cooperation

The existence of different levels of development relative to sanitation systems in different parts of the world requires different types of actions. In the case of countries with the lowest levels of sanitation, there are two types. On the one hand, commercial actions in which companies in the sector, in a very globalised market, opt to licit for contracts that these countries put up for tender to improve their infrastructures. On the other hand, the existence of public bodies and non-governmental organisations establishing projects on how best to tackle the issue of sanitation or wastewater taking their lead from the knowledge acquired in the countries with more experience, in a process called cooperation.

Whilst the regulations in the first situation are clear and regulated by the market, cooperation processes take place in a situation which is less clear. With the best will on both sides, the process is not without its difficulties. Often, the party with the most experience forgets to listen to the other party and so identify the real problems (and the authors of this book will not be the ones to throw the first stones), by trying to apply methodologies that are not valid in the new context. Experience tells us that only after real dialogue, with identification of the problems and real action possibilities, with active involvement from the different agents, with lots of listening by both parties, can useful results be achieved. And it also tells us that when this occurs... the effort made is fully justified.

1.6 Future trends. Incremental changes or a new paradigm?

There are currently different pressures occurring on urban water systems, which may be addressed individually, producing gradual changes:

- Modification of the water quality standards exiting the urban water system to include emerging pollutants, particularly those products derived from the consumption of drugs and personal care products, with the subsequent development of technologies that improve treatment performance of these pollutants.
- Change from treatment to reuse. The end user of the water (the client, in the words of a urban water system manager) is no longer just the river or the receiving environment, but there is a new agent: the reuser. The cycle is beginning to close. The water does

not return to the environment once it has been used and cleaned, but it is used for anthropic purposes such as agriculture, ornamental uses, watering parks and golf courses, recharging aquifers and even for human consumption.

- Consideration of the problem of rainwater in the sewer systems to reduce its impact, at the same time as improving the knowledge of these systems to reduce problems relating to odours and corrosion.

However, when decisions are being made, it must be taken into account that these solutions have a cost.

- a) Each time a new indicator is incorporated into the treatment process, this becomes more complex and causes an increase in the consumption of products and energy, and, above all, the appearance of by products from the treatment process. A key example is the sludge generated by the biological treatment process. Investments for the treatment of sludge may turn out to be greater than those for the water line.

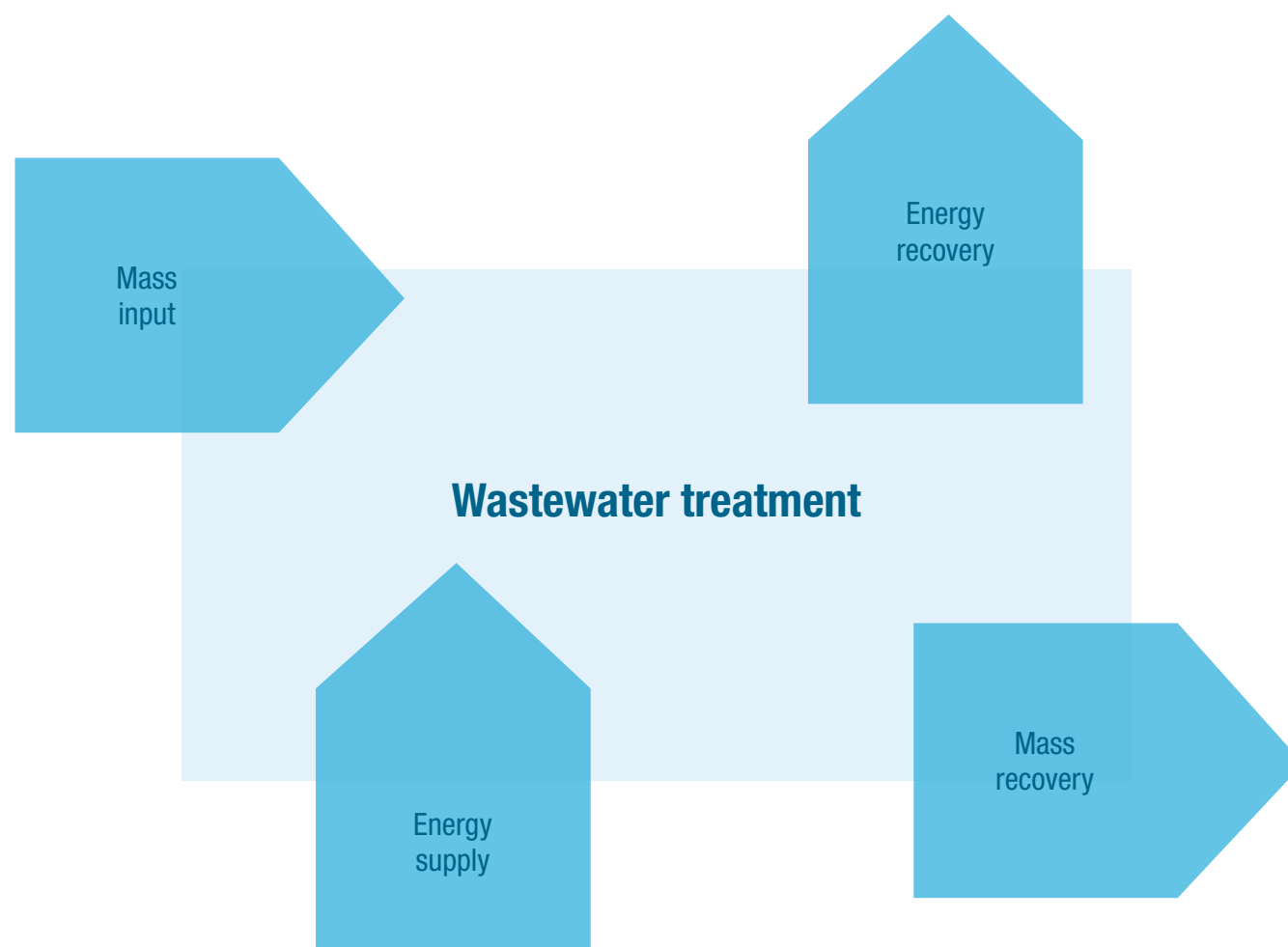
This creates a situation in which some of the problems are partially solved but creating, if not increasing, other impacts (increased energy consumption and the generation of by-products etc.).

“The wastewater challenge is not just a threat, but a challenge where we can find opportunities relative to employment, social wellbeing and health”

*His Royal Highness Prince Willem-Alexander from the Netherlands
President of the General Advisory Board for Water
and Sanitation at the United Nations*

- b) The environmental impact that has a bearing on aspects such as energy, climate change and the carbon footprint.
- c) The water may be reused, but as the number of cycles increases, so does the concentration of stubborn elements with regard to treatment. Simultaneously, wastewater contains elements and compounds that may be incorporated into other cycles (nitrogen for crops) and these are lost in the current treatment processes. We are using energy to change nitrogen compounds to N_2 gas, whilst, afterwards, we use energy to produce fertilisers.





Resource recovery, not wastewater treatment

◀
Figure 1.6.1.
 This diagram introduces us to what may be the new paradigm for the urban water cycle: in terms of wastewater; to consider it not as a problem but rather as a resource. We have to think not only the reuse of water but its interrelation with energy and other natural cycles (carbon, nitrogen and phosphorous etc.). It is not just a water issue; it is an economic, ecological and social problem.

New paradigm

The realisation that addressing the problems individually is not the answer, but that we are in a time when gradual changes have to be substituted with a new paradigm, is a reality that is taking hold. However, there are different considerations that may be the driving forces behind this new paradigm:

- Some authors consider that there are three key elements, mainly related to aspects of urban planning and water flow management: decentralised management, reuse and management at times of rainfall.
- Other experts believe that the paradigm shift may be caused by the separation at source. An idea that has been around for some time, which already affects work done and even has an impact on the design of bathrooms. In our opinion, this case concerns a significant change, not just for the implications of the change in the quantity and concentration of pollutants in the wastewater entering the plant, but it is the first time a structural change is being considered from the end of the pipe to the source.
- Other experts consider quality aspects relative to the paradigm shift, among which include the treatment of emerging pollutants as a new logical stage, after treatment of the organic matter and nutrients.

- Without doubt, the water-energy ratio is another aspect to be considered. In our opinion, this question is currently raised in a too partial manner, focusing solely on reducing energy consumption, rather than a more integrated assessment.

These elements are changing our conception of wastewater treatment. However, still maintaining the concept of wastewater as an element that must be treated as waste, rather than as a resource. It must be considered not only as a waste element to be treated, but also as an element providing resources (not just water).

In our opinion, the real paradigm shift in the coming years will be the one which is summed up well in a great sounding expression that is gaining popularity, as can be seen in some Internet forums: “resource recovery, not wastewater treatment”.

This expression means that wastewater should be considered, as a whole, as a resource and not just a quantity of water, but of its constituents. That is to say a system in which there is an input (human, energy, material) and a recovery that is of material (water, organic matter, nutrients) and energy is recovered. A new paradigm with a more sustainable balance than the current one.

2 Decisions



In the previous chapter, we discussed the need for tools that help with decision making relative to urban water system. To develop these tools, which may be useful at a later date for application in the real world, firstly, we need to start by defining what we mean by decisions and analysing how these decisions are made at both individual and collective level. In the case of decisions at an individual level, it reflects on the process that humans follow, both from a conceptual point of view and incorporating the definition of schemes for intelligent computational systems. The second aspect that we have looked at is how decisions are made in self-organising systems that correspond to the so-called emergent systems. With this information, we move onto an analysis of the types of decisions made around urban water systems or influence them. We propose a three-level classification for decisions with different impacts. Finally, we analyse the interrelationships between the levels established, in order to propose, in later chapters, tools that have been able to help with decision-making at different levels.

2.1 What is a decision?

The impulse to seek causes is innate in the soul of man.

L. Tolstoy

A *decision* (from the Latin “*decidere*”, to cut) is the end product of a cognitive process that involves choosing just one action or option from a set of possibilities or alternatives that are mutually exclusive and not necessarily known *a priori*. This choice may be conscious or not. Decisions may be individual or collective and may be made by an intelligent machine or a set of them and by groups where individuals and machines interact.

The fact is that we make many decisions throughout the day without even stopping to think about them: red wine or white wine? Left or right? Others require an effort that requires our utmost concentration to avoid errors in choosing: Chocolates or roses? Barcelona vs Real Madrid or a trip to the theatre? The amount of time required to make a decision affects the type and quality of the information used to make this decision. This means that individuals who make decisions quickly use aspects readily available in the environment to make them or base them on previous experience. What is interesting here is that some decisions are made correctly if they are made quickly. For example, we are often able to make good judgements about a person after meeting only briefly. If we *like* them at first, we will probably continue to like them. Spending a lot of time thinking about whether we like someone or not is unlikely to improve our judgement or make it any better.

On the other hand, if someone is considering a situation where important features may be hidden among thousands or millions of pieces of data, then make a speedy judgement is not a good idea. This requires an information search and

processing that results in a piece of better quality information so we can make a choice that is more measured. The underlying question is: how do we develop this ability that enables us to *decide* if we think or do not think about a situation before making a decision? In this situation there are also other components that inform the decision mechanisms in the form of criteria, namely: certainty, risk and uncertainty.

- *Certainty* means that the outcome of an action is known for sure. This requires perfect knowledge of a situation and its evolution.

The following two aspects mean that the decision-maker has incomplete knowledge of the situation. They are used in competitive and non-competitive environments. Decision-making theory is based on the development of methods and criteria for making decisions in these environments.

- *Risk* indicates that we do not know what the outcome of certain decisions will be, but we know what could happen and the probability of this.
- *Uncertainty* indicates that we do not know what the outcome of certain decisions will be, but we know what could happen between various possibilities.

To summarise, we can say that a decision, which is a mental output, may be made to be executed as a task and may modify the environment in which the task is performed. As the complexity of the process to be controlled increases, so does the complexity of decisions and how they are made. Thus, the decision-making process is a reasoned or emo-

tional process that can be rational or irrational, which may be based on explicit or tacit assumptions, which allows individuals and/or groups to achieve goals that allow them to interact with the environment or with other individuals and groups successfully and, ultimately, to survive.

In our case, we are interested in studying the rational processes undertaken by an individual, a machine or both together in order to make a decision that we would describe as *rational*. To be able to behave rationally when making a decision, a clear understanding of the options is required through which a goal or objective can be achieved in accordance with the circumstances and limitations existing. There is also a requirement for information and the ability to analyse and evaluate the plausible alternatives in accordance with the goal set out. Finally, one needs to have the desire to arrive at the *best* solution through the selection of alternatives that achieve the desired results in the best way. Such efficiency when making environmental decisions must be respectful of the natural environment, and comply with applicable and optimal legislation from an economic and social point of view.

The inherent complexity of environmental problems, in terms of information, not only current but also that which has been accumulated historically and the possible impact on the environment and in economic terms, make the appearance of automatic decision making systems necessary. Even using these systems, in most cases all the possible alternatives cannot be analysed even with the very latest analytical techniques and computers available. Therefore, the goal is to make an approach towards the most acceptable solutions possible.

Who makes the decisions?

Decision-making in an organisation involves four vital functions. They are: planning, organisation, management and control. For our study, the function of selecting missions and objectives is particularly relevant as are the actions needed to achieve them. This function sets short and long-term objectives for urban water systems and the strategies to achieve them. In addition, we assume that these decisions are limited by *a)* the information and knowledge available, *b)* the ability to calculate availabilities, *c)* the length of time the decision is made in so that it is useful, that is to say the time available to generate a set of valid alternatives to choose the solution from, and the time required to decide. This process is called bounded rationality and was introduced by H. Simon; it allows a course of action to be chosen, which is satisfactory or good enough, given the circumstances, that is to say, within the boundaries of *rationality* in accordance with the size and nature of the risks involved.

In environmental situations, there are two possible options for the decision maker. This gives rise to two manners for the provision of tools for the decision support systems. These are what are considered in the next two sections.

The first is to accept the existence of a central agent that makes the decisions concerning water. The “Governing body”, often represented by a Water Agency, which can cover the whole country or a given management unit, usually a basin. In this case, one entity makes the decisions or a *decision maker*, who, when making their decision, takes the different agents involved in the process into account. Agents that are, in some way, incorporated into the governing body's management or advisory bodies.

In the second case, the approach by which you can choose is to have different interacting agents, each with their own interests, and willing (and somehow with the ability) to change the overall behaviour of the entire system. In extreme cases, the system could be considered as a network of components, without a central control element and with a few simple rules of operation to provide complex collective behaviour.

▼
Figure 2.1.1.
 There is a link between the amount of information and the relevance of decisions, possibly establishing a scale for the way in which each of the steps develops to reach the top level.

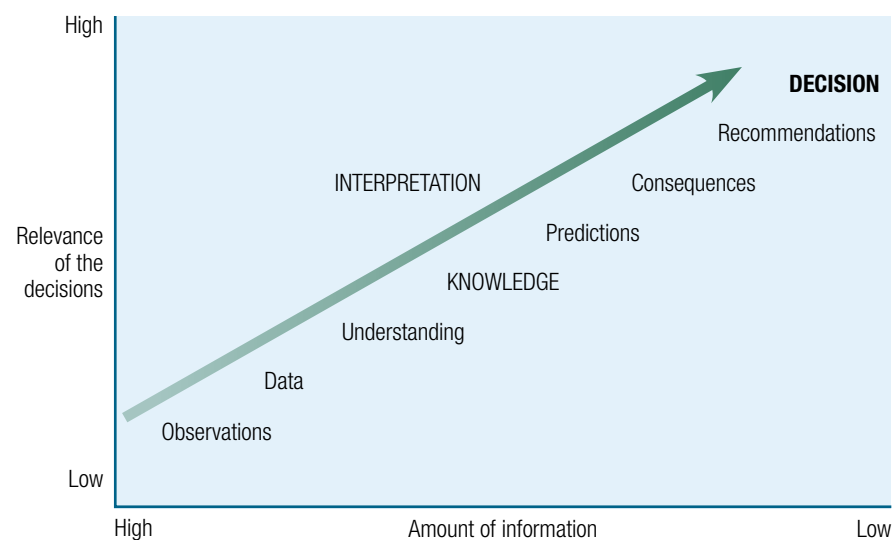
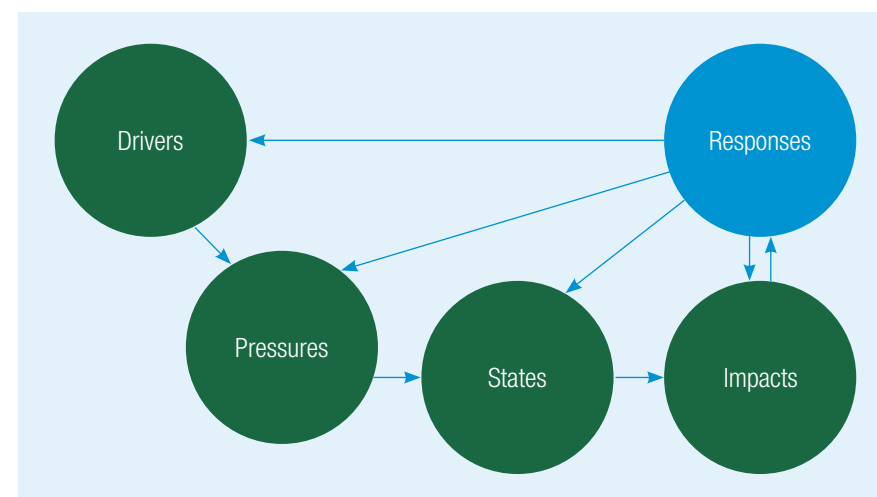


Figure 2.1.2.



DPSIR. A generic framework proposed by the European Environment Agency to help structure the decision-making process.

The proposal of this framework is based on the relationship of the decision-making task with the different elements that condition it. Thus, we need to assess the Drivers in play, their environmental Pressures, the consequences for the States and their Impact. From the analysis of impacts, we can determine the appropriate Responses for directing the final effect in the desired direction (reduction in environmental damage).

DRIVERS: The driving forces required. In the case of sanitation systems, the need to achieve a more sustainable ecological state in the environment, with minimum social, economic and ecological impact (or maximum benefit).

PRESSURES: These are the pressures on the environment exerted by human activities as a result of production and consumption processes. There are three main types: (i) the excessive use of environmental resources, (ii) changes in the use of the land, and (iii) emissions (of chemical products, residue, radiation and noise) in the air, water and soil.

STATES: As a result of the pressures, the state of the environment is affected in the different environmental vectors (air, water and soil etc.) and in relation to their roles in the ecosystem.

IMPACTS: The changes to the physical, chemical or biological state of the environment determines the quality of the ecosystems and the well-being of human beings. In other words, the changes may have environmental or economic impacts on the functioning of the ecosystems, their vital support systems, and, lastly, the human, economic and social health of a society.

RESPONSES: A response from those responsible for the society or the policy is the result of an unwanted impact and may affect any part of the chain between the drivers and the impacts. The responses demonstrate the efforts made by society (for example, politicians and decision-makers etc.) to solve the problems identified for the impacts evaluated; for example, policy measures and action planning.

The relationships between the different parts of the model are described in the diagram.

2.2 How do human make decisions?

In terms of urban water systems, the decision-making process can be hierarchical, meaning that in the end it is a person or entity that makes the decision. To try to describe it, we need to consider the mechanisms used in this case. We should take into account the fact that decision-making mechanisms have always received lots of attention from different perspectives. A decision is made through a combination of the decision-maker's experience and the information available on the probabilities of an alternative being successful, in addition to the wishes and interests of the person making the decision. We will assume that the decision-making process is a continuous cognitive and rational process that interacts with the environment to be successful and survive.

Generally speaking, the decision-making process comprises four phases:

1. Development of the premises
2. Identification of alternatives
3. Evaluation of the alternatives in terms of the goals to be achieved
4. Selection of one alternative, that is to say, make a decision

The decisions may be influenced by elements external to the environment where the agent's action is situated and may be irrational, such as superstition and other beliefs, or non-scientific models that skew the decision-making mechanisms. Therefore, on a day-to-day basis, it is difficult to know how some decisions are made and if the mechanism used has followed a rational course or not. *Positive or negative* experiences are an important part of decision-making; this means that there is an efficient way of remembering the outcome of a decision made and comparing solutions: *making similar decisions when faced with situations with similar problems*. In addition, in many cases, the most important thing for individuals or groups is the outcome and not the process.

Each problem-solving strategy, each style of thinking, each knowledge-representation scheme – each works in certain areas, but fails in other domains

M. Minsky

Background information falls into one of four categories shown below and the results of the consequences of the decision can also be separated into types of consequences.

Categories	Consequences
Certainty	Determinists
Risk	Probabilities
Uncertainty	Unknowns
Conflict	Influenced by opponent

From a *normative point of view*, decision-making analysis is related to the logic and rationality of the process and to the choice of alternative invariant solutions in similar situations. Therefore, from this point of view, the decision-maker finds the *best* decision possible assuming they have the whole *information, precise calculations and rationality*. From this point of view, we can analyse the mechanisms used by human experts when making decisions to solve problems in a specific area. Problem solving is another cognitive process that makes use of decision-making and ends when a satisfactory solution is found to a problematic situation or when it is abandoned.

It is important to differentiate between support for decision making and problem solving, since the latter refers more to a management stage, that is to say once a decision is made.

Types of problems

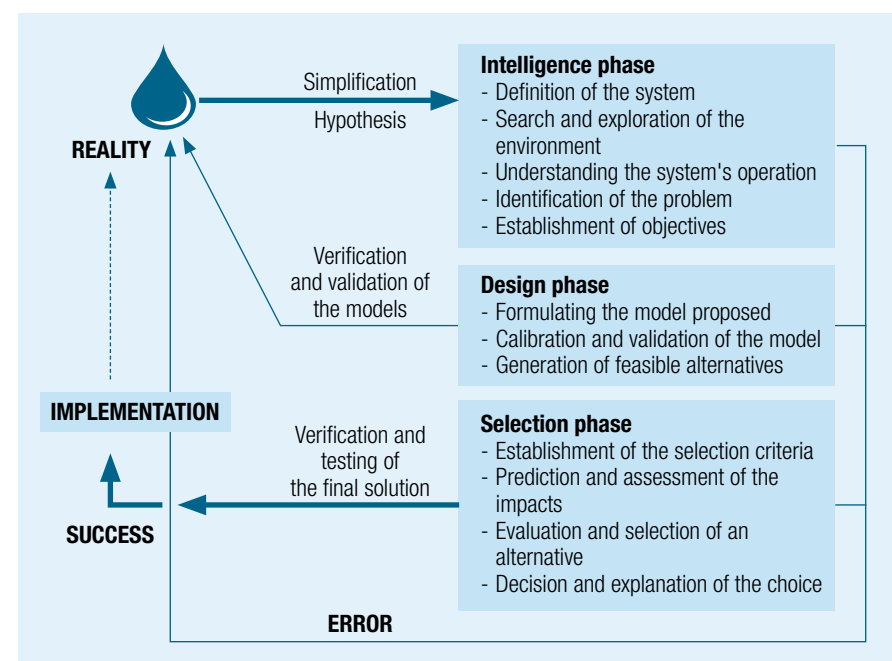
We need to make a decision when we want to go from a current state to a desired state and where we encounter three situations: -when there are visible, feasible and available alternatives; -when the choice may have a significant effect that is difficult to define relative to the current situation, or at least part of it; -when, sometimes, there is an uncertain glimpse of a viable alternative for those making the decision. We can summarise the types of problem as:

- well-structured,
- ill-structured and
- unstructured

Types of decisions

The alternative solutions available from which we must decide range from the known and clearly defined to the experimental and ambiguous. In critical processes such as wastewater treatment, how is an *experimental* solution adopted for a problem if possible damage to the environment is to be avoided? Is there a place for *creativity* in decision-making?

▼
Figure 2.2.1.
Diagram of the decision-making process.





Rationality or irrationality of human decision

Joan Manuel del Pozo

Philosophy Department. University of Girona

A question of great philosophical interest is the rationality or irrationality of human decisions. It is indisputable that, except for very routine or automated acts of life or moments of passion or psychophysical destabilisation, a decision is understood as an intellectual operation, called *rational* because it seeks to ensure, through the analysis and weighing up of various *reasons*, in the sense of arguments, an optimal outcome among the options considered as possible for our action. If so, we could say that the decision-making process is rational, because reason will guide the analysis that provides us with the best logical conclusion to facilitate our choice and final decision. This rationale can be postulated as a starting point - we all think that reason guides our decisions: so we are used to saying that *we know* what we are doing-, but we do not necessarily pervade the whole process let alone always manage to explain the end result. This is why in life we never, or hardly ever, come up with *conclusive* reasons that enable us to make *safe and rational choices and decisions*. Put another way, we know that deciding almost always after accepting that the reasons in favour of one of the options are counterbalanced -often with a similar magnitude- for similar reasons in favour of other options, which greatly weakens the rationality of the decision, because the reason is *divided*; it may be drawn in favour of the two different options, which, *rationally*, leads to the process stopping: this is the case of Buridan's ass, the famous medieval philosopher who was just as hungry as he was thirsty that upon finding a bag of tasty straw and a bucket of fresh water but, after considering that he had no *reason* to give priority to the straw or the water, died from hunger and thirst.

But we also know that in the whole human decision process, there are not only reasons to counterbalance others -which means that the decision based on some of them may not be fully rational and, therefore, must be at least partially irrational - but the intelligence of man cannot act alone -as *pure* reason-, but acts by constantly mixing other sources that may influence behaviour to cancel it out: emotions, feelings, passions, or instinctive or reflex reactions, mental disorders, physical illness, severe pain, exulting pleasures, mental inertia, beliefs, prejudices, interests, conscious or unconscious interests -build up a picture of complexity of the real decision-making process that reduces the concept of *reasonable decision* almost to a joke, that is not to say that *decision rationality* is a bad joke. In fact, if Buridan's ass had been only *slightly human* - and not been a purely rational machine - he is sure to have ended up deciding to bite furiously into the straw or to dip his head enthusiastically into the fresh water, and then he would have seen how to continue. Survival instinct would have given a lesson to the supposed 'pure reason'. That is to say: he would have decided *irrationally* as we often do as humans. Or not?

Because, depending on which concept of rationality we adopt, we should consider it very rational -in the sense it being well suited to our condition, endowed with reason but not only reason- that life flows although the reasons alleged to be *intelligent* do not allow this in some cases. That is to say we may see it as purely rational that the *mechanical* reason for abstract analysis of the conditions for the choice is not considered to be critical for deciding our actions, but only as another criterion, certainly desirable and important but not decisive, to accompany them. Maximum rationality -or a certain 'metarationality'-, therefore, we can say that it recognises and incorporates its own rational limitation and the presence of irrational elements in the decision,

which enhances and disqualifies it at the same time: hailed as open to its own and significant limitations and discredited as the safe instance it is purported to be. Therefore, we can say with Searle (Rationality is not entirely, or even largely, a matter of following rules of rationality).

Since the classic dictum wisely advised that "primum vivere, deinde philosophari": life cannot simply follow reason. So there is someone who has earned a place in heaven, among contemporary celebrities, for having coined, *mechanically rationally*, "emotional intelligence"; but it is like someone discovering the Mediterranean, because the concepts there have already been present in the philosophical debate since its Greek origins. What do you think Heraclitus was thinking if he wasn't under 'rational human performance' when he wrote: "We do not need to act or speak like sleepy people" (DK-73)? Assuming that we are *sleepy* means that the Apollonian body of reason -sleepy because it is not seen clearly- does not usually guide the decisions in our life. Hence his advice.

The presence of the irrational component in our vital decision-making process is that which Kierkegaard used to establish a unique philosophical concept, surprising when formulated in the 19th century; although he described the *jump* as an essential attitude to life to decide the way to the religious stage of life, considered necessary in all major decisions of individual existence - let's remember that he is considered the father of the famous 'existentialist' motion of the 20th century- that cannot be governed by a logical, gradual or rational conceptual shift -Hegelian inspiration, against which he rebels, but which requires a leap of faith, often blind, made of pure volunteer work and risk.

Finally, let's not forget that there is an argument worthy of consideration in the analysis of the rationality of human decision. If human rationality always acts with full effect, that is to say establishing a full guarantee of the safety of every decision, without reasons to the contrary, without the presence of non-rational impulses of behaviour, then it would have annulled human freedom. We would be completely rational, but we would have lost our freedom. Paradoxically, freedom is born from reason -it is because we are reasonably able to understand and weigh different options up that we can begin to be free - but we would die at the hands of a safe reason, because we would be *determined* because *we could not fulfil* its exact dictamen: freedom lives, then, in the ambiguous terrain of rational limitation, which allows us to reflect and ponder, but not to *close* in on an exclusive and binding dictamen; because we have freedom we have rational insecurity, at the expense, of course, of suffering the agony of choice, Sartre: the anguish of being "condemned to be free"-.

Here we see the need to complete the *limited rationality* -or partially irrational- process of decision-making, which is no freedom with the anguish of having to *jump* and make an unprepared choice without security, with the ethical requirement to direct freedom towards objectives that *evaluatively justify* that which, intellectually, should be closed. Or, in terms of collective decisions, which are *democratically justified*. But these are very different stories.

2.3 Collective decisions. emergent systems?

...the human conscience is an emergent property of our brain

Systems theory tells us that when different elements interact in a system (like in urban water systems) the response from the system as a whole is different from the sum of the individual responses. New properties are emerging called *emergent properties*.

These emergent properties can only be detected and analysed when the system is looked at as a whole, as when we talk about a colony of ants, bees or termites or even the human brain. In this sense, the human conscience is an emergent property of our brain. In the same way as the ants that form a colony, no neuron itself contains complex information such as self-awareness, hope or pride. However, the sum of many neurons in the nervous system generate human emotions such as fear or joy, neither of which can be attribut-

ed to a single neuron. It is thought that consciousness arises from the oscillation and synchronisation of the neurons in the cortex. Although we still do not know enough about the human brain to be able to identify the mechanism that generates the emergence of the functions, neurobiologists agree that the complex interconnections between the parts give rise to qualities that only belong to the whole.

These emergent properties are sometimes called collective intelligence as they often coincide with capacities greater than the strict sum of the capacities of the individuals when considered individually. In terms of making decisions on urban water systems, an interesting discussion point that could be raised is whether the set of agents involved in it could improve their behaviour if they interacted directly with each other, if decisions were made based on their direct interaction, without a hierarchical organisation. Conceptually, the point is interesting since it indicates the goodness of using different, much less hierarchical organisations, than the current ones.

But it now seems clear that a system with this way of working would not be operational for managing urban water systems, which does not mean that, in some cases, it might be interesting to contemplate the existence of decision processes constructing methodologies based on emergent systems. This is why most decision support systems presented in the text correspond to systems that are capable of managing knowledge existing between the different agents involved in a urban water system, but presupposing the existence of a person or entity (*decision maker*) that makes the final decision, since this is the most common situation in urban water system management. Simultaneously, it seems interesting to continue working on developing decision support systems to help to rebuild

the behaviour of the emergent systems, from the identification of their individual goals and then from the study of their interrelationships.

The tragedy of the commons

The ability that systems have to provide different responses to the sum of the individuals forming it is not always positive. Sometimes something called the "tragedy of the commons" occurs; this is an expression coined to describe what happens to the common part of a system formed by a group of individuals when the selfishness of each of them and their interest in obtaining maximum individual benefit means that the group gets worse results, and the majority lose out. Of the many environmental examples that may be mentioned when human behaviour is studied, one of the most significant at the moment is related to climate change. A common good such as the atmosphere, where changes have a direct impact on the survival of the human species, is affected by individual interests that try to maximise their benefits or convenience, meaning that the common good loses out which may lead to serious collective damage. It is curious that most of the examples that discuss this type of behaviour, which in the end leads to almost everyone losing, are obtained from human systems, in which we assume individual intelligence greater than that of other animals, among which we find examples of collective intelligence. In any case, this debate goes beyond the aim of this book, which simply aims to study this type of behaviour to offer better tools for the decision support systems relative to urban water systems.



We are not ants, but studying their organisation may help us.

One of the most studied emergent systems are anthills. It is a good example of collective intelligence, since from a group of elements (the ants) that are only able to perform a small number of actions individually, the system (the anthill) as a whole is able to develop a complex society which is even able to build sophisticated structures. It appears that one of the keys to this success is the fact that the individual elements strictly observe their reduced instruction programme without ever considering thinking at higher levels. Therefore, it is difficult to draw comparisons with human societies, in which the individual has free will. But this does not mean that the study of ants will not be useful for developing computer algorithms to help with complex optimisation processes. Thus, recently, so-called *ant colony algorithms* have been proposed, which try to reconstruct the behaviour of ant colonies for the search for food, a task that, collectively, shows great efficiency. In nature, ant colonies base their behaviour on the search for food and the transmission of information through modification of the environment. For this type of communication, which is called stigmergy, the ants use the deposition of pheromone. They randomly move away from the anthill in search of food and, if they find it, they deposit a certain amount of pheromone on their way back to the anthill. When other ants smell this pheromone, they follow it so there are increasing numbers of ants in the area where the food is located. This greater concentration of ants generates a more intense pheromone and whilst it does not evaporate, it encourages more ants to follow and find the food.

Simulating this type of behaviour, ant colony algorithms try to find a solution close to the optimal, using simple computational entities as artificial ants that move randomly around a solution search space, applying a probabilistic strategy called state transition rule. Iterative solutions are constructed through their movement. When they are viable, they deposit pheromone. Cumulative quality is related to the quality of the solutions. This includes a certain degree of pheromone evaporation, to enable exploration into new areas, with new components, in the search for better solutions and slowly forgetting the previous area.

Basically, all the ant colony algorithms are comprised of three stages:

- The construction of solutions, in which the group of ants constructs solutions from the elements comprising a finite group of components for a possible solution. New components are added to the partial solution at each stage. The choice of a component is guided by the state transition rule, in which the pheromone and the heuristic information is deemed to be relevant. If restrictions have been defined for the solutions, it is deemed to be viable if they are met and unviable in the opposite case.
- The application of local heuristic improvement methods that try to improve the solution constructed by replacing the movements of the solution's components in the local environment of the solution search space.
- Updating the pheromone trail, which should increase the value associated with a component that can be part of a good solution, or decrease it otherwise.

Once again, observation of nature and the study of the complexity of relationships can help us to better understand not only their behaviour but also the other aspects that may seem as unconnected as the optimal allocation of industrial waste, as discussed in a later chapter.



*Emergent behaviour
is not just a
fascinating scientific
extravaganza;
it is the future*

The New York Times

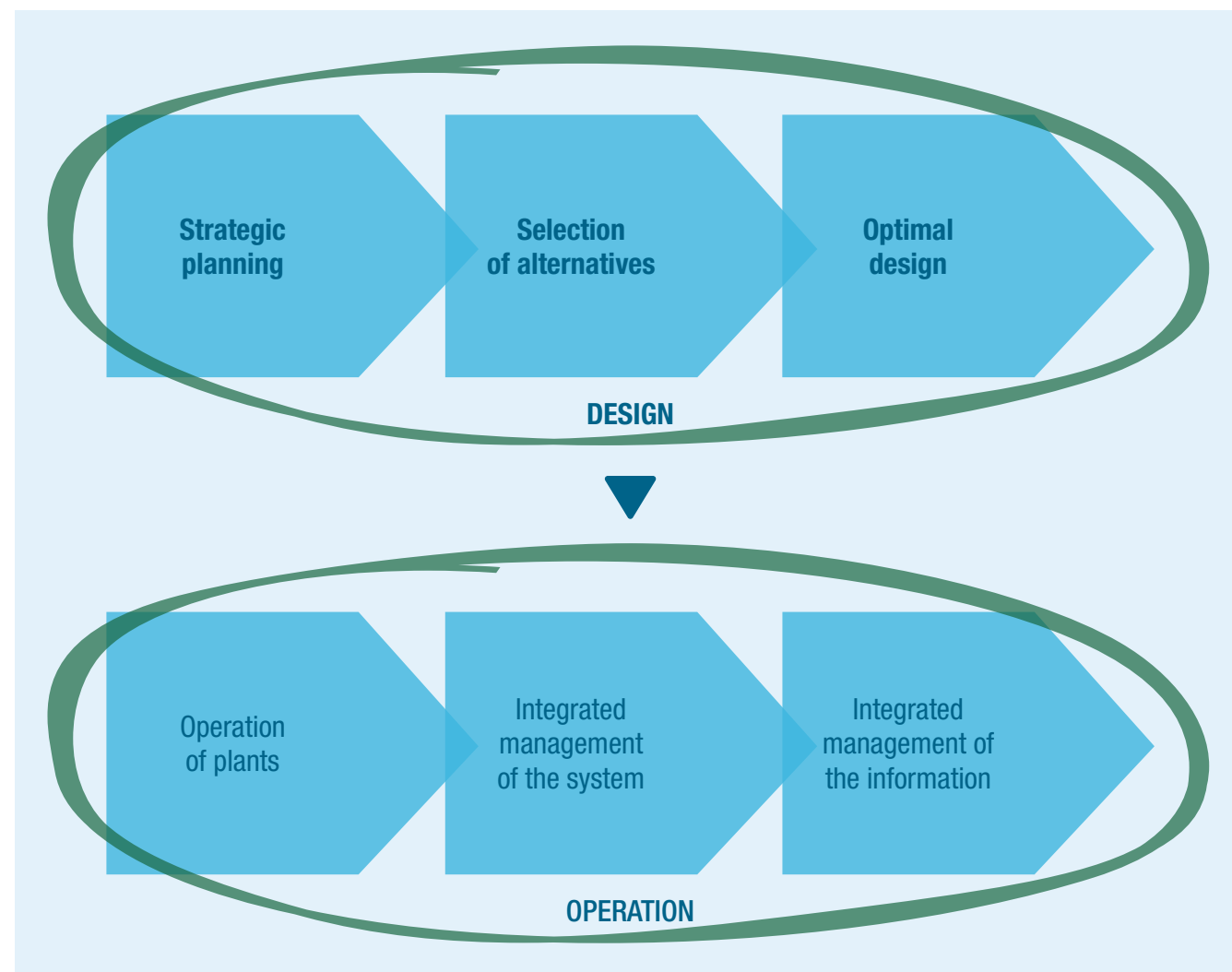
2.4 Decision levels in the design of urban water systems



Figure 2.4.1.

The existence of different levels in the design of wastewater treatment is well-known. Thus, Glen T. Daigger considers five levels to identify in which of the design process stages mathematical models can be used in. Based on this diagram, we propose the existence of six decision-making levels divided into two sections (design and operation).

An important aspect for decision-making support is, firstly, to identify the existence of different decision levels that form part of the urban water system management



First level

We understand the first level to correspond to **strategic decisions**, which, mostly, are not directly related to the urban water cycle, but condition its design and operation. Our goal is not to provide an exhaustive relationship, although it does seem important to point out some of the planning elements that condition, often indirectly, urban water systems. Usually the administration responsible for water management has little influence. Among these, we would like to highlight:

- Urban planning, which may be more concentrated or extensive and will condition the amount of wastewater generated and its concentration, the distribution of collection systems, the possibility of using more extensive or intensive treatment systems...
- The funding policy for the costs associated with the water cycle treatment. The European Directive sets out that the costs should be recovered directly from the water cycle and that the system must be self-sustainable. This is a model that is still along way off being applied in those countries affected by the Directive, but this is not unique; and in practice, different countries have different funding models with different weights given to public-private investment.
- Industrial development and its link to the urban water cycle, with the existence and size of industry in town centres or the definition of the integrated treatment policy (domestic/industrial) for wastewater. This affects the quan-

tity and quality of the water entering the sewer system.

- General environmental policies, which make reference to the existence of collection and/or re-use regulations relative to rainwater, to source separation within the home, or to the recycling of greywater in buildings, with the existence of piping for this.

Second level

At the second level, decisions are made concerning the **selection of the configuration** of collection and treatment systems. At this level, and from the information provided at the previous level, the configuration and technologies most suitable for achieving the objectives and restrictions defined in the previous level are selected. This is a level that includes new elements that influence decisions, particularly related to the technologies available to achieve the objectives defined in the previous level. In terms of treatment, the following must be included for each technology:

- Its treatment capacities for the different types of pollutants. We have to take into account the fact that different technologies have been developed over a period of time during which priorities and objectives have changed, and with different objectives. Therefore, there are different characteristics for different pollutants.
- Investment, operation and energy costs. If, like we often do, we take the investment cost into account, we should consider the total cost of the plant's useful life, which may change the order of preference relative to only considering the building cost. Simultaneously, and with the gradual increases in the cost of

energy, the energetic cost must be considered at this stage.

- Compatibility with other treatment operations. Not all treatment operations are compatible with each other or have the ability to adapt to the changes that the system may experience over time, such as possible extensions. Therefore, this aspect should be taken into account as part of the decision-making process.
- Secondary effects, impacts and generation of by products. Urban water systems are designed to reduce the environmental impact of wastewater, but they are industrial plants so they also have an impact. Today, we do not just have economic costs but also by-products and impacts associated with their activity, such as the emission of greenhouse gases.

Third level

The third level corresponds to the design and optimisation of the equipment and is a **fundamentally technical level**. Previous levels have identified the sequence of operations to be included in the urban water system, which achieves the first level objectives. The third level is necessary to identify the dimensions associated with each of the units involved. At this stage, we need to identify the volumes, surfaces and power etc. of the pumps, pipes and reactors involved. We should also consider aspects of plant operation to ensure optimal performance later, so you must include the control elements and define operating conditions for maximum process efficiency. While, for the first plants, the calculations were done by hand (you can still find excellent manuals that allow the relatively easy calculation of the dimensions of much of the equipment used), the scientific efforts made to obtain models increas-

ingly tailored to reality, the complexity has been obtained by considering different options and the computing power of computers has led to widespread use of this equipment at this level.



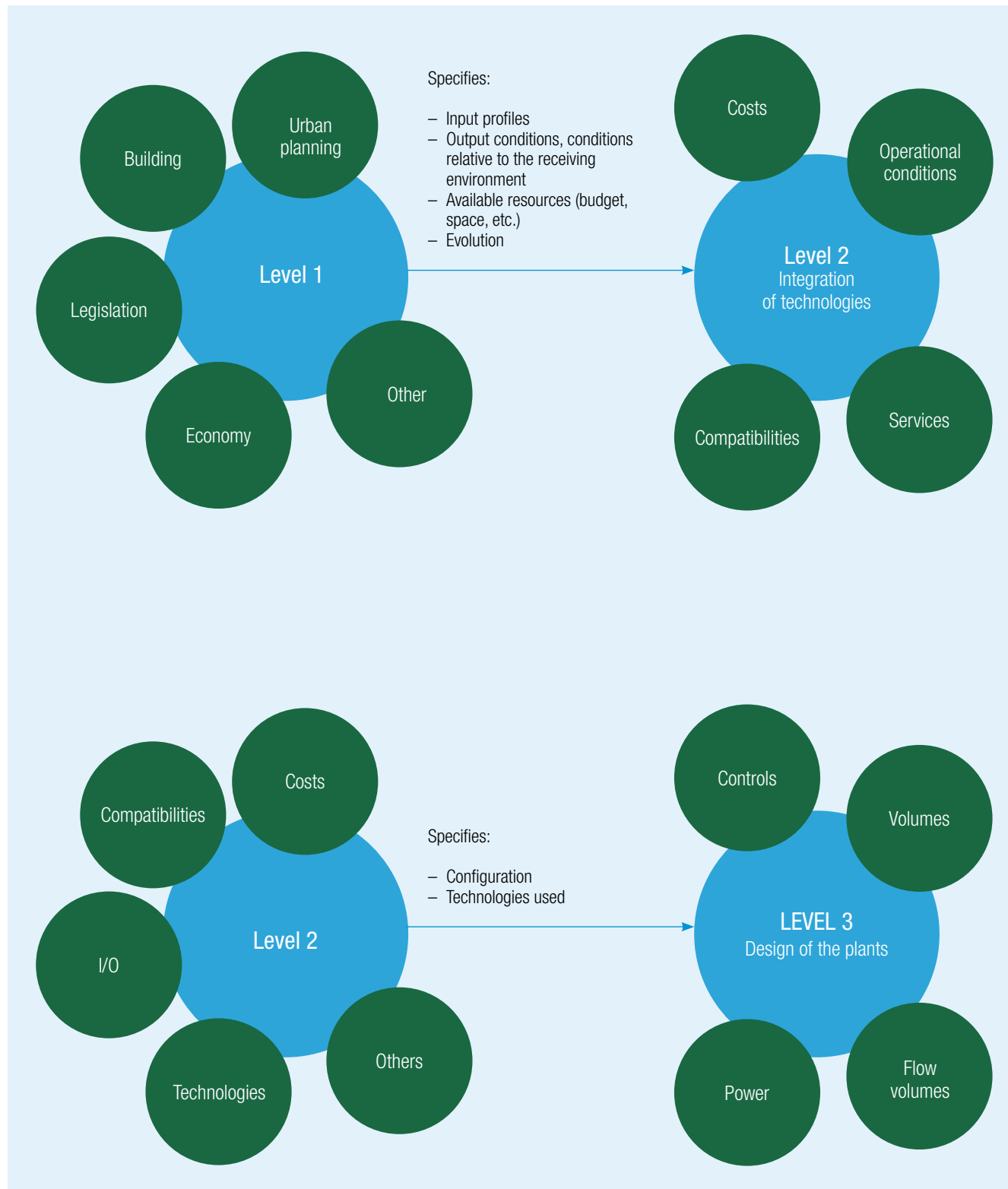


Figure 2.4.2.

Our proposal identifies a first level that conditions subsequent decisions to be made in the design of urban water systems. In this first level, areas other than treatment (such as urban planning, legislation or economic factors) influence decisions that affect subsequent levels. Thus the set of decisions made at the first level condition both input profiles to the urban water system, and the specifications that they must comply with as well as the availability of resources (budget, space, etc.) provided. In turn, the second level relates to the making of decisions that are restricted by new elements, such as the availability of technology, performance, costs, operating conditions or compatibility.



Figure 2.4.3.

According to the diagram proposed, in the second level decisions are made corresponding to the selection of the sewer system and the treatment technology. This case includes restrictions corresponding to a new set of knowledge, which is more characteristic of and specific to treatment. This corresponds to the capacities, services and restrictions relative to the different technologies available, which, together, respond to the requirements set out. At the third level, decisions are made relative to the operational dimensions and conditions of the equipment and plants, which should be optimal from an economic, ecological, and operational point of view.



Figure 2.4.4.

Variables affecting the strategic level

Second level. The selection of the configuration of the collection and treatment systems. At this level, and from the information provided from the previous level, the configuration and technology most suited to achieving the objectives and restrictions defined in the previous stage are selected. We need to keep in mind the specifications of the water leaving the system (taking the sensitivity of the receiving environment or the use to which it will be allocated into account); the characteristics of the water entering the system and the condition it arrives in; and the resources available (at economic level, but also relative to space, technology and energy etc.).

2.5 Complexity of the decisions

An interesting aspect of the establishment of three levels in the design of urban water systems is that we can better visualise some of the characteristics that have evolved throughout the design process. Somehow we are identifying the basic elements that identify the complexity of the decisions made at each stage, allowing the simultaneous determination of the suitability of the agents involved in decision-making at each stage.

In a previous study by the authors arising from the original ideas from Funtowicz, three levels of complexity were considered associated with the three levels of decision in the design of urban water systems.

First level

The first level corresponds to really complex systems where there is high epistemological or ethical uncertainty, and where what is at stake may involve conflicts of interest between the parties involved in the process, as well as a significant risk. In this case, it is important to recognise the need to consider a plurality of perceptions and perspectives. In urban water systems, this corresponds to the management of a unit mass of water, where different factors, economic, technical and ecological, come into play and each factor is associated with different goals. Therefore, there is a need for collaboration between the different actors, which also implies different objectives and different experiences that must be integrated.

Second level

The second level relates to the selection of the configuration and would correspond to systems with a lower level of uncertainty, but that are difficult to represent in a satisfactory manner, by applying a standard model that can be reproduced anywhere and by any competent practitioner. In this instance, the personal element and acquired experience is important, so the presence and participation of an expert is significant. This selection will vary by location and the assessment that the person responsible made of the importance of the various phenomena involved. Certain quality standards have to be maintained at the output and there are different options available to achieve them and the selection of one or another configuration depends on the person responsible for the design and their own experience.

Third level

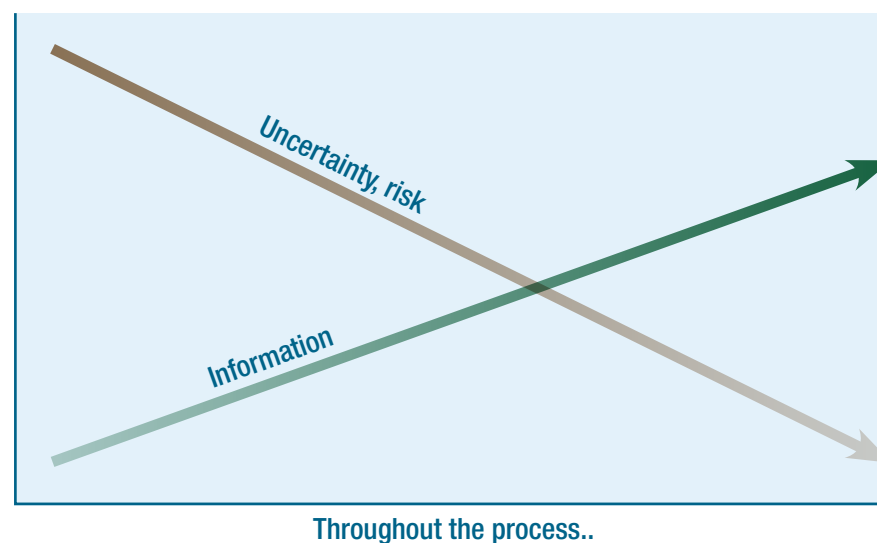
The third level of design is for less complex systems where uncertainty is reduced and what is at stake has less importance, since the degrees of freedom and investments have been reduced. These are systems which can be represented using a single perspective and where you can find a model that provides a satisfactory description. The input is perfectly defined, the number of alternatives is limited and the available information is sufficient to discriminate between them.



Figure 2.5.1.

There are two characteristics that evolve significantly throughout the design of the process:

- The impact of the decisions on the project's costs as well as the number of options to be considered, will decrease as the project nears completion. This finding, which seems obvious, is, curiously, not always related to the effort that goes into the different stages. Often the time and resources required to make decisions do not match the impact they may have on the final cost of the project. It is one of the obvious truths that is sometimes forgotten.
- The amount of information available increases as the definition of the project evolves. Not only do fewer options have to be dealt with, but there is usually more information and this has less uncertainty. The uncertainty aspect is important as it affects the confidence in decisions made; therefore, the minimisation of uncertainty should be one of the key elements in decision support systems.

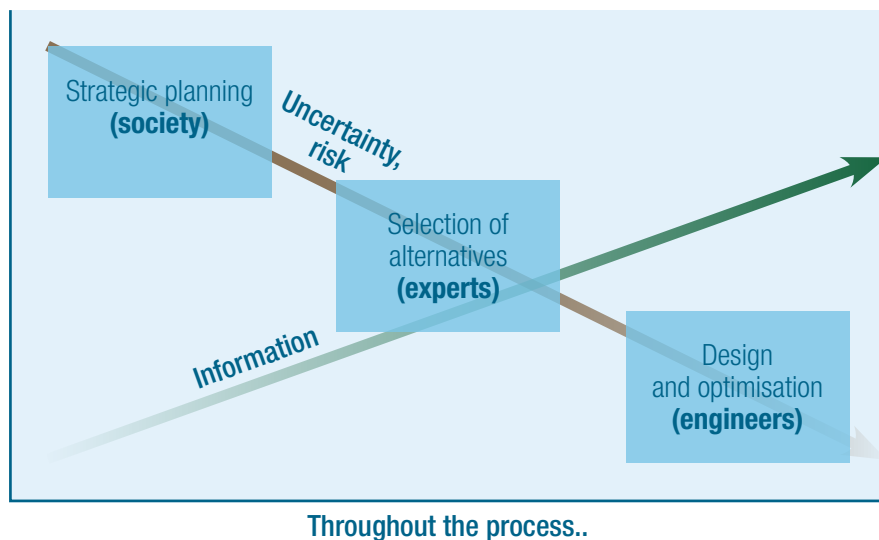


An interesting aspect of the establishment of three levels in the design of urban water systems is that we can better visualise some of the characteristics that have evolved throughout the design process.



Figure 2.5.2.

The integration of the variation of the impact of decisions with the information available at each level allows us to identify both the existence of the different skills involved in making decisions and the different agents. In addition, each of these levels established different relationships between the agents and with the decision-making process. The first decision level comprises important political components (in a broad sense) which, as noted, may have some clear intentions, which are difficult to quantitatively translate, so decision support systems will be needed to manage this characteristic. At the second level, the key characteristic is experience; the decisions will mostly be made by experts, who may come from various fields. Each can be an expert in their field, but the decision support system must be able to manage the "paradox of expertise", which reminds us that the more you know about a subject, the harder it is to explain the reasons behind the proposed decision. At the third level, instrumental behaviour becomes more important. There is less uncertainty and more tools are available, which are able to quantify the processes that take place in the system. It is the environment in which the engineers and operators can evolve with more comfort and efficiency.



Each level presents different complexity and requires different decision-makers

The complexity of defining the complexity

To try to understand some of the things that happen, the first of the affirmations is that the world we live in is complex. And defining complexity is one of the main difficulties. As they say with pornography, we know what it is when it is in front of us but it is difficult to define it. We say that something is complex when it has interrelations and its limits are not well-defined, or when the responses to changes are significant, since they can vary from one day to the next. Thus, we say that our brain is complex, but so is a forest, or a set of social networks. In this context, how can a decision's level of complexity be measured? In an excellent book introducing the topic of *Complexity: A guided tour*, its author, Melanie Mitchell, dedicated a good number of pages to looking for a definition that quantifies the level of complexity according to the size of the system, the amount of information to be processed and depending on the degree of hierarchy in the structure etc. She concluded that the existence of such possible measures is an example of the fact that it is difficult to find one that encompasses the whole problem. In any case, there is a consensus that there are three common elements that can be used as indicators for a definition, so that the larger they are, the greater the system's complexity.

- The existence of a set of elements that interact through a network structure.
- The system provides responses that are non-trivial and difficult to predict from the analysis of the individual elements, generating what is called emergent behaviour, without the need for a central brain to exist.
- Some of the interrelationships may change over time, so that the system tries to adapt to its environment, through learning or evolutionary processes.



2.6 Decision levels in the operation of urban water systems

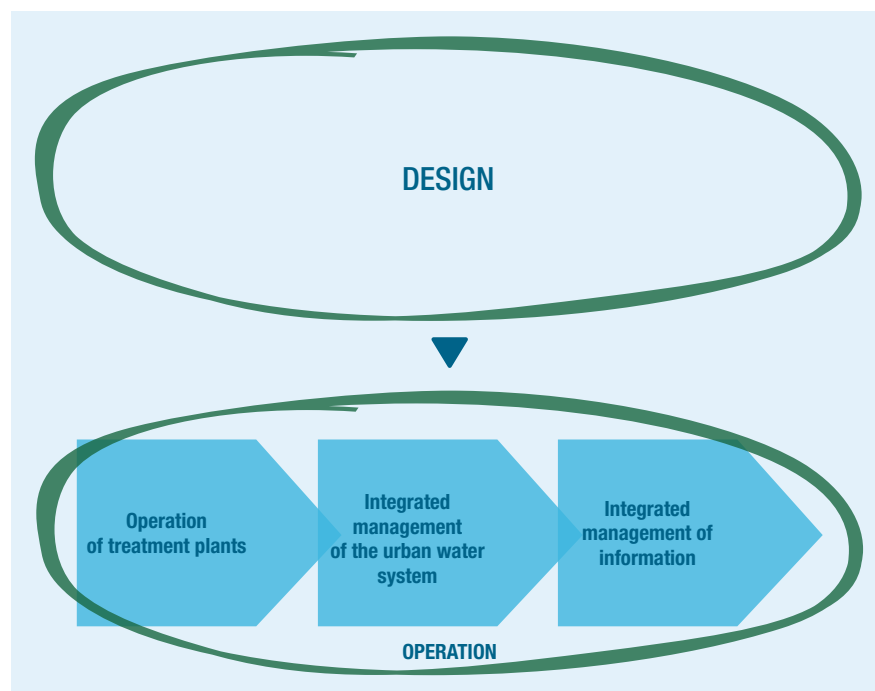


Figure 2.6.1.

Similar to the design process, this section also proposes the existence of three decision levels. And if in the case of design, the proposal goes from a more general level to a more specific level in the case of operation our impression is that it works in reverse. Firstly, an effort is made to ensure continuity in the urban water system's elements, mostly individually, the sewer system on the one hand and the treatment plant on the other. More and more work is taking place to address the problem in a more integrated way, making decisions that take the whole urban water system into account, considered as a unit, in line with the integrated framework Directive, finally considering, at least at the level of knowledge management, to a whole basin.

Once the urban water systems have been designed and built, we proceed with their operation ensuring this is as efficient as possible. This involves making decisions to guarantee efficiency and optimal maintenance

First level

In the case of the operation of urban water systems, the first decision level corresponds to the treatment plants or sewers separately, individually. It is here where operational decisions are made relative to controller set points, cycle times, chemical addition, etc. The current plants are able to provide important information, which is difficult to process by a single person, unless you have tools that aid in the interpretation of data in real time to identify the problems that arise at each moment. At this level the decisions are, mainly, technical and correspond to the third level of complexity.

This does not mean that there is no complexity. There is a risk, as it is the derivative of the poor performance of the sewer system or the treatment plant, which may lead to the discharge to the environment of raw sewage and there are subsystems, which, in turn, are the result of complex phenomena, such as the ecosystem that treats the water in a biological treatment. In a similar way to Russian dolls, detailed analysis of each unit allows us to observe that complex situations are reproduced at different levels.

Second level

A second level of complexity in the management of urban water systems is that which appears when it takes place seamlessly between the sewer system, the treatment plant and the receiving environment. In this case, the information provided by each of the elements is used by the other two, which may allow global optimisation of the process. In our opinion, although this benefit is clear, there are still a few systems that use it, for two reasons:

- Firstly, because administrative problems sometimes occur. The competencies of each of the systems may correspond to different administration

levels (local or regional etc.) or even on the same level of administration, it does not ensure coordination, as skills can be divided into different departments, which does not always maintain smooth relations.

- Secondly, because there is an increase in epistemological complexity. There is not only more information to process but it is a different type of information. Therefore, the processes that take place in the sewer systems are associated with the movement of flows, and although an effort is currently being made relative to the consideration of the biochemical processes taking place, so far our knowledge is limited. This situation is different in terms of the treatment processes, where, in recent years, significant efforts have been made to describe the biochemical processes taking place. Incorporating the receiving environment's management involves a specific type of knowledge. This diversity has meant, in some countries, that the majority of the professionals for each of these systems come from different training backgrounds (civil engineering, chemistry / chemical engineering, biology).

Third level

Finally, the third level corresponds to the use of information obtained from a set of urban water systems, whether grouped by geographic area or by type of treatment. Each system has its specific problems, but there are behaviours that are repeated and can be generalised. It is important, therefore, to have decision support tools allowing the automatic and useful extraction of knowledge relative to all the information to be obtained in order to apply it in new designs or in everyday management.

Figure 2.6.2.
It is important to note that the three decision levels involve different levels of integration in the operation of the urban water system.

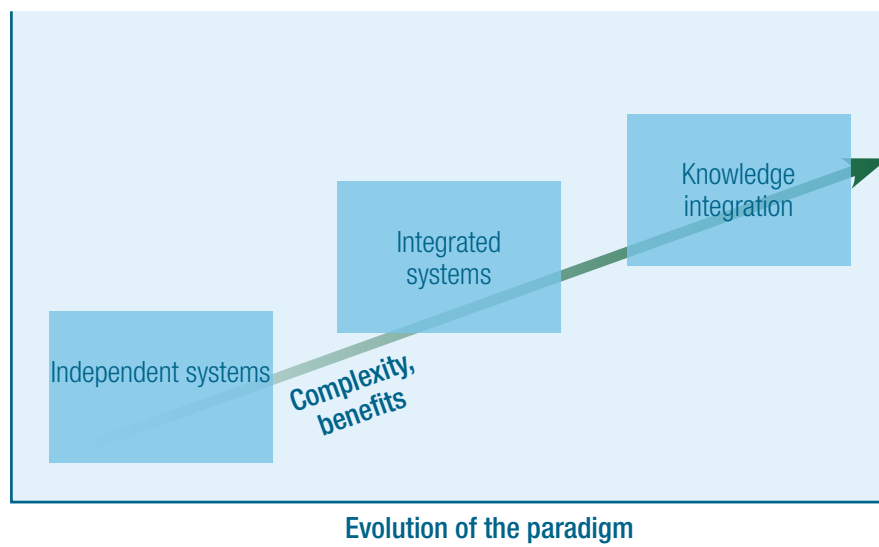
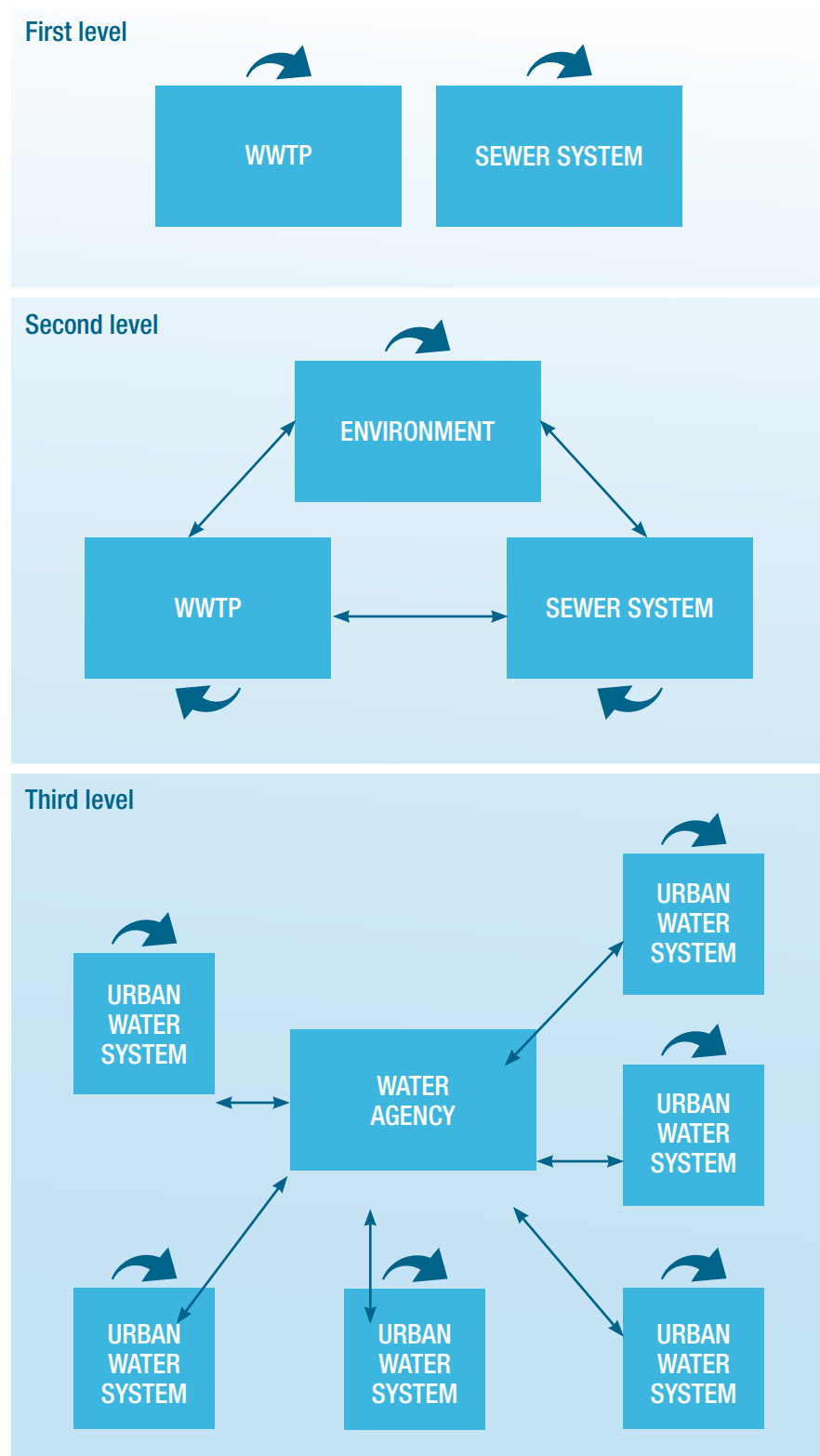


Figure 2.6.3.
There is an important variable that differentiates decision levels between the design and operation of urban water systems this is the time variable. Unlike the design stages, which can take months or even years, and in which decisions are taken discontinuously over this period, urban water systems must operate continuously every hour of the day every day of the year. That is why, at operational level, the operation of the individual systems is initially secured, although it is not the optimal way. It is based on the knowledge acquired in this operation when we have tools available to plan increasingly integrated management.

2.7 Interactions and feedback

One might think that the consideration of the three levels in the design and operation of urban water systems, and their presentation in linear form, means that the decision-making at each of the levels is done independently, conditioned only by the decisions from the previous level. That is to say as a linear process in which every decision has a history and produces results.

Nothing is further from the truth. As has been repeated throughout the text, the issues addressed in urban water systems are complex and one of the characteristics of the complexity is the existence of interactions between the different elements. Each decision not only produces results (better or worse) in relation to the problem solved, but it also produces side effects, affecting other elements in the system.

How to help at each stage and help each of the agents who make decisions is the aim of this book.

The system does not just work as *top-down* but also as *bottom-up* within the cycle itself and between cycles. There is also feedback from the impacts of the decisions between the lower levels and the upper levels

Figure 2.7.1.

One possible conceptualisation of decision-making relative to urban water systems would be linear, in which each decision is made to solve a single problem and produces a single result.

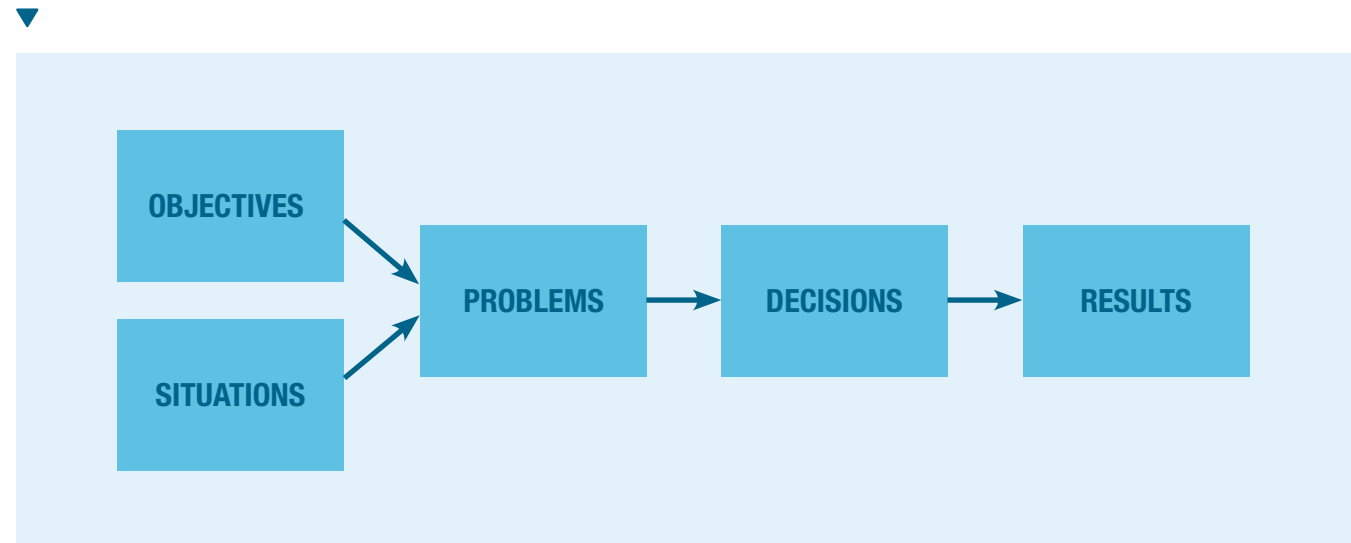


Figure 2.7.2.

In practice, decisions are made simultaneously at all levels. Whilst the pricing commission is deciding the price of water for the next year, there is a WWTP manager changing the age of the sludge in order to solve a sedimentation problem, or a user assessing how much reused water is required to water a golf course, depending on the weather. This means that the flow of decisions is not unidirectional. There is not a cascade of decisions going from the top level to the lower levels, that they implement. The system does not just work as *top-down*, it also works as *bottom-up*, within the cycle itself and between cycles. There is also feedback from the impacts of the decisions between lower and upper levels. The price of water may be conditioned by the efficiency of the treatment system, which may require further investment to meet its operating capacity, or the operation of the facility, in turn, being contingent upon the final use made of the water reused by the user. This feedback increases the flexibility of the system, and, therefore, the decision-making mechanism so, if you want it to be efficient, it cannot be linear.

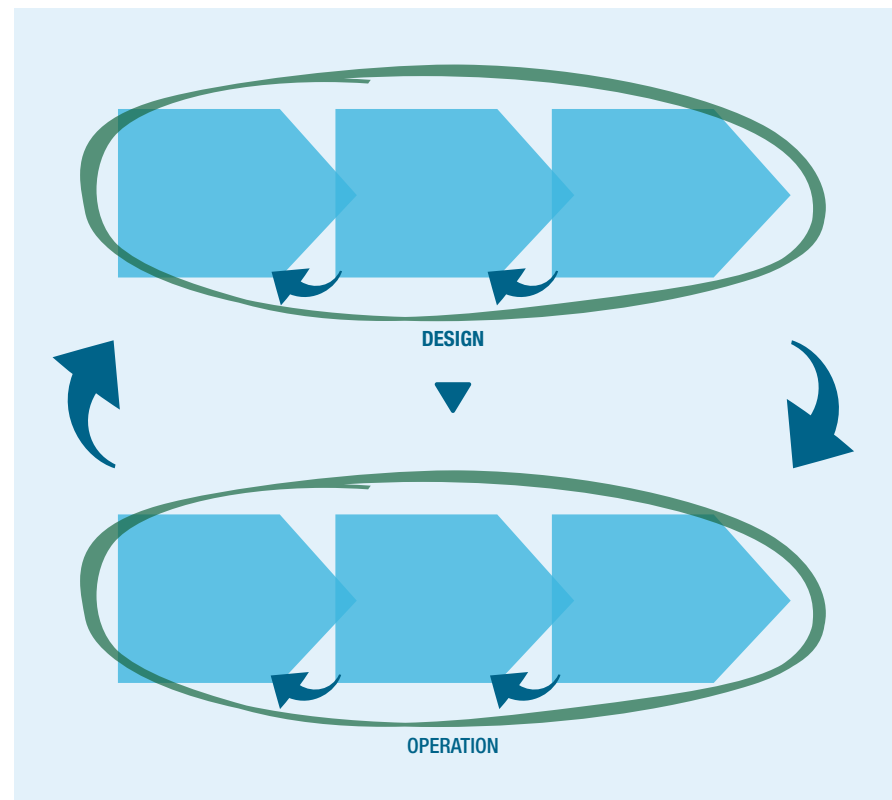
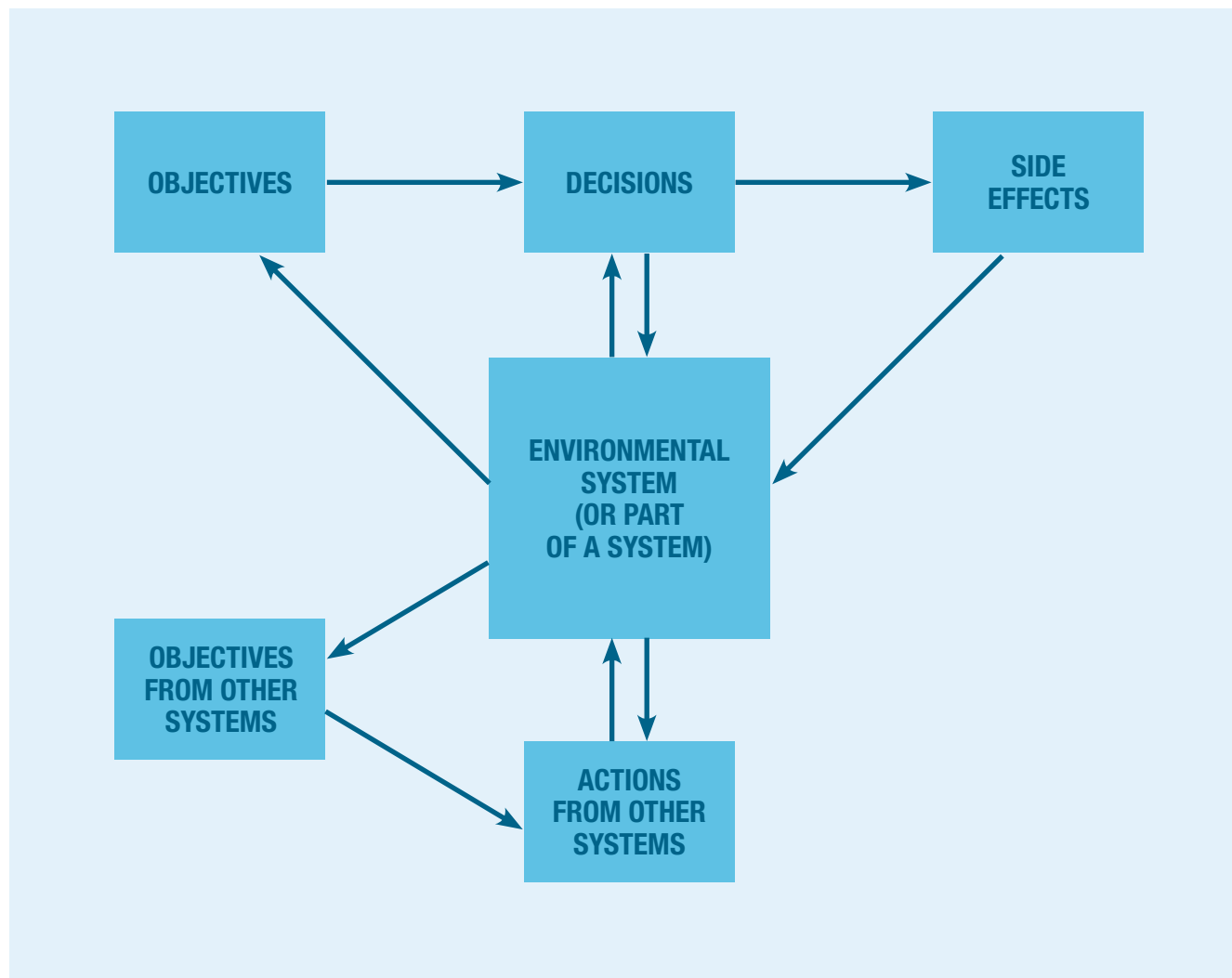


Figure 2.7.3.

Decisions on complex systems are not only conditioned by a single goal, but must take the objectives of other levels or other elements in the system into account, who also make their decisions, and should, above all, evaluate the side effects of decisions made.



The black swan

The term *black swan* was introduced by Nicholas Taleb to refer to a set of situations that present three characteristics: are highly unlikely; have a significant impact when they occur; and it is possible to find explanations and justifications for them... after the event. The black swan refers to sudden changes that take place in processes or in society and that (almost) no-one expects beforehand, causing an impact that changes the pre-existing situation. In today's society, it is not difficult to identify black swans in the form of crises or terrorist attacks that have changed our perception of the world. The author takes the term to refer to the view in Europe of the existence of black swans. As none had ever been seen, it was concluded that they did not exist... until black swans were discovered in Australia.

The existence of the phenomena is associated with complexity. It is one of its characteristics. The existence of an interrelationship between the various processes/decisions and side effects of some actions, many of them unknown, means that the system's behaviour ceases to be able to be extrapolated so as to become unpredictable. This phenomenon also occurs in urban water systems. Although the term is recent, several decades ago, M.B. Beck confirmed that biological wastewater treatment processes worked... until they stopped working. It is an experimental fact that those responsible for operations can be experienced in their professional life, when suddenly -without knowing why- the process alters its behaviour. So now we know that a black swan has appeared.

3 Environmental decision support systems, EDSS



In previous chapters, we looked at the complexity affecting decision-making relative to urban water systems. This problem, which does not just affect these systems but relates to a large number of complex systems, has led to the development of a set of tools that, under the generic name of decision support systems (DSS), have been proposed to improve decision-making. However, the specificities of each case have led to the development of more specific and better adapted tools. This is the situation for environmental processes, where, over recent years, various groups around the world have proposed tools that can be categorised under the heading of DSS (or EDSS, for Environmental Decision Support Systems). This chapter presents the proposal, put forward by the book's authors, of a methodology for the building and operation of DSSs for urban water systems. The chapter begins with a definition of what is understood by a DSS, with special emphasis on an operational definition of the constituent components and what the objectives are which, in our view, the system must meet. After this definition, the characteristics are presented that enable the DSS to address the complexity of urban water systems, and a brief reference is made as to how this has evolved in such systems as they have been applied and improving their capabilities.

In the last two sections we make a presentation of our proposal for the building and operation of EDSS applied to urban water systems in schematic form. We want to emphasize that this is not the only approach possible, and that it is a flexible one. It is not a "recipe" in the sense that by following certain strict guidelines results in the desired product, but we understand it to be a guide, a road map that may be helpful to persons who have to make decisions on urban water systems and consider that these tools may be useful. This guide is what we have used over the years and we have refined through the construction of the EDSS presented in the second part of the book.

3.1 What is an EDSS?

Decision support systems (DSS) applied to environmental systems were born in the 80s with the aim of providing decision-making support, help that was simultaneously beyond that offered by the mathematical models that had restrictions relative to incorporating qualitative knowledge and beyond what would be a simple accumulation of difficult to manage experience. Since their inception, they are systems that bring different tools from different fields together. This versatility, and their recent development, means that there is no single definition for them.

Thus, Fox and Dax, in their book *Safe and Sound* consider a decision support system to be a computational system that helps anyone responsible for decision-making, in the process of deciding between alternatives or actions, applying knowledge about the field to achieve recommendations relative to the different options. The system includes an explicit decision process based on a set of theoretical principles justifying the "rationality" of the process. In this case, the authors focus their attention on the need to include the justification of the proposal as a significant element, but without referring to elements such as DSS response time, which may be important in the case of application to linear process management.

However, this second aspect focuses on the proposal from Cortés, who defines a DSS as an intelligent information system, which helps reduce the time needed to make decisions and improves the consistency and quality. Decisions are made when a deviation from the state of the system expected or desired is observed (or predicted). This implies awareness of the problem which, in turn, must be based on information, experience and knowledge of the process. In this case, there is also strengthening of the ability to integrate different types of knowledge, which must be presented by a DSS.

From a more operational point of view,

we can define an EDSS as an interactive, flexible and adaptable system able to link numerical and algorithmical methods with artificial intelligence techniques, geographic information systems and environmental ontologies.

This definition, displayed in the figure this section focuses on, reinforces the idea of EDSSs as integrative tools that incorporate methodologies from different fields as elements capable of describing the complexity of the systems studied - in our case, urban water systems - because they simultaneously manage numerical data, qualitative knowledge and ontologies, as well as incorporating spatial (with GIS) and temporary dimensions (with mathematical models).

This does not mean that all EDSSs must integrate all these tools, as its builders will choose the most appropriate for each case, but in our opinion there are some elements that must be included:

- They must enable data management, but also, and importantly, knowledge gained from experience.
- They must incorporate results and knowledge from different areas, different experts and different levels of description etc.
- They must allow recovery of data and knowledge in a manner that is easy and useful to the user.
- They must be able to justify the proposals, indicating what and who supports them, that is to say the reliability of the results provided by the EDSS

Figure 3.1.1.

ARTIFICIAL INTELLIGENCE TECHNIQUES

Over the years, artificial intelligence has been developing tools able to mimic human behaviour relative to perception, learning and reasoning abilities. Tools that have been applied to the management of complex problems, and that have demonstrated their ability to cope with them, especially when integrated with numerical tools, as they complement the limitations present when applied to complex problems with unstructured domains where expert knowledge is significant.

In terms of urban water systems, as in other complex systems, the use of these techniques has evolved over time, from their initial applications with isolated tools to the use of more deliberative tools applied in a more integrated manner.

GEOGRAPHIC INFORMATION SYSTEMS, GIS

Geographic information systems are information systems, usually implemented into specialised software, which supply, process and collect geo-referenced information easily for the user.

The ability to separate information from different elements (location of industrial facilities, population centres and sewer systems etc.) into different layers, and the ability to connect them is an element that is of great help in the decision-making process, since it helps to identify possible relationships between different elements. Therefore, the Snow map, represented in section 1.3, may be considered as a conceptual pioneer of this type of system, which currently has great potential.

EDSS

ENVIRONMENTAL ONTOLOGIES

Although, originally, the concept of ontology and metaphysics comes from the study of existence, in the computing environment into which this book fits, ontology is considered as a tool that aims to define the relationships or categories of an entity, in our case urban water systems. This corresponds to the knowledge on the topic, defining the coding structure to be considered and, above all, information that is incorporated into each element.

Knowledge must be consensual, as it will be used by different agents throughout the process of building the environmental decision support system. In this sense, ontologies provide a way to share knowledge in the form of concepts that define the domain being studied (urban water systems), their properties and relationships. The knowledge must be consensual so it can be shared and reused. This homogenisation ability, a common basis for different views, is what explains their increasingly widespread use. In this sense, ontologies provide a way to share knowledge in the form of concepts that define the domain under study, their properties and relationships.

NUMERICAL METHODS

Numerical methods, the use of equations of varying complexity, have traditionally been the most valuable procedure for describing real-life processes, such as urban water systems. Undoubtedly, their reliability has been increasing as the knowledge that is available on these systems has improved and they have been able to describe a larger number of relationships. This process has been accompanied, synergistically, by two significant developments: the analysis of the elements that have improved the monitoring and calibration processes, and the calculation capacity of computers. In this latter case, some authors are even ironic about the cause and effect of this interrelationship. In any case, the complexity of the problem faced today (and in the near future) makes it hard to believe that there are models describing the complexity of urban water systems, and the interrelationships between the different levels of decision taking place in them.

3.2 Why use an EDSS?

Since the early DSS proposals in the 80s, they have been applied to different environmental problems, especially those related to water management. It is far from the objectives of this book to carry out a thorough review of the EDSS's applied to environmental management, but different classification criteria can be set that may help us to identify their potential.

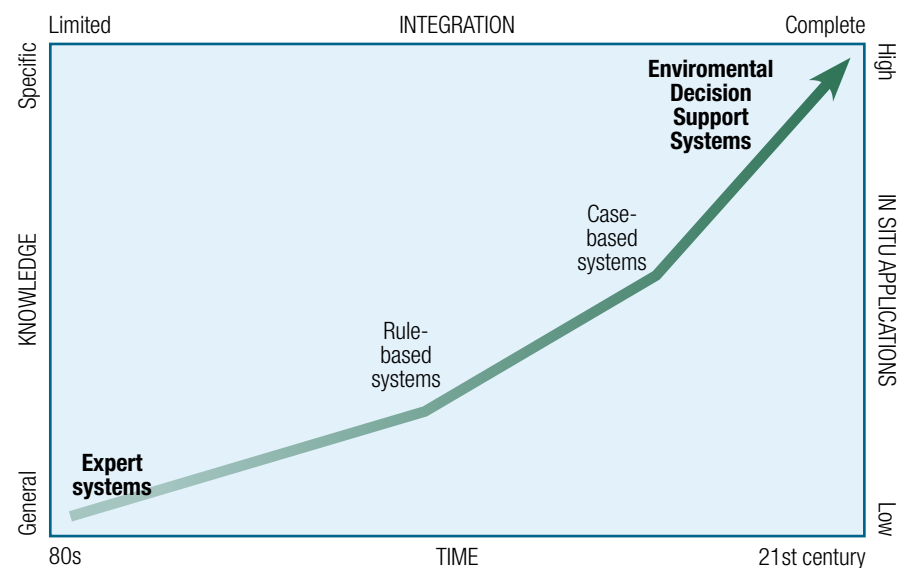
- On the one hand, EDSSs have been applied to planning, where they have demonstrated their ability to incorporate qualitative knowledge from different agents that may intervene at this stage. In this sense, the progressive increase in the incorporation of participatory processes in decision-making leads to the existence of an ever growing set of information and details. The consideration of different types of expertise and interest in these processes is often not spelled out specifically; there is disperse knowledge that makes it difficult to use traditional numerical techniques. Therefore, the use of ontologies and artificial intelligence techniques specialising in the emulation of human behaviour have allowed EDSSs to be used as systems capable of integrating all this knowledge and providing -in a manner that is easy to understand by users- reasoned proposals that are used as elements of discussion to reach consensual solutions.
- Simultaneously, there has been an evolution in the incorporation of EDSSs into dynamic management systems. This has involved the incorporation of monitoring technologies, including data acquisition, their validation and use in real time, in order to be able to provide answers and actions according to operational needs. The incorporation of expert knowledge to complement classic control systems can be considered as one of the major challenges in the use of EDSSs.

Through the application of EDSSs, the following has been shown:

- Their ability to acquire, represent and structure knowledge, being able to process uncertainty relative to both data and knowledge.
- The ability to separate data models, and therefore, the possibility of working in more general and broader spectrums.
- The ability to work with temporal and spatial dimensions.
- The ability to provide expert knowledge integrating specific knowledge bases.
- The ability to provide objective *off-line* and *on-line responses*.
- The ability to be used for diagnosis, planning, management and optimisation.
- The ability to help the user when formulating the problem and the selection of methods and models to solve it, enabling different alternatives to be assessed.

EDSSs include an explicit decision process based on a set of theoretical principles that justify the "rationality" of the process. Thanks to this rationality, EDSSs

1. can solve complex problems,
2. can cope with problems where experience provides significant and/or essential assistance for finding a solution,
3. reduce the time taken to identify the problem, and the time required to make a decision and
4. improve the consistency and quality of these decisions.



Over the years, and as their use has allowed experience to be acquired, EDSSs have evolved to adapt to the problems they faced. The figure has outlined this development by focusing on three aspects:

- The type of knowledge used
 - The application to real situations
 - The capacity for integration relative to the problems studied
- In the first case, in the beginning of EDSSs, very generic knowledge was incorporated, so their ability to address specific issues was limited, since it was necessary to incorporate specific knowledge of the problem being studied. This evolution has been closely connected with the development of knowledge acquisition tools, which are what have allowed us to move from the use of procedures applicable to general situations to those applicable to specific situations required by users. It is noteworthy that these changes have integrated contributions from fields such as artificial intelligence or mathematics to be able to develop tools for the acquisition of knowledge both from interviews with experts and the use of large databases more and more frequently.
 - In the second case, it is interesting to study how EDSSs have been incorporated into the real world in a meaningful way. Although from their beginnings, a tool was born with the desire to be useful in solving complex environmental problems, most of the systems developed in the early years were from universities and research centres, in many cases - and here the authors of this book plead guilty once again - more concerned with the study of the tool itself than its application. Keep in mind that this was a new methodology, which was complex and, perhaps as an excuse, it can be argued that it was not easy to develop. But it was not until this paradigm changed and the focus centred on the approach to the environmental problem that EDSSs were used in a wider context. A process in which it is important to note the addition, as a virtuous cycle, of managers of companies or authorities, as they have been reporting the virtues of EDSSs being added to their arsenal of tools.

- In the third case, taking the complexity of environmental systems in general and urban water systems in particular into account, early efforts focused on trying to address problems that may be faced efficiently with the ability of the EDSSs developed initially. As tools that integrate EDSSs have been refined and the results of their practical application have been even more satisfactory, the ambition of their implementation has increased, so that new elements have been integrated into the environmental system to be considered. In this context, we understand that this book is a good example of this evolution, since EDSSs are developed by the authors with different levels of integration, both in the design and operation of urban water systems, which achieves a reasonably broad perspective of the tool's potential.

This has led to the shift from the initial situation of very static systems, which established long dialogues between the user and the EDSS -like the original expert systems similar to those used in medicine to diagnose patients- to the actual existence of dynamic environmental decision support systems, which are capable of: -acquiring information in line with the system being studied; -processing this numerical information; -acquiring knowledge from it; -processing it together with previously acquired knowledge; -establishing a process of learning and self-improvement relative to the DSS itself; all this to propose solutions for implementation in the form of plans and actions for increasingly complex systems that deal comprehensively with an entire urban water system.

It's not all a bowl of cherries...

As indicated, EDSS are tools that can be very useful in the design and operation of urban water systems. Currently, as examples are available - and those presented in this book constitute a representative set - of EDSS that have been applied efficiently and have shown that their application improves the performance that can be obtained using some of the tools individually (modelling, geographic information systems) or based only on the experience of an engineer/operator or expert. But this does not mean they have already gone all the way, or that they may be considered as serving as a panacea to solve all the problems that arise in urban water systems. There is still a lot of work to be done to improve their building and operational procedures and then they just might be considered standard tools.

In the early stages of building, their own capacity to integrate different tools from different areas means that this integration is sometimes complex, and, in our opinion, is not yet resolved in a completely satisfactory manner with the defined protocols existing, and still requires the use of the experience of their own designers.

Another aspect in which we continue to work and are obtaining more efficient methodologies, but where more effort is still needed to apply to solving real-life situations, is the improvement in knowledge acquisition methods. EDSS use different knowledge sources, which leads to different ways of representing, extracting and combining information. The very nature of the problems that the EDSS want to help solve makes the knowledge acquisition stage a real bottleneck. For most problems, there are massive amounts of data about the process, but this does not mean that the level of information about causal relationships or dependencies between variables is known.

Once this knowledge is acquired, and perhaps because of the tool's "youth", there are currently no definitive solutions for sharing the knowledge acquired, both the generic and the more general, for the design of other EDSS. This is an area in which there have been some encouraging results, so hopefully this can be resolved satisfactorily in the near future.

But if there is a critical issue in the use of EDSS, this is in the relationship with end users, and their involvement throughout the development of its construction. In general, the user's role is poorly defined, especially considering that these systems are developed to support those responsible for making decisions about complex problems. Users must be involved in the system's overall design and development process to ensure the usefulness of the final system. The degree of user involvement will determine, ultimately, their level of confidence in the final system and, in the worst case scenario, mean that the system is not used. And finally, we should remember that they are decision support elements. EDSS may be able to manage existing knowledge, to make the most "reasonable" diagnosis possible, but the final decision rests with the user ... at least for now.

◀
Figure 3.2.1.
Evolution of the EDSSs developed

3.3 How is an EDSS built?

Although there may be different nuances from one case to another depending on the characteristics of each problem, we propose the realisation of five sequential steps.

Given that there are different proposals for what can be considered as a decision support system, you can also find different proposals for how they can be built. This chapter presents our proposal, which we have used over the years to build the EDSS presented in the second part of the book. Although there may be different nuances from case to case, depending on the characteristics of each problem, we propose the realisation of five sequential steps. They begin with the approach to the problem, which will be to identify what is expected of the EDSS and the elements that come into play for its building, including material aspects, but, especially, the definition of relations between the agents involved (who coordinates, who asks for information, what its flow will be or who can access which parts of the system). In the second stage, we believe it is important to stress the complementarity between data collection and knowledge acquisition. From our experience, we understand it is important to collect knowledge from experts and well as the use of tools, which allow knowledge to be extracted from databases. It will be specific knowledge from the system under study, but important to complement the theoretical knowledge that can be obtained from literature or the experience of the experts interviewed. The third stage of analysing the results of cognitive analysis is important because it is often a turning point in the building of the system. A point at which you can revisit some of the initial objectives, from the reality observed in these stages. The fourth model selection stage is conditioned by the type of knowledge acquired and the previous experience of the developers, but in any case, one of the EDSS's strengths is its ability to integrate quantitative and qualitative aspects. We believe this step is key to the EDSS unlike other tools, which are also very useful, but very conditioned on this. The final integration and implementation stage is more technical. If in previous stages, leadership can be by more experienced people in the area of sanita-

tion or water in general, leadership in this part corresponds to engineers or scientists with expertise in computer systems.

Once these stages are finalised, when it seems that the EDSS is about to be used, there are two remaining tasks that are critical, and hopefully we can learn from our mistakes. Because they correspond to work that should not be done at the end, as is unfortunately sometimes the case, but it should run in parallel. On the one hand, the validation of each of the tasks to be performed. We do not have to wait until the end to rethink some objectives or evaluate the reliability of some results. On the other hand, the required transfer of the product built to the end user. A EDSS is a product that is usually built with input from many people, but that will surely be used by a smaller number of people and should be involved in the project from the start to feel at home, especially from an involvement point of view.

We recall, finally, that this proposal is presented as a decision support in the construction of a EDSS for urban water systems, and can be taken as a general guide, but the reader may be, when you want to build one, someone who may (and should) be changing it depending on the conditions of each particular case.

EVALUATION PROCESS

So that the EDSS obtained provides reliable results, it should be evaluated in relation to different indicators, to be debugged from errors in each of the stages. This task should be performed simultaneously for each of them. In addition, this process can provide information that involves the review of any decisions made in previous stages, detection of possible errors in the system's specification, or semantic or syntactical errors. Finally, after the partial evaluation process, the system needs to be validated prior to use. Like any knowledge-based system, the EDSS needs to be evaluated in terms of what we can learn, how quickly, and it also with reference to what it "knows" how to use what it "knows" and how to "explain" and "justify" what it proposes.

Figure 3.3.1

ANALYSIS OF THE PROBLEM

It is a key stage where the first thing to consider is the reason for building the EDSS. What do we hope to achieve? At which decision level is it going to intervene? Which system is going to be studied? Which agents are going to contribute knowledge? Who will use it and in what context? How long is its building expected to take? What infrastructure is available? What is the plan for use and maintenance? These are some of the questions to be answered to clearly guide the later stages, questions that, in many cases, will get a response that is modified later in the evaluation process.

DATA COLLECTION AND KNOWLEDGE ACQUISITION

Once the problem has been defined, the data collection and knowledge acquisition phase starts, which will support the proposals made by the EDSS. There are several sources to rely on at this stage, which can be grouped into three main sections: the literature existing on the general problem of the issue being studied; the databases found on the system; and visits to plants and interviews with experts. These sources enable us to incorporate theoretical and empirical data and experiences. Their combination has to allow us to integrate views, perspectives and objectives from different disciplines and traditions.

COGNITIVE ANALYSIS

Once the data is obtained and the knowledge acquired, this should be analysed to achieve the maximum return. In the case of data, it needs to be selected and data mining tools will be used that allow us to classify it, identify clusters and patterns of behaviour and interpret it to draw knowledge from it, which we can encode. In the case of knowledge, the use of interviews to identify specific knowledge acquired over time in a domain, taking the paradox of the expert into account, reminds us that the more you know about a subject, the harder it is to identify the reasoning processes used to give an answer.

STATISTICAL ANALYSIS

DATA MINING

AUTOMATIC LEARNING

MODEL SELECTION (artificial intelligence techniques, statistics, GIS, numerical simulation and optimisation models)

Model is a word with many interpretations, which means various things depending on the listener's specialisation. In our work, we have considered four types of models: *a)* those that come from the use of geographic information systems (GIS); *b)* numerical models, on their deterministic side, in terms of using equations that describe the knowledge we have of a process, either in its empirical aspect, as used in equations based on the system's behaviour; *c)* statistical models that estimate the future likelihood if an event from its previous behaviour; *d)* artificial intelligence models, particularly those based on rules, cases and agents.

INTEGRATION AND IMPLEMENTATION OF MODELS

In the integration phase the different models used are grouped within a functional structure. We need to take into account that different models can work in parallel to obtain a result, or in series, with output corresponding to one and input to another. All these tools must then be implemented in a computer programme that performs the integration of different models, and whose executions obtain proposals, which act as decision support.

ENVIRONMENTAL DECISION SUPPORT SYSTEM (EDSS)

3.4 How does an EDSS operate?

The diagram presented in this section corresponds to the most general case, which includes five operational levels, although not all of them are used in each case

Just as there are different ways to build a decision support system, there are different operation methods. This section presents the architecture used in the EDSSs shown in the second part of the book. The diagram presented in this section corresponds to the more general case, which includes five levels of operation, although not all are used in each case.

The EDSS starts working when data is entered, which may be supplied by the user or obtained directly from the urban water system, when the DSS is working on-line.

▶
Figure 3.4.1

DECISION SUPPORT

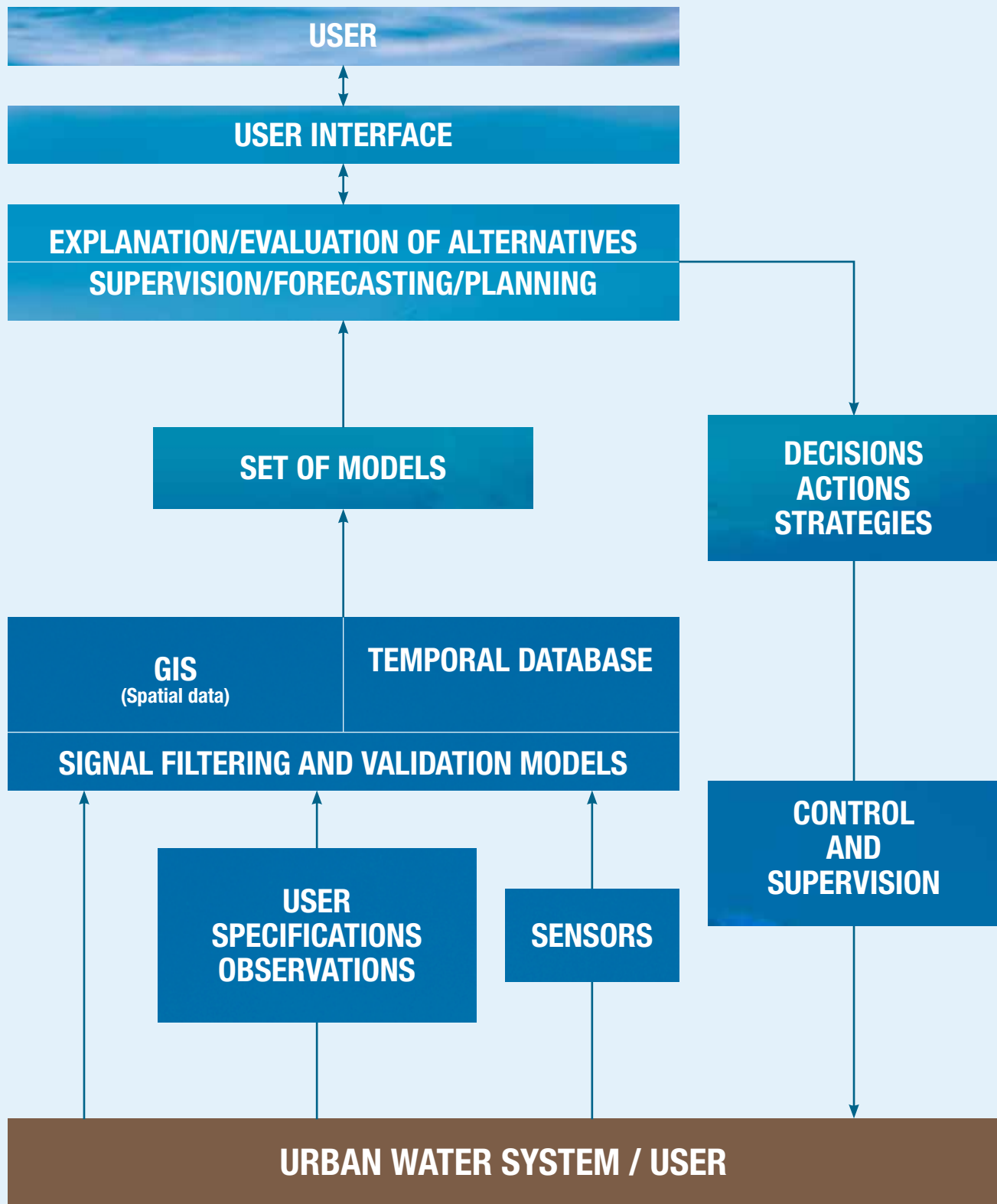
The third level sets out the supervision tasks, which integrate and process conclusions derived from the previous level, until a diagnosis of the system is achieved, identifying the causes and applying the knowledge available to propose different alternatives. At this level, user interaction is important, through an interactive interface, which is, above all, easy to use. In the case of online operation, the EDSS can be connected to the SCADA installation system.

DIAGNOSIS

The second level includes reasoning models used to infer the state of the process from the information available and subsequently allowing a proposal for action to be made. It is this stage that makes use of the models implemented in the EDSS.

DATA INPUT

The first level performs the tasks involved in the process of obtaining input data, which will begin the EDSS's process of operation. It is important to consider the EDSS's mode of operation. If you work off-line, the variable response time is not usually critical, and the input data usually corresponds to information for which you have set the corresponding interactive input screens in which the user can provide the information, as occurs mainly in cases of design application. In the EDSSs applied to operations, in that expected in the on-line response system, this input information is supplemented with direct links to on-line measurement devices that provide system status. We should remember that the data obtained often contains gaps, which involves the application of procedures for data processing and filtering, before they can be recorded in an understandable and interpretable format.

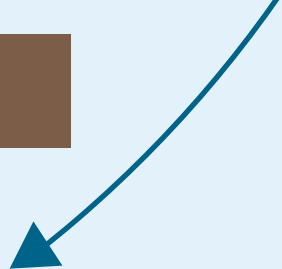


PLANS

The fourth level is where the plans are formulated which propose a solution to the problem, appearing as a set of suggested actions for managers. These actions are, at this level, fully integrated as they interrelate to each other.

ACTIONS

Finally, the fifth level proposes the specific actions to be executed as a result of the application of the plans. The system does not just recommend one action (or sequence of the same) but a value that must be evaluated by the decision manager. This is the last level in the architecture, and the one that, with its application, closes the cycle.



4 Strategic planning



In accordance with the decision levels considered in the design of urban water systems, at this level decisions are made that have the most impact themselves, but often appear as side effects from other decisions. Given that the purpose of this book is to provide tools to assist in decision-making, after reviewing the issue of context, this chapter describes studies carried out by the authors which may be able to help predict the impact of decisions and optimise them. Firstly, it presents a EDSS that can incorporate the sensitivities of different social agents to identify the impact of certain proposed urban water systems in the overall management of water resource quality. The following section presents the work performed relative to nutrient management in a basin to obtain the design and operational criteria for the urban water system at a more specific level. Finally, the last section proposes the use of an agent-based methodology to manage the behaviour of a self-organising system applied to a real problem, such as permits for industrial discharge.

The presentation of the case study follows a methodology based on the proposed building and operation of a EDSS. Thus, the first part of each example considers problem analysis, data and knowledge acquisition, the selection of models and integration and implementation stages. The second part presents the mode of operation considering the input data, the method of diagnosis and response provided by the EDSS developed.

4.1 Integrated river basin management

“In environmental management terms... a lineal approach is no longer useful. Finding a solution to each and every problem is not enough”

Francesc Baltasar (2008)

Conseller de Medi Ambient. Generalitat de Catalunya

Analysis of the problem

One of the complex problems facing the authorities responsible for the management of water from a basin is the definition of the actions to be carried out to achieve the desired quality objectives. In the case of European Union countries, these objectives focus on achieving an adequate ecological state as defined by the Water Framework Directive.

The problem may be positioned at the maximum level of complexity because of what contributes to it:

- The presence and intervention of a large number of actors within civil society (organisations, institutions, corporations and individuals etc.) that are affected by different forms of resource management.
- The significant interrelationships between the issues, their triggers and the actions required to solve the problem. One problem may be caused by different triggers, one trigger can cause different problems, or a corrective action can act on different issues / triggers, or may even cause side effects that act as new triggers.

The following coexist simultaneously:

- a) Different time scales,
- minutes/hours (storms that can clog storm drains, discharge points, flow variations caused by hydroelectric plants, water residence time in a treatment plant)

- days/weeks (growth of algae, changes in consumption at weekends, impact of news in the papers, residence time of water in a surface course)
- months/years (construction/upgrade of a facility, percolation of spills on the floor, a government mandate, landfill, construction/renovation of a water treatment plant, rain and seasonal variations in consumption)
- years... (construction of major infrastructure, implementation of new paradigms in water culture, residence time of water in an aquifer)

b) Different levels of uncertainty in the description of processes. Therefore, we can describe them:

- with enough precision (dynamics of flow in a pipe and performance of a treatment operation etc.),
- only approximately (short-term provision for consumption),
- as having high uncertainty (evolution industrial growth/decrease, rainfall over the next few years) with even the "black swan" phenomenon appearing, which was mentioned in section 2.7.

This should be coordinated by the competent authority, to which corresponds:

- seeking information and knowledge, processing it, making proposals for actions and implementing them after getting the necessary consensus.

And with a necessary sustainability approach to management (economic, ecological and social), it is sometimes difficult to see the big picture, since the proposals:

- have to respect the environment, but not at any economic and/or social cost,
- must be economically bearable, but not at any environmental and/or social cost,
- have to seek social equity (personal and territorial), but not at any environmental and/or economic cost.

That is why we have to find solutions that are able to manage this complexity, describing the interrelationships and side effects. In this context, we present the work carried out to develop an environmental decision support system (an EDSS) to **define the actions to be performed in the Baix Ter basin as pilot experience.**

The aim was to build the conceptual framework of a an EDSS in an automated manner so that it was able to manage, in an integrated way, water resources based on legal criteria, expertise, resources and policy decisions, justifying the proposed decisions in each case.

The following were established as objectives of the system:

- integrating data and experience,
- incorporating results from different areas, different experts and different levels of description etc.
- analysing the alternatives,
- justifying both the choice of proposals accepted and those rejected, indicating their effects and economic and environmental costs.

Data and knowledge acquisition

At this level, different types of data and knowledge converge, which can be accessed to build the environmental decision support system. In this case, the following was selected:

- Hydrological and water quality data (flows and indicators of the system's inputs and outputs).
- Previous reports on the state of the environment incorporated into the IMPRESS document.
- The experience of local authorities, organisations, experts in the fields of ecology, technology and sociology etc. Some of this information was in a previous document summarising the diagnosis of the problems, collected from a participatory process, which identified the problems that exist in the area and their possible origin.
- The actions proposed by the citizens participating in various workshops, including analysis, for each of them, of their viability.

LEVEL 1

Identification, for each of the basins, of the existing problems and their possible causes (the same problem may have resulted from more than one cause).

Documents/study bases:

- IMPRESS document (general)
- Participatory processes (localised problems)

LEVEL 2

Listing of each of the measures available to solve problems or to regulate the trigger activities.

Search for links between problems –triggers– measures.

Justification of how each of the measures can address the problems identified.

Documents/study bases

- Executed/revised and planned/ pending plans and programmes from the authorities
- Related regulations

LEVEL 3

Quantification of the improvements experienced by each of the bodies of water after application of the measures envisaged in the plans and programmes.

Tools/methodologies:

- Simulation programmes for the evolution of water resources and water quality
- Interviews with experts to represent/quantify relationships

Model selection

In order to relate the existing problems to the polluting activities and measures that can potentially solve the problems or regulate activities, we have designed a three-level application where we have included all the possible combinations between the three sets of variables. This makes it possible to manage information based on the variable of particular interest. Therefore, the system must be able to collect information facilitating:

- All the activities and processes that generate a specific problem.
- All the measures that may solve a specific problem
- All the problems that may cause the same activity or process
- All the measures that may regulate a certain activity or process
- All the problems and activities/processes that can fix and/or regulate a particular measure.

◀
Figure 4.1.1.

Map of the Baix Ter basin.

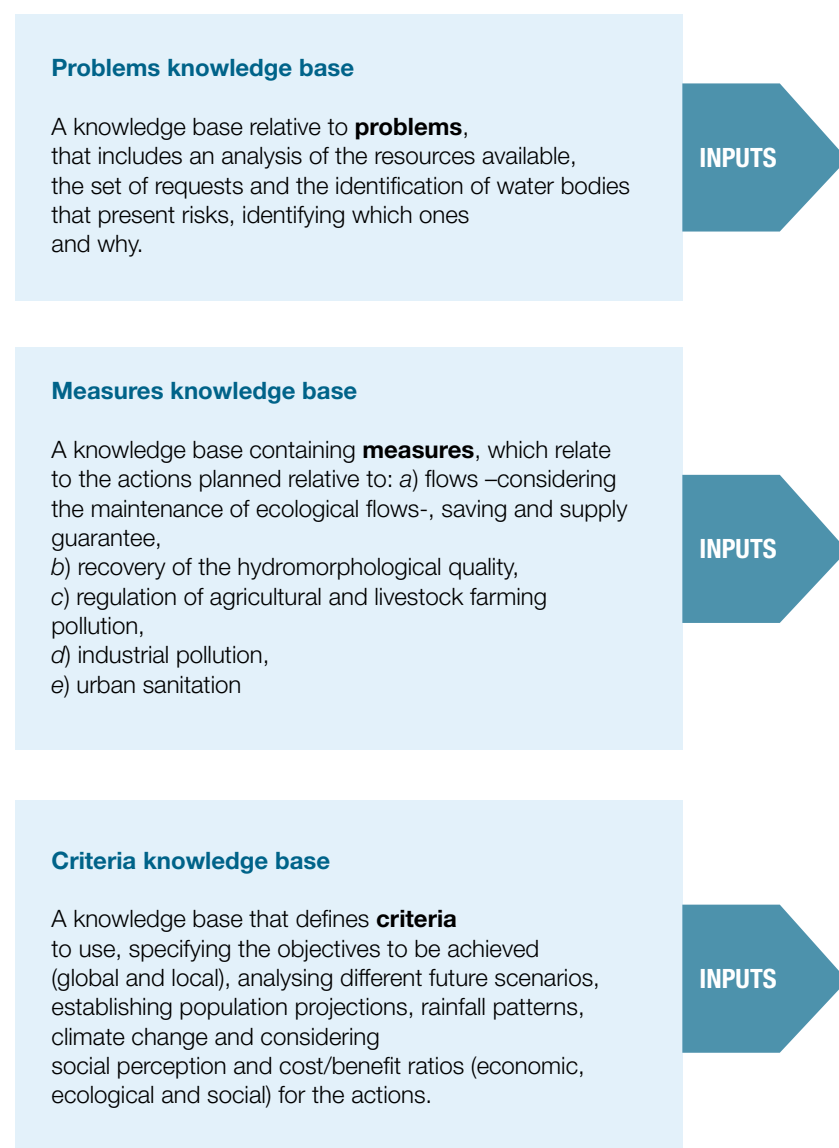


OPERATION

The inner workings of the EDSS identifies and lists the problems identified, the causes and/or triggers and their relationship to performance measures or proposals, as outlined in the figure (for some of them, simplifying relationships for better representation).

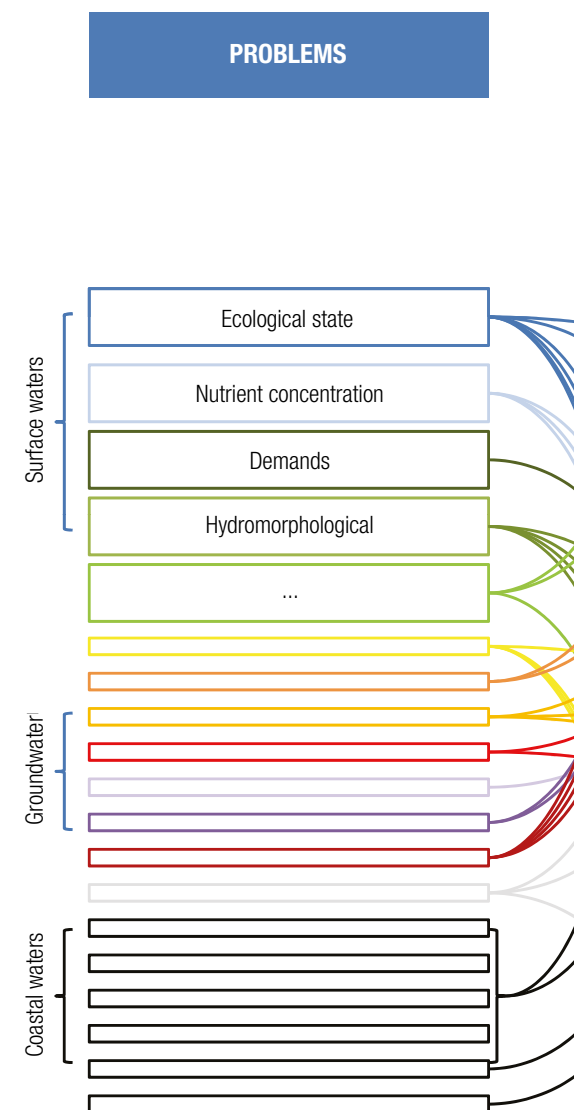
Data input

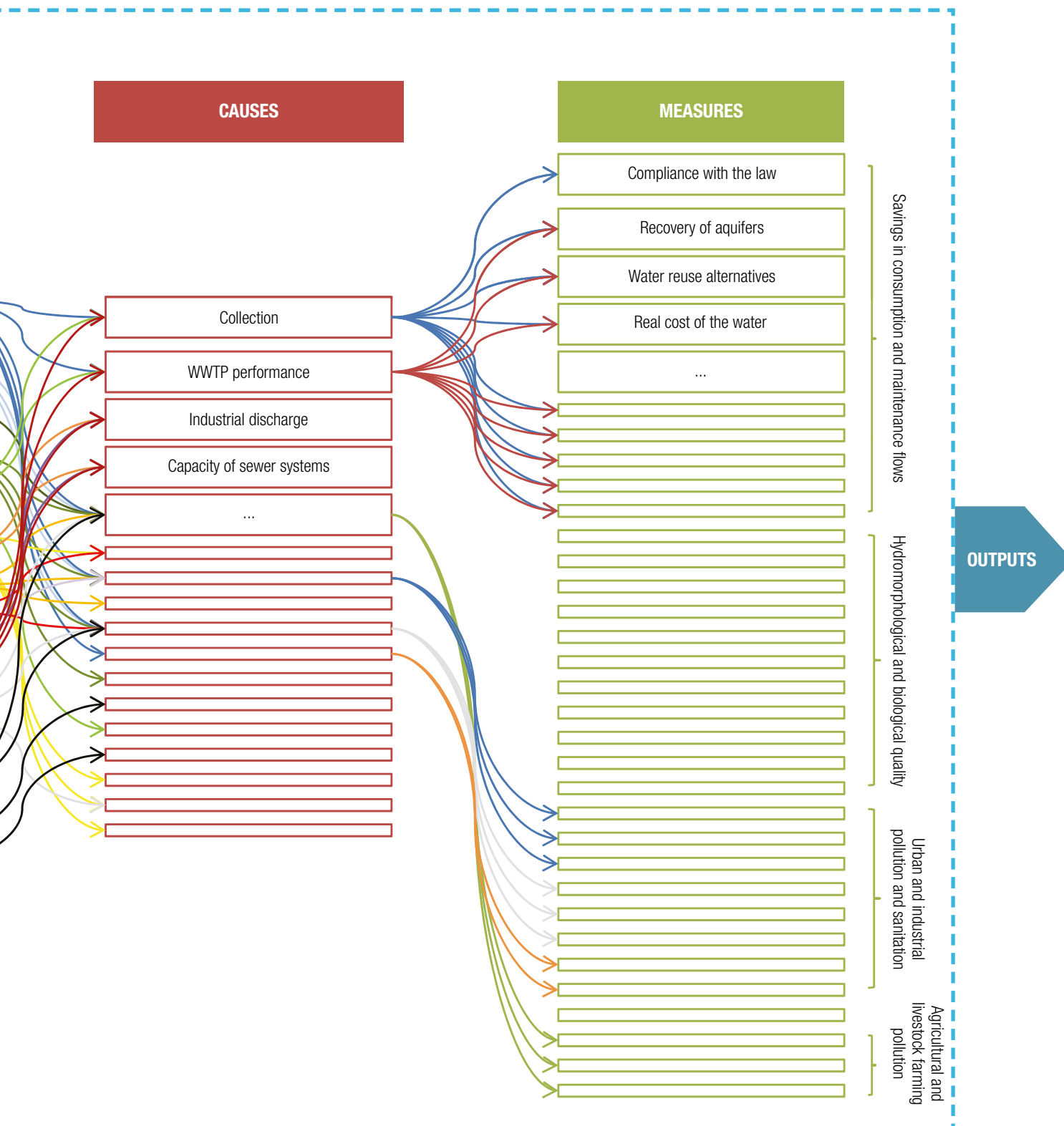
The operational structure of the EDSS is based on the use of three knowledge bases:



Diagnosis

This knowledge is processed in the EDSS in accordance with the operational scheme presented in the figure. Here the proposals for action are related to the different problems and the cost/benefit ratios. Its evaluation using mathematical models or expert knowledge (encoded in the form of rules) is used to determine if the set is adequate to achieve the desired objectives. At this stage, given that knowledge is contributed by different agents (government experts, scientists, institutions of the territory, participatory processes etc.), it is important to identify the source for the embedded knowledge.





Results

Overall result: interrelationships between problems, activities, processes, triggers and actions proposed by the authorities or in participatory processes.

Specific results:

- Diagnosis of the state of each body of water in the zone being studied (Baix Ter)
- Identification of the trigger for each problem and its location in the territory
- List of all measures proposed by the authorities or in participatory processes, identifying the cost and impact.

End result:

Explanation of why and how the measures proposed can achieve the objectives at a lower economic cost and with a greater degree of consensus from the participation process.

4.2 Nutrient management at river basin scale

Problem analysis

Nutrient management at a basin level is complex due to the existence of different impacts from point and diffuse sources, relative to the different ecosystem responses to these impacts and the different water uses and demands which may occur in the basin. There is still a significant lack of knowledge on some of the impacts of human activity, especially in Mediterranean-type rivers with great variations in flow, and the system's behaviour when faced with hydromorphological alterations or significant discharge.

Decision-making in this context, in line with the recommendations from the Water Framework Directive, requires the incorporation of different disciplines that take both quantitative and qualitative aspects (chemical, physical, biological and hydromorphological etc.) into account, integrated into tools for the efficient management of knowledge.

This section presents the work carried out on the development of the Streames EDSS, performed in the context of a European project, with the participation of water research groups and agencies from different countries. Its objective was to identify and efficiently manage the nutrient retention capacity of different types of streams of river, the diagnosis of the problems that may occur, especially those related to excessive nutrient loads, the causes of the problems identified and possible actions to resolve or mitigate the consequences of the problems.

Data and knowledge acquisition

Given the complexity of the problem, we resorted to different sources to obtain the knowledge required to be incorporated into the environmental decision support system. General knowledge was obtained by reviewing existing literature and input from experts, while, for the heuristic knowledge, basin managers and ecologists were consulted. To acquire more exhaustive knowledge on the responses of the rivers, there were a series of experimental campaigns in different basins in the Mediterranean region, from Portugal to Israel, and in some Central European basins to identify relative differences. They analysed the relationship between the nutrient retention capacity of the river in terms of its functional or structural conditions. Finally, the existence of a forum between the working team's member proved to be an effective interaction tool.

Selection and implementation of the models

The models selected included:

- An expert rule-based system, in support of the system's response to those problems the solution of which involves diagnosis and qualitative information and knowledge processing. The knowledge acquired is organised in the form of decision trees for ease of review by experts, prior to its implementation in the knowledge base. The final list of decision trees considered included: excess ammonia, excess nitrate, eutrophication, excess organic/anoxic/anaerobic matter, alteration of the riparian forest, water stress, changes in the morphology of the bed, toxic discharge, metabolism of dissolved oxygen and anthropogenic salinity alterations.
- A numerical model (Moneris) adapted to the conditions in the Mediterranean region, to estimate the point and diffuse loads that the basin receives. This also included empirical models

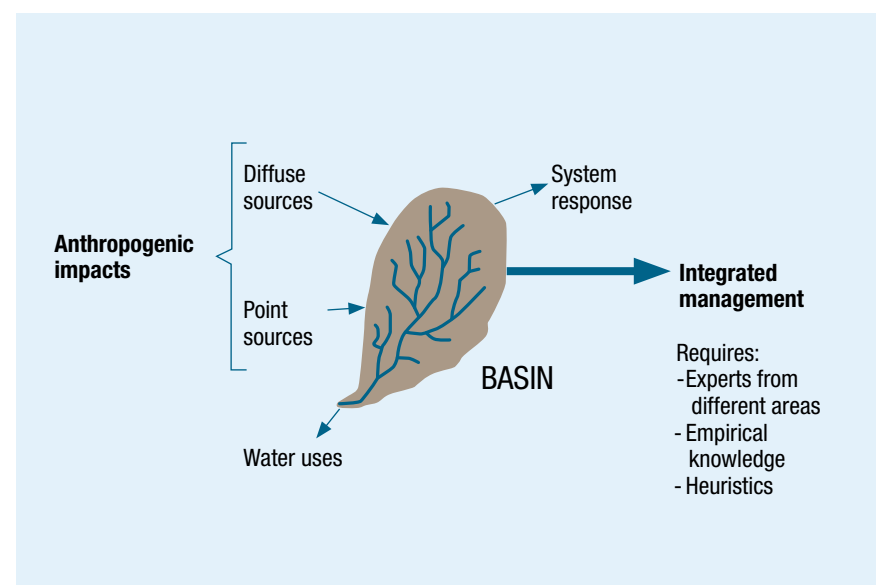
to assess the degree of alteration to vegetation, the environment's potential self-treatment capacity, the assimilative capacity and its ecological state as an integrated assessment method.

- A geographic information system (GIS) to manage spatial information relative to the type of soil, slope and use of the land etc..

The different elements are coded together with an interface for easy interaction with the user, allowing

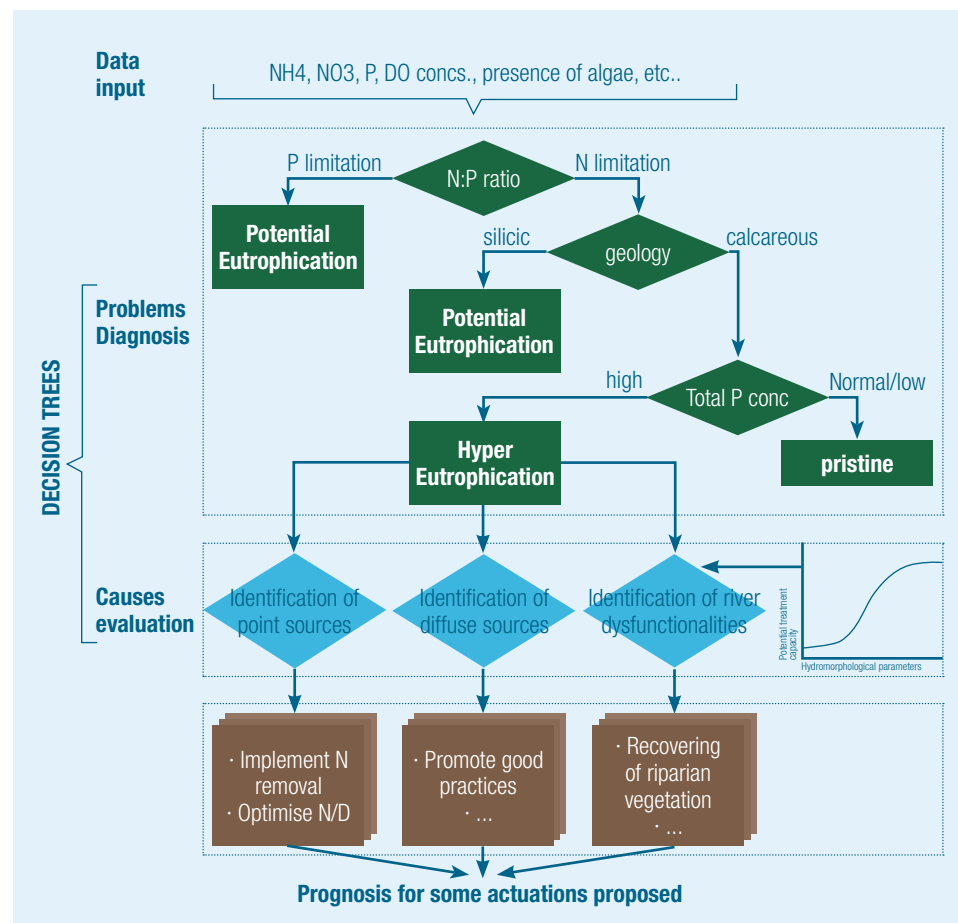
- the inference of the state of the quality of the stream of river considered relative, not only to structural and physical-chemical parameters, but also to the functionality of the ecosystem, for example the self-treatment capacity relative to nutrient retention capacity,
- the evaluation of the nutrient sources and loads relative to the stretch studied.

Figure 4.2.1.



We need to know the river's response to be able to manage the nutrients in a river basin

Figure 4.2.2.
Simplified diagram of a decision tree for eutrophication.



Consideration of eutrophication A complex problem

Eugènia Martí. Researcher. Centre d'Estudis Avançats de Blanes, CSIC

One of the major problems associated with high nutrient concentrations in rivers is eutrophication, which can be defined as the changes in the ecosystem's conditions due to high loads of nutrients causing an excessive growth of algae and aquatic plants, which can drive episodes of anoxia in the water.

In the Streames EDSS (www.streames.net), the general decision tree related to the assessment of eutrophication was divided into three classification levels of the problem, each of which focused on a distinct management aspect, to optimize the differentiation among the different stages of reasoning.

- The first decision tree contains the knowledge to diagnose the existence and severity of the eutrophication problem, in which both quantitative and qualitative information is crucial. In relation to quantitative information, the most important is the concentrations of nitrogen (N) and phosphorus (P) (total and dissolved); with them it is possible to calculate the molar N:P ratio and identify the potential limiting nutrient. The limits were obtained from both the literature and the experimental campaigns done within the STREAMES project. Other important aspects considered in the quantitative information are the water pH and the streambed substrata. Based on the values of the quantitative information, the EDSS determines the severity of the problem. In terms of qualitative information, the EDSS is able to provide a diagnosis based on the observation of several factors such as the presence of filamentous algae, conditions of light availability, water velocity, sediment stability, and the presence of aquatic plants.
- The second decision tree structures the knowledge to evaluate the causes and effects of eutrophication. This phase starts once the problem and its severity has been diagnosed. The objective of this phase is to identify the causes that may be responsible for the problem. The causes are grouped into four categories. Two of them are related to point sources such as effluents from wastewater treatment plants and discharges of sewage water. The other two categories are related to diffuse sources, with one considering agricultural and farming activities and the other considering urban sprawl areas without treatment systems. This tree also considers two additional causes related to the alteration of the ecosystem function (i.e., nutrient uptake capacity) associated with alterations in the riparian zone or with a reduced in-stream self-depuration capacity compared to that in equivalent sections of river not subjected to eutrophication.
- The third decision tree integrates the different action strategies. Proposed action strategies are based on the results from the two previous assessment steps. For a given problem and cause, the EDSS includes action strategies at different spatial scales, which can also target at different aspects. In each case, the EDSS identifies the link between the particular causes and the proposed actions.

OPERATION

Data input

To operate the system, the user is asked for a) the general description of the site to be studied (width, length and depth,

It is important that the input data is systematic as well as being interactive and intuitive for the user

water velocity, flow, geological nature of the river basin), b) characteristics of the stream (both the riparian area, with information on its width, vegetation type, cover, soil characteristics and water

table, the presence of anthropogenic structures on the banks, and the river bed, indicating slope, sinuosity, Manning coefficient, type of substrate dominant, slow and fast area, presence of small dams, presence of algae, microphytes or biofilms), c) information regarding the river water quality (with quantitative data on concentration of organic matter, nutrients, pH, conductivity, temperature or qualitative data that indicates the presence of algae and macrophytes, or to provide information on sunlight, turbidity, sediment colour, odour), d) information from specific sources (wastewater treatment plants, discharges) and diffuse nutrients (land use, erosion and crops etc.).

This information is entered using screens as presented in the figure, providing an integrated view of the factors that influence the biological conditions of the study area.

▼ Figure 4.2.3.

Decision support

There are three stages in the decision support system:

- Diagnosis, in which the state of the river is diagnosed and the causes of the problems.
- Solutions, where proposals are put forward relative to how to solve the problem.
- Prognosis, where the effect of alternatives is evaluated, answering questions like: What would happen if...?

In the **diagnosis phase**, the EDSS infers the quality of the river water, determines, through the calculation of certain functional and structural characteristics (for example, the treatment capacity, the nutrient assimilation coefficient, the matter transfer coefficient or the recovery time) if the river system is working properly, and finally identifies the problems relative to the stream identified. There is a seven stage process for identifying these problems:

1. Assessment of the river's symptoms to detect the potential problems the stream may face; there may be one or several.
2. Assessment of the parameters enabling the existing problems to be diagnosed.
3. For each problem detected, a degree of affectation is provided through indices and quality categories.
4. Determination of the side effects of each of the problems.
5. A list is established of all the problems detected and hierarchised according to the degree of affectation of each one.
6. The "river alteration" degree is given for the stream studied, integrating the characteristics of the entire river ecosystem.
7. Determination of the sources causing the problems.

In the **solutions phase**, the EDSS generates management proposals for solv-

ing the problems identified. The system comprises over a hundred different types of actions; each one includes the following information:

- Name of the action, technique, description, advantages, limitations, comments, scale of application, efficiency of the action in the scenario in question and response time of the same and ratio between the environmental benefits and the force applied.

The actions offered by the EDSS fall into three large groups:

- Control and reduction of point and diffuse nutrient loads,
- Restoration and recovery processes for riparian vegetation,
- Measures to increase the nutrient retention capacity, both for the aquatic environment (self-treatment capacity) and riparian vegetation.

In each case, the proposals are generated from the diagnosis and identification of the causes identified in the previous stage. These actions will be provided to the user and organised according to the scale of action (river basin, riparian area or river bed) and according to the parameters that affect them (hydrogeomorphology, chemical aspects, biota, good practices or river flow regime). In this case, the category corresponds to the type of parameters affected by the actions proposed. At the same time, it also includes an assessment of each of the actions proposed relative to environmental costs versus the efforts made to carry out the action in the specific case.

The **prognosis phase** enables the assessment of new scenarios from the actions proposed or simply from the modification of certain concentrations. Depending on the performance provided, for example, a reduction in the concentration of the parameters generated from the problem and from new values assesses the effect of the action through a material balance. In this respect, the

numerical Moneris model is useful for generating the new scenario as it allows much tighter estimates of the concentrations of different substances evaluated, especially nutrients.

Results

Figure 4.2.5.
Examples of action proposals.

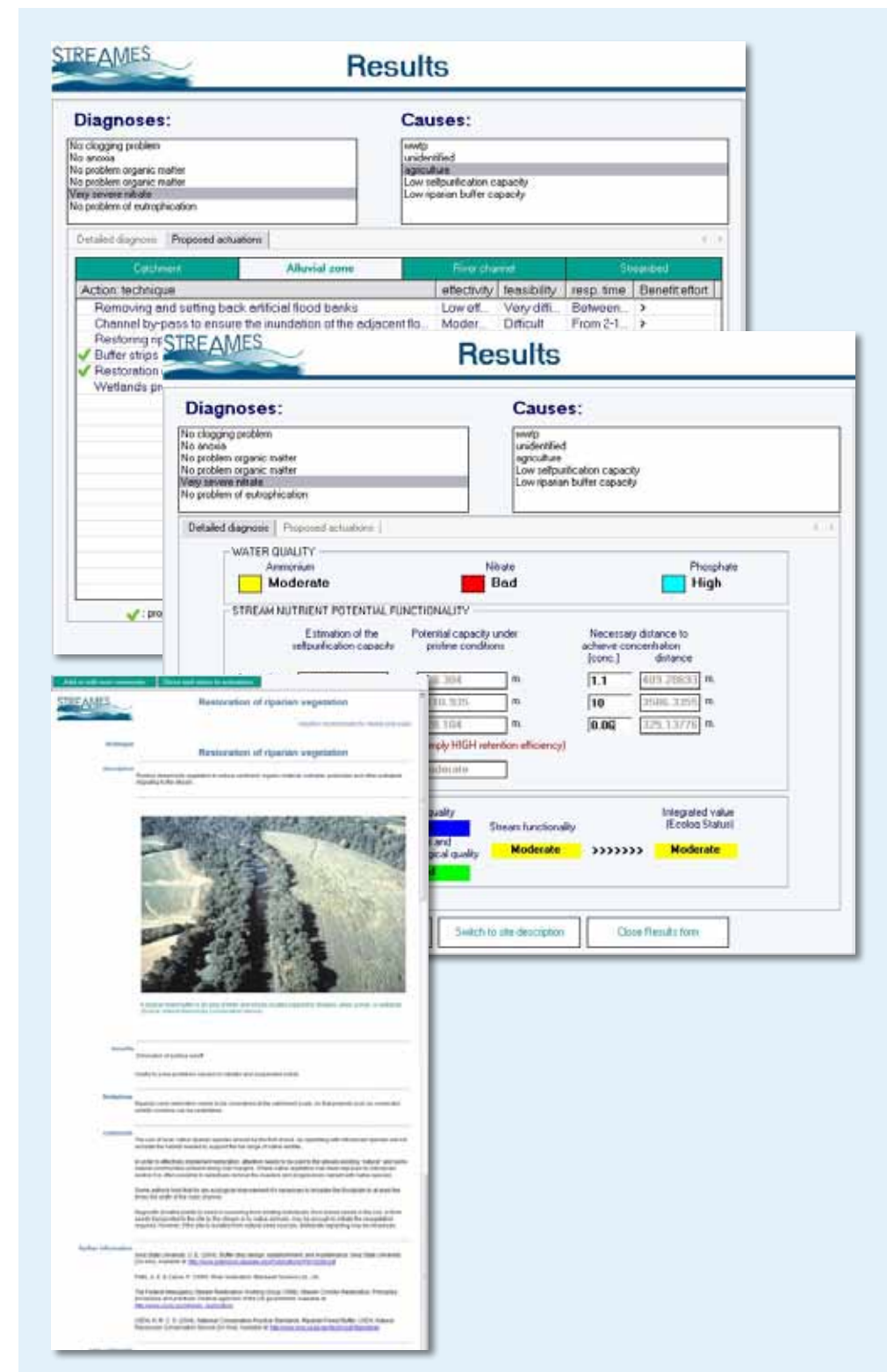
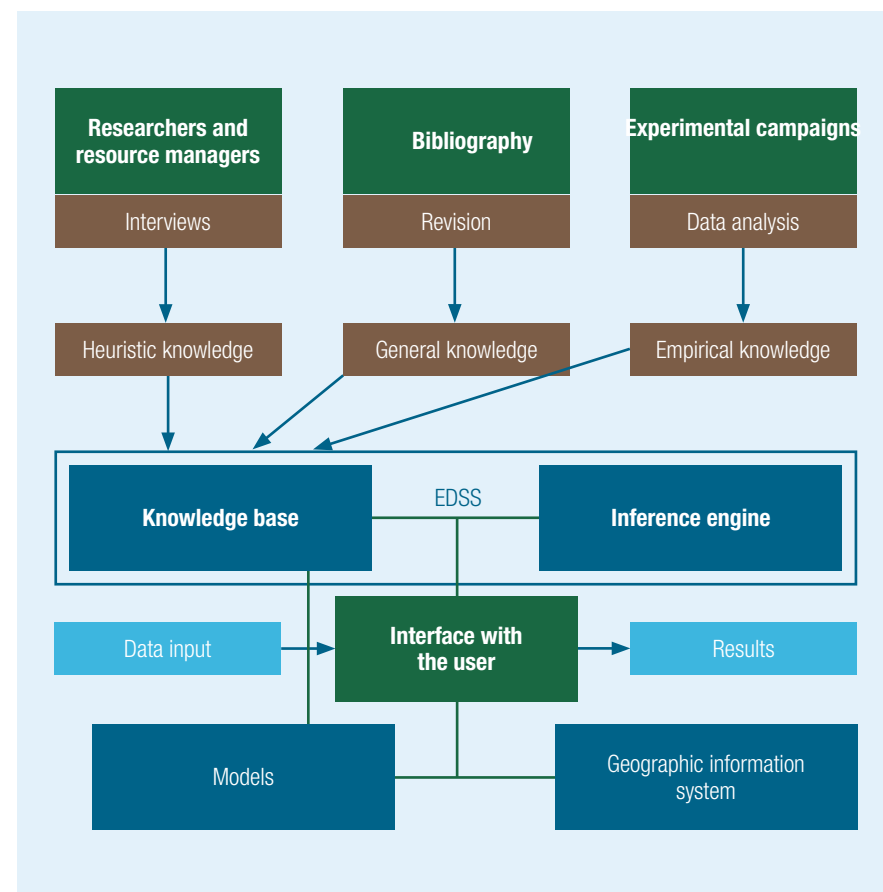


Figure 4.2.4.

Outline of the operation of the Streames EDSS for nutrient management in a basin.



4.3 Industrial discharge management

Analysis of the problem

Authorisations for industrial discharges into sewer systems mainly come from the analysis of the characteristics of the industrial plants that generate them (depending on type of products manufactured or the anticipation of its evolution), the treatment system's conditions, and the sensitivity of the receiving environment. It also takes into account the status of the development of technologies to produce those products, which serve as a framework for integrated guidelines for the prevention of pollution. These authorisations are granted for specific time periods (annual scale), establishing, simultaneously, monitoring and control protocols to prevent upward deviations of discharges from the values allowed.

From the point of view of the authorities, it is possible that the granting of permits and treatment system managers belong to different authorities or different units within the same administration. This sometimes means that there are discrepancies between the discharge authorised and the capacity of the plants that have to receive it. Furthermore, it should be noted that, in this context, the authorisations correspond to peaks with the intention that they are not exceeded by the industrial plant. But sometimes they are not used up to the limit, either by industrial activity operating situations (stops, cleaning, holidays) or because the production scheduling (and thus the generation of wastewater) may shift over time.

In terms of the treatment system, this permit methodology, which is very common, causes two distorting factors:

- Firstly, for some of the time, the flows received are below the maximum allowed, and lower than the treatment system can handle, or

even for those it was designed for, leading to inefficiencies.

- There are situations where the wastewater flow and concentrations that are received are higher than the system can handle, and even when all industries comply with the limits that have been set, the sum of all permits may exceed the wastewater treatment plant's design capacity.

There are different ways to tackle the problem, but certainly **the most efficient route from the point of view of managing the integrated system would process, in real-time, information**

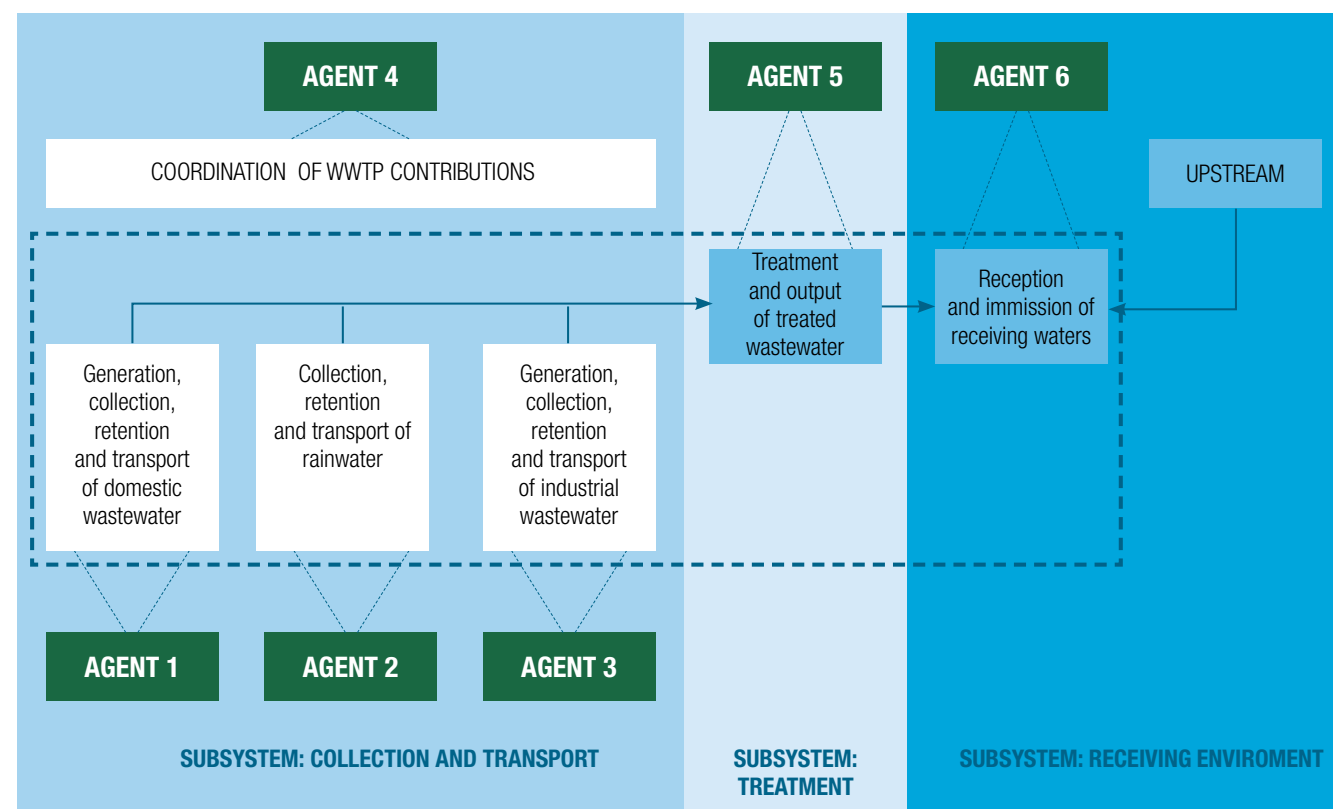
on the discharge intentions for each of the industrial plants, together with the actual capacity, at all times, of the treatment system. In this case, the system itself may be setting the discharge authorisation limits in real time, based on a) the characteristics of the receiving environment, b) the state of the treatment system and c) the discharge needs, that is to say the system regulates itself. The authority does not have to establish them constantly, beyond monitoring.

Data and knowledge acquisition

To achieve this goal, various elements must be coordinated in real time:

- Information on the flows (or their proposal),
- Knowledge about the state of the treatment system,
- Ability to predict the state of the system based on discharges authorised at all times, taking the amount and types of pollutants into account,
- Ability to process all of this information intelligently,
- Operational capacity and control so

Figure 4.3.1. In the model showing the roles of agents, a role can be shared by more than one agent and an agent can be associated with more than one role. The agents capture the state of their environment (characteristics of the wastewater generated, volume and pollutant loads in treatment, etc.) through measurement sensors, and should be able to make the right decisions for the best execution of their specific functions. Also exchanging information about their status with other agents and modify their environment to suit optimum overall performance, so the coverage of your needs is as high as possible without harming good overall performance.



that the proposed actions are implemented according to the results of the previous stage.

Some of these elements require hardware (instrumentation), whilst others require software (communications and interactions between the different elements involved).

Model selection

From an environmental decision support system point of view, it is a process in which each component (considered as an agent) has incomplete information to execute, individually, optimum overall performance management. In this case, the global optimum must take the interactions between different components into account, to obtain a system response strictly greater than the sum of the best individual situation for each of the components.

To solve the problem, an EDSS has been proposed in which different basic system functions have been outlined as "roles" or functions of a set of agents. In this context, an agent is defined for each of the elements involved in the process:

- An agent for each of the industrial activities authorised to discharge. In this case, it is considered that these activities have a regulation tank of a fixed size, in order to roll the flow of wastewater generated,
- an agent for rainwater (or meteorological water in general), collected to be discharged into the treatment system or, in the event of excessive overload (due to unfavourable weather conditions), its forwarding to the receiving environment,
- an agent for domestic wastewater up to its discharge into the treatment system.

- an agent for the treatment system,
- an agent for the receiving environment of the wastewater treated, with the aim of suitable harmonising its characteristics.

Figure 4.3.2.

The arrows on the model indicate the direction of the communication. We can see that almost all of the communication channels are bidirectional. These channels are established based on interaction protocols between roles, which the following is attributed to: the nature of the interaction, the role of initiator, the answering machine, the input, output and processing of data during the interaction. The information provided in many communications is relative to the volumes and concentrations of pollutants in wastewater.

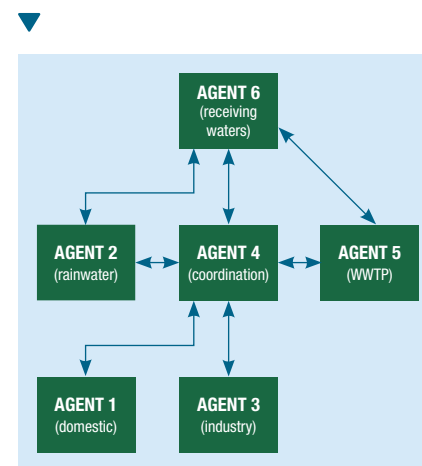
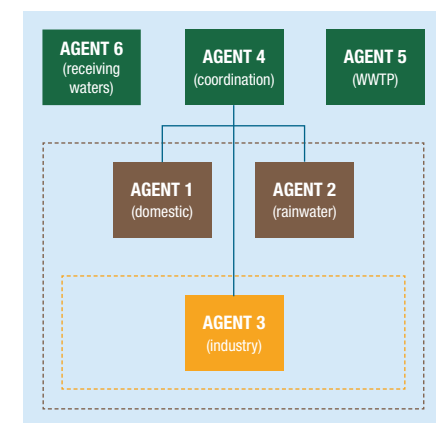


Figure 4.3.3.

Firstly, the coordination of agents' decisions for the WWTP and the receiving waters is performed. Secondly, the coordination agent will consider the contributions of the agents for domestic wastewater and storm water. And based on the above processes, the discharge managed by the agents for industrial activities will be authorised or prioritised.



What is an agent?

In this context, an agent is considered as a computational entity located in a particular environment with which they can interact and has the following properties:

- Autonomy, understood as the ability to make their own decisions relative to achieving their own goals. Their decision-making is performed individually based on their environment and without the direct intervention of other elements.
- Reactivity, or ability to perceive their environment and make decisions that provide a response to changes that occur in it.
- Pro-activity, to show behaviour clearly aimed at an objective by taking initiatives (plans).

- Sociability in order to interact with other agents and exchange information. This ability is acquired in order to coordinate their actions.

In addition, some agents may also have characteristics relative to mobility, truthfulness, benevolence and rationality etc.

The level of complexity in the decision-making process defines the type of "reasoning", which is related to the degree of "intelligence" associated with each agent. There are two basic types of agents:

- Reactives, which have no explicit representation of complex symbolic knowledge but offer immediate responses to environmental stimuli.

- Deliberative agents, which do have explicit representation of complex knowledge and make decisions based on logical reasoning. Within this type of typology, perhaps the most representative model is the BDI agent (Belief-Desire-Intention).

From here, a multiagent system consists of a set of agents, usually heterogeneous, which are coordinated to solve a complex problem as a computational organisation consisting of several interacting "roles".

OPERATION

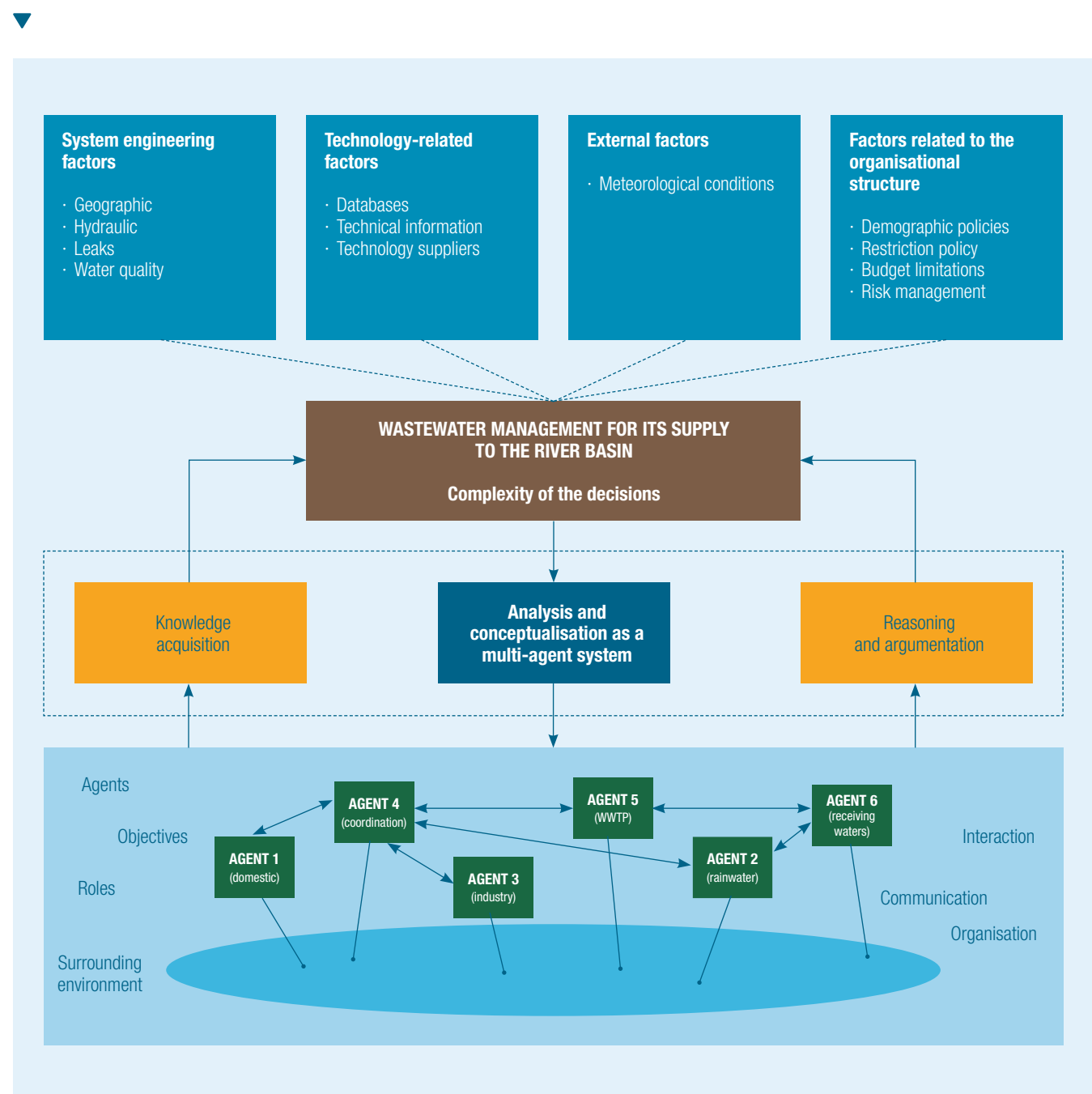
Input data

In the EDSS proposed, data acquisition begins when an industrial unit seeks to make wastewater discharge of a certain volume with a certain concentration of suspended solids, biochemical oxygen demand, chemical oxygen demand, total nitrogen and total phosphorus. The information is sent to the coordination agent, who also receives information from other industrial units wanting to make wastewater discharges. At the same time, it is requested information of the state of the system in real-time.

Based on this information and that received with respect to the estimate of the amount of stormwater and domestic wastewater that the treatment system can treat, the EDSS performs the diagnostic stage to determine the availability of the system to receive industrial wastewater. If the capacity available is sufficient to accept all the proposals, they are accepted; if this is not the case, an industrial discharge prioritisation process begins. This prioritisation process aims to find an optimised solution that provides a combination of the maximum possible discharge volumes for each industry that can be performed without exceeding the allowable limits for the treatment system, which corresponds to the stage of defining and implementing action plans.

Figure 4.3.4.

In the urban water system, a multitude of factors add uncertainty to decision-making, from factors that are part of the technological and engineering field, to social, economic and weather-related factors. Management decisions involve high complexity, which can be treated as part of a multiagent system. The behaviour of the agents drifts towards knowledge acquisition that may constitute new support for the proper management of the system and can be strengthened with the acquisition of the ability to reason and argument within the system.



Diagnosis

The proposed agents are organised into a multi-agent system similar to how individuals organise themselves and work together in society. The abstraction needed to define the configuration of the multi-agent system is realised based on the structure of the treatment system, in subsystems (sewer systems, treatment plant and receiving environment), and analysis of the interactions that the operation of its components presents. The following is defined for the agents:

- a dynamic environment,
- an organisational structure of roles,
- and a communications structure in which communications are exchanged, being informed of information regarding the state of the roles that reflect the interactions of the components. Each communication leads to the definition of a specific role interaction protocol. The structure of interactions can define a certain decision hierarchy.

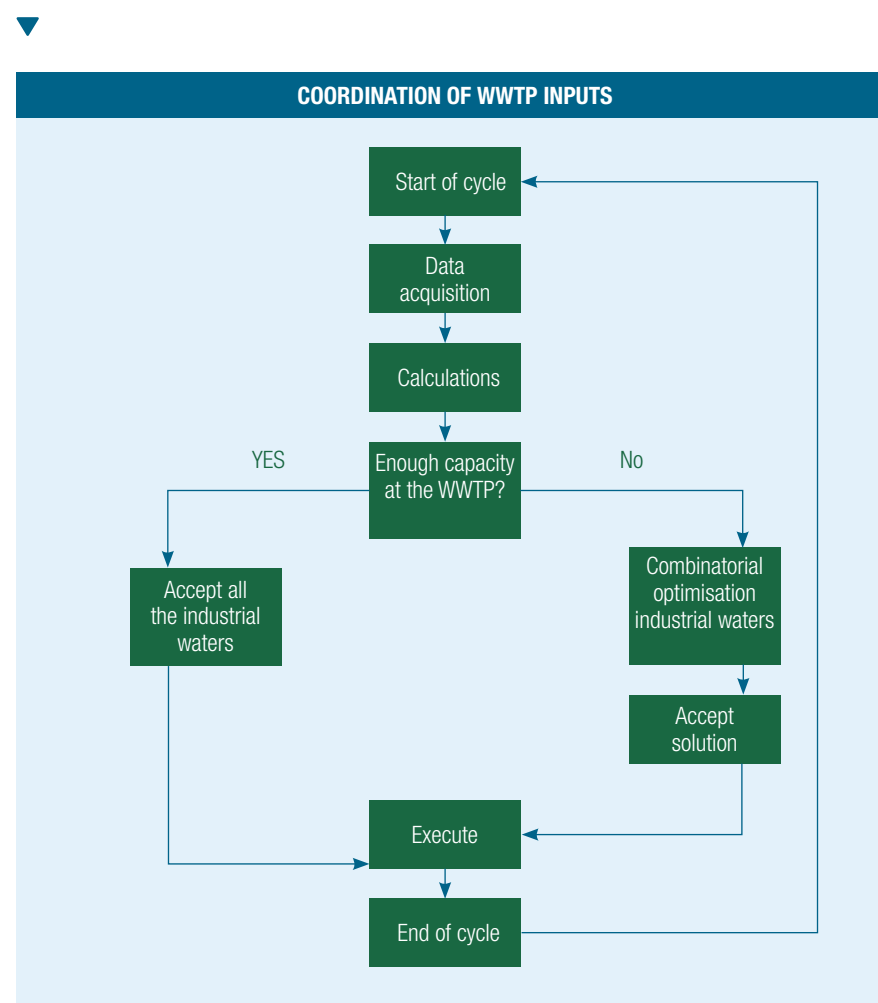
Based on the relative ranking of decisions in the multi-agent environment, we have defined three structural levels:

- the highest level corresponds to the coordination agent and the agents defined for the treatment system and receiving environment,
- the middle level is for the agents corresponding to domestic wastewater and stormwater,
- the lowest level corresponds to agents for industrial wastewater generating activities. These agents are at this level because the decision to authorise discharge or not, at any given time, will depend on the available capacity of the WWTP once domestic wastewater and stormwater is accounted for.

Figure.3.5.

The operation of a discharge authorisation process is cyclical, following the order shown in the flowchart.

- Reception of data from the agent for industrial activities, with their corresponding generation or generation forecast data and composition characteristics.
- Reception of data from the WWTP agent, relative to its treatment capacity for this cycle.
- Reception of data from the agent for domestic wastewater relative to the volume generated and its composition characteristics.
- Reception of data from the stormwater agent relative to volume collected, if any, and its compositional characteristics.



Results

The EDSS has been applied to different working conditions and can vary widely regarding generation of discharges by industry agents, both in quantity and quality, involving, most of the time, the need for the prioritisation process, which was done through an ant colony algorithm. The end result has found that the EDSS is able to ensure that entry into the treatment station is almost constant, which is in the interest of its operation.

In our opinion, we consider that the stage for processing information intelligently, considering the system as a self-regulating entity, has been satisfactorily resolved. There is already a less feasible restriction for the management of discharges in real-time, provided that other conditions (real-time information system state discharges, controllability in the time when the amount of applications exceeds instantaneous capacity of the treatment system etc.) and a regulation that recognises it. It can be considered an example of interaction between different decision levels, with technical solutions that may be viable but may face restrictions on other agents, regulation for example.

5 Selection of alternatives



The decisions made at the strategic planning level yields a set of information that is the basis of the decisions made at the second level, which corresponds to the selection of alternatives, to translate the objectives of the urban water system and its conditions for the integration of all technologies that can successfully fulfil these conditions. The first problem is identifying the number of possible alternatives. It must be kept in mind that, over the years, different types of technologies have been developed that can satisfy, to varying degrees, the required conditions, and therefore it comes to selecting those that offer the best combination for the specific problem. In this book, and from the experience of the authors, although the general problem may be the same, there are differences between populations with a large number of inhabitants and small population centres (which are estimated at less than 2,000 inhabitants) and different approaches are recommended. That is why, in the following sections, there are two EDSS developed for both situations, indicating the steps followed, so that the reader can evaluate and exploit those areas that may be most useful.

5.1 Eco-selection of alternatives

Analysis of the problem

Having defined the conditions that the urban water system must meet and the constraints that arise in each case (space, budget, environment etc.), the selection of the set of technologies that would achieve these objectives, in the most efficient way possible, is not an easy task. There is no single solution in the sense that there is not a single technology for achieving the goals set in any one case, but the solution is the combination of different elements, grouped into different levels of treatment, offering solutions to the problem.

We also have to keep in mind that in the case of treatment, the number of technologies for the treatment of wastewater has increased over time, and there are increasing numbers of emerging technologies with better performance from a return point of view (for traditional parameters solid, organic matter, nutrients- or for new emerging pollutants) or from an energy consumption point of view and minimising overall impact.

The need to combine different technologies, and the existence of a progressively greater number of such elements that can be used, makes the number of alternatives to be considered higher. Some authors, using the combinatorial estimate, think that if we consider combinations of the elements available, the number of alternatives to be considered is in the billions. More realistically, other authors put the options available to tackle the problem at tens of thousands.

At the same time, the criteria to be used to evaluate the suitability of the design are increasingly elaborate. It is not just to achieve levels of water quality, but to consider additional aspects such as operational safety, costs (with

special attention to energy costs), the environmental impact of the plants themselves relative to causing emissions and reuse etc. This involves the use of increasingly complex tools both to identify the elements to be considered, such as the life cycle assessment that integrates different impacts, or to evaluate the effect of different weights by using multicriteria analysis mathematical tools .

Finally, the knowledge is distributed among different actors whose collaboration may obtain symbiotic effects. On the one hand, researchers who develop new technologies (usually on a laboratory or pilot scale) and allow for innovation. On the other hand, businesses or engineering specialists with extensive experience in the design of plants and in some cases with their own patents that set them apart from the competition. Finally, the corresponding authority with its own staff is responsible for getting the best water quality possible with the resources available. It is about getting the best technology available but not entailing an excessive cost (called BATNEEC).

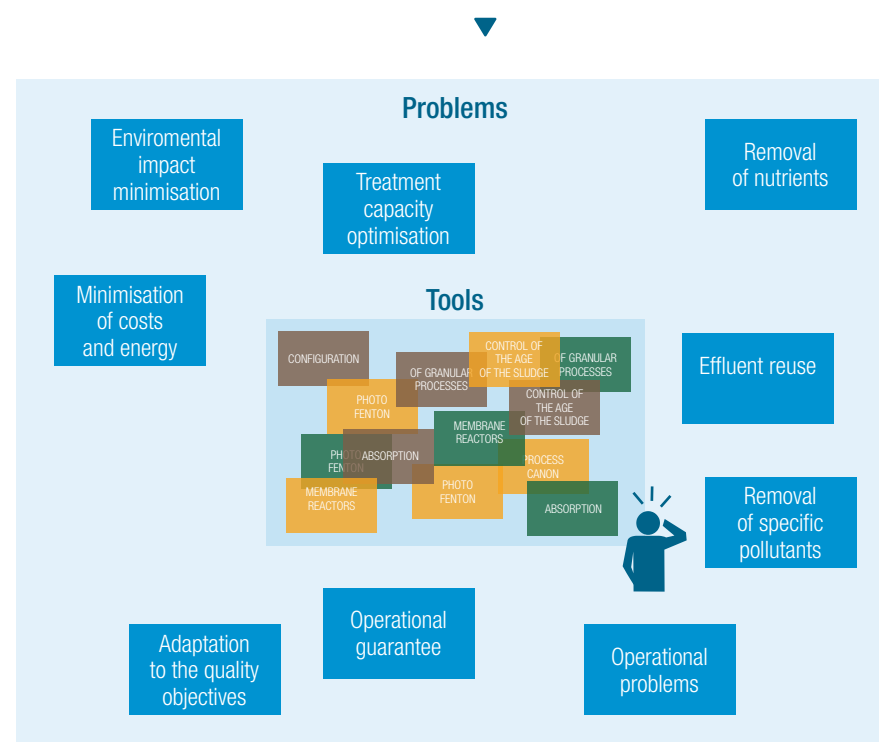
One aspect that adds uncertainty to the decision's flexibility is the ability of the proposed process to address changes that may occur in the future, remembering that the average life of these plants is tens of years. During this period, plants must continue to adapt to technological changes both relative to their own equipment, and to changes that cause decisions to be taken at the first level. An example of this evolution is the urban water system in Zurich, which we are lucky to have been told about by Willy Gujer together with the evolution of his research interests.

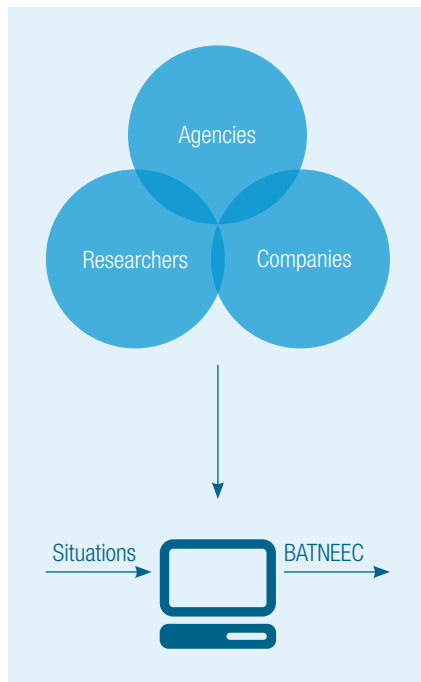
Data and knowledge acquisition

Traditionally, the integration of all these elements was practically seen as an art. And art as such, is difficult if not impossible, to systemise. Maintaining the idea that there will always be elements that require human experience, an effort has recently been made to provide elements that can help at this stage, systematising the knowledge acquired and, especially, establishing systems in which different types of knowledge can be integrated and therefore, providing answers that go beyond specific knowledge. Ultimately, it is about helping in the decision-making process to go from a very large number of alternatives to a manageable number in the later stage of a detailed design, where more systematic evaluation elements, such as those offered by mathematical models, can provide optimal solutions to the problem.

Figure 5.1.1.

We must not forget that the decisions involve a large number of options that must meet multiple objectives. This level of complexity of systems means that environmental decision support systems can be useful while allowing the integration of different types of knowledge and assisting with the difficult task of providing the best possible solution at a non-excessive cost.





▲ Figure 5.1.2.

The development of the EDSS for the systematic design of wastewater treatment plants is performed within the framework of the WWTP Design Project from the 21st century. “Development, implementation and evaluation of technologies for the treatment and recovery of wastewater resources” (Novedar – Consolider), which involves 11 research groups, 29 companies and 14 administrations responsible for water management, which has made a wide range of experts available who, together with the literature, have been key knowledge acquisition elements (www.novedar.com).

Model selection

Two types of structures have been defined to organise knowledge:

- One which corresponds to the organisation of treatment plants, for which three abstraction levels have been defined.
 - A generic level (*meta-units*) corresponding to the stages that can be assumed as existing throughout the treatment process (primary treatment, secondary treatment, tertiary treatment, sludge treatment, returns and odour treatment).
 - The second level (*sub meta-units*) covers groups of technologies required in the process according to the objectives (for example, the usual chemical and biological treatments are considered in the treatment of odours).
 - The third level (*units*) identifies the individual unitary operations.
 - Another corresponds to the characteristics of the units, for which we

Consideration of the different elements at different levels is based on structural (connectivity), behavioural (how they operate), functional (its role in the process) and teleological properties (goal and justification). This structure, based on the hierarchical decision process criteria consists of decomposing the problem into a set of elements easier to analyse and evaluate, as different levels of abstraction modify the amount of knowledge and detail in each stage, allowing the decision to be focused on a smaller number of concepts at all times. So, if you define a new requirement, all options that do not meet the specifications are discarded at a more generic level, avoiding the generation of alternatives and it can be determined if they will not meet specifications.

have defined three knowledge bases:

- **Compatibility knowledge base (C-KB)**, containing information on the different interactions between treatment technologies and determining the different levels of compatibility between them, having established five levels of interaction from high compatibility to no compatibility.
- **Specification knowledge base (S-KB)**, wherein for each of the 274 treatment units, the following is considered, according to the information available: information about the influent, information on the expected effluent, generation of by-products, operating conditions, costs and environmental impacts.
- **Legal and environmental information knowledge base (E-KB)** requires the identification of the operation limits and the subsequent assessment of global impacts.

The figure shows a complex data table with multiple columns and rows. The table is organized into several sections, with some rows highlighted in different colors (green, blue, purple, red). The columns represent various parameters and performance metrics. The rows are grouped into sections such as 'OPERATION DATA', 'SUBPRODUCTS', 'IMPACTS', and 'EFFECT AND OPERATION PERFORMANCE'. The table contains a large amount of numerical and categorical data, likely representing the results of a simulation or analysis.

◀ Figure 5.1.3.

OPERATION

The EDSS proposed, as an aid for the selection of alternatives in the design of wastewater treatment plants, has two interfaces and operates using the following three steps: input data entry, diagnosis and proposal of reasoned solutions.

Input data

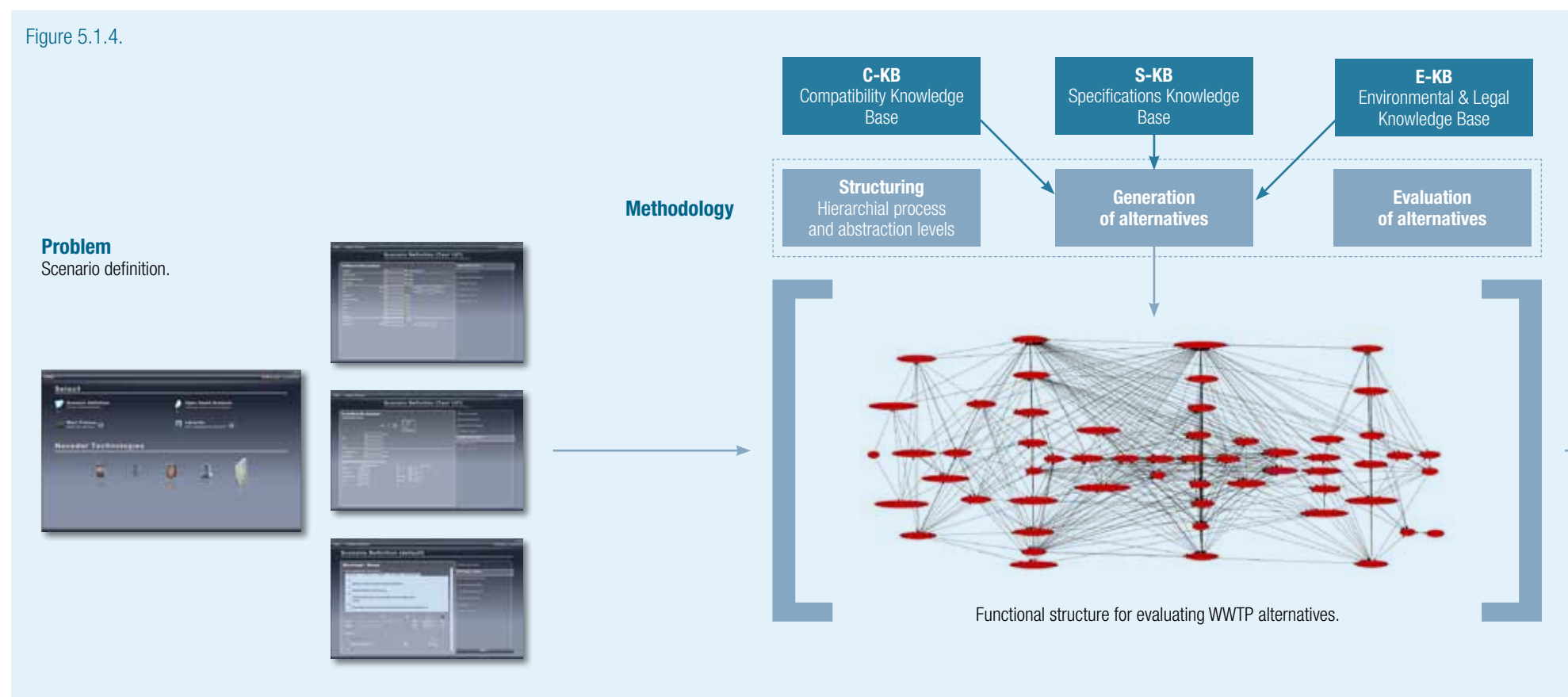
In terms of the input data, the user defines, through a set of screens, in a hierarchy, the location in which to place the facility. Then, firstly, the system ask for the characteristics of the water to be treated and the quality of the water expected to exit the plant (including whether the final destination is a return to the environment or reuse, for which the user has a set of alternatives related to the standard specifications for each case). Then the user can indicate their prioritisation regarding availability of space, importance of the presence of odours, costs and energy consumption etc. This prioritisation can end up changing at different stages of the design, so you can evaluate the impact of having different prioritisation in the design proposal.

Diagnosis

The **first phase** relates to the generation of alternatives. Therefore, a network structure is established composed of nodes, where each node represents a technology and is connected with the specifications knowledge base, so that it can access all the information related to the corresponding unit, and by connections linking the connectivity properties between the units specified in the connectivity knowledge base. Initially, in the *meta-unit* levels, a first selection of technologies is performed to determine which combinations are able to meet the specifications requested by the user. This allows an initial reduction of the search space for later, in the *sub-meta unit* levels and units, identifying possible combinations that result in different flow diagrams, comprising the combination of treatment units whose consistency has been evaluated using the knowledge base.

In the **second phase**, from the flow charts generated, which correspond to solutions that meet the specifications provided by the user, one proceeds to their evaluation. This provides for an information propagation stage through the nodes called recursive evaluation. This stage takes 54 factors into account that characterise each technology and are likely to be tested (final concentration of pollutants, total cost and possible operational problems etc.) either qualitatively by the user, or through quantitative multicriteria decision analysis methods. From here the proposed solutions are sorted according to a score. Remember that this score can be modified by the user, because their priorities may vary defining different scenarios. Considering that in the definition of knowledge bases, the source of the information was added, the system can reconstruct the trace of the proposals.

Figure 5.1.4.



Results

The obtainment of viable alternatives is given in a hierarchical process where users can design their most favourable option as the level of detail increases. Once the scenario is defined, the EDSS initially evaluates viable secondary treatment options and provides a list of technologies that best fit the specifications entered, and where the user has full ability to explore different performance metrics and other indicators. Subsequently, selection of one of the technologies launches the evaluation process and the user can display the different primary treatment, tertiary and biosolid lines that best fit the technology, while the stage is set. Again, the user can assess the results of the recommended lines selecting those that are more suited to their priorities. Finally, through this integrated and hierarchical evaluation, the user gets the most realistic full configuration adapted to the scenario proposed.

Solution
Specific alternatives
to WWTP.



Integrated assessment

One of the aspects that is evolving quickest in selecting the best treatment is its evaluation process. Currently, it is not just about meeting water quality criteria at the exit, but the process must be optimal with respect to a set of sustainability indicators, among which there are obviously economic, operational and technical implications but also environmental issues to assess their impact on different areas. Thus, we selected a set of analytical methods that allow a comprehensive analysis of each alternative. The most commonly indicators are as follows:

- **Benefit-cost ratio (BCR):** One of the most widely accepted instruments at economic level. It is a rational support and systematic decision-making tool and it is used to compare the economic viability of the application of different proposals. This indicator is obtained from the theoretical costs (investment, operating costs, maintenance and energy consumption) and the benefits (sale of reused water, increased value of biosolids and biogas production).
- **Benefit-cost analysis of environmental externalities:** This technique enables the consideration, in economic terms, of the environmental benefits associated with wastewater treatment. This methodology quantifies the theoretical benefits of avoiding discharge into the environment of a set of pollutants (COD, BOD, TSS, nitrogen and phosphorus).
- **Life-cycle assessment (LCA):** Essential indicator for assessing the environmental impact (contribution to global warming and depletion of natural resources etc.) associated with the treatment process. The variables required for the calculation are: Electrical consumption (Kwh), Kg Nitrogen, Kg Phosphorous, Kg DQO, Kg biosolids produced, Kg of CO₂ eq., Kg chemical reactives, Kg. Solids obtained during pre-treatment and transport (km/tonne of biosolid).
- **Carbon Footprint GHG Analysis:** A technique to calculate, at a theoretical level, total greenhouse gas (GHG) emissions generated during the selected process. Greenhouse gases are considered as CO₂ (indirect emissions from construction, transport and electricity consumption), CH₄ and N₂O.
- **Qualitative data analysis:** There is a set of variables that are difficult to quantify but which must also be taken into account. In this sense, data such as process reliability, robustness, visual impact, the potential for odour generation, ease of operation, frequency of problems and the need for expertise etc., must be incorporated into the evaluation and therefore developed a set of ranges for these numerical values.

The calculation of the above indicators can be applied to the results of different methodologies that help us to select the best alternative. Thus, you can apply classification algorithms to multicriteria analysis methods that allow the reconciliation of a comprehensive set of objective data and the priorities of the user interested in designing the treatment plant.

5.2 Small communities wastewater treatment selection

Communities with less than 2,000 inhabitants have different characteristics with respect to larger populations

Analysis of the problem

These population centres have some different characteristics.

Firstly, a social dimension. Unlike large towns where hardly anyone knows the conditions of the urban water system or location of the treatment plant, these communities are living very closely to the implementation of their sewer system, with greater sensitivity, both to the negative impacts that may occur and the benefits for the environment.

Secondly, an environmental dimension. In many cases these small communities are located in areas at the headwaters of the rivers where the flow is less, or in areas of special environmental protection, so the impact of the facility is significant. That is why the impact on the ecological quality of the receiving environment should be taken into account.

Thirdly, a technological dimension. While there may be differences between the various alternative treatment systems for major population centres, they are grouped around changes in the activated sludge process. However, in the case of small populations, there is a set of treatment systems, such as natural systems or low-cost or extensive systems, offering a performance that must be taken into account.

The combination of these three dimensions leads to added complexity in the selection of urban water systems for

these communities, which is reflected in the fact that some regulations, instead of imposing numerical limits on water quality at the output of the urban water system, introduce a more diffuse concept, which is *adequate treatment*.

Managing this complexity is not easy, as appropriate solutions for quantitative values must be combined with qualitative variables, or even subjective assumptions. This will not only require the inclusion of design equations, but also knowledge of different areas, from the specific area of the community where the urban water system will be installed, to experts in the dynamics of the receiving environment, or people with experience in more intensive or more extensive technologies (curiously, it is difficult to find people with experience in both areas). For a specific situation, we may consider using brainstorming, but when a consensus solution is obtained, from which proposals are made for an area where solutions for hundreds or thousands of communities are, it seems clear that it is necessary to use a system to intelligently manage knowledge and be able to provide reasoned responses to each situation taking the different dimensions of the problem into account.

The need to integrate different skills, disciplines and points of view was that which lead the Catalan Water Agency to order an environmental decision support system (EDSS - PSARU) to establish the most appropriate proposals for communities with less than 2,000 inhabitants. Under the coordination of Agency officials, the work was carried out by a group of universities and

research centres grouped in a thematic network, which involved researchers from different fields, and a group of engineering and consulting firms that provided knowledge of the different ways in which work was distributed.

Knowledge acquisition and management

Three main sources were used to obtain data and acquire knowledge:

- Experts in water management and treatment and in the definition of the quality of the receiving environment.
- Knowledge taken from the bibliography and from other places containing experience in the development of sanitation programmes for this type of population centre.
- Analysis of historical data to raise awareness of communities requiring treatment and the state of the receiving environment.

The three sources of knowledge worked simultaneously to obtain additional information. In the case of experts, the obtainment of knowledge was based on the realisation of a series of interviews with people from the administration and the social sectors involved, as well as from the scientific and engineering world with experience in the field. These interviews allowed us to obtain specific heuristic knowledge of the study area, obtained from years of experience working in the same field, which was considered necessary for the proper functioning of the decision support system. This specific knowledge gained from experience is completed with information from books or specialist journals, and visits to places having already developed treatment programs for small communities. Finally, this study was supplemented with historical data on the water quality of the receiving environments and urban

water systems operating at that time because this allowed for the identification of the strengths and weaknesses of different types of plants.

Cognitive analysis

The results obtained in the previous stage was organised into three knowledge bases:

- A knowledge base with the characteristics of the receiving environment. A receiving environment is understood as the ecosystem that receives the effluent from the treatment system that is selected in each community (or group of the same). This knowledge base includes information relative to the amount of water, the presence of aquifers sensitive zones, nitrate contamination, vulnerabilities and protected zones. In addition to historical data on flows and qualities, it was considered important to incorporate the aspect of a possible discharge point of discharge for the urban water system and its environment. This knowledge base defined the (minimum) treatment required for each case, in line with the state of the receiving environment.
- A knowledge base including the characteristics of the community requiring treatment, with a mention of the community's characteristics and identification of the places available for the discharge from the urban water system. This knowledge base was obtained from surveys of representatives of all affected municipalities, conducted by consulting firms, which incorporated data from the community, its surroundings and the existing treatment.
- A knowledge base of technological treatment alternatives with information on characteristics, performance, space requirements, climatic, geo-

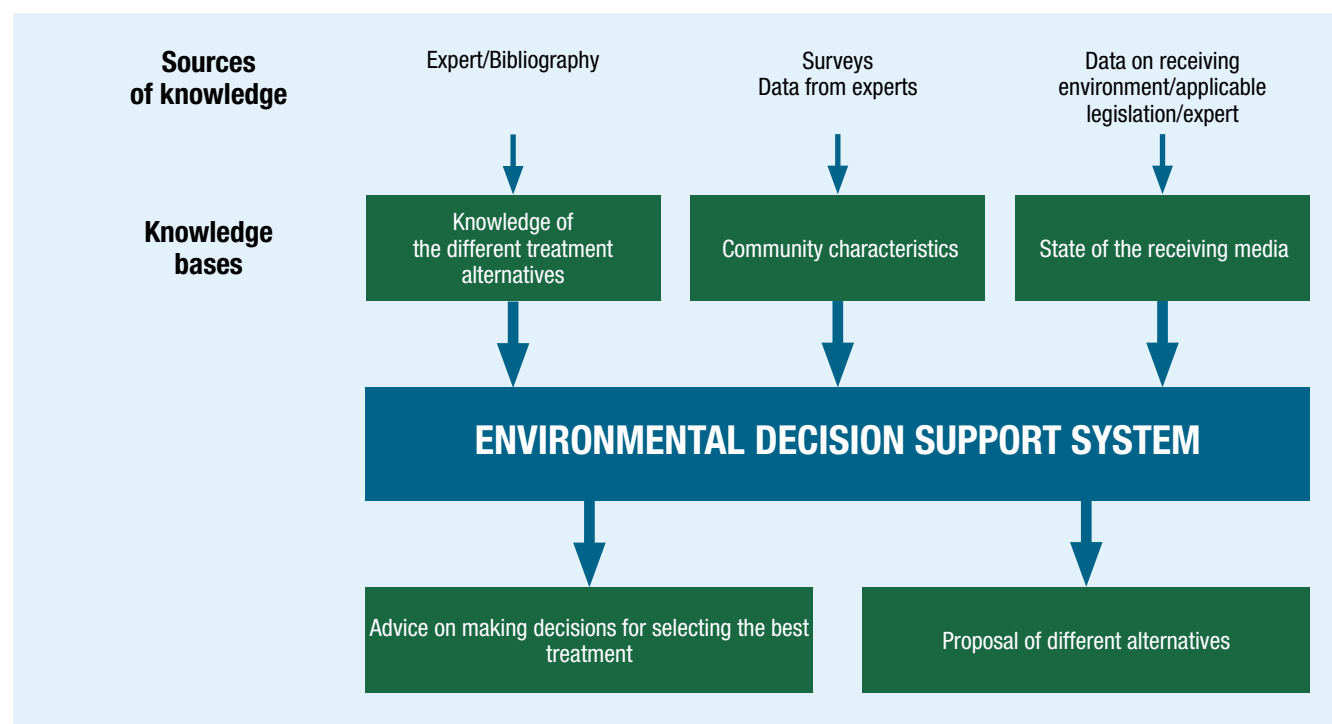


Figure 5.2.1. General diagram of the EDSS-PSARU from the collection of data and knowledge for obtaining results.

logical and hydrogeological restrictions, maximum heights where the systems are applicable, slopes or restrictions due to the presence of aquifers. This knowledge base also includes installation and maintenance costs, and other considerations that could affect social aspects, such as the generation of odours.

Coding of the knowledge and implementation

Different models of codification were chosen as a function of the different knowledge type.

In terms of treatment systems, knowledge is coded in the form of matrices. One provides a qualitative comparison, based on economic, impact-related, technological and social criteria, of the different urban water systems considered. Another associated specified treatment levels, depending on the receiving media, with levels of treatment by the different urban water systems. From these two matrices, we constructed a discriminative hierarchical table from different revisions to avoid contradictions and redundancies - thereby obtaining consensus from different ex-

perts with different levels of expertise in the different treatments- and this was established as a central element in the decision support.

The four variables that were established as key in the hierarchical table were: equivalent inhabitants, establishing different intervals; the level of treatment required (primary, secondary, secondary with nitrification, denitrification and secondary with denitrification and phosphorus removal); the flow conditions of the receiving media and months per year that had water flow and available GIS information (surface, slope).

We considered the possibility of incorporating a set of safety rules, to incorporate knowledge related to geographic information systems (vulnerable areas, special plans), or any specific area (seasonal population) that could encourage, discourage or even exclude some treat-

ments that are not suitable to climatic conditions (temperatures, foggy days, height above sea level).

OPERATION

The EDSS-PSARU's operation follows the stages proposed for input data, diagnosis and decision support.

During **input data**, the user enters the code for the system or the name of the basin to be treated. From here, the system accesses the database containing the characteristics on the community, obtained from the survey (except the height above sea level or vulnerable areas, which are derived from the geographical information system). These data are filtered to avoid erroneous data and sometimes categorised for establishing categories that are used in the diagnosis process (for example, an available surface of 3 m² per inhabitant is considered low, whilst over 8 m² is considered high). The water flow of the receiving media is used as a first approximation of the environment's dilution capacity, while the available surface will differentiate where extensive systems may be used.

In the **diagnosis**, the system activates a set of rules to assess the population equivalent, the level of treatment required from the treatment system, the water quality of the receiving media and the available surface. This stage concludes with a list of treatment systems that meet the requirements. Then the safety rules are activated - which can invoke other rules or procedures- to obtain a list of possible treatments.

An important aspect to consider now is the need to decide between different alternatives when selecting their urban water system for two or more communities that are relatively close. In this case, options to clean them up individually or jointly must be considered. In the latter case, considering the options of a new treatment facility in one of the communities or in an existing treatment system. For this problem, a expression containing three terms can be weighted differently according to the priority

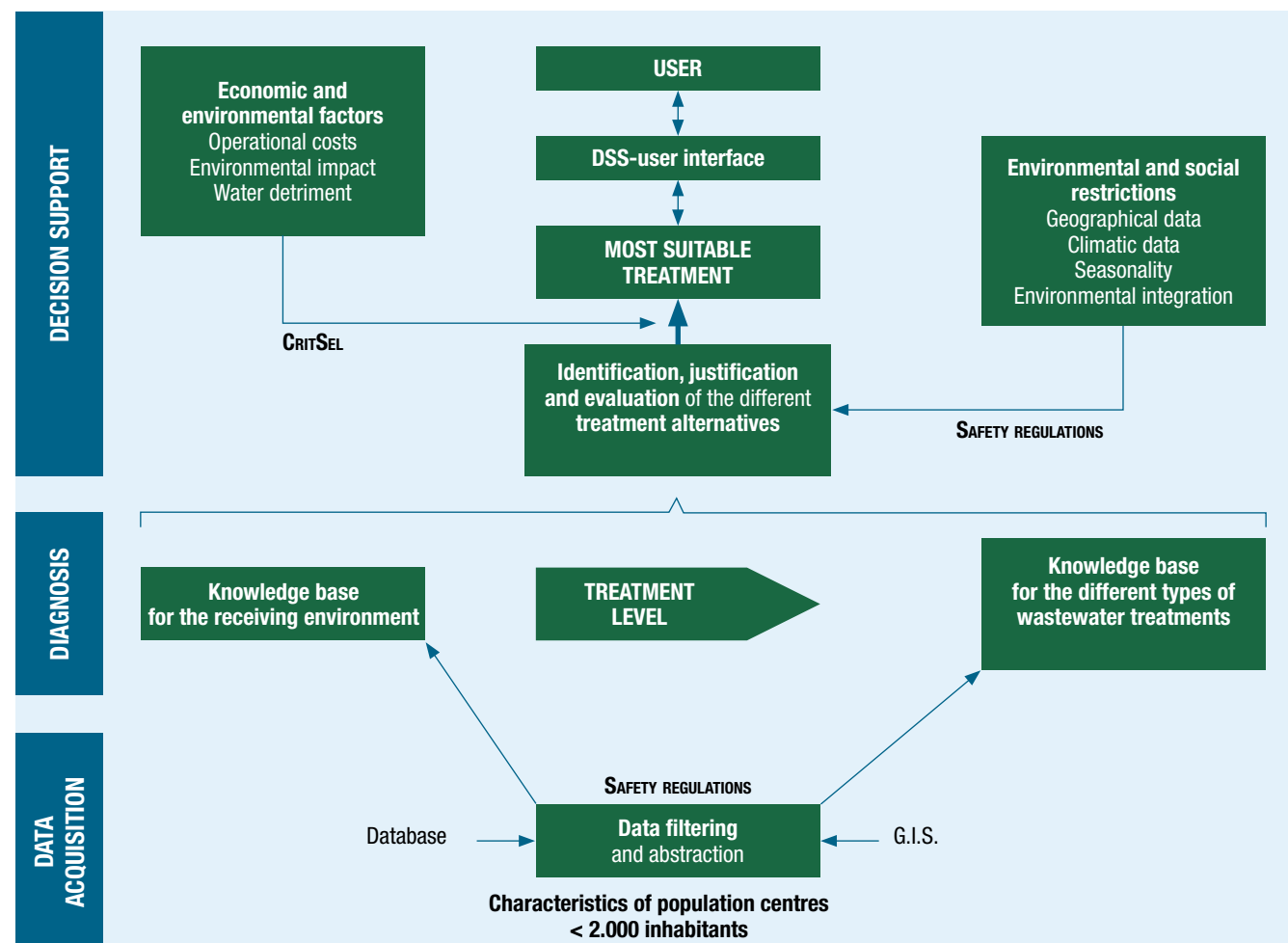
objective in each case. This expression was agreed between representatives of treatment experts in the receiving environment either the administration or other social agents and evaluates each alternative treatment system: the energy or economic impact; the environmental impact in the receiving environment relative to altering the dilution ratios, and the effect on the flow from the receiving media, reflected in the distance the water flows through sewer systems instead of the natural environment.

In **decision support**, the EDSS proposes a set of feasible alternatives, arranged hierarchically from the most appropriate (ac-

ording to specified criteria) to those that are less suitable.

For each alternative, the system provides justification of the reasons for selecting the alternatives proposed and for those discarded, and the corresponding economic evaluation of the building and operation costs.

▼
Figure 5.2.2.
Representation of a EDSS-PSARU's operating process for the selection of treatment systems in communities with less than 2,000 inhabitants.



The case of the river Fluvià basin

The environmental decision support system was applied to the different basins managed by the Catalan Water Agency, obtaining a set of reasoned proposals for possible treatment systems for each population centre. As an example of the results obtained, here is a summary of the EDSS-PSARU proposal for the river Fluvià basin.

The river Fluvià has its basin the North-East of Catalonia and flows through the regions of Garrotxa, Pla de l'Estany and Empordà. It has a steady state and Mediterranean behaviour with a significant decrease of flow in the summer months. Its tributaries have some similar features; many of them staying dry for long periods of the year. There are 76 small communities located in its basin, so suitable treatment is required. At the time of the study, the distribution of the population in this basin with respect to these communities indicates that there is a greater number of populations with less than one thousand inhabitants.

In addition, we can highlight the contribution of the seasonal population and the existence of agro-industrial activities. The latter involves the appearance of some problems related to treatment and the presence of fats, which influences the definition of the primary treatments. The receiving media of these communities was identified as 40% river, while the rest is divided among intermittent streams and dry. An important aspect of this basin is the existence of protected areas of natural interest and zones particularly sensitive to nitrate contamination.

As a result of the EDSS's application, it was recommended that 51 communities treat their water individually, 9 treat it jointly and 16 treat their water using existing treatment systems, establishing the corresponding connections.

It was interesting to analyse the differences between the results obtained in this basin with others located in different areas of Catalonia.

For example, in the Tordera basin, with a similar number of communities but with a different population distribution, the number of activated sludge plants proposed was bigger, an alternative that has higher operating costs and a greater visual impact, but with greater efficiency for bigger communities. In the case of Noguera Ribagorçana, with a higher ratio of communities smaller than 200 inhabitants and a greater altitude above sea level, the number of constructed wetlands is significantly lower and there are more fixed biomass systems.

Level of inhabitants	Number of communities
<50	1
50-100	20
51-200	33
201-1000	20
1001-2000	2

Constructed wetlands	31
Sequential reactors	1
Stabilisation ponds	3
Intermittent sand filters	5
Buried sand filters	4
Application to the ground	3
Activated sludge	2
Bio discs	1
Others	5



Figure 5.2.3.

This basin has a high percentage of constructed wetlands proposed as secondary treatment.

6 Process design

A photograph of a beach at dusk or dawn. The sky is a deep, dark blue, and the water is a lighter, shimmering blue. A signpost, consisting of a dark rectangular sign on a thin pole, stands in the shallow water. The sign is blank. The water reflects the sky and the sign. The foreground shows the wet sand of the beach, with some small pieces of debris and a dark, possibly wet, object in the lower left corner.

With the advances in the process design of the treatment system, the problem complexity decreases, reducing the risk and the impact of decisions, while increasing the information available, which allows for greater precision and greater use of numerical tools, encoding this information.

In this context, in recent years, the development of mathematical models has experienced a significant increase in both the development of new models, which are increasingly able to describe the complex relationships that occur in urban water systems, and in their application. After many years of participating in this area, our experience is that its use has become widespread and that the younger generations who have grown up in an environment where computers reign, use them widely. It is a clear example of positive feedback, as more is used, more information is available which results in better models, which increase their reliability and therefore are increasingly used.

In this section, we introduce a chapter presenting some basic concepts of the model approach and an example of evolution that is now widely used to describe the behaviour of processes that occur in treatment plants using activated sludge, as an example of this progress.

This widespread use of models in this design section should not obscure its limitations. Limitations associated with the difficulty of describing the complexity of the processes taking place in urban water systems, limitations in the calibration of the models, but also more conceptual limitations, arising from the difficulty of expressing experience acquired in mathematical equation form, following the paradox of the expert, which indicates that the more you know about a process, the more difficult it is to systematically express the reasoning used.

Another problem that is becoming a major effort is in the treatment of uncertainty and the need to incorporate the existence of multiple criteria at the time of making a decision. In this sense, the development of new methodologies and new tools based on models and their incorporation into environmental decision support systems, as presented in the second chapter, we believe it may take a significant leap in the coming years by significantly modifying the procedures used so far.

6.1 Mathematical models

A **mathematical model** uses a set of equations that represent an approximation of the real world. The nature of these models may be **deterministic** (when the mechanisms governing the process are known) or **statistical** (when the mechanisms are unknown but there is sufficient reliable data to propose equations that, without the need to incorporate a description of the processes, has the ability to describe its behaviour). The latter are also known as **black box** models, in contrast to the hybrid (**grey box**) models, which combine numerical correlations with a certain amount of empirical knowledge on the system's behaviour.

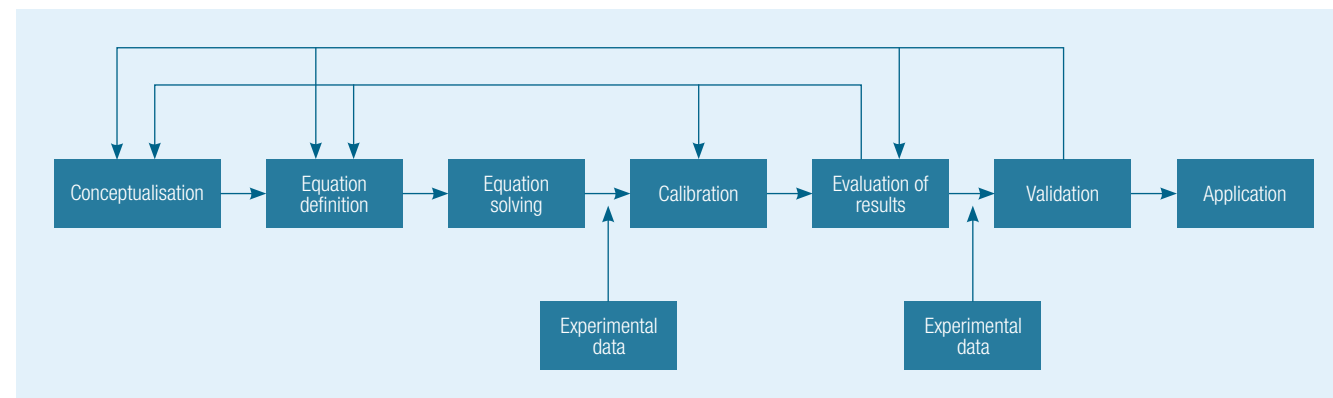
Stages in the development of a model

The development and application of a model requires the execution of a set of steps:

- Firstly, identifying the *problem that needs to be solved* with the use of the model. The level of description required and the effort to develop it must be appropriate to the objectives. It is not the same a medium-term planning, for which a steady state model can be enough, than modelling the dynamic impact of the rain on the sewer system.
- Secondly, definition of the equations which will give rise to the mathematical model. For deterministic models, which will be considered in this text, these equations are based on the general concepts relative to the conservation of matter and energy, and transport phenomena.
- The third step relates to the calibration process, in determining the values of the parameters shown in the model's equations. Typically, determination of the parameters is performed by comparing the output values provided by

Figure 6.1.1. ▼

The models attempt to describe the behaviour of a real system predicting the response from input data and a set of equations which has incorporated the knowledge we have of the system to be simulated. The figure shows a general diagram of the construction process.



the model's equations, with which they are determined experimentally.

After the calibration process with reasonable adjustment, the model can be used to simulate the effect of different alternatives and scenarios. Its reliability is always subject to the assumptions and the suitability of the fit obtained.

Submodels and interrelations

When trying to simulate the whole **urban water system**, we have to take into account the different processes that occur in each element, since there movements occur that are associated with the water flow, but thermal variations may also occur, and interrelations between various quality or pollution indicators. This means that in order to build a good model, three submodels are required: a hydraulic submodel, a thermal submodel and a (bio) chemical submodel. Although, conceptually, the three models are interrelated, the relationships between the thermal and hydraulic (corresponding to changes in water flow due to temperature) or between thermal and (bio)chemical (corresponding to the variation in temperature

due to (bio)chemical reactions) are small enough so that the system can be solved in cascade. Thus, from the mass balance in a three-dimensional element, which will consider the terms of convective flow, diffusive and generation, you can get the general equation describing the system.

In practice this equation is generally difficult to solve, so it is necessary to establish different simplifying assumptions tailored to the characteristics of each element under study. Thus, in the sewer-systems, a plug flow model is generally accepted, while in the treatment plant's reactors, the assumption of complete

mixing is usually the most used.

It is not the same to talk about modelling a process than to **simulate** its behaviour. In fact, for the majority of users, we solve, for a given scenario, the models developed previously by an expert.

Simulation involves the use of a problem that enables the model to be solved mathematically. These programmes may be widespread (advanced mathematical packages such as Matlab etc..) or specific to the sanitation field (Mouse, SWMM, West, GPS-X, Simba, Biowin, etc..).

Figure 6.1.2.

General equation for the balance of material for a differential volume element considering a unidimensional model.



$$\frac{\partial(CA)}{\partial t} = - \frac{\partial(uCA)}{\partial x} + \frac{\partial}{\partial x} \left(DA \frac{\partial C}{\partial x} \right) + S$$

"where

- C = concentration of the substance being studied
- A = flow area
- u = average flow speed
- D = diffusion coefficient
- x = distance
- t = time
- S = terms associated with generation and growth etc.."

The activated sludge process as an example of the coding of knowledge in a complex system, in the form of mathematical models

While all the elements of the model to describe an urban water system are important, the (bio) chemical model for the **activated sludge system** is the one that has received most attention over the years and has more widespread use. In fact, the mathematical foundations of this model go back to 1914 when Arden Lockett first described an approximation of the biological processes relative to wastewater treatment. Since then, many experimental studies developed kinetic aspects, variables for the determination of substrate and biomass and nutrient removal mechanisms etc., so that we now have a set of sufficiently standardised models, with a common notation, which are widely accepted by the international community. This set of models is known as the **ASM family** (*Activated Sludge Modeling*), promoted by the IWA (International Water Association), which includes ASM1, ASM2, ASM2d and ASM3.

ASM1: This is the first model launched by the IWA; it includes the main transformations and components required to discover hydrolysis, carbon oxidation in aerobic and anoxic conditions (denitrification), and the nitrification process, in which the ammoniacal nitrogen is oxidised to nitrates. The model is based on Monod kinetics and the most consolidated biological reactions for the growth of bacteria, and maintains the oxygen balance through the use of the chemical oxygen demand (COD) to express the concentrations of its components. The input is defined based on its soluble, particulated, degradable and inert fractions both for its carbon source and for the nitrogen. Bacterial growth only occurs in the presence of soluble substrate, whilst the death of the micro-organisms is modelled based on a regenerative estimation, where the product of the lysis is partially transformed into inert material and into the particulated substrate, which, once hydrolised, forms part of the soluble substrate, which can be used again for the active biomass.

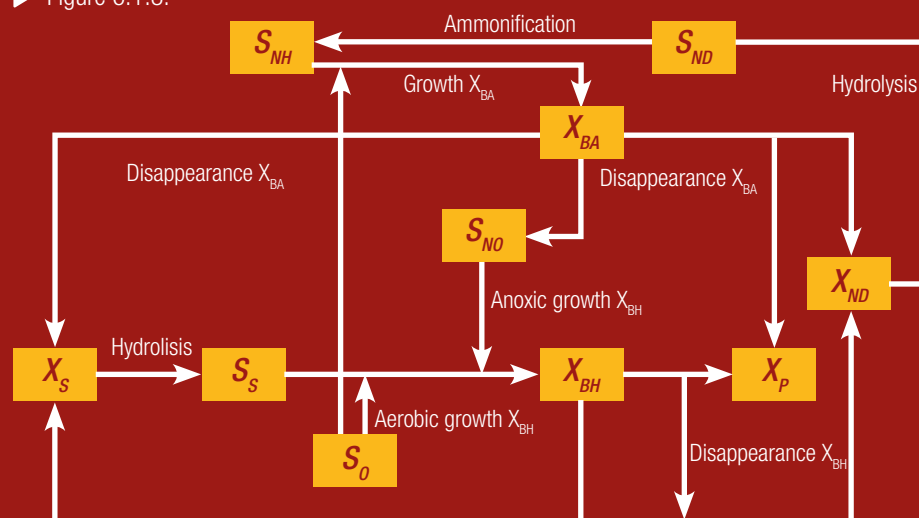
ASM2 and ASM2d: The ASM2 model was developed some years later with the aim of incorporating the biological phosphorous removal. The metabolism of the phosphorous accumulating organisms (PAOs) was described using internal storage products (PHA polyhydroxyalkanoates and Poly-P polyphosphates, but not glycogen, despite the fact that there is currently a consensus on the role it plays in the metabolism of the PAOs). ASM2 considers the growth of the PAOs in anaerobic conditions and does not include its denitrifying metabolism. In order to minimize the number of state variables, the nitrogen and phosphorus particulates are described in a simplified way, estimating them from a relationship with the particulate COD state variables.

The inclusion of the metabolic activity of the PAOs in anoxic conditions lead to the publication of the ASM2d model. The slow kinetic growth of the PAOs in anoxic conditions is described in a similar way to the growth of heterotrophic bacteria in aerobic and anoxic conditions in ASM1.

ASM3: The last of the models in the ASM family was given the name ASM3, and although it includes biological phosphorus removal, it is described by a new approach to carbon oxidation, nitrification and denitrification. ASM3 assumes that the bacterial growth mechanism is a stage prior to the intracellular storage of the substrate. The model describes, more specifically, the description of the processes relative to the accumulation of organic substrate and endogenous respiration, separating the activity of heterotrophic bacteria and nitrifying.

However, in the near future, significant changes in existing mathematical models for wastewater treatment systems are still expected. Aspects such as the formation and proliferation of filamentous microorganisms, the removal of emerging pollutants, the production of N_2O or other gases that significantly contribute to climate change, the new routes at different stages for the elimination of nitrogen, biomass granulation biomass, fouling of the membranes, recovery of phosphorus or other pollutants, the dynamics of the sulphur, the reactions that occur in the decanters and the physical transfer processes etc.

► Figure 6.1.3.



Simulators are increasingly powerful and easy to use, so it is also increasingly common for them to be used for different applications by many users. It is essential to know about every detail of the models hidden beneath the friendly user interface, and especially its limitations or restrictions, because, otherwise, we risk to getting beautiful plots of dynamic behaviour for a significantly different process we want to simulate. For example, a convincing membrane bioreactor icon may contain a model that do not simulate membrane fouling.

Other key factors so as not to misinterpret the results of the simulations are the correct performance of **calibration** on the model's parameters (although it is sometimes better to use their default values), take into account that typical rules of thumb used by engineers and consulting companies usually including safety factors (while models attempt to reproduce the real system), and ensure quality and consistency of input data, since, if this data is incorrect, the results will be as well-garbage in, garbage out-.

6.2 Optimal design

Analysis of the problem

Once, in the previous stage, the configuration of the treatment plants is defined, it is necessary to determine the numerical values that can be used for implementation. Although the optimal design of the operational units corresponds to the third level of decision, and therefore the complexity and uncertainty has been significantly reduced, the margin for manoeuvre is broad enough to rely on the best available technologies for the decision-making process. Currently, the design of the units previously selected is usually based on a combination of art and science to optimise a functional objective, where the experience of the person responsible for the process is complemented by empirical correlations, spreadsheets, statistics, safety factors, models, services and fashions etc., some recovered from old notes or more or less updated design manuals, others incorporated from more innovative approaches that contemplate a more ambitious dynamic of the process. The end result can lead to more or less conservative proposals, with higher/lower operating costs in return for a lower/higher initial investment, which meets or exceeds strict legal limits of discharge, more or less easy to operate, with more or less consumption of chemicals, more or less flexible, with more or less room for optimisation, more or less robust to perturbations, more or less safe from any accidents or natural disasters etc. Most of these criteria have already been taken into account in making first and second level decisions, but their quantification has not been carried out in a rigorous way to get the detail on the optimal sizing of the units.

An important consideration at this level is the need to design plants thinking, not only about their behaviour under optimal stationary conditions, but about dynamics, anticipating that it will suffer oscillations

during operation. Therefore, it is important to simultaneously consider the equipment specifications and control thereof. The plant must be efficient, not only for a set of design conditions, but also when there are shocks and variations in the input conditions, or in its operation.

The management of objective and systematic disparate criteria for the optimisation process and the existence of models and other cognitive analysis combined with the uncertainty of the data, knowledge base and design objectives, favours using decision support systems compared to more conventional approaches. Thus, the design process is more transparent and can justify any decision and would enhance the reuse of certain aspects in the future design of similar processes and the review of certain calculations before a change of scenery etc..

Simultaneously, as has been indicated throughout the book, this includes the fact that the integrated analysis that takes place in this third level of optimisation may call some of the decisions previously made at higher levels into question, so it would be convenient to generate a feedback flow of knowledge, which does not always occur.



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A mathematical model can be considered as a package of knowledge on process dynamics. Providing appropriate models, they can be used as powerful tools for process designers or operators. They can give advice on possible control actions and be used to make predictions. The accuracy of the model will probably never be sufficient to enable them to make quantitatively reliable predictions for long periods of time (\approx weeks), but can still describe the interactions between the different unit processes and values, or at least the trends would be in the correct order of magnitude. It is im-

portant to understand that a model is never going to satisfy all needs. Rather, it requires a wide range of models, depending on the purpose and the user. In wastewater treatment, the need for dynamic models is apparent for various groups of individuals:

- the *designer*, who wants to explore, not only the average properties of a plant, but also its robustness to dynamic changes. This analysis must be carried out before the plant is built. Obviously, the model cannot provide specific responses about concentrations for a specific plant;
- the *process engineer*, who wants to explore different configurations or the operating principles of an existing plant;
- The *operator*, who requires a decision support system, where different "what would happen if" situations are explored,
- the *professor* who will use the model to teach the dynamics of the plant to different types of people, ranging from operators to researchers;
- the *researcher*, who will use the model as a condensed version of current knowledge. The model can explain the various basic phenomena and process interactions.

It is quite obvious that different users want different answers from the models. Some have to calibrate the model for an existing plant, while others have to use the best available estimates of the plant's parameters. Different users are interested in different time scales and also have different demands on the model's details. While the researcher wants to be able to modify almost everything in the model, the plant operator emphasises ease of use and reliability of the model for their purposes. The most important thing: the model is not reality; it is our best knowledge of reality. We should not fall in love with the model!

Integration and implementation

Optimisation of a conventional problem consists of finding a solution that represents the optimal value for an objective function. However, in the case of the design of urban water systems, the simultaneous optimisation of more than one objective is required. That is why a multi-objective approach, where the fulfilment of each objective is measured based on the different criteria selected, seems the most appropriate approach.

The classification of the criteria included in the different categories (economic, environmental, technical and social for example) assigns overall weights to each category and facilitates the use of sensitivity analysis to determine the relative importance of the criteria in the optimisation process. This process can also be performed within each category, playing with the values of the weights assigned to each criteria.

One of the keys to optimal design lies in the correct quantification of the criteria which are intended to measure the

achievement of objectives. In the best cases, particularly with respect to the hydrodynamics of the process and to biological processes, sufficiently standardised mechanistic models are available for quantification -detailed and dynamic- of criteria relative to performance, water quality and costs etc. However, correlations, *rules of thumb*, black box models, models based on the empirical knowledge of the person responsible for the design, enable the rest of the criteria to be quantified.

In terms of optimisation, we should remember the **uncertainty** inherent to the data and models we use, given that this prevents us from predicting their behaviour with absolute certainty. This is particularly relevant to the case of WWTPs. The low predictability of certain aspects in the treatment of wastewater, such as influent characteristics, the response from different bacterial communities or simply the occurrence of events that are beyond our control (such as equipment failure) has forced process engineers to apply high safety factors, oversizing the designs. Uncertainty analysis identifies the main

sources of this variability and evaluates it (qualitatively and quantitatively) in order to eventually provide tighter designs.

Finally, implementation of the EDSS for design optimisation requires a framework that allows for the management of data and information, which facilitates quantification of the criteria (some of which require the execution of models) and dynamic scenarios; that fits the mass balances, and enables the performance of sensitivity analyses on the assigned weights and simulations to predict the impact and propagation of uncertainty (for example, by Monte Carlo analysis). The integration of different tools and software in a single EDSS facilitates user interaction and allows rigorous and iterative analysis with the various stakeholders in the process.

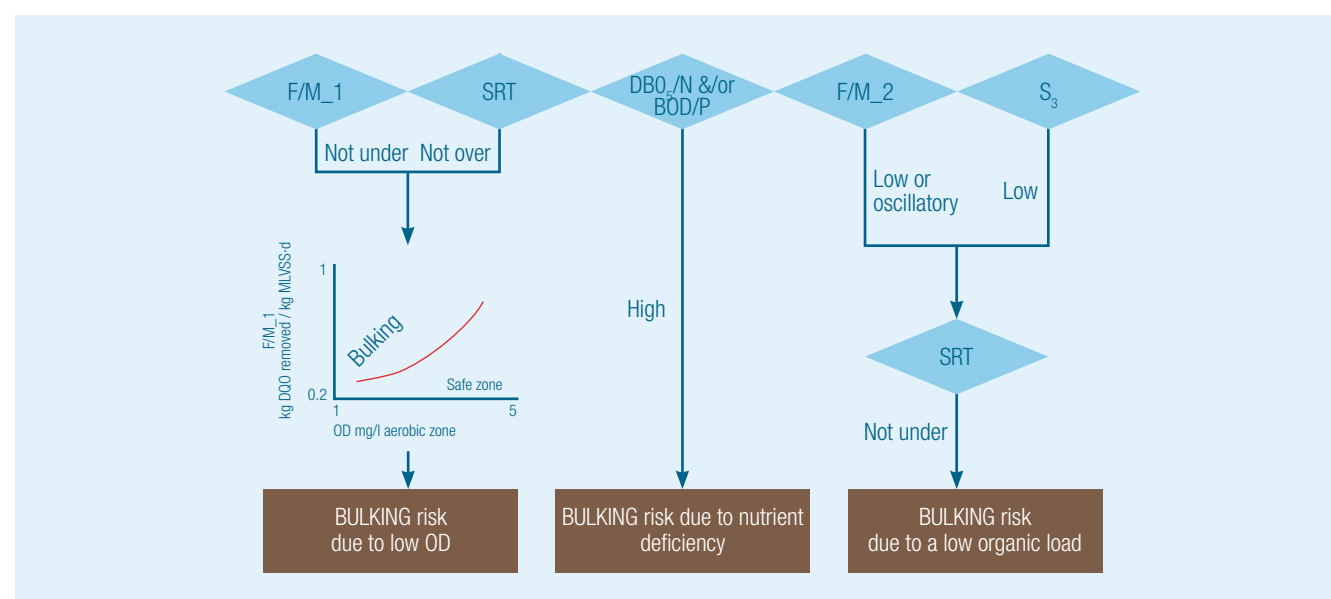


Figure 6.2.1.

One of the capabilities of the EDSS is the possibility of incorporating and managing different types of knowledge. For example including the possibility of assessing the risk of occurrence of filamentous bulking in the activated sludge system, whose description is not yet sufficiently reliable so no deterministic models exist, making it necessary to rely on operation rules provided by experts.

OPERATION

Input data

The quantity and quality of data in the knowledge base determines the real possibilities of optimising the design of an urban water system. In some cases this data is provided by the authorities or by the client (although in this case some decisions have been made previously), while in others it is the designer who has to carry out the measurements, estimates and future predictions.

Assuming the legal framework that regulates the final limits relative to discharge, emission, safety and quality for the possible reuse of water etc., and restrictions on space and budget, design optimisation requires details regarding the quantity and quality of the flow to be treated. In the worst case, it provides an estimate of the population connected to the treatment system, but an optimal design needs to have the profile of the influent (with averages, peaks, profiles, schedules, seasonality and everything on quantity and quality), the projection of future events expected to alter the system (some of which can be unpredictable, as this corresponds to complex systems), any existing measures for mitigation of such events (regulation tanks, derivations etc.), the industrial, commercial and institutional contribution and infiltration and/or losses from the system etc.

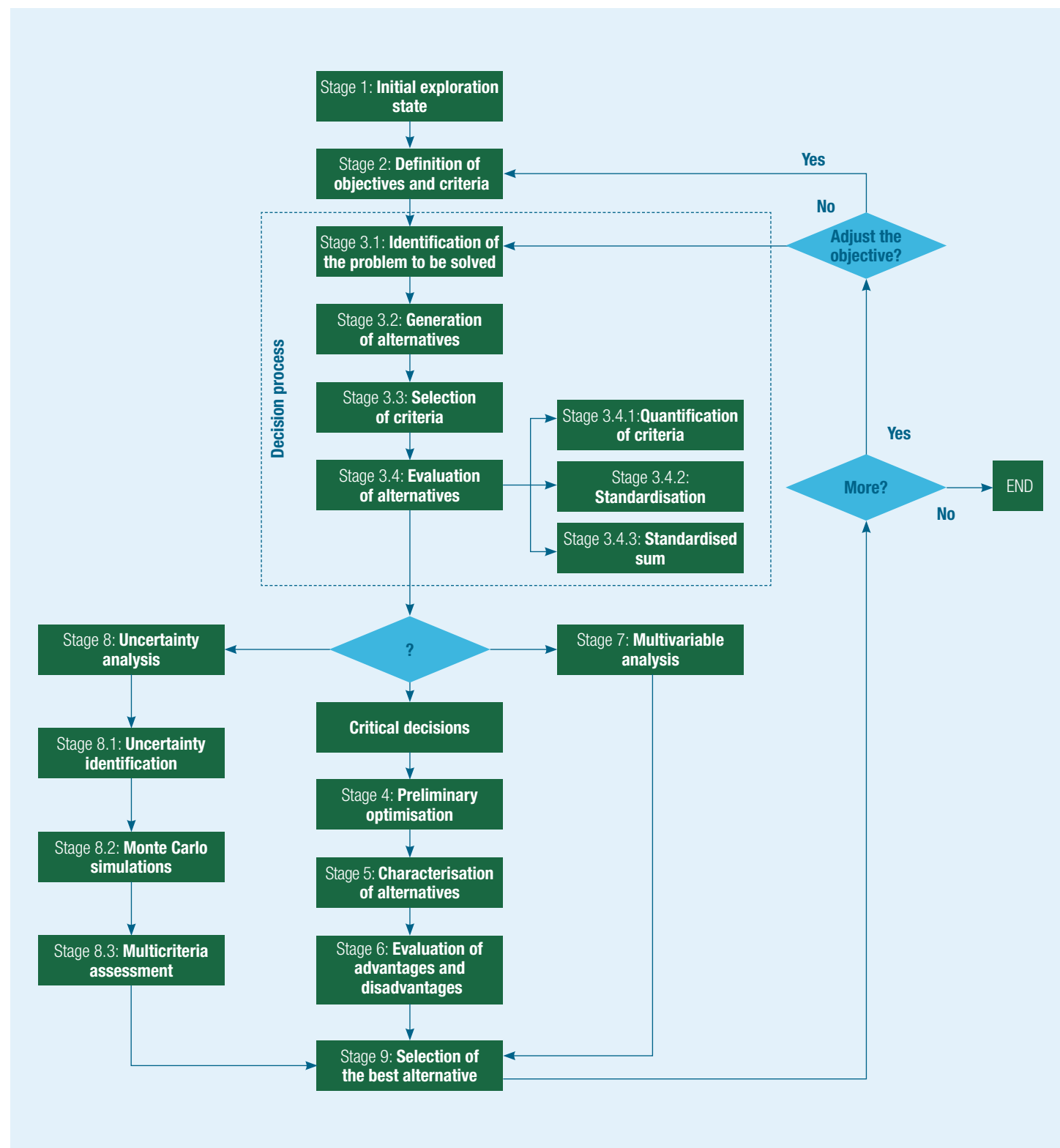


Figure 6.2.2.

Flowchart for the operation of the system developed indicating the options that can be established for the realisation of the optimal design.

Diagnosis

In this case, the proposed methodology consists of nine stages.

- **Stage 1.** Analyses information provided with the aim of defining the context in which the system design will be carried out.
- **Stage 2.** Includes the definition of the objectives and evaluation criteria to measure the degree of their satisfaction. To determine its relative importance, we need to use weighting factors.
- **Stage 3.** Identifies the problem to be solved, generating alternatives and its evaluation for measuring the degree of satisfaction of objectives.
There are three sub-steps for the evaluation of the alternatives:
 - Criteria quantification
 - Standardisation
 - Standardised addition

At this stage, the system may request the application of multivariable statistical techniques (step 7) and uncertainty analysis (step 8).

- **Stage 7.** Involves analysing the results using multivariable statistical techniques including cluster analysis, principal component analysis (PCA) and discriminant analysis (DA).
- **Stage 8.** Firstly, identification and quantification of the various uncertainties that have been identified in the system (step 8.1), and then to perform a set of Monte Carlo simulations (step 8.2) and finally, in step 8.3, to perform a multicriteria evaluation of alternatives generated.

If the users decide to make a critical decision analysis, the system applies three intermediate stages.

- **Stage 4.** Corresponds to a preliminary multi-objective optimisation, which compares the most promising alternatives located close to the optimum conditions obtained from dynamic simulations.
- **Stage 5.** Proceeds to identify the strengths and weaknesses of each option by using rules derived from classification trees.
- **Stage 6.** Involves the assessment of *trade-offs* (advantages and disadvantages) between the gains and losses in the process. This takes place with dynamic simulations and the qualitative knowledge extracted during the design process.

Finally, in **stage 9** the system proceeds with the selection of the best alternative, in accordance with the specifications realised throughout the process.

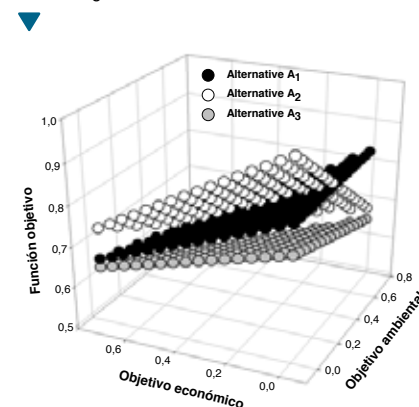
Decision support

Redesign of a treatment plant

In a study on the redesign of a system to remove nutrients, from a plant that initially consists of an aerobic zone, the following objectives were established: a) achieving the limits set by Directive 91/271 in reducing nitrogen and phosphorus, b) minimising the environmental impact (as established, in this case, as an impact on the receiving media), c) cost (construction and operation) and d) improving the operation of the treatment plant in terms of stability, flexibility, control and minimisation of risks associated with microbiology-related solids separation problems. Each of these objectives was assigned a weight. Three alternatives were evaluated; for each of them, the values associated with each of the objectives were obtained. As a notable feature, decision support represented analysing how the scores obtained by each of the alternatives varied, by modifying the relative weight given to each of the objectives. This allows the building of a decision space in which the end user can assess the impact of possible changes and, therefore, take them into account when making the decision.

Figure 6.2.3.

The change in the prioritisation of objectives (environmental and economic) changes the configuration selected.

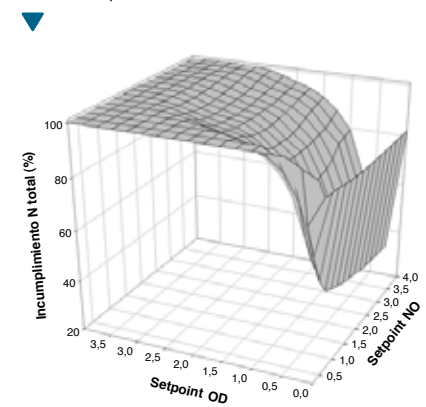


Control system selection

As mentioned at the beginning of the topic, the need to ensure water quality conditions of treatment systems, minimising the impacts of disturbances, makes the design of control loops a key point for the proper operation of the treatment plants. A second example shows the optimisation of the setpoints for the two controllers, one for dissolved oxygen (DO) and one for nitrate (NO_3) in a treatment plant for the elimination of organic matter and nitrogen. In this case, the existence of aerobic and anaerobic zones determines the performance of the system, so a compromise must be made between the set points for dissolved oxygen and nitrogen. Again, the performance of the system developed allows the user to identify the impact of their decisions on different objectives, which are the same as above.

Figure 6.2.4.

Impact of the variation of the nitrogen and oxygen set points on the behaviour of the treatment plant.



7 Operation and maintenance



Once built, the operation and maintenance of urban water systems are key to obtaining the best performance. At this stage, where online decision-making is required, a significant effort is made to increase the amount of information that can be extracted from the system. This increase in information means, simultaneously, the need for tools for processing, in order not only to apply this information to immediate management, but also to extract knowledge that can improve the operation of the system.

In our opinion, this new knowledge gained from experience in the operation of urban water systems should be complementary to that used in the design of the plants, and although there is sometimes a conceptual distance between those responsible for the areas of design and areas of operation, it seems clear that gradual integration of these two areas is desirable. At the same time, there will be greater integration in the operation of the elements that make up the urban water system, so that, in future, further integration will involve more complexity. This increased complexity, which has to result in more efficient operation, will require new tools, including environmental decision support systems which will become increasingly common.

In this context of gradual evolution to greater integration, this chapter presents four sections corresponding to the building of four EDSSs developed for four different situations. The first section, as an example of the integration of large volumes of data with expert knowledge, presents a EDSS developed for the operation of wastewater treatment plants that can use different configurations of the activated sludge system. The second section examines the specific case of treatment plants based on natural systems, widely used in small populations, which have distinctive features such as less instrumentation and the need for more qualitative information and expert knowledge.

The last two sections present two EDSSs developed more recently, at different stages of implementation, which correspond to higher levels of integration. The third section presents a proposal for the joint management of urban water systems considering the sewer systems, treatment plants and the receiving media, while the last section discusses a proposal for the integration of knowledge from different urban water systems.

7.1 Supervision, control, management and energy optimisation of wastewater treatment plants

Analysis of the problem

An urban wastewater treatment plant (WWTP) consists of a set of primary physical or chemical treatment operations, followed by secondary biological treatment aiming to remove organic matter, nutrients and suspended solids from the water to be treated. Like other environmental processes, WWTPs are complex systems in which interactions occur between physical, chemical and biological phenomena. For example, we have to consider aspects such as kinetics, catalysis, mass transfer and separation processes etc. The optimal management of this process is a complex task that involves the integration of different types of knowledge.

Some of the characteristics that define the complexity of the process are:

- **Intrinsic instability.** The composition and quantity of wastewater is dynamic, which causes changes in the already complex ecosystem responsible for the treatment, modifying most of the physical and chemical properties and the composition of the population of microorganisms involved.
- **Modelling difficulties.** Many of the processes taking place cannot be characterised by a deterministic model on its own. As indicated in its use for the design of systems, the models developed include a large number of parameters, which, for the real time management of the plant, should be identified continuously.
- **Large amount of data.** In recent years, new instrumentation has been developed, which has dramatically increased the amount of data to be processed, sometimes creating a volume that is difficult to process.
- **Uncertainty.** Despite the increased volume of data, they present uncer-

tainty (sensors problems) and imprecision (a very complex environment is being analysed). A large amount of qualitative knowledge is presented simultaneously and, in many cases, in an approximate and subjective way.

- **Heterogeneity and scale.** In the WWTP processes take place simultaneously. They present different timescales, from dissolved oxygen transfer that takes seconds, to the growth of microorganisms that takes days, including hydraulic residence time, which takes hours. All this makes the characterisation of easily identifiable parameters difficult.

Because of the complexity of managing the treatment process, even the most advanced numerical control algorithms have found significant limitations, especially when faced with situations that require qualitative and heuristic reasoning for their resolution. To describe these qualitative phenomena or

to evaluate the circumstances that may cause a change in the control strategy, we need some sort of linguistic representation based on the concepts and methods of human reasoning. This is the reason why, until now, human operators are the final stage in the plant control process. As has been explained throughout the text, in this context, environmental decision support systems may be useful tools as they integrate knowledge management tools with numerical techniques, allowing optimum use of all available information on the process. **This section presents the work carried out on the development of ATL, an EDSS designed for the supervision, management, control and energy optimisation of WWTP.**

Model selection

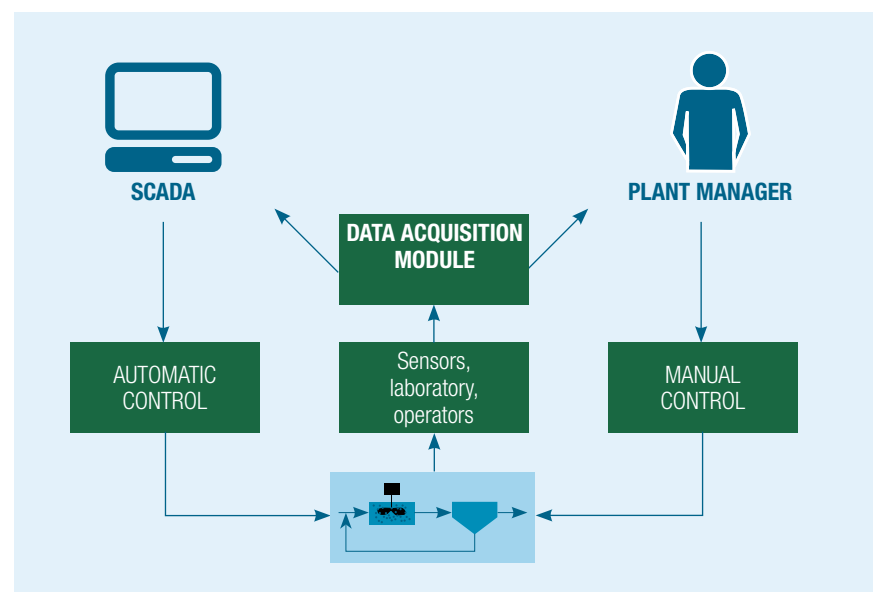
In the model selection phase, two types of tools were included: **mathematical models** (numerical and statistical) and **artificial intelligence models** (rule-based systems and case-based systems), both types of models are complemented with *fuzzy* logic.

The mathematical models use numerical expressions to approximate the behaviour of a system (**numerical models**) or characterise the numerical data available to estimate the future behaviour of a system (**statistical models**).

Among these artificial intelligence models, **rule-based systems** offer a set of advantages that improve the limitations of other techniques: they facilitate the integration of heuristic knowledge obtained from experts, including the ability to manage qualitative information. Knowledge is presented in an easily understandable and recognisable way by experts (rules); a well-validated system can provide adequate answers in the form of perfectly systematised plans for each problematic situation. As an additional feature, these systems enable the creation of a broad knowledge base that can be applied flexibly to any WWTP. Simultaneously, they have limitations relative to the difficulty of incorporating new knowledge once structured.

Case-based systems exploit the fact that the second time we try to solve a problem is easier than the first, because we remember the previous solution and repeat or modify it depending on the evaluation. The basic idea is to adapt solutions applied in the past to particular problems affecting the operation of the plant, and apply them to new problems that are similar, which can improve the outcome compared to other methods that start from scratch again. A case is defined as a set of knowledge representing an experience that provides a fundamental lesson about

▼ Figure 7.1.1.
Current most common diagram for the operation of WWTPs.



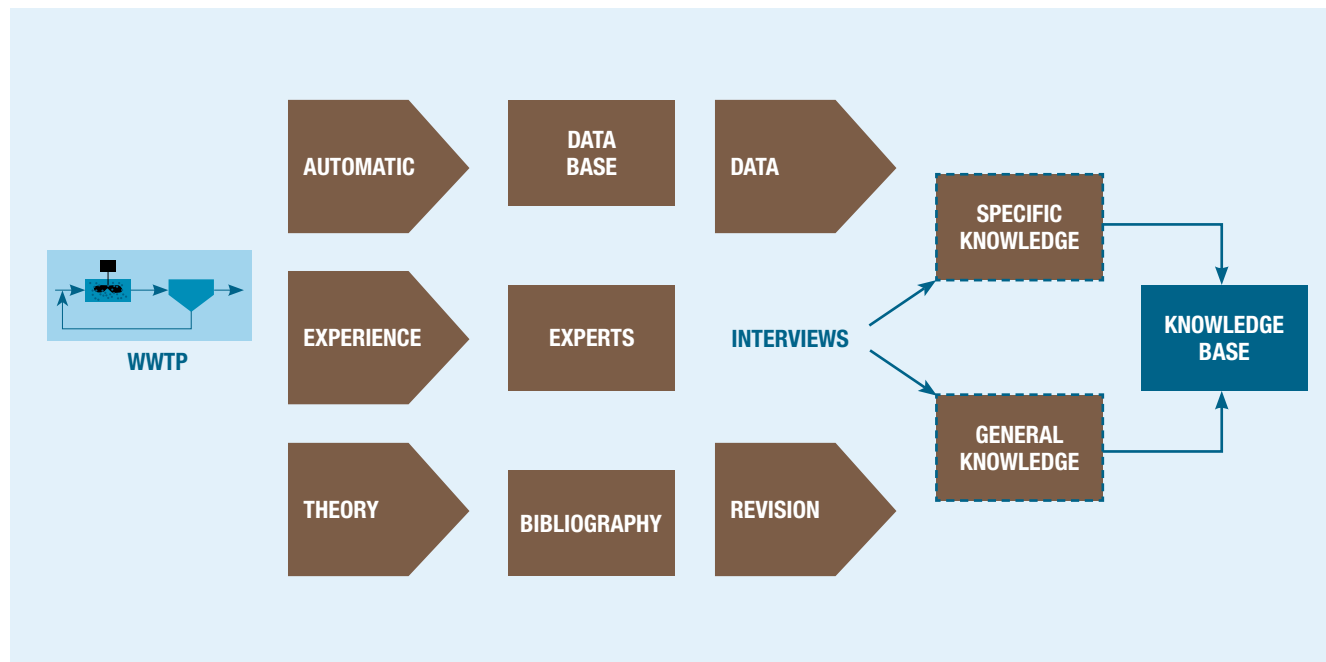


Figure 7.1.2.
Knowledge acquisition

Firstly, interviews were held with the WWTP managers. This method, which enables qualitative knowledge acquisition, presented certain limitations in terms of the difficulty of the experts in systematically explaining the reasoning used, as your knowledge increases. This knowledge is mainly in qualitative form. Secondly, the existing bibliography was used for information on the problems with operating these WWTP. In this case, the limitation relates to the information obtained being generic and not specific to the plant whose operation needs to be improved. The *know-how* obtained through these channels was supplemented by the knowledge extracted from the automatic processing of data stored in the historical databases. These three methodologies enabled the design of a comprehensive and robust knowledge base.

how to achieve the desired objective (in this case, the proper functioning of the plant).

A case-based system requires a library of cases so that it can cover the broadest spectrum of potential problems. These cases are indexed in the memory, so that they can be retrieved when the stored experience can contribute to improve the performance of the process. The library includes successful and failing experiences since we can learn from both. It is advisable to start the library with a set of situations that may be considered generic, obtained from the literature or people with experience in the process. Thus, the case-based system can propose solutions from the beginning to problems that are similar to those included in the initial seed.

The initial seed could be obtained from the historical database of the process, covering a sufficiently wide range of problems facing the WWTP, in both common and sporadic situations. The

library is updated with new cases as knowledge of the process progresses; so this type of system is evolving, improving its ability to cope with new cases. Given the significant amount of information processed, a procedure exists to select which ones are incorporated, from those that provide more relevant information.

The EDSS developed can be implemented in the WWTP based on activated sludge technology, regardless of the aeration system and configuration.



OPERATION

The different tasks performed by the environmental decision support system are carried out in cycles: input data, diagnosis and decision support.

Input data

The main task at this level is the updating of the databases. The acquisition of the latter takes place *on-line* through SCADA on those variables that have sensors and related equipment, and *off-line* for the chemical and biological indicators analysed in the lab, and for the microscopic observations and other qualitative notes. This level of operation implements signal filtering methods as a step prior to storing the information in the corresponding evolutionary databases, to make it available to the control, monitoring and optimisation modules.

Diagnosis

Once the information is updated, it is sent to the control module, where mathematical models perform a first diagnosis of the scenario's main processes (aeration system, internal and external recirculation of sludge, sludge residence time, etc). This review is supervised and supplemented by models based on knowledge of the monitoring and optimisation modules. Therefore, the EDSS not only detects the possibility or existence of a problem, but also identifies the cause, suggests solutions based on modifications of previous performances to match the peculiarities of the new situation while optimising the process in energy terms, always under the final premise of ensuring the final water quality.

Results

The conclusions drawn in the diagnosis phase are transmitted to the decision support module. The end result of this process is communicated to the person responsible for the operation through the corresponding interface. In designing it, end users were actively involved, always striving to make the system as easy as possible for those who use it.

Figure 7.1.4.

The EDSS suggests an action plan resulting from the supervision and prediction tasks, integrating the results of mathematical models and experts' recommendations made by the rule-based system, and the experience retrieved by the case-based system. This action plan consists of a set of actions to be implemented that are displayed on screen, but they may be transferred directly to the process through communication from the EDSS with the WWTP's SCADA.

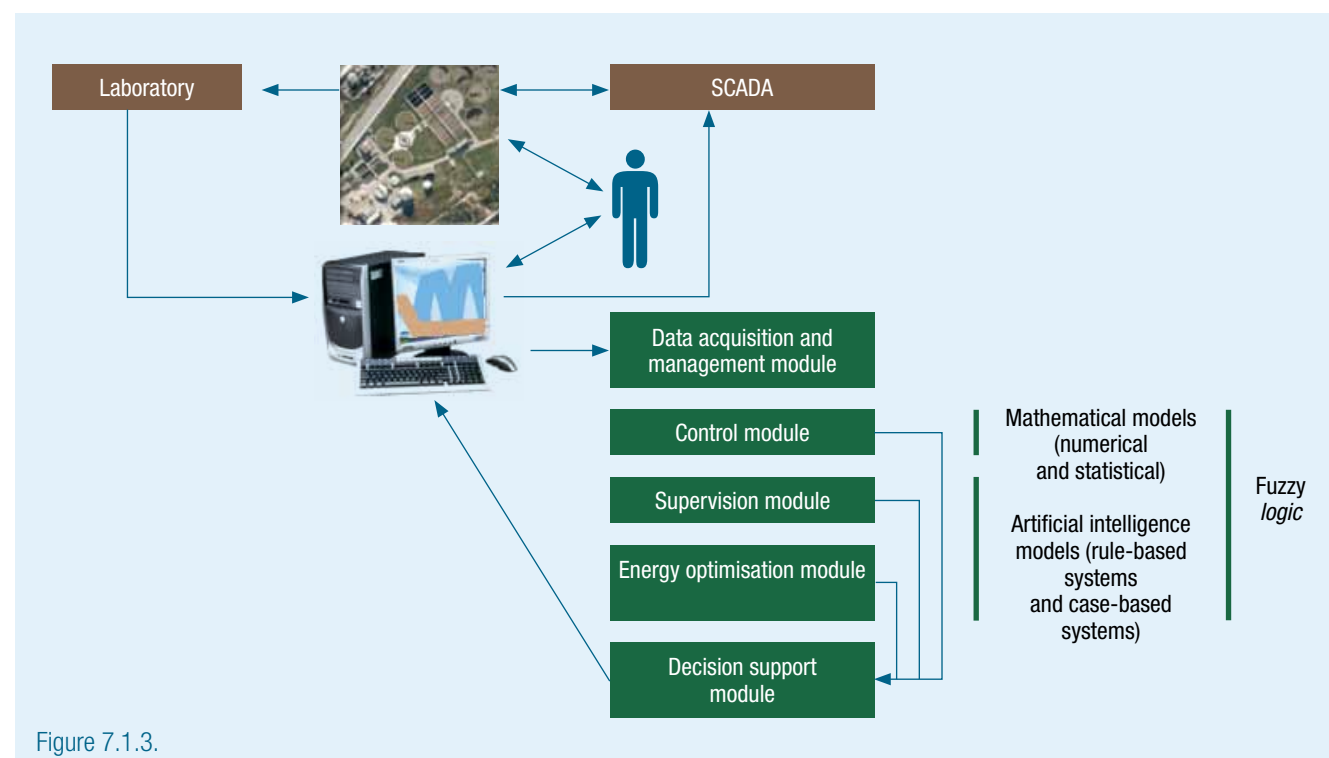
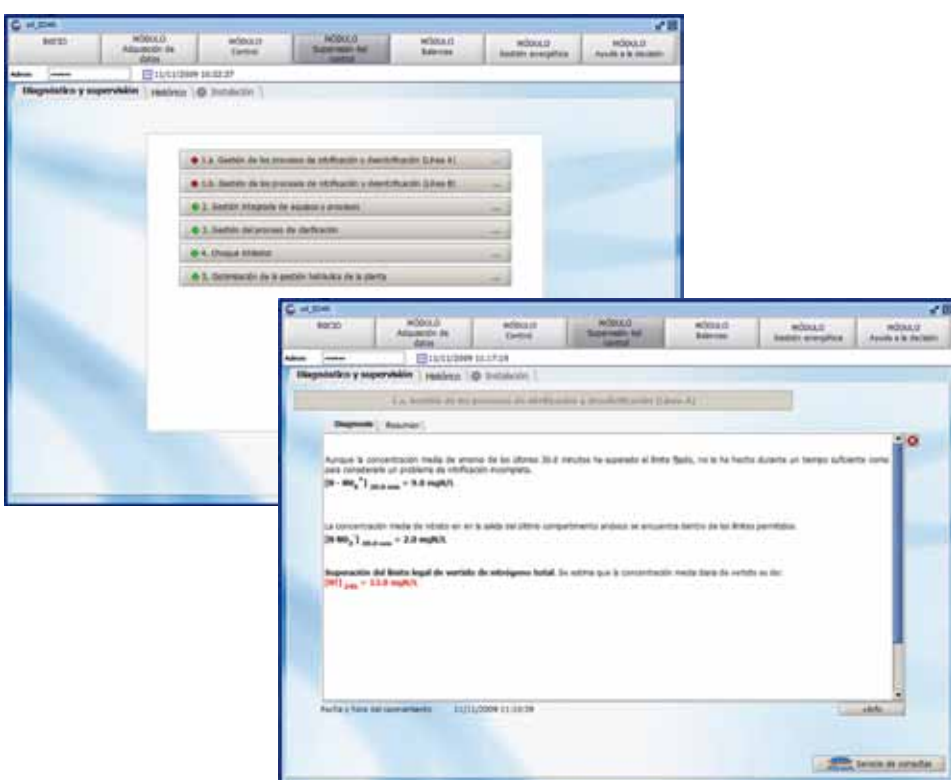


Figure 7.1.3.

Figure 7.1.5.

The results of the implementation of these actions (or modifications considered appropriate by the plant manager) are evaluated later, to learn both the positive and negative aspects. This evaluation is performed by whoever is responsible for the plant, which closes the case-based system cycle, including, if necessary, a new case to incorporate the new knowledge.



Fail so as to succeed

The decision support system (EDSS) for the management of a wastewater treatment plant (WWTP) was the first we began to develop. At that time, few people knew about EDSSs and no-one had much experience with their application in this field. This involved a double-learning process. Firstly, learning about the proper construction of the EDSS, acquiring knowledge, analysing it, deploying it to a set of programmes that were built as we were learning. However, above all, learning involved discovering what a EDSS was and what possibilities (and limitations!) it could have. It was a long process lasting many years, during which, building on past experience, we were able to develop other DSSs. But our determination was that it was to be useful and could be applied. Therefore, from the beginning, we interacted with other research groups to learn the theory, but above all we interacted with businesses and governments to learn the practice relative to the operation of WWTPs. And only when we had several theses, research projects and several cooperation agreements, we realised that to see our EDSS installed and running in several facilities we had to create a so-called spin-off company so that we could put it on the market and sell it. Thus, the authors of this book took all the necessary steps, we presented all the requests that were needed and got support from relevant agencies responsible for the field, recognising that we had a good product ready to be transferred, and there was an emerging market for it, since there was nothing like it available. So Sanejament Intel·ligent S.L. was born. (SISLtech) on the market, with its ATL product ATL (ATL= 'water', in the language of the Aztecs, as tribute to the Mexican heritage of one of the members of our team.

However, although it was clear, and we knew we needed a significant degree of involvement, and this was our will, we were unable to get the product to succeed, we were not able to install our environmental decision support system in real plants, beyond some implementation facilitated by personal contacts. So the company languished for several years and despite our efforts, our potential customers repeated that the idea was interesting but they did not want to buy the product. Finally, we realised that we had fallen into a first-year handbook type error, one that from the very beginning we had been anxious to avoid. Unless you are a large multinational company that is able to convince of the need for any gadget in the world of urban water systems, you have to listen to the customer. Do not try to sell something we think is interesting, we have to develop what the customer really needs. And when we were about to throw in the towel, the entity with which we initially started the project, who had accompanied us from the start and was able to verify the virtues of the development in its own plants, made an increase in capital and took over management of the company. From there on in, with the responsibility assumed by people in the field of urban water systems, those knowing the real and daily problems, the company became a success. Keeping the product's original idea, it was redesigned it from a user's perspective, identified their real needs, and not those of a group of academics, with the best intentions, we believe. The number of implementations is spectacular and so far, more than forty WWTPs treating more than a million cubic metres of wastewater everyday are using an updated and adapted version of that original EDSS, and this is growing every day and all over the world. Perhaps for a company to work, it must be the same as eggs and bacon. The level of implication needed is that of the pig and not that of the hen...

7.2 Operation and maintenance of natural treatment systems

Natural systems are a good alternative for the treatment of wastewater, provided that they are well designed and properly maintained

Analysis of the problem

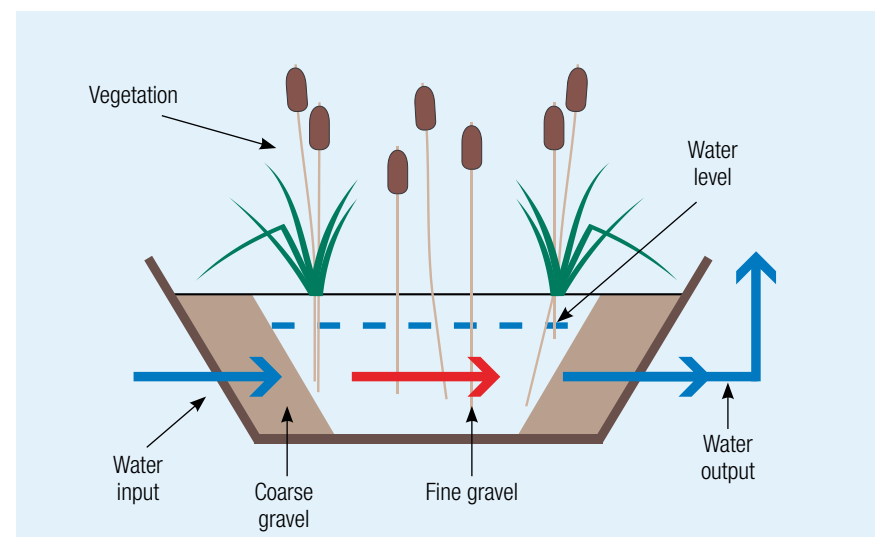
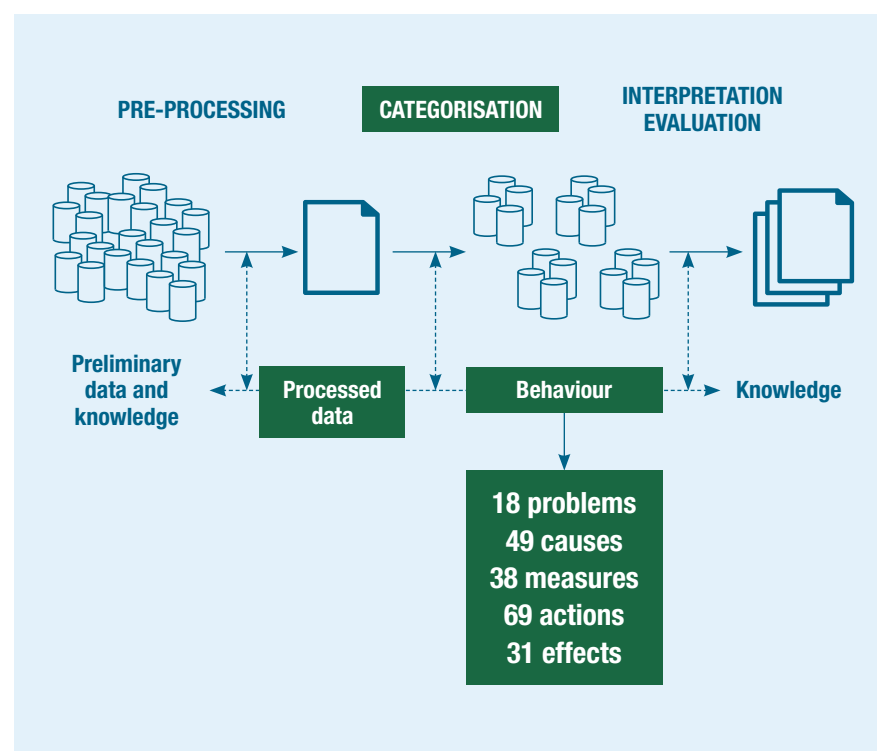
Operation of natural systems, usually used for small communities treatment (less than 2,000 inhabitants), have some special features. Given that they can provide good performance with reduced building costs and low power consumption, they are often among the most adequate treatment systems. However, these properties will result provided the design and building are appropriate and there is proper maintenance of the plants. Experience shows that to achieve the best performance, it is necessary to use the most appropriate operation and maintenance procedures, although they may differ from one system to another, by design, for the receiving media, or the environment in which they must work. This means that it seems necessary to have a system that helps in defining the operation and maintenance protocols for such small plants, so as to guide and assist us in monitoring systems, according to the particularities of each plant.

It is for this reason that the Catalan Water Agency (ACA) required an environmental decision-support system for constructed wetland systems (CW), since they were among the most recommended treatment systems in different basins by the EDSS previously used by the agency to select the best alternative for small communities.

Constructed wetlands are artificial wastewater treatment systems consisting of shallow (usually less than one meter deep) ponds or channels which have been planted with aquatic plants, and which rely upon natural microbial, biological, physical and chemical processes to treat wastewater. They typically have impervious clay or synthetic liners, and engineered structures to control the flow

direction, liquid detection and water level. Depending of the type system (free surface, vertical subsurface or horizontal subsurface) they may or may not contain an inert porous media such as rock, gravel or sand.

The EDSS aims to identify any problem that may occur in the operation of a CW, and define a protocol to prevent, detect and correct these problems. This protocol should propose a monitoring programme and a set of preventive and corrective actions, according to the characteristics of each CW where the EDSS will be applied.



▲ **Figure 7.2.2.** The knowledge was acquired through interviews with experts, documentation, experience and analysis of the results obtained from the different CWs in operation, from which information was obtained. This data and knowledge was processed according to the diagram shown in the figure, proceeding with the categorisation, which would systemise the behaviour of the CWs, grouping the different problems, causes, measures and actions to be carried out.

◀ **Figure 7.2.1.** Diagram of a subsurface flow constructed wetland

Acquisition and analysis of data and knowledge

The knowledge acquired falls into four knowledge bases:

- Environment knowledge base. Includes information on climatic, environmental and wastewater characteristics of small communities where the EDSS can be applied. It characterises each small community and the discharge point of the treated effluent.
- Knowledge base for design features. Includes the design of characteristics that may vary between CWs: hydrology (free surface, vertical subsurface or horizontal subsurface), cultivated vegetation (plant type, renewal procedure, density and planting periods), configuration and structures (characteristics of porous media and its distribution, number and arrangement of wetlands in series or in parallel, shape and depth, type of waterproofing, synthetic liners or compacted, the input and output structures, the water distribution system, dams), other wastewater treatment units (the wetland could be used after different primary treatments or as a tertiary treatment following an activated sludge system or an intermittent sand filter).
- Knowledge base for problems. Includes information on potential failures relative to the CWs. This knowledge allows the identification of each problematic situation according to the following aspects: methods (how a CW may fail when the expected efficiency is not achieved), effects (the consequences of a problem that can cause an environmental impact), causes (things, events or actions that cause a problem), monitoring (set of measurements that provide information about how a CW is working and the identification of the onset of

a problem), preventative actions (actions taken to prevent the emergence of problems) and corrective actions (actions taken to solve problems once they have appeared).

- Knowledge base for the control and frequencies of actions. This latter knowledge base includes data and information that gives frequencies to controls and to actions that are defined. Certain controls and actions must be undertaken to prevent, detect or correct problems. Once the problem occurs, the intensity of the consequences may vary, depending on the sensitivity of the receiving media. Therefore, taking this sensitivity into account as well as the dilution capacity in the receiving media, the presence of ponds or aquifers, po-

tential uses of water reuse and the area's environmental sensitivity.

Selection and implementation of the model

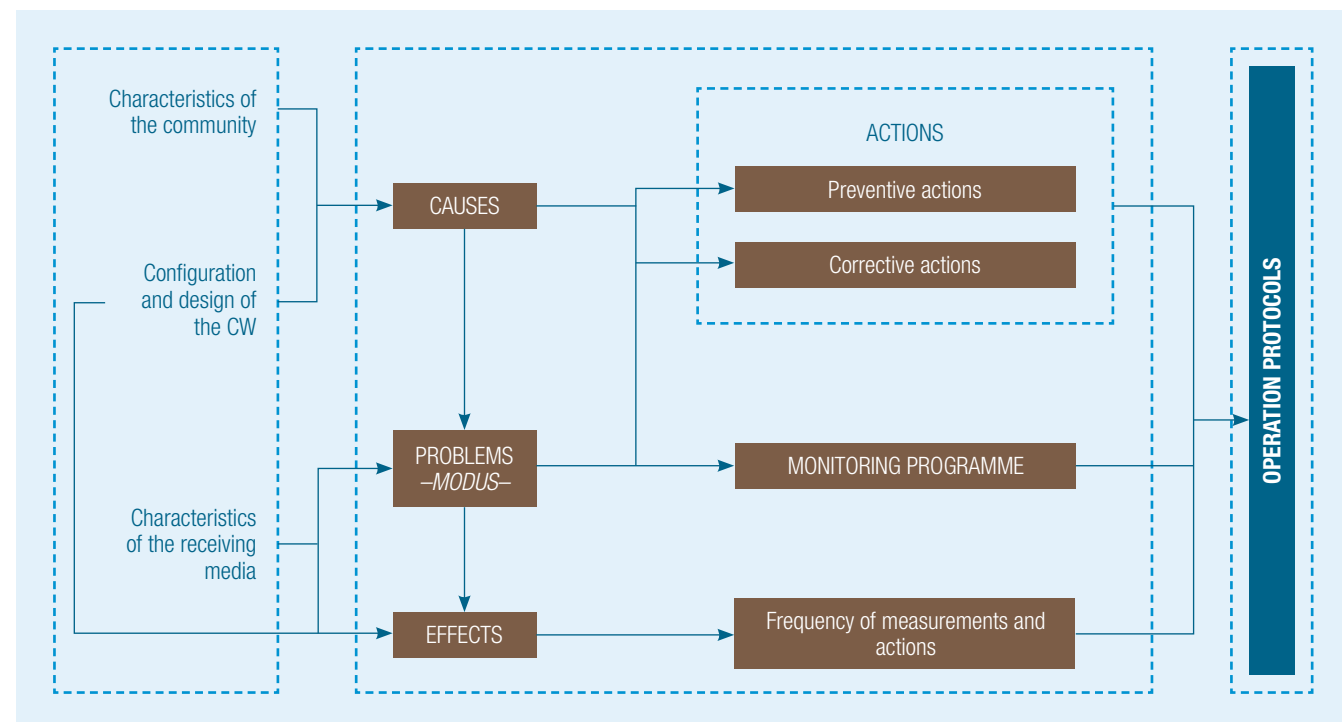
Among the various statistical models, numerical models and artificial intelligence tools available, we selected the rule-based system (RBS), as it was considered to provide the best representation of the knowledge acquired to define the monitoring and maintenance protocol. RBS is a model able to simulate many human processes in decision-making relative to a specific problem. This is formed of two main independent modules: the

knowledge base and the inference engine. Whilst the first contains general knowledge on the process, generally coded by heuristic rules, the inference engine is the software that controls the RBS's reasoning operations. The application of the operation and maintenance protocols provided by the EDSS in real plants may also be a future source of information and knowledge.



Figure 7.2.3.

Diagram of the relationship between aspects that shape and define the problems that can appear in a CW, and that are considered in the appropriate knowledge base.



OPERATION

The EDSS follows the operational diagram proposed by the authors, setting out, in this case, the stages relative to input data, diagnosis and decision support with the definition of plans and actions.

Input data

For each CW, information corresponding to the following must be entered via a series of screens:

- The characteristics of the community in question, with aspects such as number of inhabitants, seasonal inhabitants, information on industrial wastewater, etc..

- The receiving media properties, especially those relating to its volume of flow or seasonality, sensitivity, type of protection, the presence of aquifers, etc..
- The features and design of the constructed wetland, taking into account aspects such as height above sea level, distance from the population, distance to the receiving media, plot size, the plot's enclosure system, water and energy sources, year built, pre-treatment types, dimensions, slopes, water distribution and collection systems, water level control, waterproofing, plant type, plantation type and year and density etc..

Diagnosis

Knowledge about the design features and characteristics of the population is divided into two matrices that identify the factors that may trigger potential shortfalls in any CW and provide a preliminary list of potential problems. Knowledge about potential failures is structured in a matrix that includes information related to failure modes, possible effects on the process and on the receiving media, the main causes, control mechanisms, and actions to be taken to prevent possible failures or to correct malfunctions. These three matrices (design characteristics, population characteristics and potential failures) are combined and, from this combination, a set of rules is defined. The collection of these rules provides a list of possible failures and prevention, detection and correction means for these anomalies.

Finally, knowledge of the properties of the receiving environment, included in the knowledge base on controls and frequency of actions, is organised and documented in the form of decision trees. These decision trees are converted into rules that constitute the tree from the root to the leaves. These rules classify the sensitivity of the receiving media, and assign frequencies to the actions to be taken and to the controls considered in monitoring the various protocols.

Decision support

The information provided by the EDSS are the protocols that propose a set of preventive measures, procedures for corrective action in case of problems and a monitoring program for the CW. It also defines the frequency with which these procedures and controls should be implemented. In addition, these guidelines may include the failure modes and their harmful effects, whilst taking the characteristics of each type of CW into account. The EDSS provides this information in two types of documents:

- (1) the monitoring notebook,
- (2) the operation manual.

Monitoring notebook

The monitoring notebook is a document that contains various tables that include the controls required to assess a CW's state of operation and the preventive actions proposed to avoid problems occurring. These tables also indicate the frequencies with which these processes, controls and actions should be carried out. The monitoring notebook must be filled in by the person in charge when these procedures and controls take place, and also when problems occur and corrective actions are carried out.

Operation manual

The operation manual supplied by the EDSS is a document that defines the failure modes, their effects, causes and the control programme and procedures for each of the potential failures identified for a CW. In the same way as the monitoring notebook, all the information included in the manual is defined taking the characteristics of each CW into account and if some of them change the manual provided by the EDSS is changed. For example, if the sensitivity of the receiving media is high, although the proposed control for detecting the growth of weeds on the surface is the

◀ Figure 7.2.4.
Input screen diagrams.

same, the frequency proposed is greater. Another example would be if the CW is designed with a surface flow, but has the problem of high presence of insects in areas of standing water, the actions taken would seek to reduce the level of water and its distribution to avoid ponds forming.

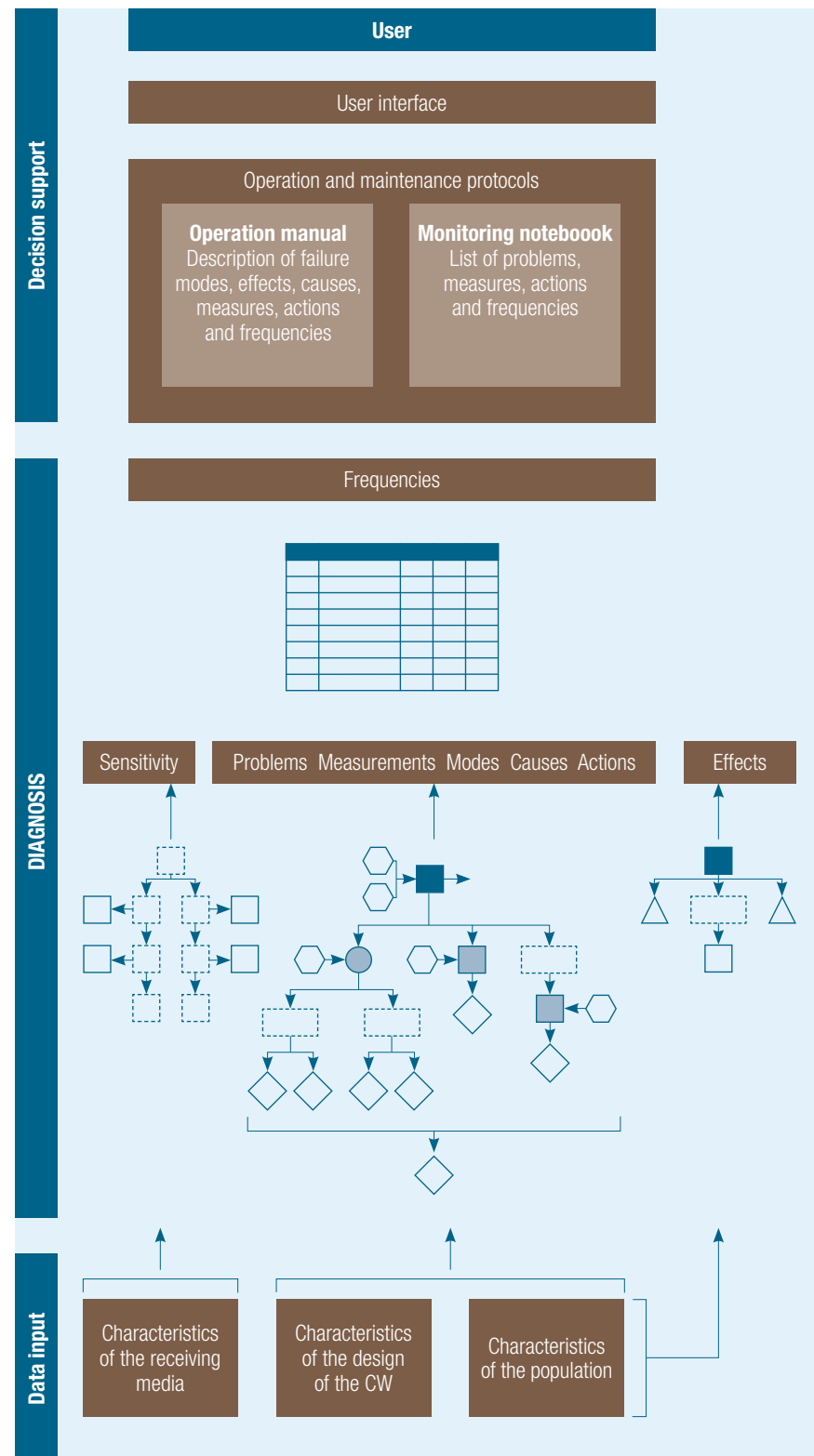


Figure 7.2.5.

For the definition of the operation and maintenance protocols for constructed wetlands for small communities, the characteristics of the location, the design of the plant and the state of the receiving media should be taken into account. The integration of these three dimensions in the definition of the CWs' maintenance and operation protocol leads to an indicator scenario that considers sustainability, technical, environmental and social aspects. To address the complexity of this problem, the EDSS can help management, engineers and plant operators to establish the most appropriate control and maintenance schedule for each CW in particular.

7.3 Integrated management of the urban water system and the receiving environment

Analysis of the problem

In the urban wastewater cycle, a common practice is that the management of wastewater collection and treatment plants is carried out by different administrative entities. Entities different from those that manage the receiving media. This implies that there is a tradition of differentiated management between the three elements, making the benefits that would allow integrated management difficult.

The reason that this integrated management has not been generalised is not just administrative. The additional technical difficulties to be resolved must be added to the benefits associated with the integrated management. These difficulties are directly related to the associated increase in complexity. Among them we highlight the need to have systems for monitoring and reporting on the three elements (sewer systems, treatment plants and receiving media) to identify their status, the need for efficient simulation tools that can quickly evalu-

ate the effects of making certain decisions, and above all, the need for decision support tools with agreed criteria for optimising the operation of the whole system, knowing that the characteristics of each element are different and their problems are as well. This is a clear example in which the consideration of the new integrated system has a response that goes beyond the operation of each of the isolated subsystems, and therefore its overall optimisation does not necessarily coincide with the sum of the optimisation of each of the elements.

This paradigm shift to incorporate the complexity is apparent in the evolution of the European directives on water. Whilst European Directive 91/271 sets out fixed limits for the quality of water leaving the treatment systems without considering the receiving media's characteristics, the Water Framework Directive from 2000 makes special reference to the impact on the receiving media, promoting the resource's integrated management.

In this context, **the existence of an Administration such as the Consorci**

per a la Defensa de la Conca del riu Besòs, with the aim of optimising the management of its infrastructure, and the previous experience of having developed an EDSS for the operation of treatment facilities, promoted the development of an EDSS for the integrated management of the three elements (sewer systems, treatment plants and receiving media).

Knowledge acquisition and analysis

This is, in this case, obtaining knowledge for a new operational paradigm. For this purpose, the knowledge acquisition phase included an initial use of scenarios to obtain information through simulation, which would be the response of the system to modify some of the starting conditions. We identified two possibilities for defining the characteristics of the scenarios (we choose the second option):

- using automatic scenario generation in a systematic way, building the area defined by the intervals of the relevant variables,
- using experts to identify which variables -and the values of the same- may be more relevant, from the experience acquired.

One of the requirements so that the scenario technique proposed may be useful is the need for sufficiently reliable mathematical models. As indicated in the section on models, so that they can fulfil their objective, this requires equations

describing the system, and experimental data for the calibration.

- In terms of the model's equations, they can be found in the software programmes that encode commonly accepted equations for each of the elements, but it is noteworthy that most of the simulation programs refer to one of the subsystems. However, the number of those that can describe the integrated system is smaller, showing, once again, the need for efforts towards integration.
- Obtaining information and knowledge to build, calibrate and use the models required the integration of qualitative and quantitative knowledge, just as in the definition of the scenarios.

Knowledge integration

The acquired knowledge has been encoded in the form of decision trees that are structured according to the problematic situations detected in the scenario analysis. Thus, we have identified four areas corresponding to the management of the system in dry weather, in rainy conditions, when faced by pollution episodes and the management of derivations between systems.

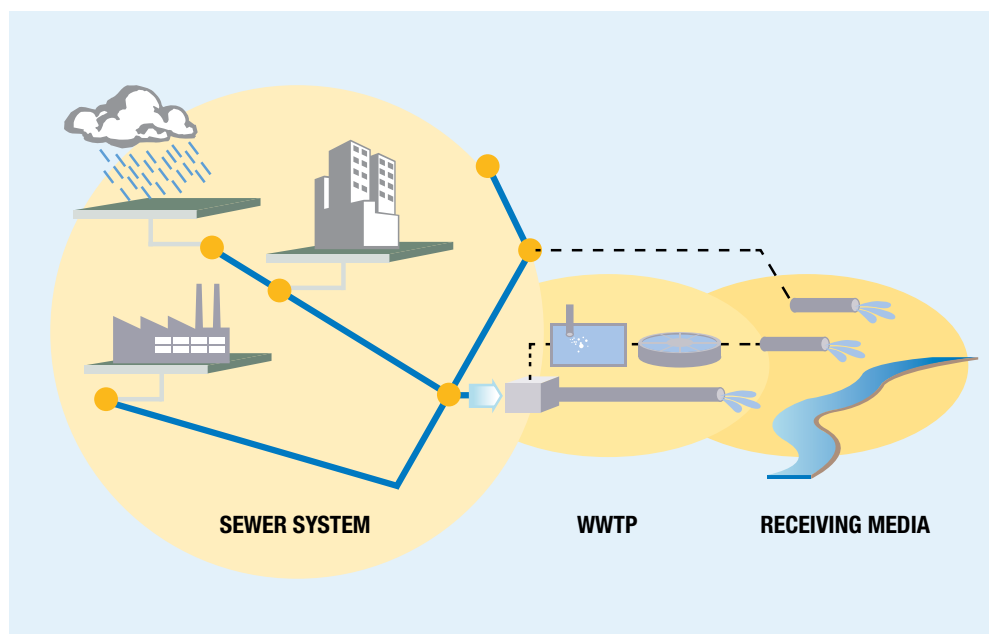


Figure 7.3.1.

At this level of complexity, the idea is to replace the individual management of sewer systems, treatment plants (WWTP) and receiving media with integrated management that allows global optimisation of the system, from both an operational and infrastructure planning point of view.

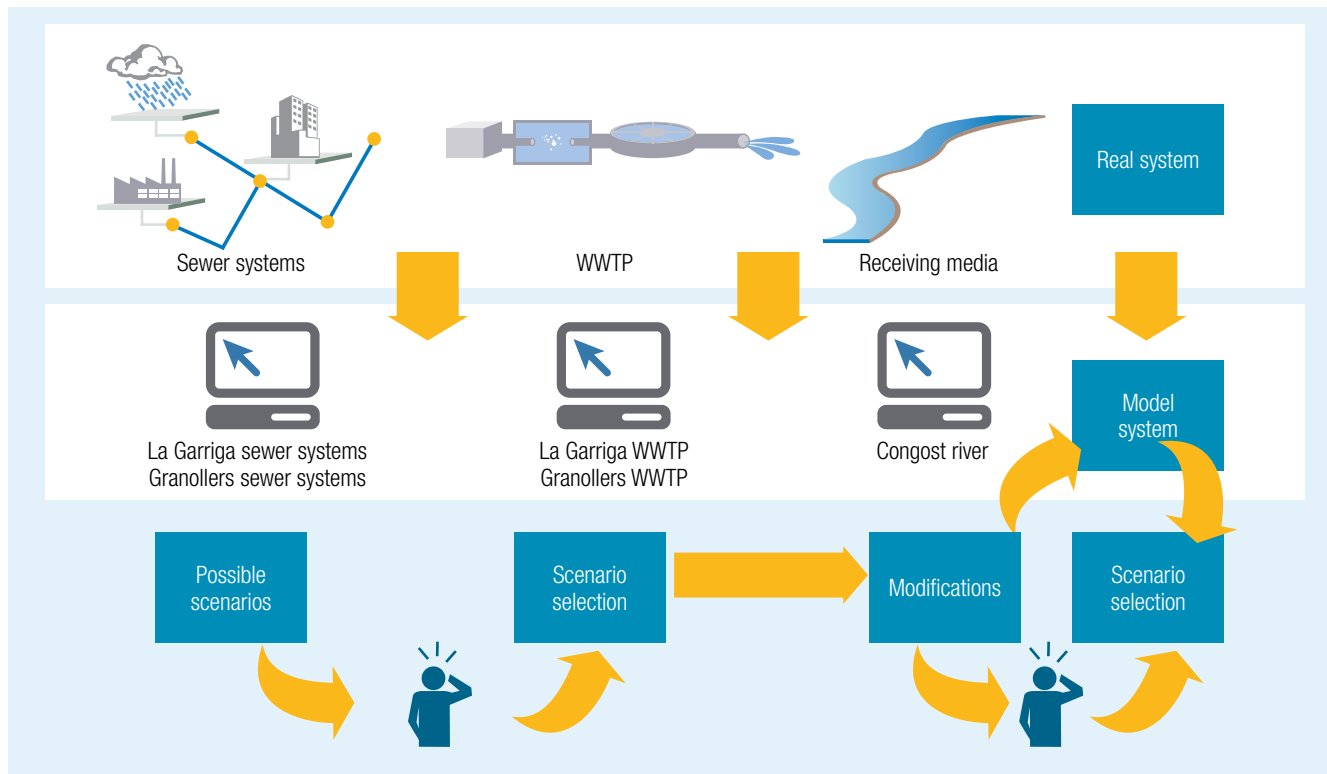


Figure 7.3.2.

One way of obtaining knowledge is the use of simulators to evaluate the effect of different operational alternatives or the modification of existing infrastructures. In this case, the scheme used is presented to coordinate numerical quantitative work - which enables simulations-, with the experience of those responsible for treatment systems to identify the relevant variables to be evaluated in the scenarios.

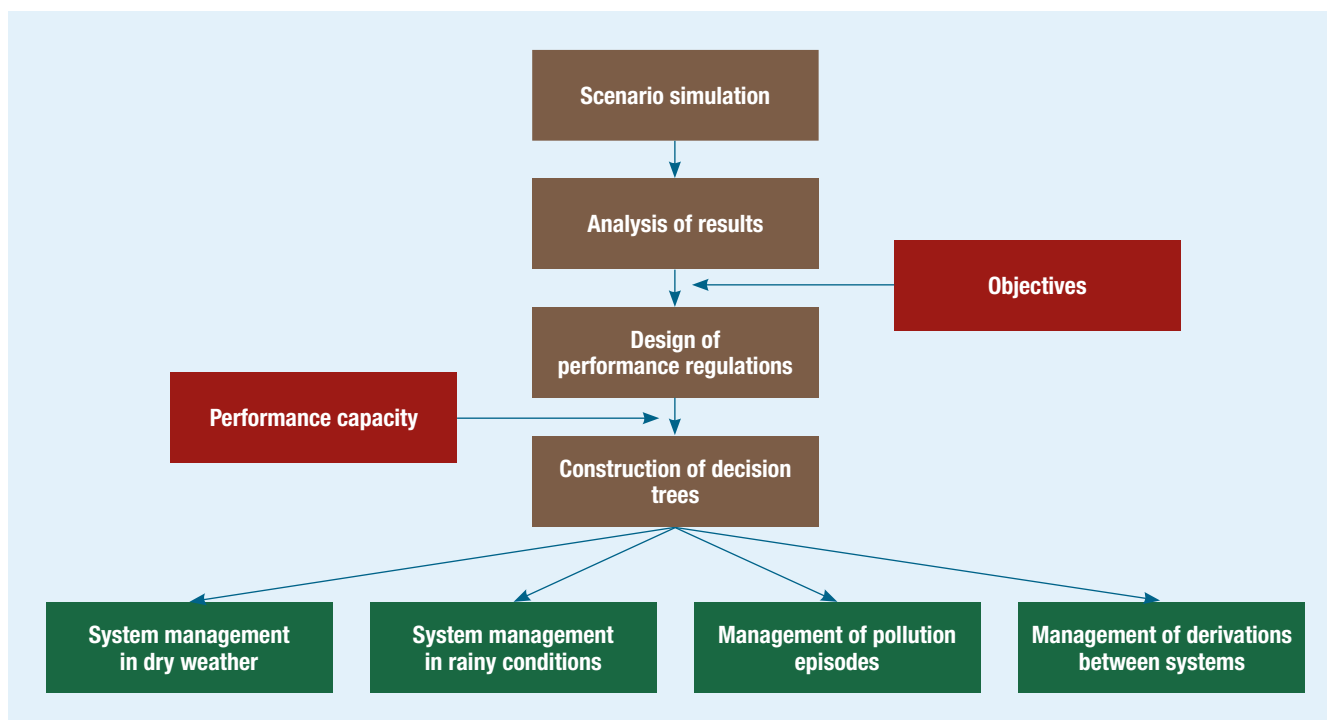


Figure 7.3.3.

Set of scenarios, defined together with experts, to assess the location and optimal sizing of the collection tanks to be incorporated into the existing infrastructure, from the impact on the receiving media.

OPERATION

In the EDSS for the integrated management of urban wastewater systems for the Consorci per a la Defensa de la Conca del riu Besòs, two types of objectives were established:

- On the one hand, its use as a planning tool to improve existing infrastructure and define the location and design of retention tanks. In this case, the EDSS is used *off-line*, assessing different scenarios.
- On the other hand, *on-line* use to improve the efficiency of existing infrastructures in normal working conditions and to prevent, identify and respond to critical incidents, especially those related to heavy rain and/or industrial discharges.

Input data

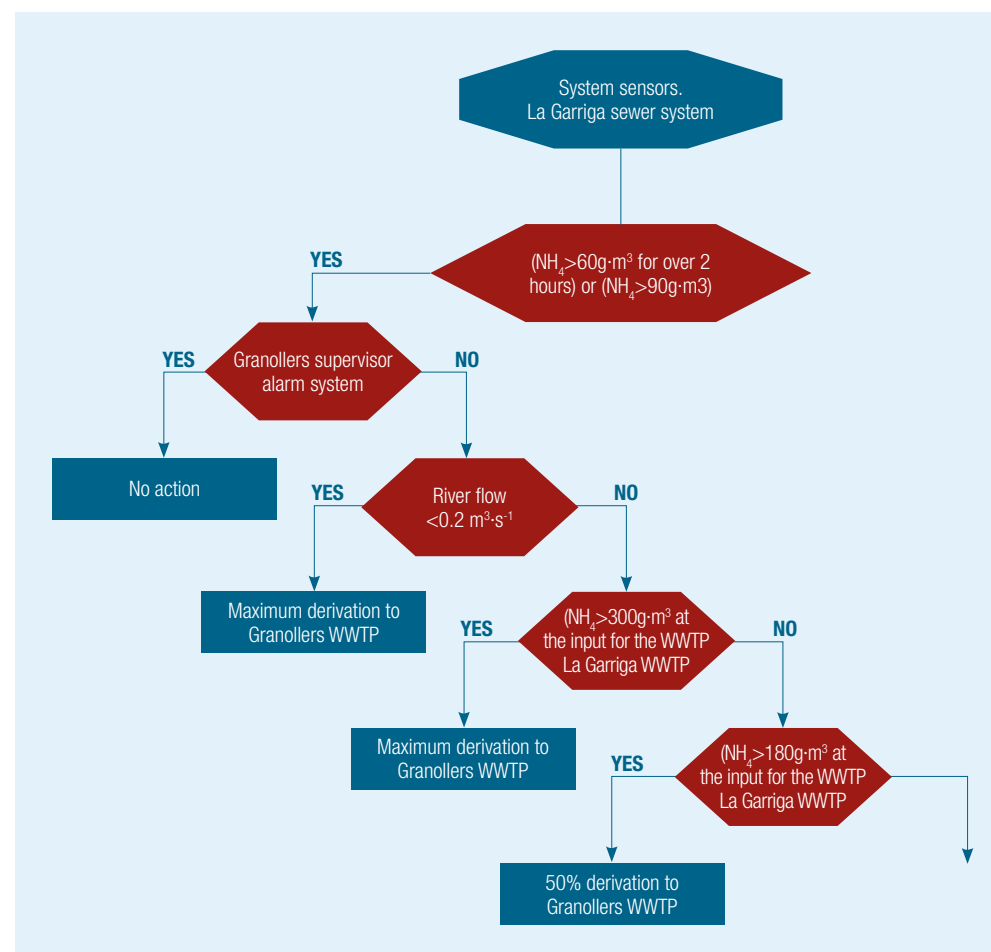
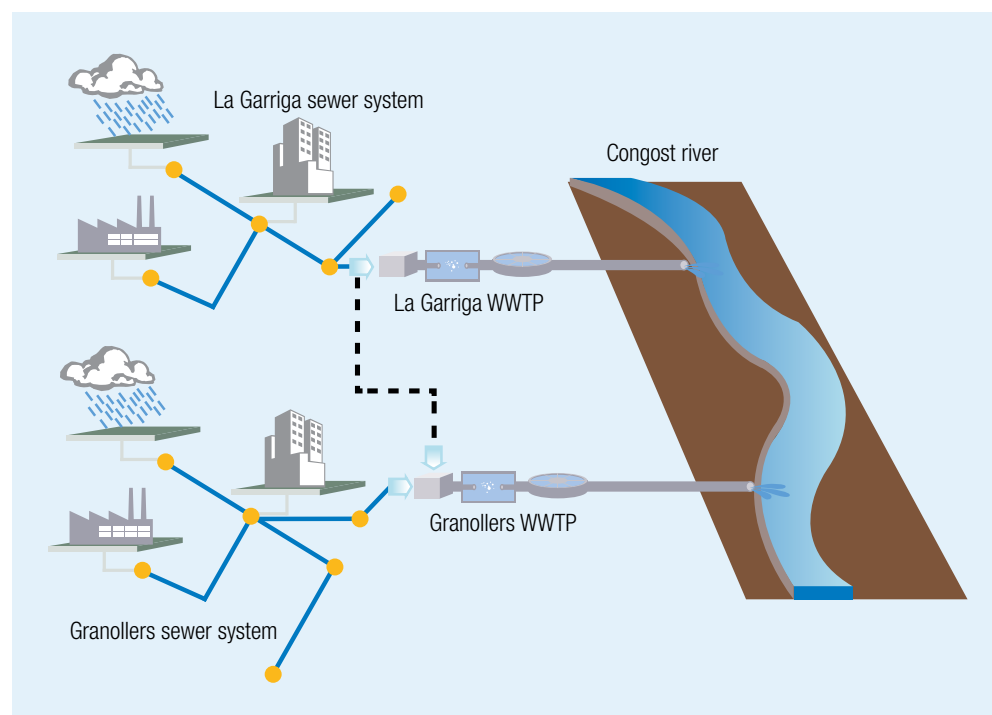
The DSS operates using input data corresponding to the values of rainfall, flows, concentrations and the known state of sewer systems, treatment plants and receiving media.

Diagnosis

From this information, and according to the decision trees built into the system, policy proposals are provided regarding how to manage the retention tanks available, the treatment plants and the derivations. It should be noted that, in this case, knowledge is already encoded in the form of rules, so no use is made of simulators when working *on-line*. This is because the time required for the simulation of complex models to describe the

entire drainage system is considered too high to give quick answers. We believe that this will vary as simplified models come into existence that are sufficient-

ly reliable, or new models or calculation methods can provide acceptable response times.



▲ Figure 7.3.5. Branch of the decision tree relative to derivation control between systems. It is noteworthy that the operation of the decision tree takes information about what is happening in the sewer systems, treatment plants and the receiving media into account. It is based on integrated information from the three elements that the system provides a proposal, always subject to the characteristics of the existing infrastructure.

◀ Figure 7.3.4. Diagram of the urban water systems studied in this EDSS. This specific case took into account the existence of an interconnection between the two treatment systems, which introduces a new action possibility, which allows a flow to be derived from one system to another.

Results

In our opinion, this EDSS is a clear example of a system that will evolve over time and will adapt to the new possibilities that the calculation and knowledge management tools will provide. In this sense, it is designed to incorporate these new capabilities, but without forgetting that "the best is the enemy of good" and that, whilst its use is recommended, it is not perfect. There are two reasons for this:

- Because the analysis of its performance will be the best guide for its improvement.
- Because it already offers improvements relative to non-use of the system, as shown in the figure, which plots the comparison of the value of ammonia nitrogen in the receiving media as a result of using the EDSS for the use of the interconnection between the two systems proposing a flow value to be interconnected.

▼
Figure 7.3.6.
Comparison of ammonia profiles along the river.



Integrated management and research: good travel companions

Josep Arraez. Gerente del Consorci per a la Defensa de la Conca del riu Besòs

For several years, the river Besòs has been considered as one of the most polluted in Europe. In 1988, the seriousness of the situation led to the municipalities constituting a supramunicipality, the Consorci per a la Defensa de la Conca del riu Besòs (CDCRB) in order to carry out all efforts, initiatives and projects that could be solutions to the basin's pollution problems and the use of its waters. From the beginning it was postulated that close collaboration with universities and research centres was certainly one way to get around the situation and achieve the desired level of water quality. This collaboration was to allow the joint development of tools that will optimise the limited infrastructure to provide good service to our customer, the river. Although I have to admit that the road has not been easy, since there are differences relative to objectives and dynamics, the truth is that the objectives achieved over the years have paid off. Currently, the daily management of our wastewater systems usually uses environmental decision support systems developed jointly with the University, with such efficacy that it even created a spin-off successfully selling this type of system. I would like to highlight an aspect that has pleasantly surprised me throughout these years; this is that researchers have not only obtained answers to many of our questions, but they have also forced us towards new questions that we ourselves would not have asked. Ah! The river is currently in excellent ecological condition!



7.4 Intelligent information management

Analysis of the problem

The first level of complexity in the management of urban water systems is the operation of their individual elements, and the second is the interaction of the three elements (sewer system, treatment plant, receiving media). We believe that a third level is set when dealing with knowledge management for an entire river basin or a set of basins corresponding to the water authority that manages them. Somehow, closing the cycle that began with the first design level, while at this level, systems have to satisfy the society that funds them. While, conceptually, one might think that this raises the same level of complexity in the overall operation of all systems, we do not believe this, because usually there is no interaction with the same type of agents, or the degree of uncertainty is so high, or the risk is so great. This occurs with an increased volume of information, which, if it is properly processed and generates knowledge that can be reused, you can reinvest in the selection of alternative levels (using the information obtained in the operation of facilities to avoid making the same mistakes that may occur at first when your level of knowledge is lower) or in the specific design (to improve the values of some parameters from the integration of information from a range of infrastructures that can process equivalent situations in the same area).

In this context, this section presents the bases and the conceptual design of a EDSS commissioned by the department for the operation of urban water systems at the Catalan Water Agency (ACA), and which proposed three levels of results:

- Intelligently storing and retrieving available documentary information from reports established by the same ACA or third parties. If the user needs to find information on a specific topic, they can find the related references.
- Supervising the urban water systems. Evaluating the type of performance

from the information obtained on their operation. If the operation was not within normal parameters, the problem may be operational and/or maintenance-related, in which case solutions on the market would be sought - or it may be a design problem; in which case the EDSS should show the range of alternatives. If the WWTP is working correctly, *benchmarking* must be carried out to look into the possibility of improving efficiency and the existence of optimisation possibilities.

Serves as an environmental decision support system to define the management strategy of urban water systems, incorporating aspects of service quality, problems associated with the technologies, costs and impacts.

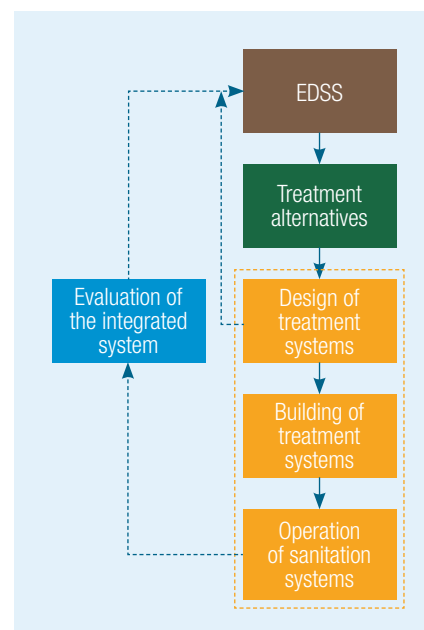


Figure 7.4.2.

The main four aspects to be taken into account for the good operational management of urban water systems can be summarised as follows: (1) The quality of service set by the limits imposed by law (including analysis and solutions to problems relative to water quality, quality variations, seasonality, emerging pollutants and quality improvement limits etc.), (2) the economic cost of operating the service (with cost reduction problems, maintenance, personnel, energy and depreciation, among others), (3) the environmental impact (the impact of the water vector on the energy vector or solid waste, life cycle analysis for the infrastructure, possible energy independence) and finally (4) problems associated with different technologies (causes of system malfunctions, remedies, recommendations, reliability of the different technologies). The set of all these knowledge areas provides responses to questions of a strategic nature, such as the approach to the future of this service (management model, economic and funding, better technologies, networked systems, or others).

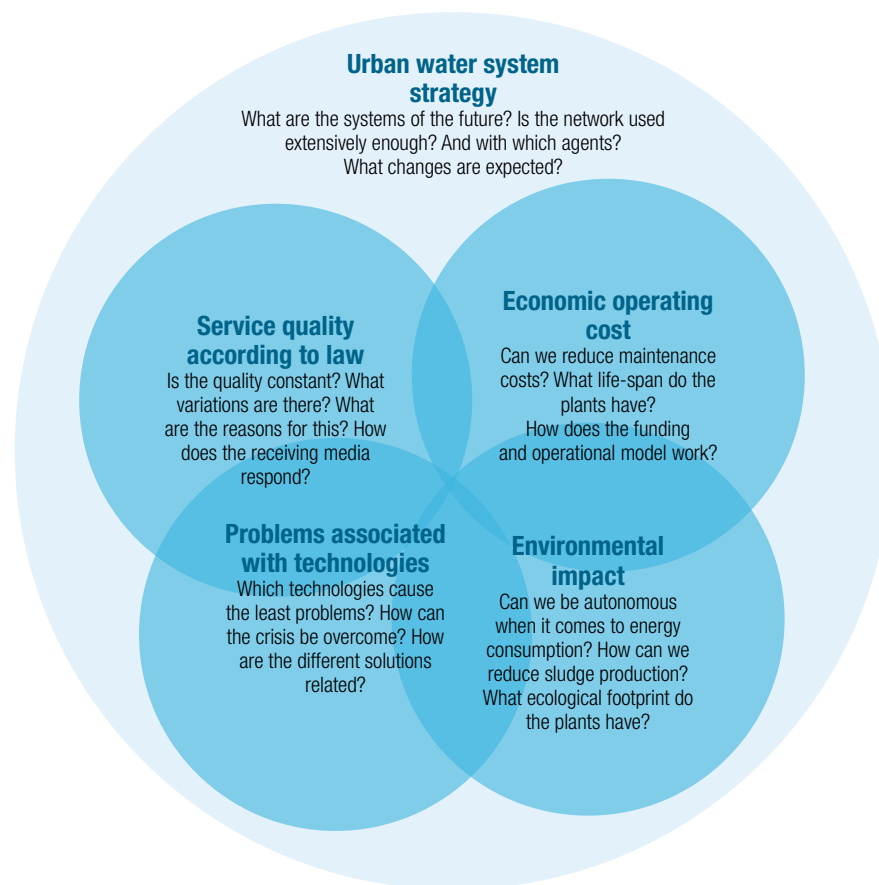


Figure 7.4.1.

Organisations and authorities responsible for the proper operation and management of urban water systems accumulate a remarkable amount of information, some at its own request and other provided by other agents (plant operators, equipment suppliers, research centres etc.) of different types (on-line data, reports analysing off-line data, news coverage of a plant or environment etc.) and many different themes, which together can generate knowledge for use with an EDSS as feedback on the other levels of design and operation.

Data and knowledge acquisition

There are two types of structures present in the data and knowledge acquisition stage. Firstly, information relative to the characteristics of the urban water systems: design data, plants and technology, associated infrastructure (such as pumps, sewers, etc), receiving media, type of influent, compliance under applicable law, business operators and technical assistance. And on the other hand, more dynamic and quantitative information for treated water flows, input and output characteristics, processes and sludge, energy consumption, raw materials, waste, costs and economic management, incidents, problems and improvements.

The cognitive analysis of this information lead to the proposal of two knowl-

edge bases: one general knowledge base, more open to the complexity of concepts but simple in the number of records, and another for operating data, much more rigid and with more records.

General knowledge base. 11 major classifiers were defined (corresponding to the authorities and business, generating activities, pollutants and parameters, infrastructure, legislation, natural receiving media, environmental policy, issues, resources, waste and recycling, technology), each of which contained several concepts (total of 45 defined, but this may reach hundreds), each concept had different terms (they can reach a thousand). Therefore, we obtained lists of key words, defining the relationships to each other according to the 5 different types of standard relationships: U-UF-BT-NT-RT (U-main term, UF-identity relationship, BT-generic relationship, NT-specific relationship RT-associative relationship) were used to encode knowledge and then easily retrieve all of this plus some features such as date of publication, source reliability, authors or utility index. These structures must be flexible and transparent for end users because they are dynamic structures that may

vary over time and with changes in policies and strategies.

Operational knowledge base. This KB is consistent with the previous one, but much more simple in concepts, organised in a more rigid and strict manner and containing a greater number of records. In order to better organise user queries, we designed a main model which details the management of the quality of treated water, the sludge generated, energy consumption and economic costs, as a first operational management model. And there was a separation of other secondary models such as incident management, maintenance management, procurement management and investment management (not less important but not as high a priority). It is important to differentiate between the different types of data: **facts** (data that can be added and must be complete and consistent, without redundancies, such as, for example the m^3 of water treated, kgs of organic matter in the influent, the energy consumed or Euros spent on operating costs), **indicators** (variables calculated from facts such as, for example, the design's wastewater flow, the influent's BOD load, kg/m^3 , kgs of suspended matter removed, the percentage of nitrogen removed or the total tonnes of biosolids generated/ m^3 treated water) and finally **dimensions** (characteristics that allow us to analyse facts such as time, infrastructures, technology and legislation).

These elements are organised into a structure, taking all the relationships into account, and especially the different hierarchies that allow the consistent browsing of the information, from the highest level of data aggregation to lower levels of detail, arriving at the record. The various analyses can be strategic, tactical, operational or analytical. And the tool provides support to solve all kinds of problems at all levels, reaching the strategic level, in which the in-

formation built from the detail has to represent suitable knowledge to serve as decision support to the agents involved, corresponding with to consistency.

Model selection

The *Online Analytical Processing* (OLAP) functions were selected as the model that allows fast operation by the user. It uses a multidimensional (cube shaped) structure that facilitates the analysis of an event from different dimensions, allowing quick viewing and multiple perspectives of the various dimensions of information encapsulated; the cubes can be rotated, the order of the dimensions can be changed, a selection of the cells can be selected and they can even be grouped.

Figure 7.4.3.

The findings suggest the diversity of the typologies in which the existing information was structured. Thus, for example, in terms of operating data level for treatment plants, about 28 concepts were handled from 7 different sources, which were received via 6 different routes and on 11 types of media.

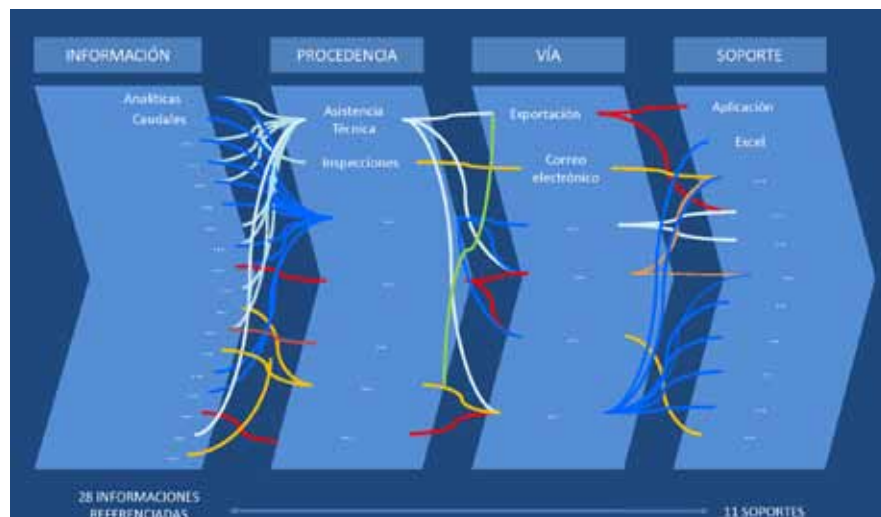
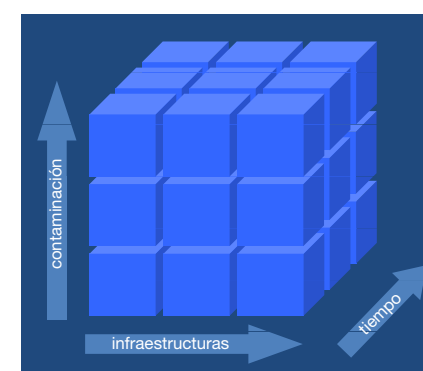


Figure 7.4.4.

Representation of an OLAP cube with information contained in the different areas.



OPERATION

The design of the EDSS incorporates reports designed to update automatically, and on which users can perform searches based on various parameters such as system name, basin, river, populations the service is provided to, systems with industrial discharges, or with stormwater, operators, or managers, systems containing regenerated water, or associated infrastructure. Some of these pre-designed reports are those that the agency receives from the different suppliers. In this case, the EDSS simplifies the search and interpretation of data into a single medium.

In addition, users also have the tools to create new reports and/or modify and browse these as they wish, provided they have a profile authorised to do so. In this case, these advanced users should take into account how this information is structured into the two knowledge bases to properly exploit the experience and improve the organisation of information. The lists of facts and lists of indicators available are important, as are the different hierarchies in all dimensions, the characteristics in which there is definition of the data and lists of terms, concepts and materials to be used for indexing documents.

Three types of EDSS users were identified.

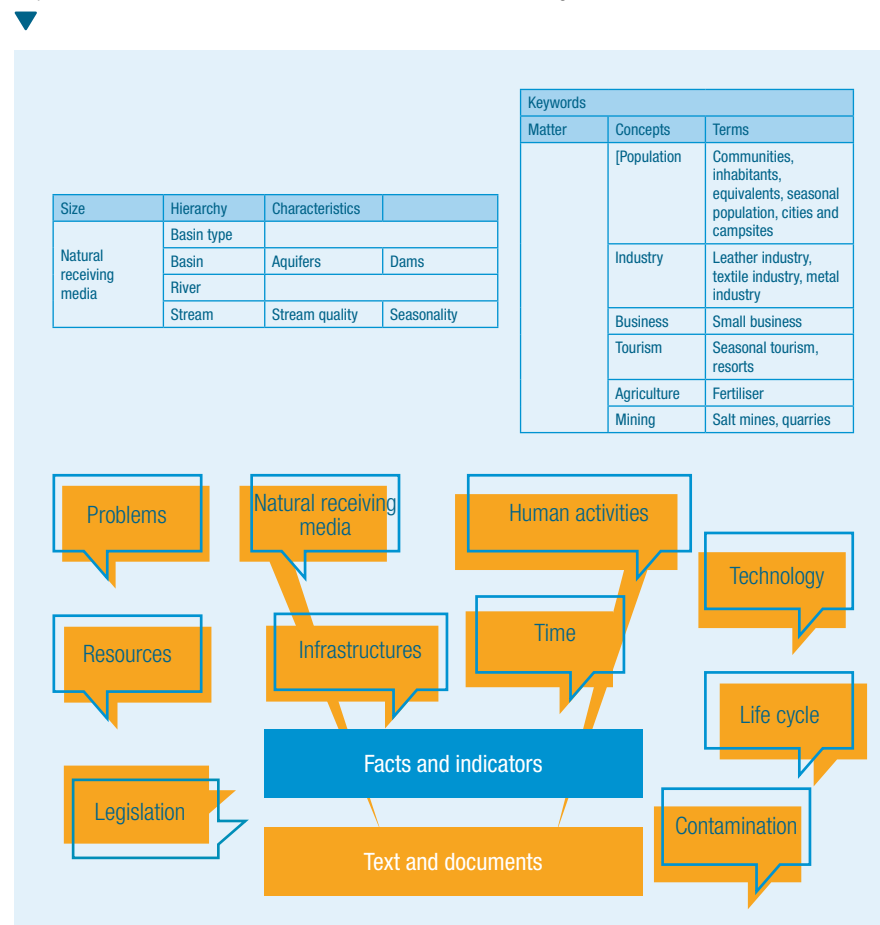
- Those responsible for providing new data and knowledge. The entry may be numerical or documental data. The first are updated automatically according to an agreed protocol on the solution selected for each situation of failure, redundancy and/or data transformation.
- Urban water system managers, who can use the EDSS to extract periodic reports on the treatment systems and operational documentation related to the latter.

- Users, who, without working directly with the data or periodic analysis papers, want to generate reports as a decision-making aid.

The proposal is that the EDSS has Web support, presenting four menus depending on the type of process being run:

- First menu: input data and knowledge (through the indications and forms relating to the knowledge base, load management of automated data in operating systems).
- Second menu: knowledge search.

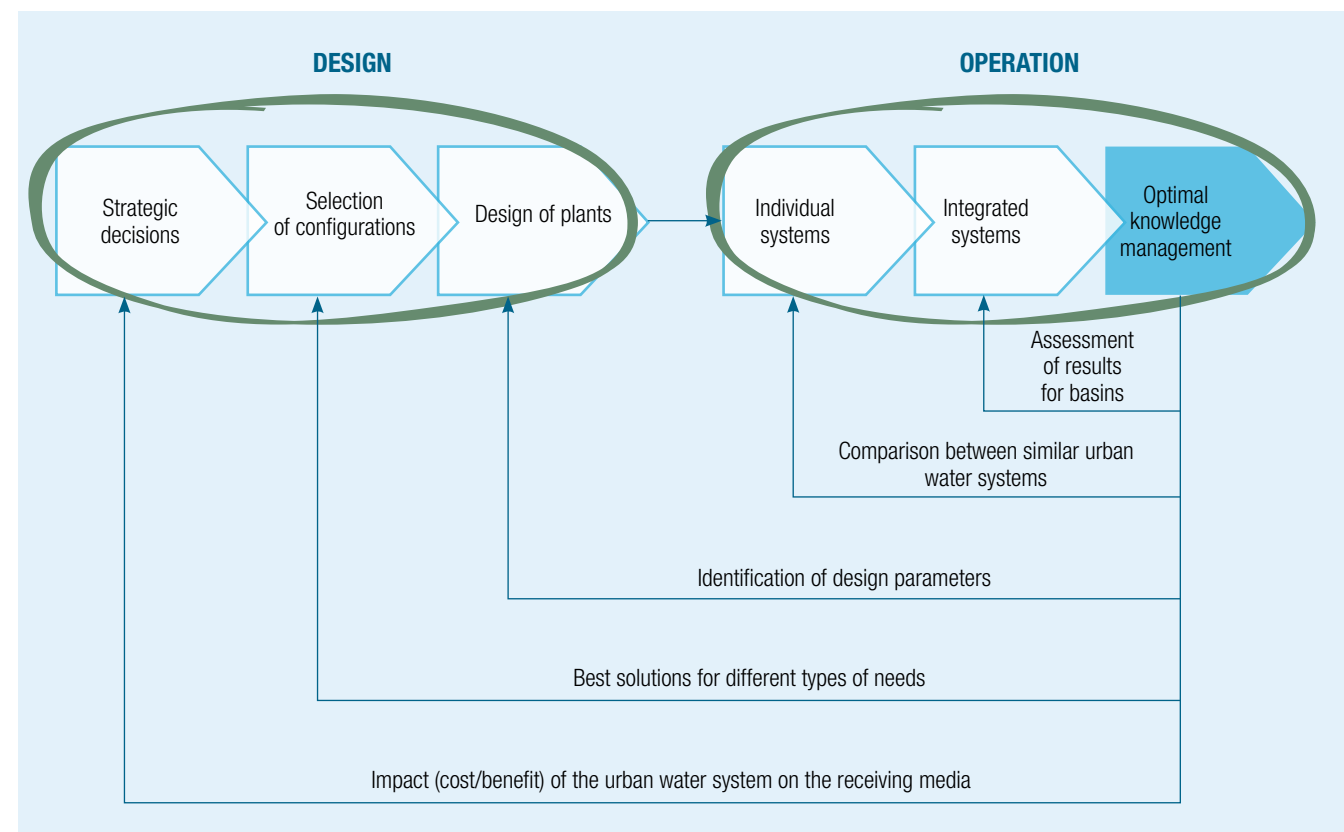
Figure 7.4.5. Representation of materials and dimensions on the two knowledge bases.



From the user's specifications (guided tours), the tool provides the location of documents that may be useful, a summary and assessment in the form of a list that can be ordered how the user prefers, according to various criteria as chronologically, alphabetically, by title or author, by use of the consultation document or according to assessment of the document etc..

- Third menu: control system search (individual or integrated, problems and basins etc.).
- Fourth menu: mixed search (in which the user gets information from both KBs). To retrieve the knowledge, the system must provide sufficient tools to choose the keywords (for knowledge) and the aspects to be analysed (for systems) that are to be consulted.

Figure 7.4.7.



The cycles close

The third decision level in the operation of urban water systems corresponds to the set of systems found in a basin unit. The use of an EDSS at this level provides a global view of the behaviour of the different systems and, therefore, answers some questions relating to sanitation. This closes a cycle that we started with the strategic design decisions.

We believe that this optimal knowledge management, in that it allows an overall assessment of the cost/benefit impact of all urban water systems in the area, may have a positive effect on strategic decisions relative to wastewater management. Obviously, in conjunction with other planning constraints (urban, legislative and financial etc.) although not as an afterthought, and not regarding wastewater treatment as an element to be addressed when the big planning decisions have already been made. An incidence that we believe is more difficult to understand without using a tool like the EDSS.

However, this is not the only feedback from the system. This information management should contribute to the improvement of other design and operational decisions. In the first case, the EDSS can help to identify the best design parameters for an area and specific conditions by evaluating the results of the operation of existing infrastructures. This can help identify the most appropriate technologies or determine real maintenance costs. In the case of operation, the comparison between plants in one area allows efficient management of knowledge that can be shared between different water managers to improve incident management or the integrated minimisation of energy consumption.

Figure 7.4.6.
Examples of communication proposals with the user.

8 Final thoughts



As highlighted in the introduction, good water management is becoming increasingly important, whilst the complexity of this problem has been mentioned throughout the text. However, this complexity should not scare us or force us to be resigned to it, thinking that since any solution will be partial and incomplete, there is no chance of establishing procedures that allow us to obtain better solutions than others. Instead, this difficulty should force us to excel in the effort to try to provide better answers to a very important issue. We must be able to convert the problem of wastewater into a challenge that is no longer regarded as a threat but an opportunity.

Therefore, in our opinion, we must be able to change some things. Firstly, the way we deal with problems. If Einstein said that a problem cannot be solved by the same mentality that generated it, but that it requires a new mindset, we must be able to develop new tools for a new way of making decisions. For a new decision-making culture.

But changing a culture of doing things is not easy, and it is far from the desire and the ability of the authors to make a global approach to a new decision-making culture, as it is far from making a proposal for a new water culture, or a new sustainability culture. Our purpose has been much more modest. If a culture does not change until the next one is ready to respond to change, our desire has been to provide tools that help to give confidence and strength to this possible change.

For this, we have begun analysing the text, from a conceptual point of view, relative to the problem of urban water systems and we have found that it was possible to establish different decision-making levels, identifying some of the elements affecting the decision, analysing the agents involved in each case to, finally, propose a tool that could help in

the decision-making process, such as environmental decision support systems (EDSS), for which we presented our proposal for definition, and our building and operation methodology.

In the same way as when addressing a complex problem, you have to accept this complexity and recognise that there is no one solution, our proposal for the construction and operation of the EDSSs is an open proposal. This proposal recognises that, in order to address the problems of the design and operation of urban water systems, we need to integrate tools from different areas of science and technology, such as more traditional mathematics -with the numerical paradigm- to areas such as artificial intelligence- with new knowledge management paradigms through geographic information systems, which can incorporate the spatial dimension- or ontologies, which can incorporate knowledge. We believe it is only after acceptance of this principle of complementarity that we put ourselves in the best position to address the problem of decision-making in urban water systems.

There is no single solution, every problem means a new challenge and each new decision support system is a new opportunity to learn. Because in its building, a process of trial and error distanced from prior success, repetitive formulas are not applied but, from the general methodology and basic elements, increasingly evolved systems are being built.

That is why, the second part of the book is very important for us since it presents different EDSSs that the authors have been building to face different challenges and problems that we have been presented with over the years. They are not all that we have developed, but we believe that they give a good idea of our work. Looking at them together, a first thought is that, over the years, we have

been facing situations at different levels of decision and that, therefore, have required different partnerships, different embodiments of knowledge, relationships with different areas, from the most general to the more specialised, with different partners and with different end users. In all cases the proposed methodology has been able to offer reasonable solutions, making a conclusion of its applicability. A second observation is that the complexity of urban water systems is varied, but, simultaneously, experts have been identified in the various fields. People who have in-depth knowledge of the different aspects of urban water systems, so that, we can go beyond simple addition. We have seen synergistic effects that have surprised us, and most of the successes are due to this.

There is a wide variety in the case studies, both in regard to the problem considered and their level of development, complexity and application. Some are installed and being extended, with commercial success; others were designed for a specific purpose and after completing their mission - we believe with some success- they were filed; others are in full swing; others are bets on the future and time will tell about their validity... not forgetting that others -there is no reason to deny it- are sleeping the dream of the just. Given this diversity, we decided on a standard format for each of the examples presented, with a section for the presentation of the problem and the building of the EDSS and one for its operation. This has involved necessary simplification that may have hindered the understanding of some of the systems. If this was the case, in the next section, the reader will find a list of our publications which can provide further information.

At this point, we hope that the people who have read the book have found it interesting enough, that it will help them and that they will have become infected with our enthusiasm for a subject as

fascinating as decision-making in urban water systems.

8.1 About the authors



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Currently:

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PhD at the Autonomous University of Barcelona under the leadership of Dr. Carles Solà (1983). He was a professor at this University until 1995 when he moved to the faculty at the University of Girona. At this University, he was Head of the Chemical Engineering, Agriculture and Agri-Food Technology Department, Dean of the Faculty of Sciences and Vice-Chancellor of Foresight and Strategic Planning. His teaching and research topics focus on the application of engineering principles to solving environmental problems, especially those related to water. He was director of a PhD programme recognised by the Ministry for its quality, responsible for projects within the National Science and Research Programme of Spain, a partner in various European projects and responsible for agreements with companies, which has lead him to publish a hundred of SCI articles and supervise twenty doctoral theses.

Specialities:

His interest has evolved from the detailed study of wastewater treatment processes to more global approaches related to the integrated management of water resources and optimising their use. Methodologically, his experience has incorporated mathematical models to describe the processes, heuristic tools to incorporate the experience of the plant managers and the needs of those responsible for resource management.

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Deputy Vicerector for European Research Funding at Catalonia Polytechnic University-BarcelonaTech (UPC), since 2012. Coordinator of the Artificial Intelligence PhD. programm at UPC, since 1991.

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Summary:

PhD in Artificial Intelligence from the Universitat Politècnica de Catalunya (1984), and Industrial and Systems Engineer for the Monterray Institute of Technology and Higher Education (1982). President of the Catalan Artificial Intelligence Conference in 2009. Vice-President of the European Artificial Intelligence Coordination Committee from 2002 to 2008. He has been visiting Professor at Beijing Institute of Technology (2012), T.U. Graz (2012), EPFL (1998) and CINVESTAV (1988). He has advised 21 PhD Thesis.

Specialities:

He is working on several areas of Artificial Intelligence (AI) including Knowledge acquisition and concept formation in Knowledge-Based Systems, as well as on Machine Learning and in Autonomous Intelligent Agents.

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Summary:

BSc in Chemistry (1993) from the Autonomous University of Barcelona and PhD in industrial engineering from the University of Girona (2000) with the thesis *Development, Implementation and Evaluation of an Activated Sludge Supervisory System for the Granollers WWTP*, awarded the special PhD prize for the 2000-2001 academic year. His research activities have resulted in more than 50 SCI-indexed international journal papers, a hundred communications at national and international conferences, the creation of a spin-off company (SISLtech) and one patent. He has participated in around 60 Spanish and European research projects, both from competitive (public) projects and research contracts with companies. He has organized and has been member of several international conferences and has supervised 7 PhD Thesis. In 2006, he was recognised by the International Environmental Modelling and Software Society (iEMSs) with the ECRE award (*Early Career Research Excellence*). Member of the International Water Association.

Specialities:

Development and implementation of decision support systems to improve the management of advanced water treatment systems; control and supervision of systems using membrane technologies (membrane bioreactors and inverse osmosis); full control of the urban water cycle (sewage, treatment and river); study of the *benchmark* system to improve the control of treatment plants. Removal of pharmaceutical compounds from wastewater.

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PhD in Industrial Engineering (1998), Masters in Biotechnology (1994), postgraduate in physical-chemical treatments (1992) and BSc in Chemistry (1992). Member of the Laboratori d'Enginyeria Química i Ambiental (LEQUIA) at the University of Girona, the International Water Association (IWA), the Water Environment Federation (WEF) and the Catalonia Artificial Intelligence Association (ACIA), among others.

His research has resulted in over 70 SCI-indexed international publications in journals, a hundred communications at national and international conferences, one patent, the creation of a new technology based company (SISLtech). He was a member of the scientific committee and the organiser of about 20 workshops and international conferences; he has participated in 40 competitive research projects (public) and those for research contracts with national and international companies and has supervised 10 doctoral theses.

He has held various management positions at the university, including deputy director of the Postgraduate School and board member for the Official Postgraduate Programme leading to a PhD in Experimental Sciences and Sustainability, coordination of the Degree in Environmental Engineering, the Institute's Secretariat for the Environment, and the position as deputy to the Vice-Chancellor in charge of transfer and innovation.

Specialities:

Wastewater treatment, mainly biological, modelling and control of wastewater treatment plants, membrane bioreactor systems, removal of micropollutats and decision support systems applied to environmental domains.

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URV-UB). Director of the Research Group on Knowledge Engineering and Automatic Learning (KEMLG) at the UPC. Assistant editor for the *Environmental Modelling and Software* journal. Member of the editorial team for the *Applied Intelligence* journal.

Summary:

PhD in Computer Science (Artificial Intelligence, AI) from the Catalonia Polytechnic University (1996). BSc in Computer Science from the UPC (1985-1991). Professor in the Languages and Information Systems Department (LSI) at the UPC since 1990. He received an honourable mention from Oms i De Prat in 1991, in the field of Applied and Experimental Sciences, for his thesis entitled *DAI-DEPUR: an Integrated Supervisory Multi-level Architecture for Wastewater Treatment Plants*. Head of the LSI artificial intelligence department (1997-2000). Founding member of the Associació Catalana de Intel·ligència Artificial (ACIA) and he was on the board (1994-1998). Founder and principle team member for the International Environmental Modelling and Software Society (iEMSs). Named a *fellow* by the iEMSs in 2005. He has participated in several research projects, both at European and Spanish and Catalan level. He has organised several international conferences in the fields of AI and the environment. He is the author of more than 100 international journal publications, including around 30 in the SCI and is the author/editor of 8 books.

Specialities:

Case-based reasoning, knowledge discovery and data mining, automatic learning, knowledge engineering, intelligent decision support system, application of AI techniques to the environment, application of AI techniques in medicine and assistive technologies, and the application of AI techniques to industrial processes.

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<http://www.lsi.upc.edu/~miquel/>

8.2 For more information and knowledge

Books

- COMAS, J.; POCH, M.; RODRIGUEZ-RODA, I.; CORTÉS, U.; SÀNCHEZ-MARRÈ, M.
Eleven years of experience in designing and building real environmental decision support systems. What have we learnt?
Editorial: Servei de Publicacions de la Universitat de Girona
ISBN: 84-8458-204-3 Legal deposit: B-51989-2002
- ULISES CORTÉS, MANEL POCH (editors)
Advanced Agent-Based Environmental Management Systems
Editorial: Birkhauser Verlag AG
ISBN: 978-3-7643-8897-3 2009

Doctoral theses

The majority of them, especially the most recent, can be viewed for free via www.tdx.cat.

- **Modelització i identificació del procés de fangs activats.**
JORDI ROBUSTÉ CARTRÓ
Autonomous University of Barcelona, 1990
- **Desenvolupament d'un sistema basat en el coneixement per al control i supervisió de plantes depuradores d'aigües residuals urbanes.**
PAU SERRA PRAT
Autonomous University of Barcelona, 1993
- **L'ús de la informació simbòlica en l'automatització del tractament estadístic de dominis poc estructurats.**
KARINA GIBERT
Polytechnic University of Catalonia, 1995
- **Adquisición de conocimiento en dominios poco estructurados.**
JAVIER BÉJAR
Polytechnic University of Catalonia, 1995
- **DAI-DEPUR: An integrated supervisory multi-level architecture for wastewater treatment plants.**
MIQUEL SÀNCHEZ-MARRÈ
Polytechnic University of Catalonia, 1996
- **Automatic Construction of Descriptive Rules.**
DAVID RIAÑO
Polytechnic University of Catalonia, 1997
- **Desenvolupament d'un protocol per l'aplicació de sistemes basats en el coneixement a la gestió d'estacions depuradores d'aigües residuals urbanes.**
IGNASI RODRÍGUEZ-RODA LAYRET
University of Girona, 1998
- **Development, implementation, and evaluation of an activated sludge supervisory system for the Granollers WWTP.**
JOAQUIM COMAS MATAS
University of Girona, 2000
- **ONTOWEDSS: An Ontology-based Environmental Decision Support System for the Management of Wastewater Treatment Plants.**
LUIGI CECCARONI
Polytechnic University of Catalonia, 2001
- **Supervisory systems in wastewater treatment plants: systematise their implementation.**
CHRISTIAN CORTÉS DE LA FUENTE
University of Girona, 2002
- **Desenvolupament d'un sistema expert com a eina per a una millor gestió de la qualitat de les aigües fluvials.**
ESTHER LLORENS I RIBES
University of Girona, 2004
- **Feature Weighting in Plain Case-Based Reasoning.**
HÉCTOR NÚÑEZ
Polytechnic University of Catalonia, 2004
- **Metodologia de disseny conceptual d'estacions depuradores d'aigües residuals que combina el procés de decisió jeràrquic amb l'anàlisi de decisions multicriteri.**
NÚRIA VIDAL ROBERTO
University of Girona, 2004
- **A Dynamic knowledge-based decision support system to handle solids separation problems in activated sludge systems: development and validation.**
MONTSERRAT MARTÍNEZ I PUENTES
University of Girona, 2006
- **Desenvolupament d'un sistema de support a la decisió ambiental per a la gestió de les infraestructures hidràuliques, amb l'objectiu de garantir la qualitat de l'aigua de la conca del Besòs.**
FRANCESC DEVESA PEIRÓ
University of Girona, 2006
- **EDSS-maintenance prototype:**
An environmental decision support system to assess the definition of operation and maintenance protocols for horizontal subsurface constructed wetlands.
CLÀUDIA TURON PLANELLA
University of Girona, 2007
- **Conceptual design of wastewater treatment plants using multiple objectives.**
XAVIER FLORES I ALSINA
University of Girona, 2008
- **Knowledge-based modelling and simulation of operational problems of microbiological origin in wastewater treatment plants.**
JORDI DALMAU I SOLÉ
University of Girona, 2009
- **Management of industrial wastewater discharges in river basins through agents' argumentation.**
MONTSERRAT AULINAS I MASÓ
University of Girona, 2009
- **Development of an air-scour control system for membrane bioreactors.**
GIULIANA FERRERO
University of Girona, 2011
- **Development of a decision support system for the integrated control of membrane bioreactors.**
HÉCTOR MONCLÚS SALES
University of Girona, 2011
- **Integrated management of urban wastewater systems: a model-based approach.**
PAU PRAT
University of Girona, 2012
- **Development of an environmental decision support system for the selection and integrated assessment of process flow diagrams in wastewater treatment.**
MANEL GARRIDO BASERBA
University of Girona, 2012
- **Avaluació del paradigma d'agents en la gestió d'un sistema complex d'aigües residuals**
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Thanks

As the reader will have already realized, the material in this book is not just the result of work carried out by the authors themselves. We have adapted it to this format, but many more people were involved in the process of constructing and operating the decision support systems presented. Although it is virtually impossible to mention them all (so we apologise to those that are not included), we would like to end the document with an explicit thanks to some that have helped us along the way.

First, the operators, engineers and managers of the urban water systems who, over the years, we have interacted with and exchanged experiences. This group is undoubtedly a wealth of knowledge that allows these systems to work efficiently and improve the quality of our environment. We have been fortunate to always find people concerned about their work and open to participating and sharing their experience and knowledge. Hopefully the book will be useful to help you to better understand what some people from the university were doing and that - we have to admit - is sometimes difficult to explain.

Structuring this knowledge is not an easy task; just ask our PhD students who, over the years, have been writing their theses on this area. And since the early 90s, in the early works of Jordi Robusté i Pau Serra, there are indications of the need to look for new tools to complement the control systems. And little did we know that these would eventually become decision support systems! From there on in, the 90's were a decade of conceptual development, discussions to develop the theoretical bases of these systems, and this is reflected in the theses by Miquel Sànchez-Marrè, Karina Gibert, Javi Béjar, David Riàño, Luigi Ceccaroni, Ignasi Rodríguez-Roda or Quim Comas. At this point, the reader will have perceived that some of them are co-authors of the book, and that, at that time, they joined the University as teachers. From these conceptual developments, the first decade of the 21st century is characterised by the application of the methodologies developed to case studies, to practical questions on urban water

systems, implying that some of the theses from those years coincide with the different decision support systems presented in the text. The theses by Esther Llorens, Francesc Devesa, Clàudia Turón, Xavier Flores, Montse Aulinas, Pau Prat, Manel Garrido, or Marta Verdaguer could be included in this section, with other more methodological theses that continue updating the conceptual bases or open up new perspectives such as those from Christian Cortés, Hector Núñez, Montse Martínez, Jordi Dalmau, or Hector Monclús. To all, thank you very much and good luck, noting with satisfaction that a large proportion of them have started their professional activity in areas related to the subject studied.

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