UNIVERSITAT POLITÈCNICA DE VALÈNCIA

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# Application of a conceptual water quality model of the river Dender (Belgium)

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# Contents

## List of symbols

| | | |
|---|---|---|
| $BOD_5$ | 5-day Biochemical Oxygen Demand | (mg/l) |
| Cd | Cadmium | (mg/l) |
| D | Water depth | (m) |
| DO | Dissolved Oxygen | (mg/l) |
| N | Nitrogen | (mg/l) |
| $NH_3$ | Ammonia | (mg/l) |
| $NH_4$ | Ammonium | (mg/l) |
| $NO_3$ | Nitrate | (mg/l) |
| P | Phosphorus | (mg/l) |
| Pb | Lead | (mg/l) |
| Q | Flow | ($m^3/s$) |
| T | Temperature of water | (°C) |
| u | Flow velocity | (m/s) |

## List of abbreviations

| | |
|---|---|
| BBI | Belgian Biotic Index |
| BOD | Biochemical Oxygen Demand |
| CHLA | Chlorophyll a |
| COD | Chemical Oxygen Demand |
| ESWAT | Extended Soil and Water Assessment Tool |
| EU | European Union |
| EUWARENESS | European Water Regimes and the Notion of a Sustainable Status |
| HD | Hydro-Dynamic |
| HIC | Hydrological Information Centre |
| RK4 | Runge-Kutta fourth order |
| SWAT | Soil and Water Assessment Tool |
| VHA | Vlaamse Hydrografische Atlas |
| VMM | Vlaamse Milieumaatschappij |
| WFD | Water Framework Directive |
| WWTP | Waste Water Treatment Plant |

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## 1. Introduction

The role of water on earth is imperative for life and that is why we need a reliable method of planning and managing water resources.

Nowadays, the pressures in the riverine systems increase due to the spatial variability of the resource and deficiencies in the water quality. These systems are also exposed to human activities which contribute to the pressure on water resources: this is due to the strong social, urban and industrial development. Furthermore, the increase of population increases the development of industries and agriculture, leading to the increment of diversity of substances produced and giving an increasing importance to the complexity in problems of water pollution.

The issues raised in the last paragraph together with the importance of water lead to talk about water quality: water quality refers to the suitability of water for the intended use and processes.

In this context, a relevant law regarding water management is the law of 1971 on the protection of surface waters against pollution. Later in 1987 and 1995, Flanders explained basic quality standards for surface water. These standards establish values for the physic-chemical of the water column and the Belgian Biotic Index (BBI), based on the presence of macroinvertebrates.

In 2000 arrived the EU Water Framework Directive 2000/60 (WFD) related to the integrated river basin for Europe aims to protect and improve the water quality: surface and ground water in the EU have to achieve good ecological status in 2015. The legislation provides several guidelines for monitoring the water bodies with its implementation left to the local governments.

As a result of the WFD, work management, planning and conservation quality resource is currently being carried out; policies on heavy metals, manure, pesticides and sustainable management are needed to obtain good chemical quality. However, the increasing complexity of the study of water resources points to the requirement of complex tools in order to study the different systems.

The tools used require the modelling of the water quality in order to plan and manage water resources. They also have to reflect the spatiotemporal water quality evolution in the modelling system. Hence, different management alternatives, pollution and resource use can be studied.

In this case, the model used is built from previous works in the Dender basin and through the conceptual water quantity model. On the one hand, the latter provides the flow, velocity and depth data in a time series format, needed for the conceptual water quality. On the other hand, the software MIKE 11 has been used previously for water quality simulations in the basin. However, due to the large number of parameters and the high computational time of the MIKE 11 water quality model, a detailed calibration could not be performed. It is also needed the calibration and validation of the conceptual hydraulic model in order to setup the conceptual water quality model. Finally, the conceptual water quality is used to simulate the concentration of Nitrate ($NO_3$), Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD) and Ammonia ($NH_3$) in the river.

## 1.1. Objective of the study

The objective of the study is to make a diagnosis of the water quality of the river Dender (Flemish part), noting the most important pressures in the river. In order to reduce these pressures, the proposition of measures have to be done to improve the water quality.

All this can be achieved by simulating the behaviour of the river, using a water quality model. Thus, the measures will be implemented in the model and it will be possible to verify which measures are the most relevant.

Secondary objectives of this report are the explanation of the processes undertaken to build the water quality model and the subsequent simulation and analysis, in which measures are put in place.

The main processes include the build-up of the model and its calibration and validation, based on the concentration of certain parameters. The validation and calibration of the model are steps that require a lot of time, but they are essential to ensure reliable operation of it.

When the water quality simulator is ready, it is possible to assess the physico-chemistry quality and its spatiotemporal evolution along the river in a continuous manner. The calibrated model is a reliable tool that can be used to evaluate the effects of different proposed measures. This approach can be used, for example, to make decisions about the optimal set of corrective measures needed to fulfil the objectives marked in the Water Framework Directive.

## 1.2. Structure of the study

The document is structured as follows:

The first chapter describes the main problems and the objectives of the study, as well as the need of a tool to diagnose the status of the river.

The second chapter characterizes the principal aspects of the Dender basin. The study of the basin includes geographical and hydrological aspects of the system and gives information of the different processes carried out in the river.

The third chapter is the analysis of the current situation in the basin. The diagnosis of water quality is made from the data of the water cycle and the development of uses. Hence, the specific concerns in the studied area can be identified.

The fourth chapter focuses on the development of the conceptual water quality model. It describes how the model is set up: the stream network, the boundary data, the hydraulic data and the air temperature and solar radiation data. This chapter also includes a background explaining the previous works in the basin and the source information of the data used.

Once the development of the model is done, the calibration of the model can be held. The calibration of the model is done manually, using an iterative process trial and error. In this process, the simulated and observed values have to be compared and the value of the error has to be as small as possible. All the reaches have to be taken into account, and the order in which the reaches are calibrated is from upstream to downstream.

The sixth chapter is about the validation of the model. In this chapter are discussed the results of the model, taking into account the uncertainties in some parameters.

In chapter seven different simulations of future scenarios are carried out. Once the different scenarios have been built and executed, the results can be analysed and the measures proposed can be validated.

The last chapter states the major findings of the study and the subjects for future research. The most important measures proposed in order to improve the water quality in the basin under consideration are recapitulated in this chapter.

# 2. Description and characterization of the system: The Dender river basin

In this section, it is intended to show the different elements that form the system in order to provide general information about the study basin. This will facilitate the interpretation of the subsequent results.

The main source used to obtain the information is a case study of the Dender river basin included in a research project on European Water Regimes and the Notion of a Sustainable Status (Aubin & Varone, 2002). Another remarkable source of information is the Vlaamse Milieumaatschappij (VMM), which is a public company in charge of monitoring the quantity and quality of water in Flanders.

## 2.1. Geographical aspects

This part includes a description of the main geographical aspects in the basin: the basic characteristics of the area and the surrounding territories in the basin, the population, the distribution of the main river and its tributaries and the main water uses.

### 2.1.1. Basic aspects

The Dender basin is a tributary basin of the international Schelde basin and is located entirely on the Belgian territory. It is located precisely at the West of Brussels, at half distance between Brussels and Ghent. The total area of the Dender basin is approximately 1384 $km^2$, of which approximately two-thirds (708 $km^2$) is in the Region of Flanders and one third is situated in the province of Hainaut (Walloon Region). Therefore, the management of the Dender requires a coordinated inter-regional approach.

The Dender is formed in Ath (Wallonia) and it flows South to North (the upstream part of the system is located in Wallonia, at the South of the Dender basin). The rivers of the basin are bordered with sites of high natural value: grazing areas, brushwood and woods.

Population is spread on all the territory, especially concentrated upstream. The total number of inhabitants is 349485 and the most important towns are Aalst, Ninove and Geraardbergen (Aubin & Varone, 2002).

The next figure shows the basins of the Flemish region. The area shaded represents the studying area.


**Figure 1. Flemish Hydrographic Atlas basin. Source: Geopunt Vlaanderen**

### 2.1.2. The river Dender and its tributaries

The Dender river has a length of 51 km and the total length of all watercourses in the basin is 868 km.

The main tributaries of the river Dender are the following (from the beginning to the end of its course in the Flemish area): the Mark (right bank), which is the most important tributary. It issues in the Dender in Wallonia; the Molenbeek - Terkleppebeek (left bank); the Molenbeek - Pachtbosbeek (left bank); the Molenbeek - Wolfputbeek (right bank); the Bellebeek (right bank); the Molenbeek - Erpe Mere, which has a small sub-basin but stretched along the West border of the Dender basin; the Vondelbeek.

At the same time, the basin is divided into twelve hydrographic zones called the VHA (Vlaamse Hydrografische Atlas) zones.

The next figure shows the location of the main river and the tributaries in the Flemish part.


**Figure 2. Dender basin: the river and the tributaries (Flemish part). Source: Vlaamse Milieumaatschappij (VMM)**

### 2.1.3. Spatial use and activities

The river Dender has local importance but with the potential of getting more regional importance, especially for boating. There is a hiking and biking path along the total length (Gilbert et al, 2007). Now, focusing on different locations along the river, there are three cities which can be highlighted: Aalst, which is an urban-industrial environment; Liedekerke is a rural area, and Kapellemeersen is a very small nature reserve area

In the regional land-use inventory, the Dender basin is classified as an open area mainly composed of natural and agrarian spaces. Urban areas are also present in the basin, where Aalst, located downstream, is the main town (Aubin & Varone, 2002).

Figure 3 shows the development of residential and industrial zones in the basin. However, a more detailed description of the development of uses is made in the section 3.2 below.

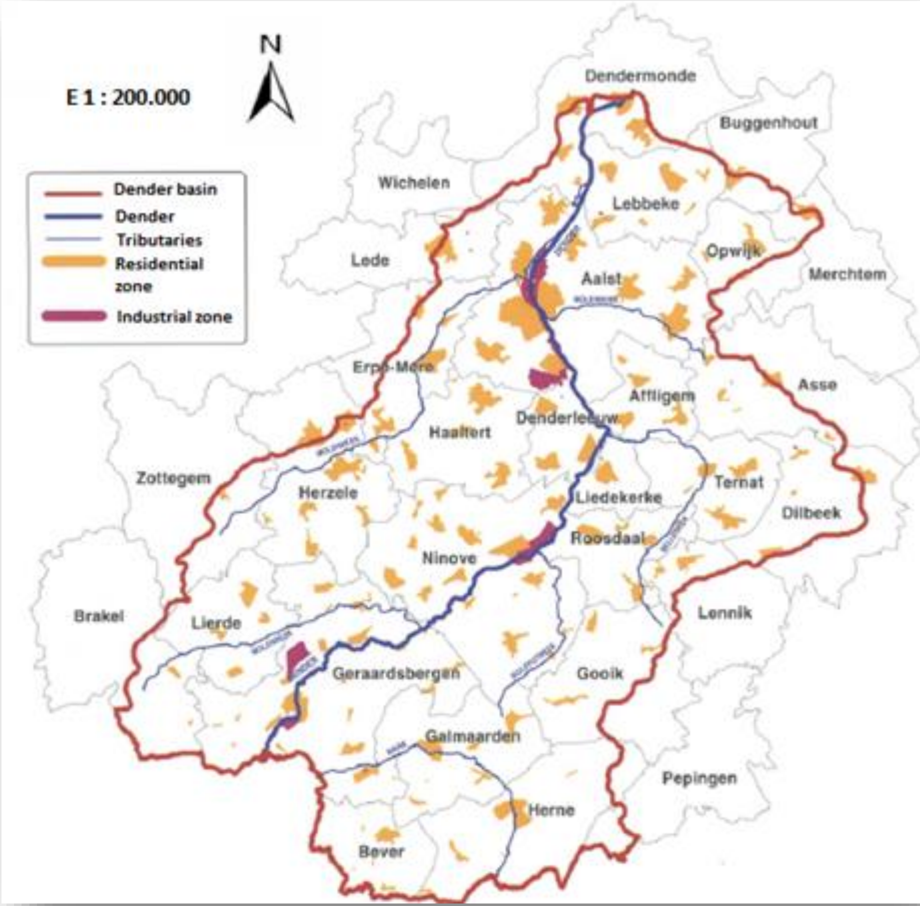



**Figure 3. Residential and industrial zones in the basin. Source: VMM**

### 2.1.4. Landscape and nature

The Dender, in the upstream of Aalst, has a distinctly green character, only interrupted by relatively small and concentrated urban centers.

Marshes, wet woodlands, interspersed with wetlands open grasslands where waterfowl inhabit; together form a blue-green corridor through the landscape. The wetlands along the river are an important habitat for rare water-flora and fauna. Also, storks and beavers inhabit in the ecosystem.

## 2.2. Hydrological aspects

This part presents the main hydrological characteristics that take place in the basin: climate and pluviometrics, hydrogeology and hydraulic structures.

### 2.2.1. Climate

The climate is humid and temperate. There is precipitation throughout the year; even the driest month has a lot of rain. The average annual temperature in Brussels is 10'3 °C and there are around 785 mm of precipitation (Climate-data.org).

Table 1 shows the historic climate data in the region of Brussels:

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mm | 68 | 52 | 68 | 52 | 65 | 73 | 69 | 61 | 63 | 72 | 71 | 71 |
| °C | 2.1 | 3.7 | 6.4 | 9.7 | 13.3 | 16.6 | 17.6 | 17.6 | 15.8 | 11.5 | 6.3 | 3.2 |
| °C (min) | 0.5 | 0.7 | 2.5 | 5.1 | 8.2 | 11.2 | 12.5 | 12.6 | 10.9 | 7.6 | 3.6 | 0.7 |
| °C (max) | 4.8 | 6.7 | 10.3 | 14.3 | 18.5 | 22 | 22'8 | 22.6 | 20.7 | 15.5 | 9.1 | 5.8 |

**Table 1. Historic data in Brussels. Source: Climate-data.org**

### 2.2.2. Hydrogeology

The major part of the Dender basin is located on clayey sediments, called the Leemstreek (silty Region in English). In the Northern part, one finds the Zandleemstreek (in English, sandy loam), localised sand layers full of water. A small part in the South West, called the Heuvelland (hill country in English) belongs to the so-called Flemish Ardennes.

From the layers of the Zandleemstreek emerge springs. In dry periods, the flow of the springs diminishes widely until it stops. To go further in details, the aquifers of the Pleistocene are important for the production of water. In the North and North West areas of the Dender basin, one finds areas of infiltration due to forming of the Eocene period. Under the same line, often near the surface, stand mainly isolated Eocene sand formations (Aubin & Varone, 2002).

### 2.2.3. Hydraulic structures

The principal channel in the Dender basin is partly canalised and equipped with several locks in order to guarantee ship-traffic. Besides every lock there is a weir which allows to arrange the amount of water in the upstream. These locks allow to maintain a determined water level and to avoid irregular flows. They are operated manually by the lock keepers and there is always enough water for shipping. There are nine control structures along the Flemish part, with the biggest one at Dendermonde that cut the Dender flow from the tidal Scheldt. They take the name of the place where they are located, namely from upstream to downstream Geraardsbergen, Idegem, Pollare, Denderleeuw, Aalst, Denderbelle and Dendermonde. Afterwards an explanation of the effects of hydraulic structures regarding the concentration of oxygen will be done.

As a consequence of these hydraulic structures, the Dender acts as a series of reservoirs during low flow conditions, with long residence times and a relatively large water depth. This can cause a problem of sedimentation and sludge accumulation.

Next figure shows the localisation of the different hydraulic structures:

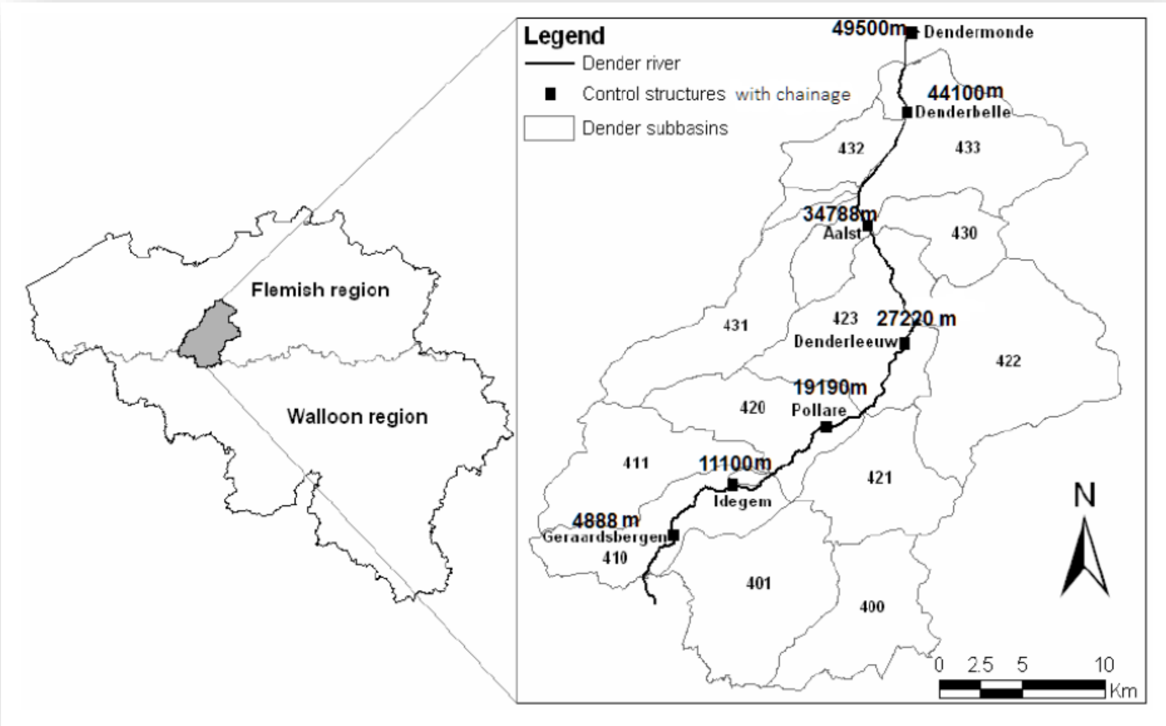



**Figure 4. Location of hydraulic structures. Source: adapted from Timbe Castro and Berlamont, 2007**

## 3. Analysis of the current situation

This part will analyse the current situation of the Dender river, taking into account the flow regime, the main pollution sources, the water uses and the diagnosis of water quality in the study channels.

### 3.1. Flow regime

The flow of the river is highly irregular; it depends basically on rainfalls: 91’5% of the flow of surface water in the basin depends on rainwater, while 8’5% of water comes from springs. Therefore, the flow can experience large variations and it can be very low during dry periods.

The river reaches flows up to 100 $m^3/s$ during the winter season and less than 1 $m^3/s$ in summer (van Griensven and Bauwens, 2000b). In November 2010, an exceptional rate of 121 $m^3/s$ was recorded.

In dry periods, the low flow rates affect the water quality of the river: the pollution which then ends up in the river is diluted too little and the flow is very slow. With abundant precipitation, on the other hand, the Dender is a fast-flowing river.

The locks and dams in the river play an essential role in the behaviour of the river: thanks to these constructions the water level can be kept sufficiently high so that shipping remains possible.

## 3.2. The water uses in the Dender basin

A wide set of water uses is embraced inside the basin. Agriculture and breeding are well developed upstream and industry downstream, along the navigable part of the Dender. The main pollution sources, which can be point or distributed, are the wastewater generated from household activity and agricultural activity.

Among the less present water uses there are:

- Water consumption: this use exists, but the major part of this water is imported from other basins.
- Hydropower

In the next sections a more exhaustive description of the uses is being made. For each source, a description of the major pollutants is discussed.

### 3.2.1. Agriculture

The impact of agricultural activities on the water quality is hard to assess since it is a diffuse source of pollution. The use of fertilizer and pesticide, soil tillage and irrigation affect to the water quality in the river. These anthropogenic activities have an impact on surface water by contributing nutrients, pesticides, sediment, and bacteria, or affecting the regime of rivers. The water quality is mainly affected by the use of fertilizer and pesticide. To the spreading of chemical fertilisers in the basin, the production of manure is added up. This latest contains nutrients (nitrogen and phosphorus), faecal coliform bacteria and often pharmaceuticals.

One of the main problems in the river caused by the presence of nutrients is eutrophication: this may contribute to anoxic conditions, turbidity, and the increment in the rate of sedimentation and plant and animal biomass.

In the Dender basin, around 80% of the basin area develops agricultural activities and 2079 farms have been registered by the VMM. These farms are specialised in intensive breeding and the production of cereals (Aubin & Varone, 2002).

The share of agriculture in the total emissions represents 80% for the total N and 76% for the total P. However, a model states that the return to the water of the spread of nutrients is around 81% for the COD, 53% for N and 54% for P basin (Aubin & Varone, 2002). This data shows that the eutrophication can be a problem in the basin.

### 3.2.2. Industry

The main problems of industrial discharges are the massive amounts of heavy metals, radioactive waste or even organic sludge. In the Dender basin there is no high radioactive pollution.

In the Dender basin there are a total of eight industrial zones: these zones are concentrated mainly between the towns of Aalst and Dendermonde, but also in Ninove and Geraardsbergen and along the motorway E40 that goes from Brussels to Ghent. It is worth noting that the total number of industries of which emissions are monitored by the VMM is 49 (Aubin & Varone, 2002). However, the industries are encouraged to purify their wastewater themselves, especially for the biggest pollutants.

Regarding to industrial water withdrawing, it is used in the basin in the production process and for cooling.

### 3.2.3. Households

Domestic wastewater play an important role in the pollution of the basin, since the population in the basin is extensive. The major constituents of these discharges are organic and inorganic solids, nitrogen and phosphorus. It can contain also toxic elements such as arsenic, zinc, cadmium, chromium, etc. In turn, domestic wastewater has the highest share in the production of BOD, COD, particles and zinc.

Among the domestic emissions, a minor percentage is sewed and purified. However, the most part are sewed and discharged without a prior treatment. In these cases, although the volume poured is not high, there is an increase in the concentration of organic matter and in suspended solids. The latter induces, on the one hand, an increase in the turbidity of the water, and consequently less light and possible proliferation of algae. On the other hand, it produces the sedimentation of bodies in suspension and organic matter. This forms a mud near the discharge which is the so-called sediment, and which requires oxygen. The consequence of these discharges is the increase of the levels of DOB, ammonia and phosphates, fundamentally.

### 3.2.4. Navigation and recreation

Navigation is a present activity in the basin but it was more important in past times. Making the river navigable caused the need of modifications in the river and the building of gates. The current navigation in the Dender basin has a recreational aim, as leisure navigation tends to develop.

Regarding to recreation, it is pleasant to stay along the Dender now that the water quality has improved remarkably. There is a hiking and biking path along the total length of the river dedicated to walking and cycling. This is important because together with different events and entertainment in the cities contribute to the regional interest of the basin.

## 3.3. Sewage and purification

The most important pollution pressure in the river is due to the high number of inhabitants in all the parts of the basin. This next to the presence of industries increases the pressure. The pollution of industry is particularly important at the downstream of the Dender basin. The impact by households is more important in the tributary basins of Bellebeek and Molenbeek-Graadbeek and the impact of agriculture is more important in the tributary basin of the Mark and at the upstream of the Dender.

With the creation of VMM, who is in charge of the measurement of water quality, and Aquafin NV, who is in charge of building and operation of purification plants, new plans emerged. These new plans were related to the infrastructure of public purification with well- funded investment programs. The main efforts in the plans were focused in building up and renovating both purification plants and main sewers.

The purification plants and the basic characteristics in the Dender basin are listed below:

| ID | Name | Design capacity |
|---|---|---|
| 1 | Asse - Bekkerzeel | 400 |
| 2 | Sint-Antelinks | 1500 |
| 3 | Zandbergen | 7000 |
| 4 | Liedekerke | 70000 |
| 5 | Geraardsbergen | 30000 |
| 6 | Ninove | 35000 |
| 7 | Ninove - Rendestede | 170 |
| 8 | Aalst | 100000 |
| 9 | Galmaarden | 10000 |
| 10 | Heldergem | 3000 |
| 11 | Parike | 1300 |
| 12 | Sint-Maria-Lierde | 850 |
| 13 | Lebbeke - Rooien | 125 |

**Table 2. Monitored WWTP in the Dender basin. Source: VMM**

| ID | Name |
|---|---|
| 1 | Asse - Bekkerzeel |
| 2 | Edingen |
| 3 | Heldergem |
| 4 | Dilbeek – Kerkeveld |

**Table 3. Not monitored WWTP in the Dender basin. Source: VMM**

Next map shows the location of the WWTP in the basin:


**Figure 5. Purification areas in the basin. Source: VMM**

## 3.4. Status of waterbodies

The existing monitoring network allows the evaluation of water quantity, physico-chemical and biological quality, diffuse emissions including industries, agriculture and wastewater treatment effluents handled by the Flemish Environmental Agency (VMM) and the Hydrological Information Centre (HIC). This network aims to develop the good ecological and chemical status of the Flemish region. The WFD determines the state of a waterbody as “good” taking into account the combination of these two indicators. The classification to assess the ecological status of a waterbody can be very good, good, moderate, poor or bad. However, the chemical status can only be good or not good.

To evaluate the state of rivers, the Water Framework Directive (2000/60/EC) considers:

| Ecological status | Chemical status |
|---|---|
| - Parameters supporting biology (general physico-chemical parameters and specific pollutants)<br>- Hydromorphological quality | - 33 priority substances (Annex X)<br>- 8 other pollutants |

**Table 4. Factors which evaluate the ecological and chemical status of waterbodies. Source: Escaut sans Frontières**

### 3.4.1. Ecological status

A sufficiently high concentration of dissolved oxygen is of great importance for life in the water, and plays an important role in self-purifying processes. The higher the water temperature, the less oxygen can be absorbed by the water.

Determination of the chemical oxygen demand and biochemical oxygen demand allows to explain any oxygen deficits.

- The concentration of dissolved oxygen in the basin declined around 90 years, reaching a value of almost 0 mg/l. In 2013, the concentration of dissolved oxygen doubled the average concentration. In the early nineties, there were very high concentrations of: more than 60 mg /l in all the reaches. Since the late 90s, the BOD remains below 5 mg/l. This contributes to a healthier water quality and to the self-purifying capacity of the river. The increase in oxygen concentration and the decrease in the BOD were due to the reorganization of domestic and industrial discharges, both in Wallonia and in Flanders.

Eutrophication occurs when there is an excess of nutrients such as nitrogen and phosphorus compounds. When this happens, a massive growth of algae and plant life can occur, producing both direct and indirect effects.

- The concentration of ammonium ($NH_4^+$) reached in the 90s limits of 45 mg N/l. After 2000, the concentration fell below 2 mg N/l, going from very poor to good.
- The concentration of nitrate has been fluctuating between 2 and 4 mg N/l, which is a good condition.
- Total phosphorus showed in the 90s the maximum value, around 7 mg P/l. After 2000 the concentration fluctuates around 0.5 mg P/l, with occasional higher peaks. Average concentration higher than 0.7 mg P/l correspond to a bad condition.

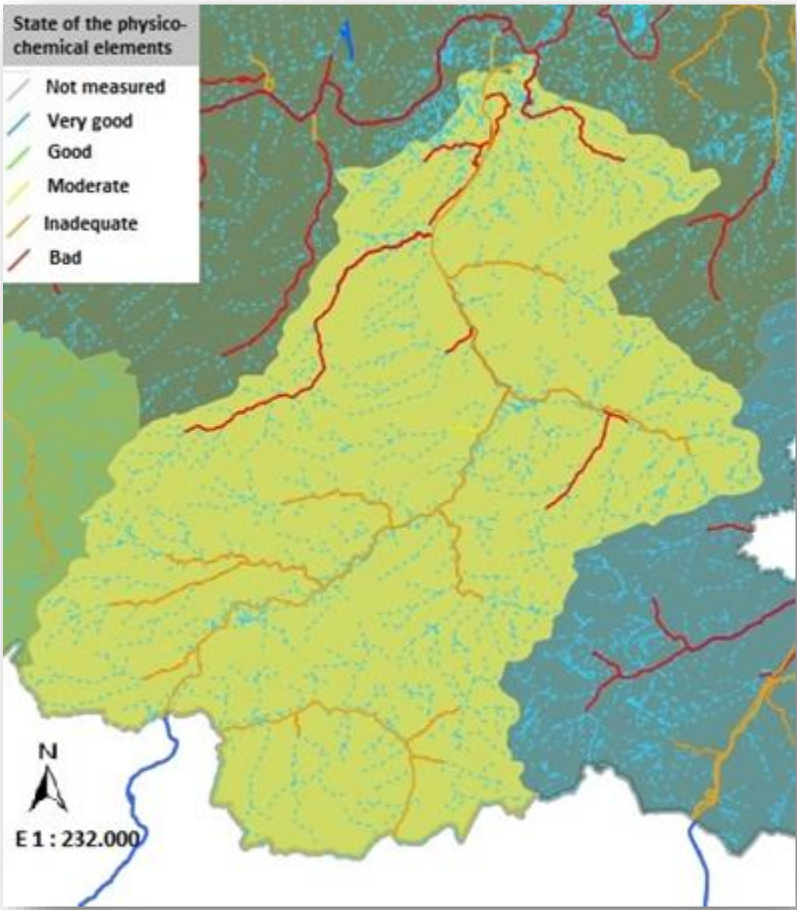



**Figure 6. State of the physico-chemical elements. Source: Integraal Waterbeleid**

Apart from the physico-chemical quality elements named above, there are biological quality elements:

- The VMM uses the Belgian Biotic Index in order to measure the biological quality. The BBI is an indicator based on the distance and presence of macro-invertebrates. The value of the BBI improved from the 90s until the present, but it is still moderate and inadequate depending on the part of the basin.
- The fish index scored moderate in 2011. The situation for phytoplankton is bad and for phytobenthos is moderate to good.

To complete this theme, highlight that hydromorphology is also an important factor that determines the ecological status of the watercourse: the more variety in hydromorphology, the more different habitats may exist. Hydromorphology includes several aspects as variability in width and depth, quantity and dynamics of water flow, river continuity, degree of meanders, structure and material of bed and banks, etc.

In the Dender basin, the predominant state in respect of hydromorphology is moderate. Only 15% have an insufficient hydromorphological state, and another 15% has a good score.

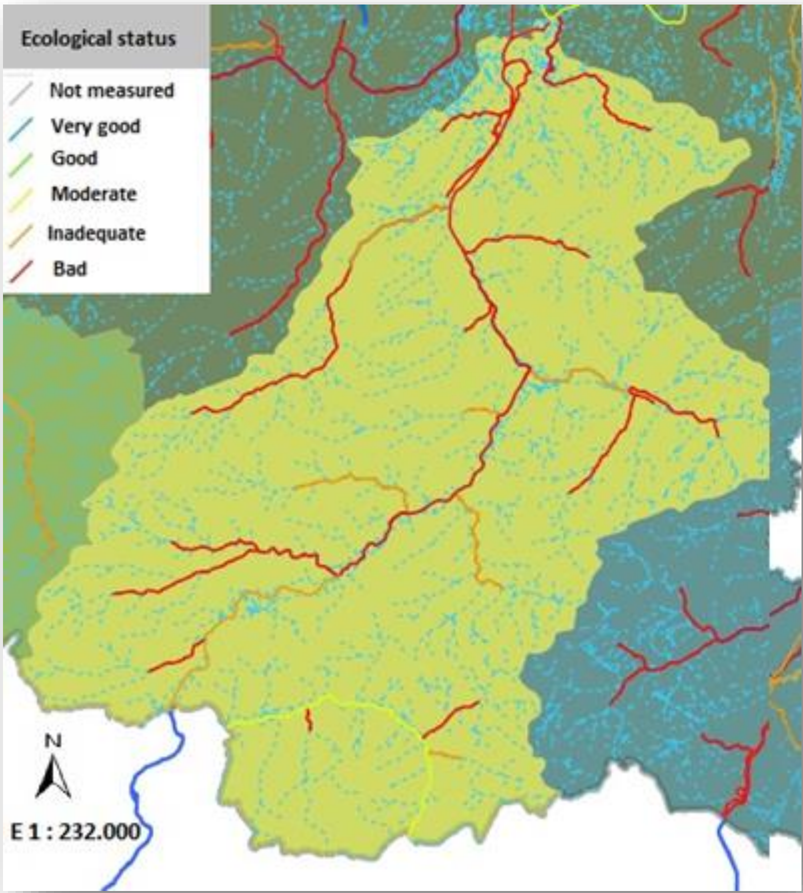



**Figure 7. Ecological status. Source: Integraal Waterbeleid**

### 3.4.2. Chemical status

The presence of hazardous substances is also measured in the basin, particularly heavy metals and pesticides. Over the period 1990-1997, the concentrations of heavy metals decreased, particularly for arsenic, chrome and zinc since 1994.

In the past, the river Dender was contaminated with heavy metals. Obviously, this had an effect downstream and on the sediment quality.

- Large improvements were measured for cadmium and lead: until the beginning of the 2000s, the cadmium peaks were 10 mg Cd/l and most of it was captured in the sediment. With respect to lead, since 2005, the concentrations are typically below 5 mg Pb/l, but there are still peaks of around 10 mg/l. For both elements, the environmental standard is respected.

- The prohibition of the use of some pesticides in the basin had a beneficial effect on the Dender. For instance, the insecticide lindane is not present now, but it was used in high concentrations (even more than 300 mg/l); the herbicide diuron almost disappeared from the Dender since 2005. However, authorized pesticides, including herbicides flufenacet will still be used in the Dender.

#### 3.4.3. Riverbeds

Concerning the soil of the riverbeds, pollution is also well present. The VMM measures its quality on 18 points in the basin. Soils are classified by the degree of quality. In the Dender basin, there are no strongly polluted riverbeds (5th class), but 22% are very polluted (4th class), 61% polluted, 17% moderately polluted and no clean riverbeds.

All in all, the quality of the surface water in the Dender basin is worrying. However, it is far from the worst situation observed in Flanders. The quality problem is global. It is noticeable that the quality of surface water at the entry of the basin is improving. Traditionally incoming water from Wallonia was of a very inferior quality. Since the last years, the development of purification in the Walloon region explains this improvement.

### 3.5. Measures taken to improve water quality

Over the years, several actions have been undertaken in the basin in order to improve the water quality: the construction of water treatment plants allowed the treatment of urban wastewater; the sensitization of farmers to make better use of pesticides or imposing strict discharge standards of industries. In the following years, the application of river basin management plans will improve the water quality of the rivers and canals. According to the article of Jérôme Delvaux of the Walloon Ministry of Environment and Water, given the current state of water bodies, it is likely that the intended purpose of a good status to be achieved between 2021 and 2027, depending on the water body.

### 3.6. Diagnosis of water quality

The assessment of the water quality can be done based on the ambient water quality standards. The standards set by the local Flemish authorities (VMM) are listed in the next table:

| Parameter | Concentration (mg/l) |
|---|---|
| DO | $> 5$ |
| BOD | $< 6$ |
| $NH_4$-N | $\leq 11.3$ |
| $NO_3$-N | $< 5$ |

**Table 5. Water quality standards for Flemish water given by VMM**

The water quality has improved considerably since the nineties for most standards, but there is still needs a lot of effort.

In 1960, the quality of the water was particularly low due to the discharge of untreated sewage and wastewater. In those days, life was not possible in the Dender: the anoxic environment only allowed bacterial life along the river. The Dender was a black, stinking river, even covered with foam in some reaches.

Thanks to the construction of wastewater treatment plants in the early 21$^{st}$ century, the strict standards and controls improved the water quality. As a consequence, the lives of fish were possible again in the Dender. In 2011, 24 species were distinguished in the river, including rare species such as loach and bitterling; the highest diversity of species was found in Geraardsbergen. However, the variety of fish is still too limited for a river like the Dender. The artificial banks, are not beneficial for the survival of fish, and the weirs and locks are barriers to fish migration. All the dams should have a fish ladder so that the fish can migrate and new species can reach the river.

One aspect which should be noted is that the river begins in the Walloon region and this is often a problem when dealing with the water quantity and quality issues.

In the sections below, the parameters which are going to be analyzed according to the Th data are: temperature, DO, $BOD_5$, $NH_3$ and $NO_3$. In order to do this, the characteristics of the monitoring network along the river are needed.

There is a total of 7 control points available along the river, which corresponds to different reaches in the river. Next table shows these relations and the number of observations in each station. The number of observation in one year is between 11 and 12, which corresponds to one measure per month.

| Control stations | Name | Corresponding reach | Measuring Point Nr. | Coordinates | No. Obs |
|---|---|---|---|---|---|
| 1 | Geraardsbergen 1, Overboelare | 1 | 511000 | E 114589 N 161380 | 34 |
| 2 | Geraardsbergen 2, Idegem | 5 | 508000 | E 117914 N 165183 | 35 |
| 3 | Ninove | 8 | 507000 | E 124586 N 168883 | 35 |
| 4 | Denderleeuw | 13 | 505000 | E 129735 N 175860 | 11 |
| 5 | Aalst | 16 | 500900 | E 127138 N 181189 | 36 |
| 6 | Dendermonde | 19 | 499600 | E 129166 N 189644 | 12 |

**Table 6. Observation stations along the river**

Next figure shows the position of the observation stations along the river.

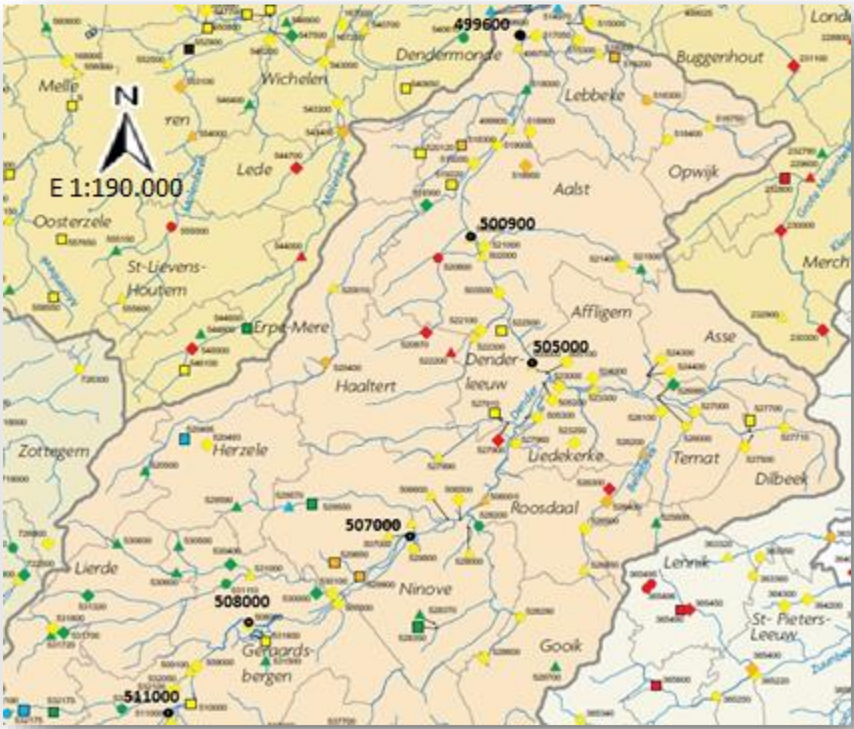



**Figure 8. Monitoring network of the available data. Source: VMM**

Thanks to the data in the different stations, the comparisons will be done by representing the data in a graphical format. In this case, the best way to clearly graph the observed data is by representing the evolution over the available period, for all stations. Therefore, it is possible to compare the maximum and minimum values, as well as seasonal changes. In this case, the period shown is from 2010 to 2012, except from air temperature. It has also been chosen to perform the comparison by showing the observation results for different days with a longitudinal analysis.

### 3.6.1. Air temperature

Air temperature and solar radiation are important factors when controlling the water quality. They influence the solubility of the gases (among them the solubility of oxygen) and salts, as well as biological reactions. The temperature, in addition, becomes a direct index of contamination in the case of discharges.

High temperature implies the acceleration of putrefaction, increasing the oxygen demand and decreasing the solubility.

High temperature can cause the proliferation of pathogenic organisms such as bacteria and parasites. These are very adaptable and lead to a high mortality of fish and aquatic animals. Eutrophication can be another consequence of the increase of temperature, since there is an optimal temperature for the different species to live:  the excess of nutrients favours the growth of algae which makes the water cloudy. The cloudy water inhibits the process of photosynthesis of the plants and this causes the decrease of oxygen in the water which makes impossible life for some species. In this way, the biological balance is damaged.

The next figure shows the data of the average air temperature for the year of study. It will be seen that the variation of temperature has different consequences in the concentration of other parameters.

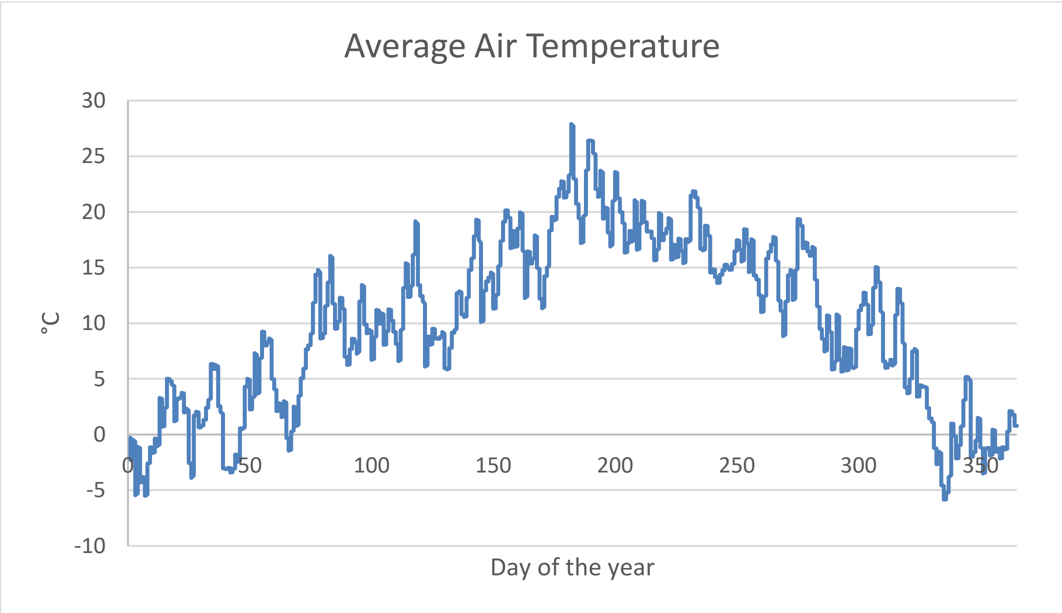



**Figure 9. Average temperature of the air in the year 2010**

The graphic shows that the minimum temperature is -5.8 °C and the maximum is 27.9 °C. The average temperature for the year 2010 is 10 °C.

### 3.6.2. Biological oxygen demand ($BOD_5$) and dissolved oxygen (DO)

The BOD measures the amount of oxygen used by microorganisms, especially bacteria, fungi and plankton, during the degradation of the organic matter contained in a sample.

It is most commonly expressed in milligrams of oxygen consumed per litre of sample during 5 days ($BOD_5$) of incubation at 20°C. As a parameter of water quality, it is an indicator of the amount of organic matter it contains.

The content of organic matter in a river depends on several factors such as: the volume of urban and industrial discharges, the capacity of self-purification of the river, the purification infrastructure, diffuse pressures such as irrigation returns, etc.

$BOD_5$ is directly related to the dissolved oxygen concentration because one of the main causes of the decrease of DO is the degradation of the organic matter.

It is necessary to ensure that the oxygen levels in the river are above the acceptable levels as it affects aquatic life, since the DO is considered as the indicator of the health of the ecosystems. The oxygen in the aquatic system is produced by the photosynthesis of plants and removed by respirations of plants, animals and bacteria.

Next graph represents the evolution of DO along the period from 2010 to 2012:

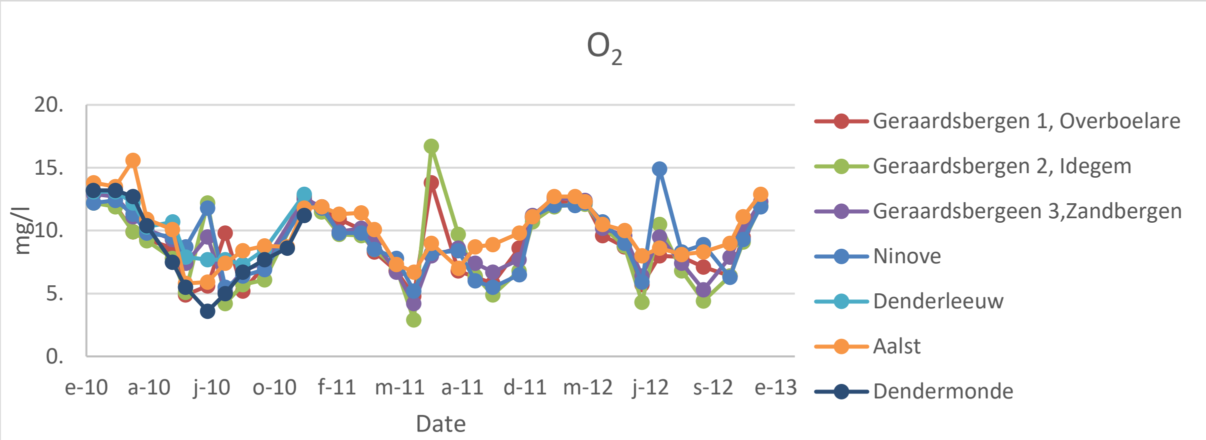



**Figure 10. Evolution of DO over the period studied for all the stations**

The graph shows that the levels of oxygen fluctuate between 2.9 and 16.7 mg/l in the three years. Comparing these values with the water quality standards (the level must be greater than 5), the dissolved oxygen level does not meet the requirements at the stations of Dendermonde and Geraardsbergen during the season of summer. During these months, the levels of DO suffer a significant decrease for the major part of the stations. The decrease of oxygen during these months can be explained with the increase of temperature:  warmer waters are able to dissolve smaller amounts of oxygen.

In the graph, it can be observed that the period in which the variation between the different stations is higher is during the summer. In this case, the peaks of oxygen in some stations can be due to the photosynthesis of the vegetation.

Dissolved oxygen follows the same shape for the years after 2010. However, higher values are found in later years.

As for the longitudinal profile:

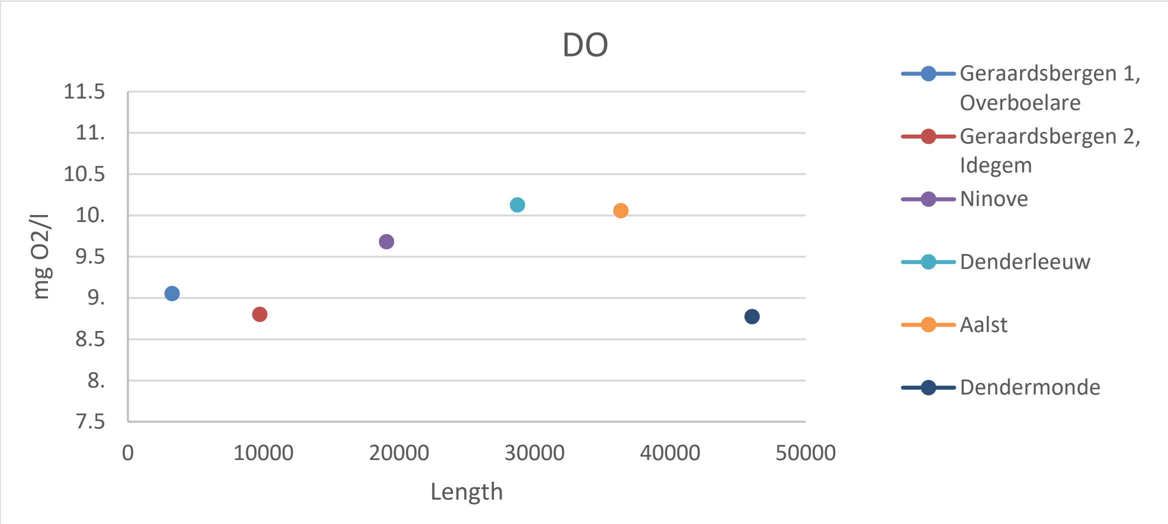



**Figure 11. Average of DO values for all the stations**

This profile shows that the DO concentrations are lower in the stations of Geraardsbergen and Dendermonde. As said before, this can be due to the households and agriculture in the basin.

Next graph represents the evolution of $BOD_5$ in the main river:

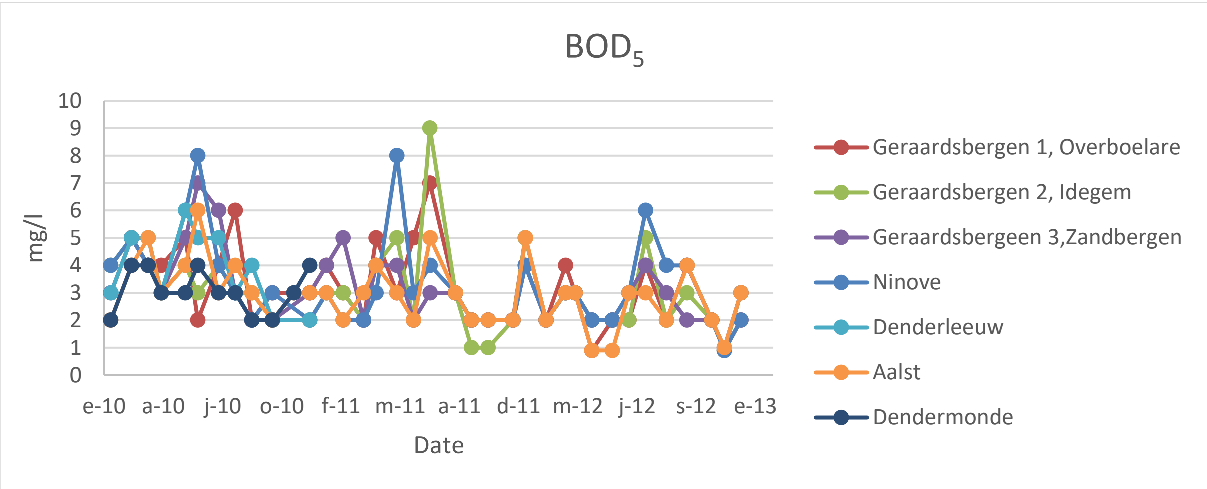



**Figure 12. Evolution of $BOD_5$ over the period studied for all the stations**

The amount of oxygen necessary to degrade organic matter in the river fluctuates between 2 and 9 mg/l. As in the previous case, the standards are not met at several stations (in this case, Geraardsbergen and Ninove) during the summer months, where the concentration of oxygen used is greater than 6 mg/l.

Now, making a comparison of the two previous graphs, it should be noted that the increase of BOD in the river is related with the reduction of DO. As said before, this can be because the degradation of organic matter leads to the decrease of oxygen levels.

Now, giving an overview of the three years, it is observed that in the years after 2010, the BOD values are lower. That is, there is a slight improvement for both the DO and BOD variables in water quality, for the years after 2010. Again, the peaks observed are due to the increase of organic matter (algae) in the water, so it is necessary to activate the algae simulation option.

In both cases, the predominant use which causes this evolution of the oxygen is the one of households.

### 3.6.3. Nitrogen and its compounds

Nitrogen comes from the atmosphere, and it is extracted by the living beings when they metabolize. Then, the nitrogen can be found in sewage as ammonia and urea. These compounds are the major sources of nitrogen for the growth of bacteria and plants in aquatic environments.

The nitrogen compounds in water come mainly from organic matter. This organic matter comes from the runoff, the metabolism of organisms, the putrefaction of vegetables and a very important part from organic substances added by men.

Ammonia compounds are found in water under reducing conditions. Ammonia is the preferred nitrogen-containing nutrient for plant growth. It can be converted to nitrite ($NO_2$) and nitrate ($NO_3$) by bacteria, and then used by plants. This process is called nitrification, and it is faster when the water is well aerated.

Nitrate and ammonia are the most common forms of nitrogen in aquatic systems. Nitrate predominates in unpolluted waters. Nitrogen can be an important factor controlling algal growth when other nutrients, such as phosphate, are abundant. If phosphate is not abundant it may limit algal growth rather than nitrogen. Ammonia is excreted by animals and produced during decomposition of plants and animals, thus returning nitrogen to the aquatic system.

A high content of ammonia facilitates the multiplication of microbes, and that is why the presence of free ammonia or ammomium ion in the water is an indicator of recent and dangerous contamination. The toxicity of ammonia is critically dependent on pH and temperature. The un-ionized form ($NH_3$) is more toxic than the ionized form ($NH_4^+$). As pH increases, $NH_4^+$ is converted to $NH_3$, and the toxicity increases. Higher temperatures also favour the more toxic form.

In addition, in surface and groundwater, an important source of nitrogen comes from the use of fertilizers in agriculture.

The following paragraphs explain and illustrate the nitrogen cycle:

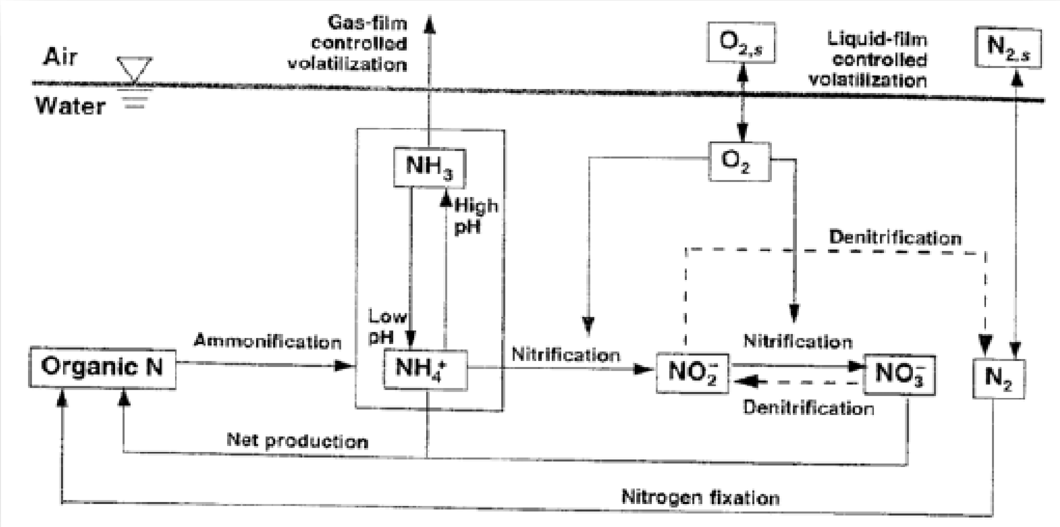



**Figure 13. Nitrogen cycle**

Ammonification

Wastewater discharges incorporate both organic nitrogen (particulate and dissolved) and ammonium into the natural systems. Different animals, plants and microorganisms carry out the process of ammonification or passage of organic nitrogen to ammonia.

Nitrification

In an aerobic environment bacteria of the genus *Nitrosomone* convert ammonium to nitrite ion. Nitrites are rapidly oxidized to nitrates in a single step mainly by the bacteria of the genus *Nitrobacter*.

$$NH_4^+ + 1.5O_2 \rightarrow 2H^+ + H_2O + NO_2^-$$

$$NO_2^- + 0.5O_2 \rightarrow NO_3^-$$

Denitrification

In aerobic media, the final nitrogen compound is nitrate. When the mass of water, for whatever reason, runs out of dissolved oxygen, the denitrification process takes place whereby the nitrate passes to nitrogen gas and the gas escapes into the atmosphere.

This process is the result of the activity of some anaerobic and heterotrophic bacteria such as *Pseudomonas denitrificans* and *Paracoccus denitrificans*.

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

Organic consumption and production

- Primary production consumes both ammonium and nitrates (greater preference for the first one)

- Death produces organic nitrogen.

Next figure is necessary to assess the evolution of nitrate in the main river:

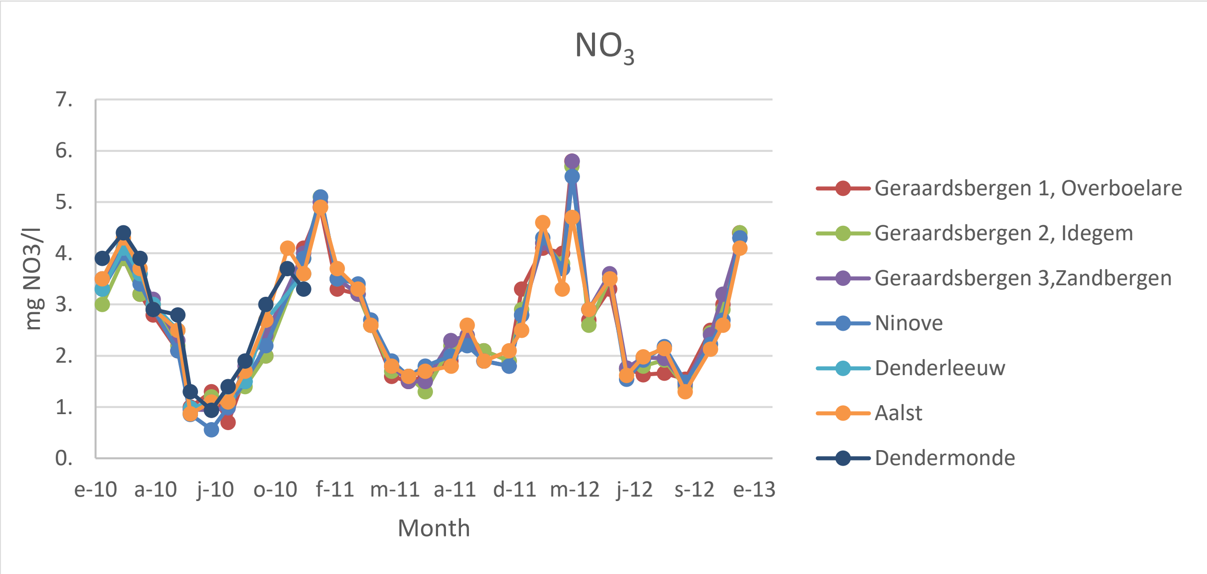



**Figure 14. Evolution of $NO_3$ over the period studied for all the stations**

The graph of $NO_3$ has the same tendency as the one of the DO. This is, the values are higher in the first and last months of the year, and they are lower during the months of spring and summer. The graph shows that there is no relevant variation for the value for the same dates in the different stations. In this case, the concentration of DO is related with the concentration of nitrate and has the same tendency because the process of nitrification is faster when the water is well aerated.

At the same time, the levels of $NO_3$ are similar for every station in each month. The levels of $NO_3$ vary between 0.56 and 6 mg/l, therefore, the standards are not met throughout the period.

Giving an overview, the same trend is observed in the three years, but in the years after 2010, it is observed that the values of this variable are higher.

The next figure represents the evolution of $NH_3$ along the river:

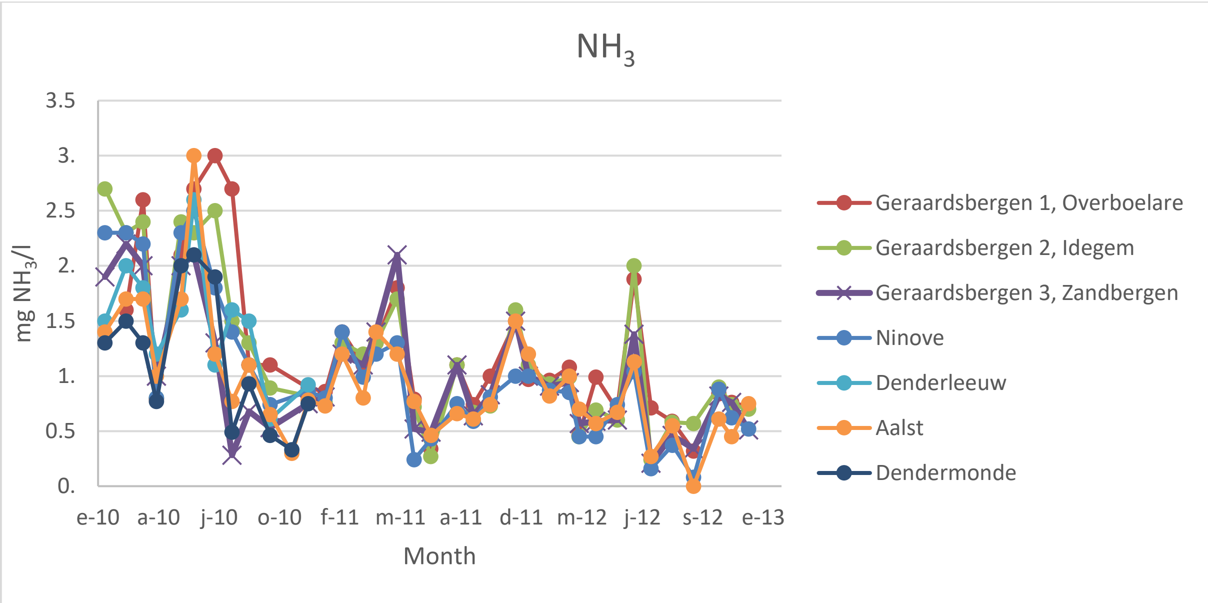



**Figure 15. Evolution of $NH_3$ over the period studies for all the stations**

The graph shows that the levels of ammonia are higher in the months of March and in the months of summer, and it fluctuate between 0 and 3 mg/l. Therefore, the standards are met during all the period and for all stations. The concentration of $NH_3$ is higher because oxygen levels are lower during those months; this means that ammonia available in the environment cannot be transformed into nitrate.

As in the previous cases, the period in which the variation between the different stations is larger is during the summer. $NH_3$ is the variable with the most irregular trend. In this case, it is observed that the values for the year 2010, for all the stations, are higher than for the subsequent years.

## 4. The conceptual water quality model

For integrated river water quality modelling, the hydraulic characteristics are to be modelled first. Because for water quality modelling in river reaches, the flow rates and velocities define the transport characteristics; the water levels or volumes determine the concentrations in the reach (Bauwens, 2015).

This section describes the tools and the process used to model the water quality in the main river and the tributaries of the Dender basin.

First, an explanation of the previous works in the matter of water quality in the Dender basin will be done. After this, the different steps needed to build the water quality simulator will be explained; this includes the setup of the model and the data processing.

## 4.1. Background

In order to build the model there are basic requirements of data from previous works in the Dender basin.

The conceptual water quality simulator uses the data that comes from the conceptual water quantity model. The latter provides the flow (Q), velocity (u) and depth (D) data in a time series format.

Other tools that have been used previously for water quality simulations in the basin are the software MIKE 11 and the ESWAT model:

- MIKE 11 modelling system: MIKE 11 is a dynamic, one-dimensional modelling package developed by the Danish Hydraulic Institute (DHI) suited for rivers and channels. It offers an integrated modelling of the river flow and its quality. The river flow and the water levels are simulated in the hydrodynamic (HD) model. The water quality module of MIKE 11 is called the EcoLab module. 'EcoLab' stands for Ecological Flow Modelling. It solves the system of coupled differential equations describing the physical, chemical and biological interactions in the river related to the aspects of river water quality influenced by human activities (DHI, 2011).
  However, using this software and due to the large number of parameters and the high computational time of the MIKE 11 water quality model, a detailed calibration could not be performed.
- ESWAT model: The term 'ESWAT' refers to the Extended Soil and Water Assessment Tool and is an extension of the SWAT 98.1 module developed by the USDA (Arnold et al. 1998). It is a semi-distributed hydrological model to simulate an integral water quantity and quality in river basins (Van Griensven & Bauwens, 2002). It deals with the QUAL2E equation (Brown and Barnwell, 1987). This model was used in previous works to calculate agricultural nutrient load.

With the available data obtained from these tools, it is needed the calibration and validation of the conceptual hydraulic model in order to setup the conceptual water quality simulator. Finally, the conceptual water quality can be used to simulate the concentration of Nitrate ($NO_3$), Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD) and Ammonia ($NH_3$) in the river.

## 4.2. The conceptual water quality model for the river Dender

### 4.2.1. The conceptual water quality simulator

The conceptual river water quality model can be used to simulate the water quality processes in the river, canal or water way. Its formulation is based on the ordinary differential equations (ODEs) of QUAL-2E transformation, from integration of the QUAL2E transformation formulations in to the CSTR-based mass balance equations. It integrates the mass-balance equation with the transformation/decay processes and solves the resulting differential equation using a quasi-analytical solution.

It can be used to simulate various conservative and non-conservative pollutants that could affect the quality of water along a river/water ways.

The conceptual river water quality simulator is based on a dynamic method, analogous to static linear reservoir approach, for conceptual modelling of water quality problems with the aim of increasing computation efficiency while maintaining accuracy and stability of the simulation results.

The method is compared with numerical solutions implemented for solving the ordinary differential equations of the QUAL2E process formulations. The SWAT river routing module is considered for classical Euler solution method of linear ODEs and the classical explicit fourth order Runge-Kuta (RK4) as well as fourth order four-stage diagonally implicit Runge-Kuta numerical integration solution methods are considered for comparison of solution stabilities under extreme conditions.

It is observed that the quasi-analytical approach gives unconditionally stable solution even when the four-stage fourth order diagonally implicit Rung-Kuta method becomes unstable. This makes the new quasi-analytical approach robust, over any computation time step, for simulating water quality variables during critical low flow periods of large residence time. Besides, it has a competitive advantage over the numerical approach for simulating water quality in controlled water ways such as navigation canals where the residence time is very large (Befekadu et al, 2016).

### 4.2.2. The stream network

In order to set up the stream network, tabular information is needed to determine the upstream to downstream flow directions.

It is noted that the main river is divided in 19 reaches, 5 tributaries and there are also 56 flood branches, which are represented parallel to the main river. There is a total of 81 objects identified, each one with its corresponding downstream reach ID, length of the reach and elevation downstream and upstream. The slope of the reach is internally calculated based on the maximum elevation, minimum elevation and the length of the reach.

The next figure shows the scheme of the main river (from 1 to 19) and tributaries (from 20 to 25) in the model:

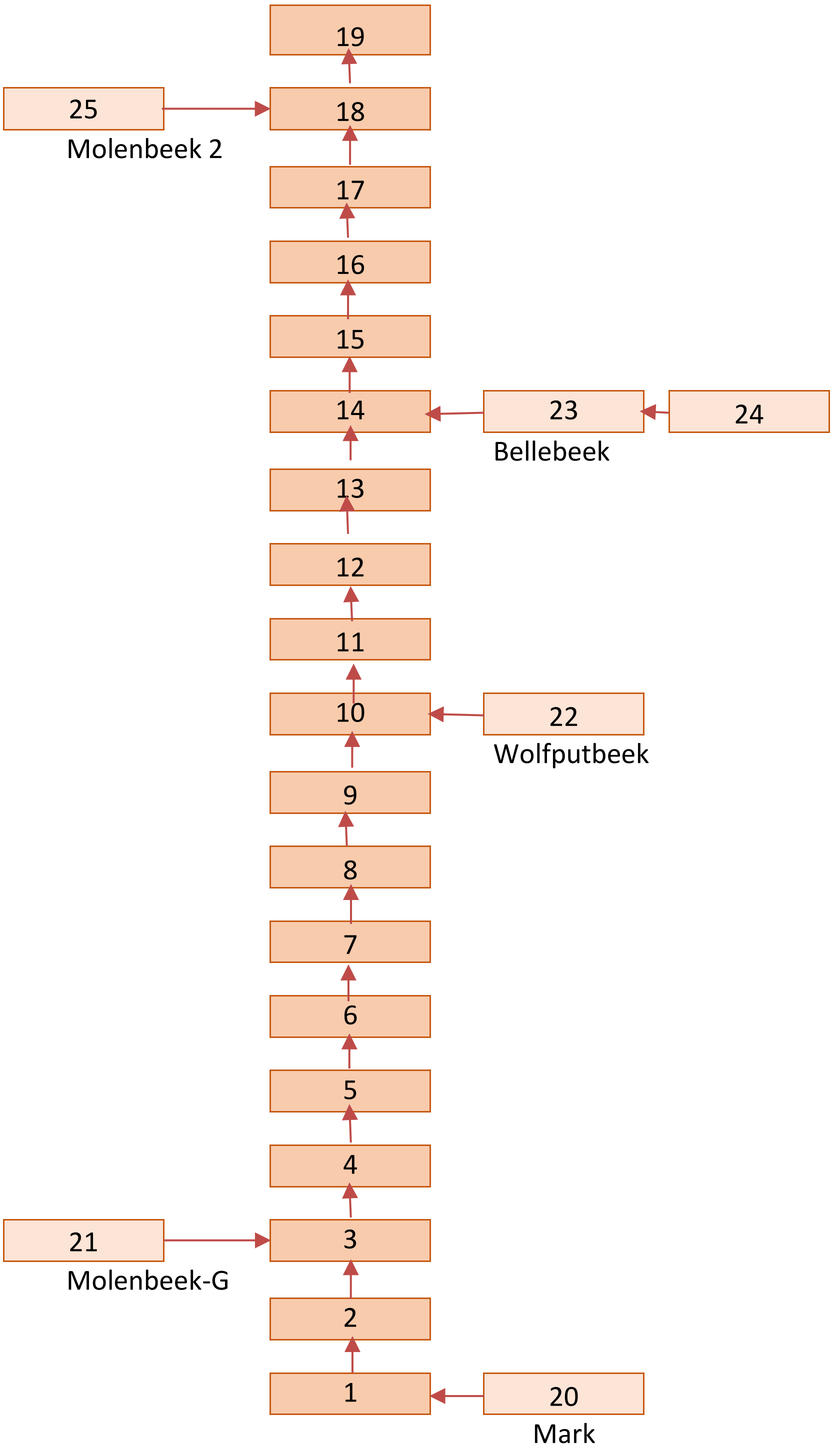



**Figure 16. Scheme of the main river and its tributaries**

### 4.2.3. Hydraulic data

For integrated river water quality modelling, the hydraulic characteristics are to be modelled first: for water quality modelling in river reaches, the flow rates and velocities define the transport characteristics; the water levels or volumes determine the concentrations in the reach.

The data required for all reaches are the discharge (in $m^3/s$), velocity (in m/s) and depth (in m). The conceptual water quantity model had already provided the information for these variables in a time series format, so the data was available from previous works in the basin.

#### 4.2.4. Temperature and solar radiation data

This data is needed in a time series format. It is required for correcting the decay constants for temperature variation, for estimating the saturated dissolved oxygen and for estimating the kinematic viscosity of water that is needed for sediment transport simulation. Solar radiation data is required for estimating algal growth rate.

#### 4.2.5. The point source boundaries

There has to be a minimum of one point source boundary at the most upstream reach of the stream network for the model to simulate without crashing. In this case, the most upstream reach represents the load of pollutant that comes from the reaches of the Walloon region.

The different point source boundaries need to have a time series format with the pollutant load (in kg/hr) entering the system. These boundaries can represent industrial, agricultural, domestic or wastewater treatment plant (WWTP) discharge. For example, the presence of a WWTP in the river has to be added as a point source boundary in order to take into account the load pollutant produced in the WWTP.

The load pollutant in the point source boundaries is the concentration multiplied to the discharge. However, for distributed sources, which affect to several reservoirs, the load pollutant is calculated in a different way:

- Domestic distributed sources: in this case, the calculation of the discharge takes into account a factor which weighs the length of the reach. This factor is multiplied to the total discharge of the boundary; the calculated flow for each reservoir is the one that will be used to calculate the pollutant load.
- Agricultural distributed sources: in this case, there are two possibilities. The agricultural runoff concentration data can be used from the results of the ESWAT model or from the average concentration of the observed data. It will depend on the results obtained later. The model also provides the result for discharge, but the results of the hydraulic data mentioned previously will be used. The calculation of the agricultural discharge takes into account the area draining to the given reach and associated to a specific rainfall-runoff boundary (in $km^2$) and the rainfall-runoff discharge (in in $m^3/s/km^2$).

In Appendix A a list is added with all the boundaries present in the model, as well as the type of discharge and number of reach that is affected. There is a total of 113 boundaries.

#### 4.2.6. Rainfall-runoff boundary

These boundaries are treated as discharge-only boundaries. Rainfall- runoff boundaries are used for agricultural sources, since this option is provided to use the same boundary as the conceptual hydraulic model when the data source of the pollutant load is different from the boundaries used in the hydraulic model. These boundaries are in a time series format and are similar to the discharge data of the point source boundaries.

### 4.2.7. Simulation options

In the simulation options, it is included the beginning and ending dates and time steps of the simulation. The variables which can be simulated in the model are nitrogen compounds, phosphorus compounds, algae, bio-chemical oxygen demand and dissolved oxygen. In this case, the interesting variables to simulate are nitrate, ammonia, bio-chemical oxygen demand and dissolved oxygen. For all the above-listed determinants, the model requires provision of timeseries values at boundaries and point sources.

The relevant simulation options in this particular model will be explained in the following lines:

- Aeration at hydraulic structures can be simulated if the structure is an overflow weir. Through the river there are overflow weirs which can increase the dissolved oxygen near these structures; it has to be modelled as a local oxygenation source. Oxygen can be transferred into the waters during the operation of hydraulic structures like weirs and small dams. These hydraulic structures can be evaluated regarding the efficiency of reaeration. In the model, the fraction of the total discharge which flows over the hydraulic structure can be determined in order to obtain the real parameters for the calibration.
  Butts & Evans, 1983 described an empirical relationship for reaeration process at weirs given by:
  $$r = \frac{c_s - c_u}{c_s - c_d} = 1 + 0.38 * a * b * h * (1 - 0.11 * h) * (1 + 0.046 * T)$$
  Where, r=oxygen deficit ratio, $c_s$= saturation concentration of DO (mg/l), $c_u$= DO concentration upstream (mg/l), $c_d$= DO concentration downstream (mg/l), $a$= water quality factor (-), $b$=weir dam aeration coefficient (-), $h$= static head loss (m), $T$=water temperature (°C). The values of coefficients ‘a’ and ‘b’ are:

| Type of hydraulic structures (dam) | “a” coefficient (-) |
|---|---|
| Flat broad crested regular step | 0.7 |
| Flat broad crested irregular step | 0.8 |
| Flat broad crested vertical face | 0.6 |
| Flat broad crested straight slope face | 0.75 |
| Flat broad crested curved face | 0.45 |
| Round broad crested curved face | 0.75 |
| Sharp crested straight slope face | 1 |
| Sharp crested vertical face | 0.8 |
| Sluice gate | 0.05 |

**Table 7. Coefficients depending on the type of hydraulic structures (Butts & Evans, 1983)**

| Polluted state | “b” coefficient (-) |
|---|---|
| Gross | 0.65 |

| | |
|---|---|
| Moderate | 1 |
| Slight | 1.6 |
| Clean | 1.8 |

**Table 8. Water quality coefficients for different pollution conditions of the water system (Butts & Evans, 1983)**

- The number of time steps, both for the input and the output: it depends on the period which is simulated.

## 5. Model calibration

The process of calibrating mathematical models consists of comparing the current data recorded by the control networks of the basin (known as Observed) and the data that the model simulates (known as Simulated).

Once the model is built it is necessary to calibrate it so that it can reproduce the real behaviour of the system. To do this, the simulated values of the pollutant load at certain nodes are compared with the observed data at the stations located at the same points along the river.

The available data for simulated values is hourly and for observed values it is monthly. For this reason, when adjusting the data, the objective is to trend the evolution of values instead of looking for a perfect fit.

In the model, the simulated period is two years, so the calibration period extends from 01-01-2010 to 31-12-2011. The choice of this period is due to the availability of previous works in the basin for this period. Furthermore, the observed data provided by the VMM is available for this period.

The calibration is performed by manual iterative trial-error, without using any other automatic calibration method. For this, the section of the simulations options explained previously contribute to the calibration: apart from modifying the parameters of calibration, the factor of hydraulic structures and the multipliers input can be modified in order to obtain a better calibration.

To calibrate the model, it is important to know which the observation stations are. As said in section 3, there is a total of 7 control points available along the river, which corresponds to different reaches in the river.

The process carried out to calibrate the model depends on the observation data available. The comparison between the simulated and observed data starts from the upstream (reach 1) and continues to the following reaches.

First, the global parameters (for calibrating all parameters except the sediment transport simulation) must be modified for reaches 1 and 5, following the upstream. The process consists in changing the factors which modify the parameters. These factors are one at the beginning of the calibration. Calibration on reach 6 has been more difficult and another solution apart from changing the global parameters has been necessary. In this case, the alternative has been to set different simulation options to obtain a better calibration of the parameters in the model.

## 5.1. Influential parameters for BOD and DO

The parameters which must be modified and which influence the most for BOD and DO calibration are RK1, RK2 and RK3, where:

| Default value | Parameter | Definition |
|---|---|---|
| 1.71 | RK1 | Carbonaceous biological oxygen demand deoxygenation rate coefficient in the reach at 20º C [day-1] |
| 50 | RK2 | Oxygen reaeration rate in accordance with Fickian diffusion in the reach at 20º C [day-1] |
| 0.36 | RK3 | Rate of loss of carbonaceousbiological oxygen demand due to settling in the reach at 20º C |

**Table 9. Influential parameters for the calibration of BOD and DO**

## 5.2. Influential parameters for $NO_3$ and $NH_3$

Regarding the $NO_3$ and $NH_3$, the most influential parameters are BC1, BC2, BC3, kd and ko2, where:

| Default value | Parameter | Definition |
|---|---|---|
| 0.55 | BC1 | Rate constant for biologicaloxidation of $NH_4$ to $NO_2$ in the reach at 20º C [day-1] |
| 1.1 | BC2 | Rate constant for biological oxidation of $NO_2$ to $NO_3$ in the reach at 20º C [day-1] |
| 0.21 | BC3 | Rate constant for hydrolysis of organic N to $NH_4$ in the reach at 20º C [day-1] |
| 0.35 | BC4 | Rate constant for mineralization of organic P to dissolved P in the reach at 20º C [day-1] |
| 0.7 | kd | Denitrification rate of nitrate in the reach at 20º C [day-1] |
| 2 | ko2 | Half saturation constant (oxygen) for denitrification [mg/l] |

**Table 10. Influential parameters for the calibration of $NO_3$ and $NH_3$**

## 5.3. Setting the parameters for all the reaches

The factors which modify the global parameters in the model must be within a fixed range. In the next sections, the results for the calibration of the different reaches are going to be shown.

To calibrate the dissolved oxygen, which has a high value in the summer for the observed data, the algae simulation option has been activated. As said before, it must be simulated that the photosynthesis is active during the summer, so the CHLA must be present during the simulation. It is done modifying the column CHLA for the different boundaries.

Besides the algae simulation, it is necessary to make some changes in the boundaries with agricultural load. As said before, the concentration of the ESWAT model was used for the agricultural load. However, the simulated values for $NO_3$ using this concentration were very fluctuating. To solve this, a constant concentration is calculated for the timeseries. The new concentration is equal to the mean of the observed data concentrations for each month.

The results obtained for the four studied variables are shown in Appendix B. They will be discussed in the following lines:

Biochemical Oxygen Demand ($BOD_5$)

Figures in Appendix B show that, in general, the model results are mostly over-estimated compared to the observed data. The simulated values show that they are among the observed values. However, it is important to note that the BOD is one of the most problematic variables.

Dissolved Oxygen (DO)

In terms of dissolved oxygen, reliable results are observed. The simulated data follow the trend of the observed in all sections.

For this variable, the peaks found in some stations are not well simulated with the calibration. As mentioned before, a better calibration for these peaks has been possible with the activation of the alae simulation option.

Nitrate ($NO_3$-N)

From visual analysis of Figures B-1 to B-5, nitrate is the best simulated parameter, both spatially and temporally compared to other water quality variables.

Ammonia ($NH_3$-N)

Regarding this variable, it is observed that the data simulated by the model remain in the range of the data observed and follows the same trend. However, along with the BOD, these two variables are the worst represented.

One of the conclusions that can be drawn from this section is the following: in all the variables simulations, results match the observed data comparatively better at the upstream than the downstream sections of the river. This may be due to the accumulation of complex processes that occur as we move away from the head of the river. Hence, it may be suggested that the balance at the downstream sections need further calibrations.

Another thing to note is that the best represented variables are $NO_3$ and DO. On the contrary, the worst represented variables are BOD and $NH_3$.

In conclusion, the adjustments of the constituents are acceptable for the model and reflect the quality processes that occur in the studied river sections. In addition, they allow the simulation of future scenarios and, in this way, they allow to evaluate the proposed measures, with some reliability.

## 6. Model validation

Once the model is calibrated, the results for another data, not used in the calibration part, have to be compared. The validation shows how robust the model is to predict. For the validation of the model, independent observed data must be used; as we used the data of 2010 and 2011 for model calibration, the model validation will be performed with the data of 2012.

This step is performed with the same values for the model parameters used for the model calibration. At this point, the number of time steps, both the input and the output is set to three years.

After simulating the model for the three years, it is observed that the model is correctly calibrated.

The results of validation are shown in Appendix B. Figures from B-6 to B-10 show a good calibration. In them, the simulated values follow the same trend as the observed ones, for each variable and in each year represented.

## 7. Scenario analysis

Once the model is calibrated and validated, it is ready to simulate the situations which involve an improvement of the quality of the water.

In this case, the simplest scenarios which can be implemented in the model are the reduction of the pollutant load. The different types of discharges that can be modified in the model are the following: agricultural, domestic, WWTP and industrial.

In the scenarios proposed, the measures taken into account will combine the reduction of pollutant load in the different boundaries. Therefore, the model will be implemented by modifying the multipliers. In this way, it will not be necessary to change the boundary data file, which is more complex.

It is intended to reduce the pollutant load by half as an order of the VMM to see how it would affect in different reaches. Based on the results obtained, we study which are the two most beneficial scenarios for the river.

The process named in the previous paragraph is carried out as follows. For example, if we want to reduce the amount of nitrate from an WWTP discharge that reaches the river in half, we will put 0.5 instead of 1 in the multiplier that affects this boundary and this type of discharge.

In total, there will be five different scenarios, in which the conditions regarding agricultural, domestic or water treatment plants discharges will be modified.

The measures proposed to generate the improvement of the water quality in each type of discharge are the following:

WWTP discharges

For EDAR discharges, a better performance of the WWTP is proposed. The quality of this type of effluent is improved when reducing the concentration of nitrogen and phosphorus that comes out of the WWTP. For this, an improvement of the biological treatment in the WWTP is needed. In the model, this is reflected by modifying the boundaries related to that WWTP discharge.

Agricultural discharges

In agriculture, the use of sustainable production methods is proposed. That is, stop using excessively nitrogen fertilizers and phosphates and start sensitizing the population. The accumulation of nitrates and phosphates can be incorporated into the groundwater or be drawn into the channels and surface reservoirs. It is also important to start using pesticides that are not so aggressive with the environment.

Another measure for this type of pollutants is to use products of which the components and their effects on the environment are known.

Domestic discharges

For discharges of a domestic nature, there has to be a change in domestic habits. Among these habits are the following: do not throw medicines, oils, ammonia or cleaning products down the toilet. In addition, it is important to recycle and dispose of all the waste to the correct site. In this type of pollution, it is very important the awareness of the population.

Now, considering that the pollutants we used to calibrate and validate the model are nitrate, dissolved oxygen, ammonia and BOD, these will be the ones that we will have to modify.

The following sections show different possibilities reflected on various scenarios:

## 7.1. Scenario description

The following table summarizes the characteristics of the five scenarios proposed. It indicates the boundaries that are modified, the origin of the discharge and the reach of river to which it affects.

The data are contrasted from the table A, in Appendix A.

| | Boundary affected | Name | Reduction | Reach affected |
|---|---|---|---|---|
| Scenario 1 | 40 | DENDER_5975_WWTP | 50% | 4 |
| | 41 | DENDER_13864_WWTP | 50% | 6 |
| | 42 | DENDER_14120_WWTP | 50% | 7 |
| Scenario 2 | 27 to 32 | DENDER_0_14140_AGRI | 50% | 1 to 6 |
| | 33 to 38 | DENDER_0_14140_DOM | 50% | 1 to 6 |
| | 39 | DENDER_0_DOM | 50% | 1 |
| Scenario 3 | 27 to 32 | DENDER_0_14140_AGRI | 50% | 1 to 6 |
| | 43 to 45 | DENDER_14140_21720_AGRI | 50% | 7 to 9 |
| | 49 | DENDER_14140_AGRI | 50% | 7 |
| | 55 to 61 | DENDER_21720_36085_AGRI | 50% | 10 to 16 |
| Scenario 4 | 33 to 38 | DENDER_0_14140_DOM | 50% | 1 to 6 |
| | 39 | DENDER_0_DOM | 50% | 1 |
| | 46 to 48 | DENDER_14140_21720_DOM | 50% | 7 to 9 |
| | 50 | DENDER_14140_DOM | 50% | 1 |
| | 62 to 68 | DENDER_21720_36085_DOM | 50% | 10 to 16 |
| Scenario 5 | 27 | DENDER_0_14140_AGRI_RES1 | 50% | 1 |
| | 33 | DENDER_0_14140_DOM_RES1 | 50% | 1 |
| | 39 | DENDER_0_DOM | 50% | 1 |
| | 95 | MARK_20800_AGRI | 50% | 1 |
| | 96 | MARK_20800_DOM | 50% | 1 |
| | 101 | MARK_24500_WWTP | 50% | 1 |

**Table 11. Summary of the different scenarios proposed**

### 7.1.1. Scenario 1

In the first of the scenarios, the discharge of three of the WWTPs present in the river is modified. To represent this in the model, the multipliers corresponding to the pollutant load of $NH_3$, $NO_3$ and BOD are halved, in the correspondent boundaries.

Once the model is executed under these new conditions, it is observed how the affected reaches behave. In this case, the modification of these parameters would affect reaches 4, 6 and 7. Among these, reach 6 is not affected at all, so the results will be analyzed in reaches 4 and 7.

### 7.1.2. Scenario 2

In the second scenario, the distributed conditions of contamination by agriculture and domestic are modified. This distributed pollution affects sections 1 to 6. In addition, the domestic pollutant load that is poured in one of the first reaches is also halved.

In this section, the reaches from 1 to 6 are affected. As the river is most affected in reaches 5 and 6, these will be the ones represented.

### 7.1.3. Scenario 3

In this scenario, several boundaries that affect agricultural pollution are modified. Three of them are due to distributed contamination, and affect reaches from 1 to 16. The other condition that is affected affects reach 7.

In this case, the reaches that will be analysed are 10 and 16. They are the ones where the most notable changes occur.

### 7.1.4. Scenario 4

In this scenario, several conditions that affect domestic pollution are modified. Three of them are for distributed contamination, and they affect from the stretches 1 to the 16. The other boundaries which are modified affect reach 1.

The reaches analysed in this case will also be reaches 10 and 16.

### 7.1.5. Scenario 5

In scenario 5, the conditions that affect the river in its upstream section and its affluent Mark are modified. In the Mark tributary, the effluent from the WWTP is modified, as well as one of agricultural type and another of domestic type. The distributed pollutant load affecting section 1, of domestic and agricultural origin, is also halved.

With all this, the first reach of the model is represented.

## 7.2. Analysis of results

In this section we try to analyze the results of the simulations of the different scenarios. These results are analyzed in the reaches of the river that are affected by the variations made in the many cases. They are represented by different graphs. The vertical axis of the graph shows the parameter to be calibrated or validated, while the horizontal axis represents the date in MM/DD format.

In addition, it is also important to get the percentage of variation between the results obtained for each scenario and the current state.

In general, most pollutants experience improvement in all cases, but it varies depending on the measures proposed.

### 7.2.1. Results for scenario 1

The following figures represent the results for reaches 4 and 7 in the first scenario.

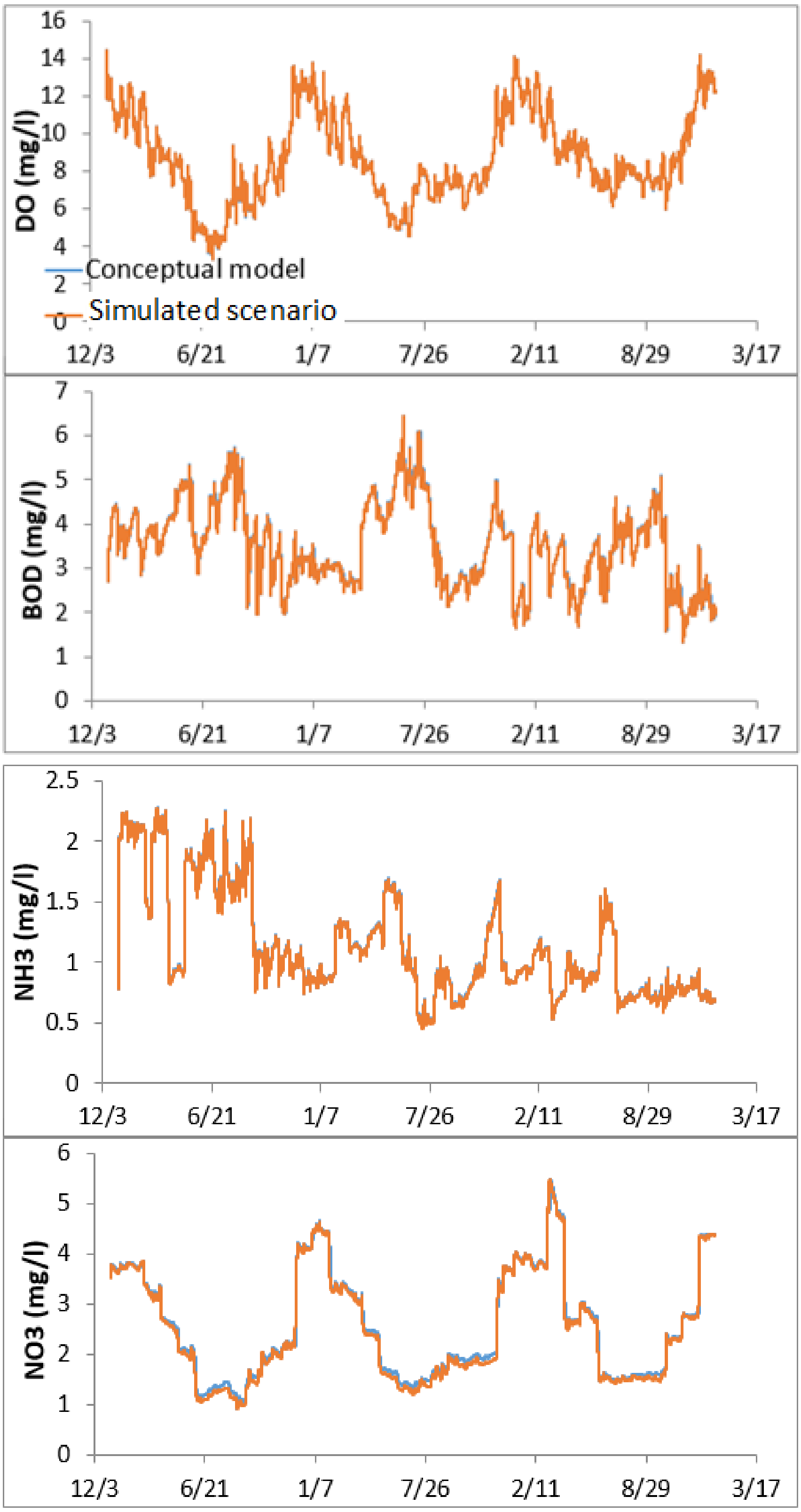



**Figure 17. Results of the scenario 1, for reach 4**

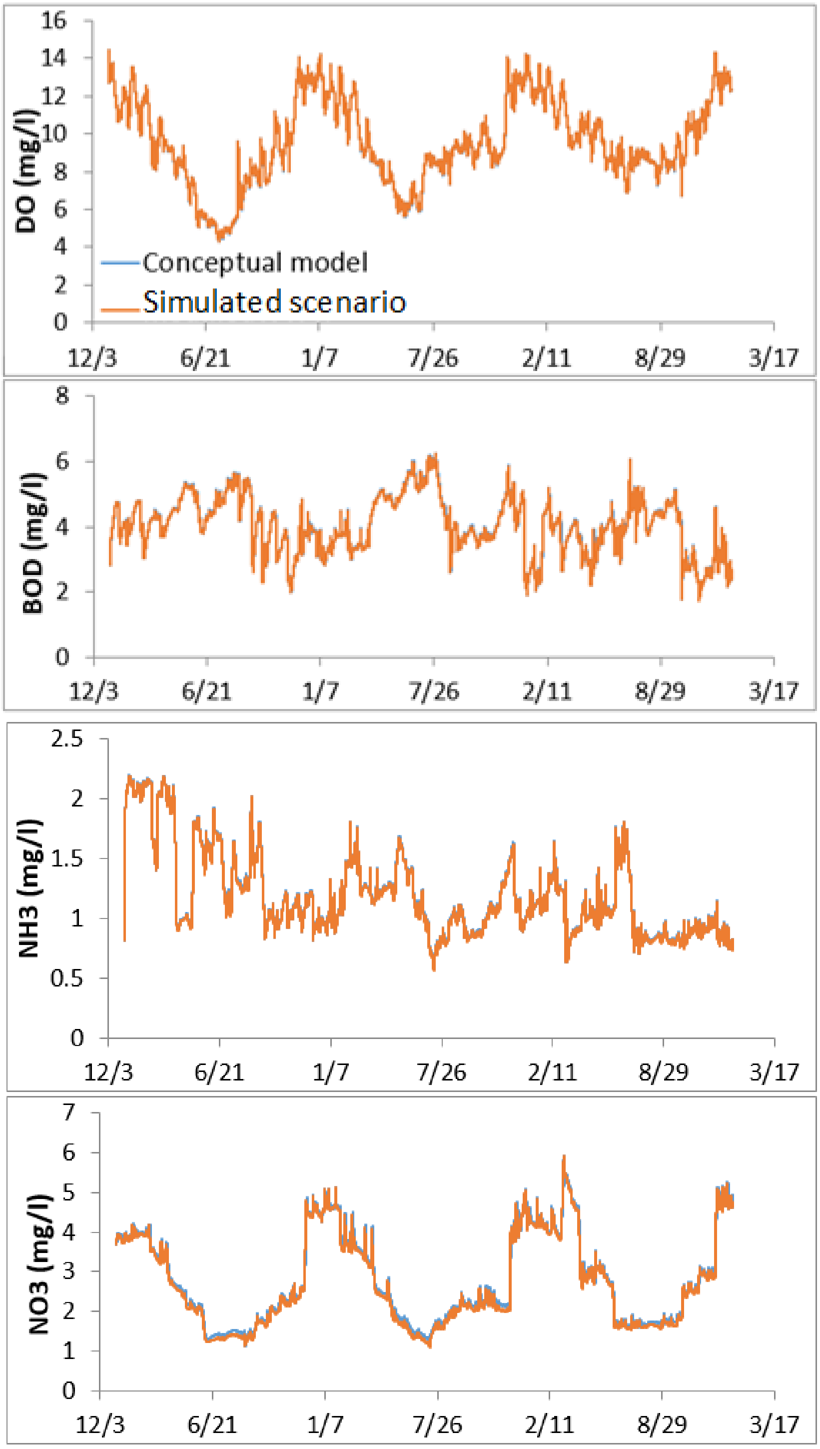



**Figure 18. Results of the scenario 1, for reach 7**

Below, there is a table showing the maximum variation between the current situation and the case proposed.

| Reach | DO (%) | $NO_3$ (%) | $NH_3$ (%) | BOD (%) |
|---|---|---|---|---|
| 4 | +0.6 | -10.13 | -4.11 | -1.66 |
| 7 | +0.89 | -9.3 | -3.2 | -0.96 |

**Table 12. Maximum variation, in percentage, between the current situation and scenario 1**

In this scenario only the dumping of the WWTPs is modified. In comparison with the other scenarios, it is observed that the DO and BOD are vaguely modified. Therefore, it can be affirmed that the modification of discharges in the WWTP does not cause a significant improvement in the state of DO and BOD in the waters. Moreover, DO levels in the simulated scenario are slightly lower compared to the current scenario in most of the study period. This happens because the BOD value does not change so much.

On the contrary, the most variable parameter is nitrate. Note that the maximum variation for this parameter occurs in the spring and summer seasons. It has been seen in section 3.6.3 that during these seasons, nitrates are reduced by the nitrification process.

As for ammonia, the concentration of this variable discharged by effluents undergoes a variation of almost 5%, which is not relevant compared to the rest of the scenarios.

Thus, it is concluded that the concentrations of nitrate discharged, as well as those of ammonia, are influenced by the type of treatment and the performance of these in the WWTP.

### 7.2.2. Results for scenario 2

The following figures represent the results for reaches 5 and 6 in the second scenario.

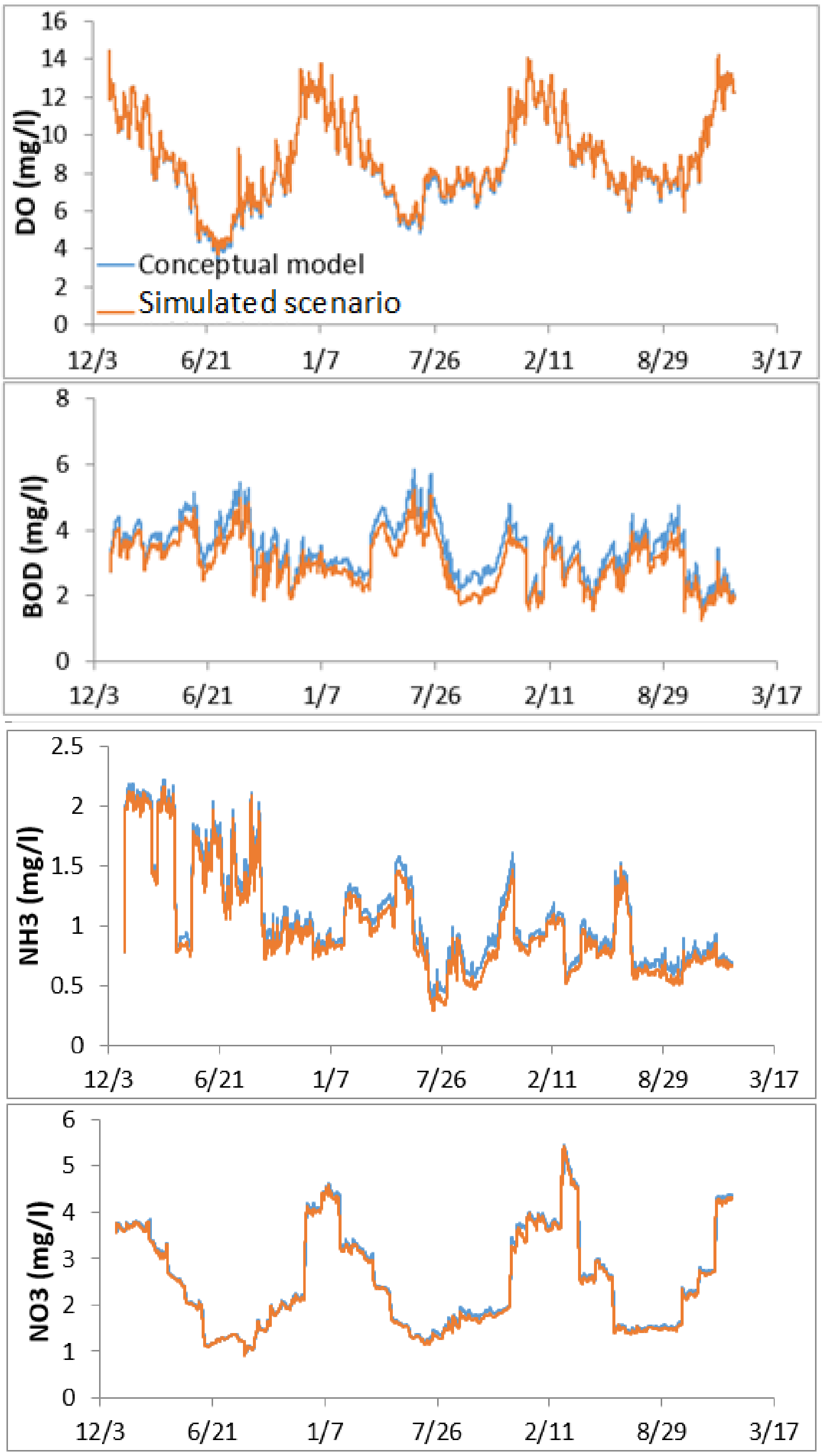



**Figure 19. Results of the scenario 2, for reach 5**

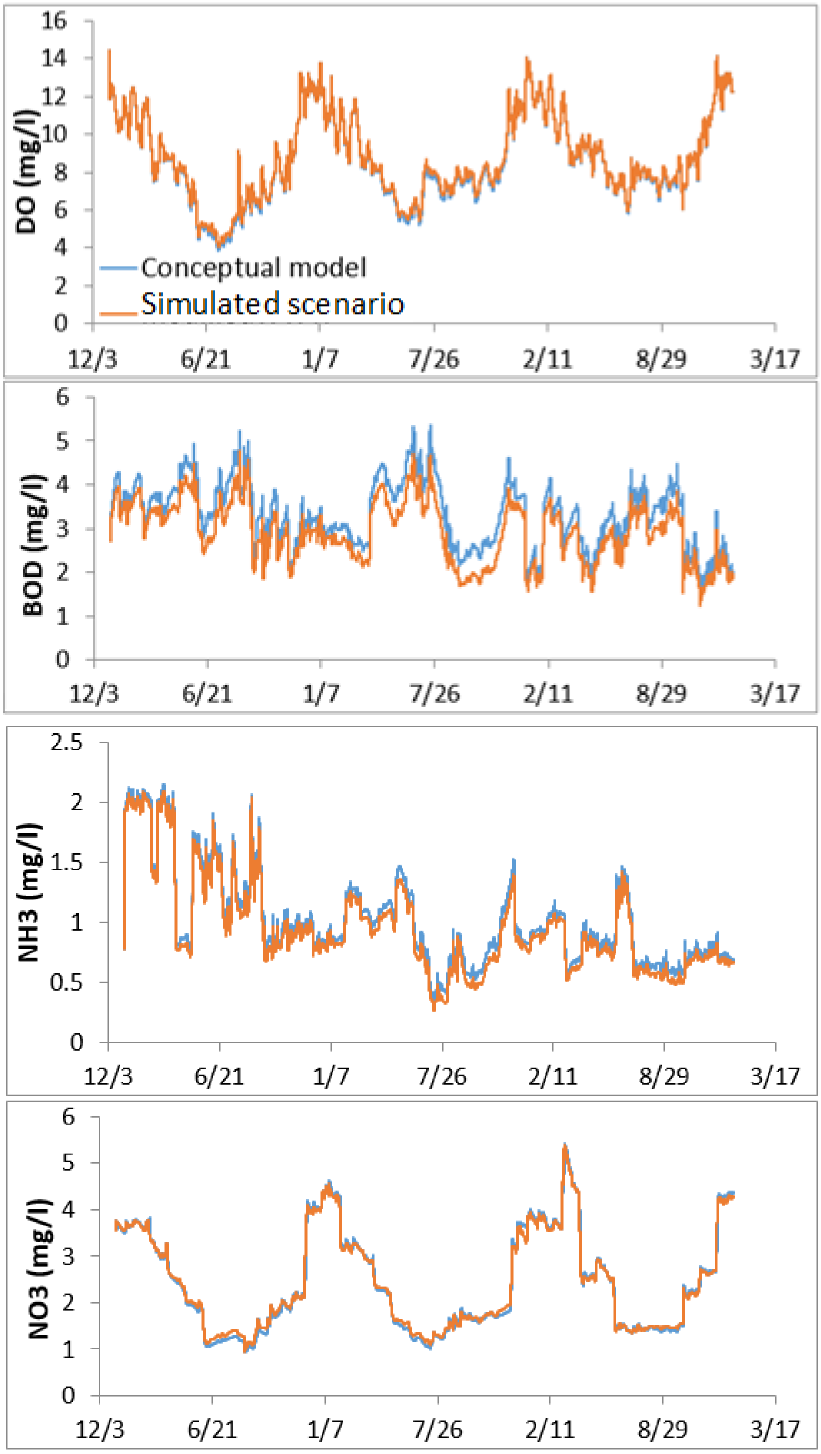



**Figure 20. Results of the scenario 2, for reach 6**

The maximum variation, in both reaches, are represented in this table:

| Reach | DO (%) | $NO_3$ (%) | $NH_3$ (%) | BOD (%) |
|---|---|---|---|---|
| 5 | +8.16 | -9.16 | -23.67 | -25.2 |
| 6 | +6.1 | -9.75 | -22.63 | -25.93 |

**Table 13. Maximum variation, in percentage, between the current situation and scenario 2**

In this scenario, the results obtained are more significant than for the previous case. The percentages of variation indicate that the change is higher.

In this scenario, the reduction of the organic matter of the effluents is highlighted. Consequently, there is a maximum of 25% reduction in the amount of BOD. Thus, during the entire period, the recorded BOD value remains within the acceptable threshold for this parameter.

Now, this relates to the amount of dissolved oxygen: by reducing the amount of organic matter, the degradation will be lower, and the consumption of oxygen too. That is why dissolved oxygen experiments a generalized increase throughout the period, recovering by 8% in the summer season, in 2011. However, it does not meet the standards during the summer of 2010, where the value is smaller than 5 mg/l. This is due to the increase of the temperature in this time of the year, which makes it more difficult to dissolve oxygen.

Regarding nitrates and ammonia, a greater reduction in ammonia is observed. The $NH_3$ is reduced in a generalized way, decreasing almost 24% in January 2011. The variation of $NO_3$ is not as significant, but a general reduction is also achieved.

### 7.2.3. Results for scenario 3

The following figures show a graph with the results for reaches 10 and 16, in the third scenario.

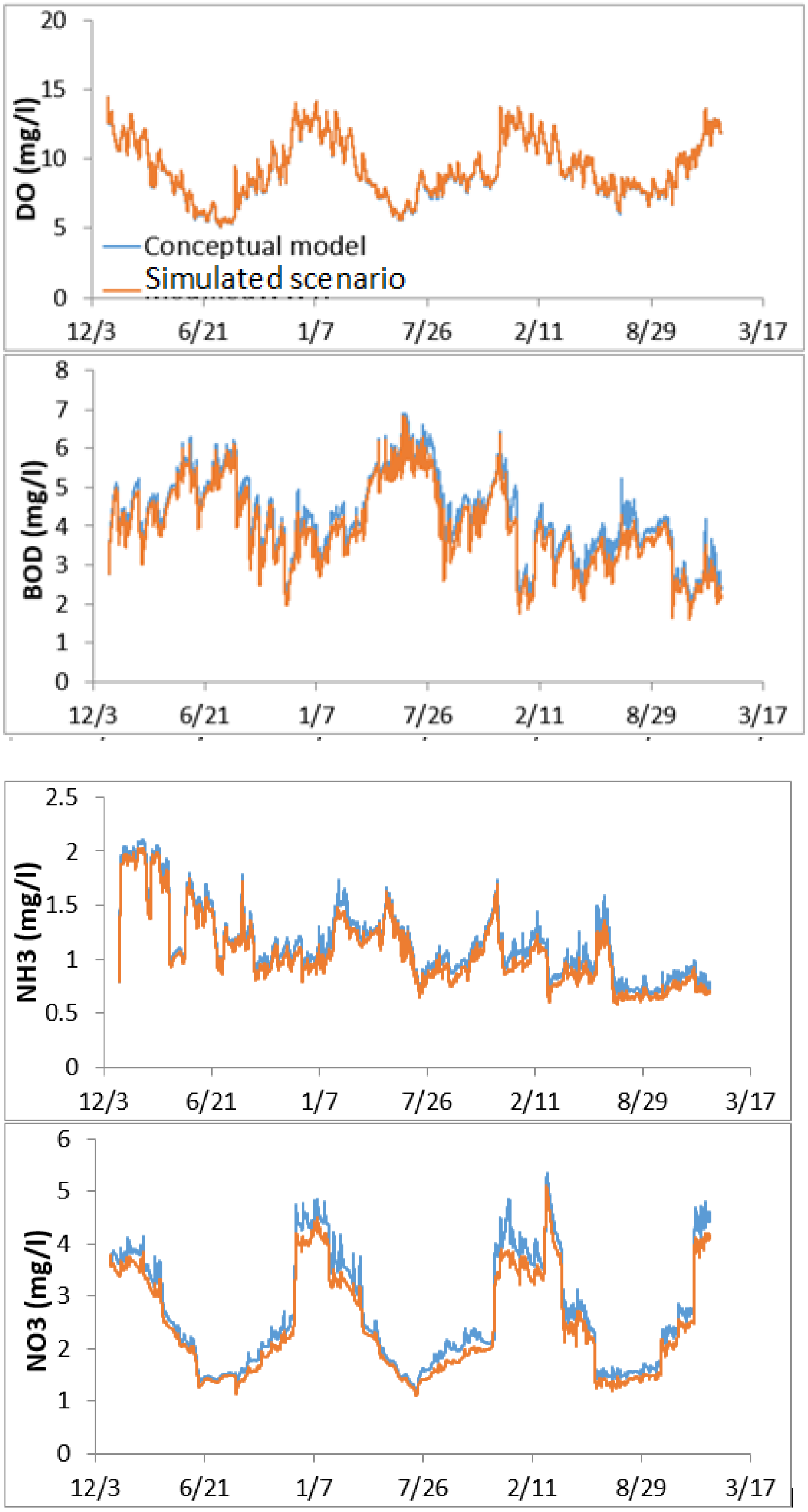



**Figure 21. Results of the scenario 3, for reach 10**

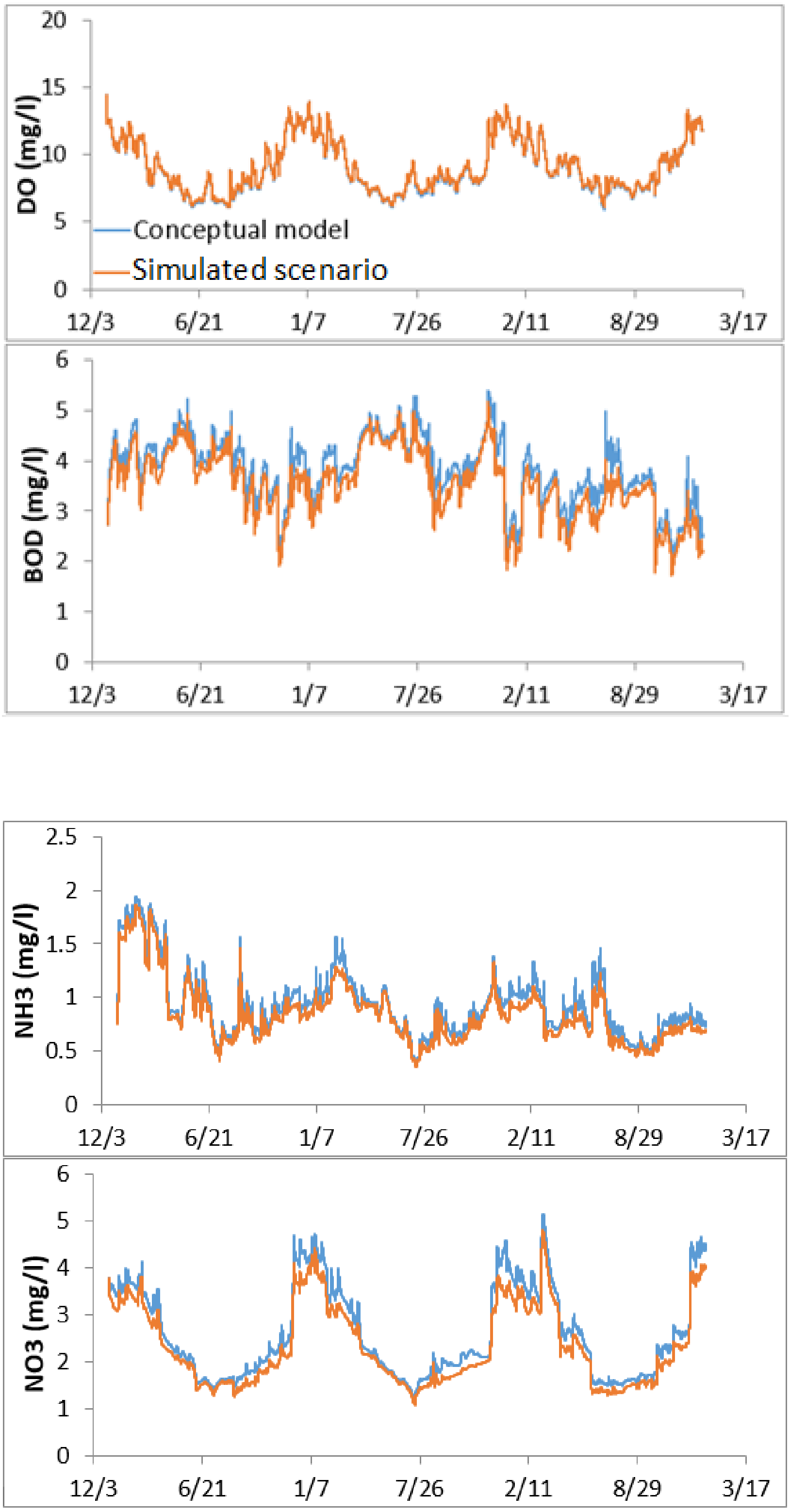



**Figure 22. Results of the scenario 3, for reach 16**

The maximum variation, in both reaches, are represented in this table:

| Reach | DO (%) | $NO_3$ (%) | $NH_3$ (%) | BOD (%) |
|---|---|---|---|---|
| 10 | +3.01 | -20.37 | -20.74 | -18.5 |
| 16 | +3.52 | -24.06 | -22.21 | -21.0 |

**Table 14. Maximum variation, in percentage, between the current situation and scenario 3**

In scenario number 3 only the agricultural pollutant load is modified.

Comparing this case with the previous ones, it is observed that the oxygen dissolved in this case, does not increase too much.

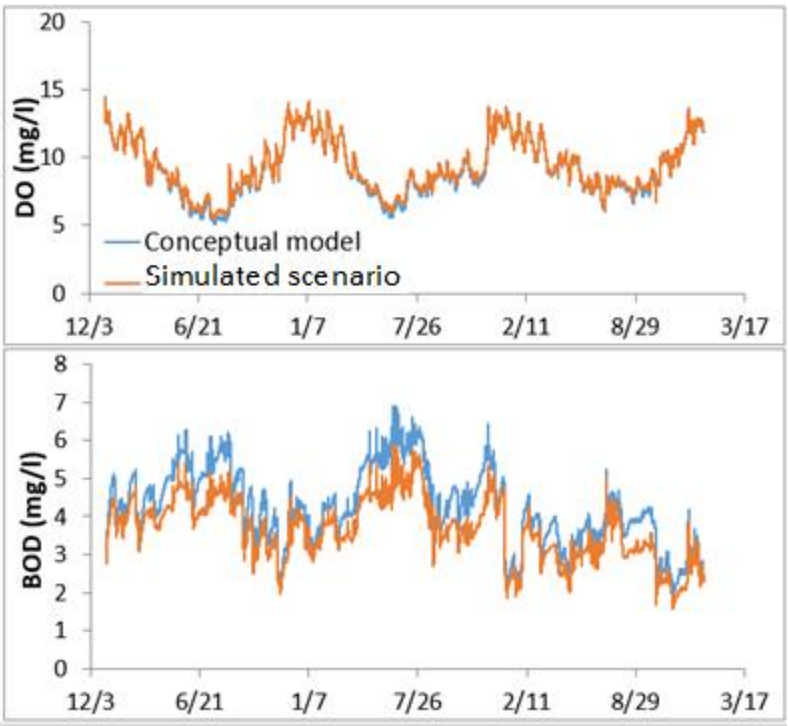
On the other hand, BOD levels decrease although not as much as in scenario 2. For this parameter, it is observed that in section 10 the standards are exceeded and the regulations are not complied in part of the summer period of 2011. However, in section 16, the value of this parameter is kept below the threshold value (6 mg/l).

In this case it is observed that the levels of $NO_3$ and $NH_3$ are reduced approximately the same amount.

Regarding $NO_3$, in both sections, the reduction of the values of this parameter helps to meet the standards (maximum 5 mg/l). There is only one peak in reach 10, where the maximum value is 5.1 mg/l.

### 7.2.4. Results for scenario 4

Results for reaches 10 and 16 are shown in the following Figures:



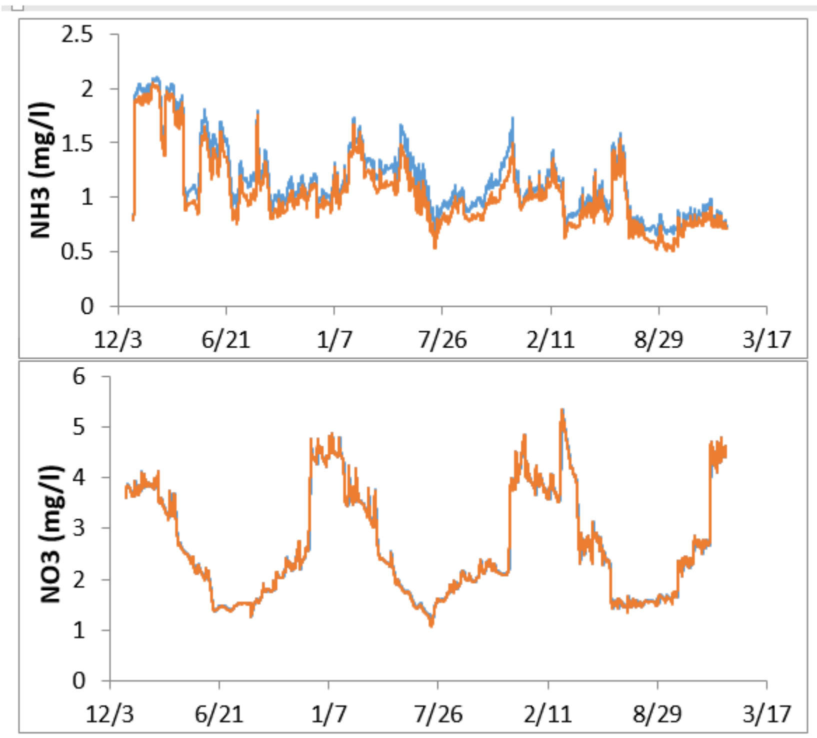
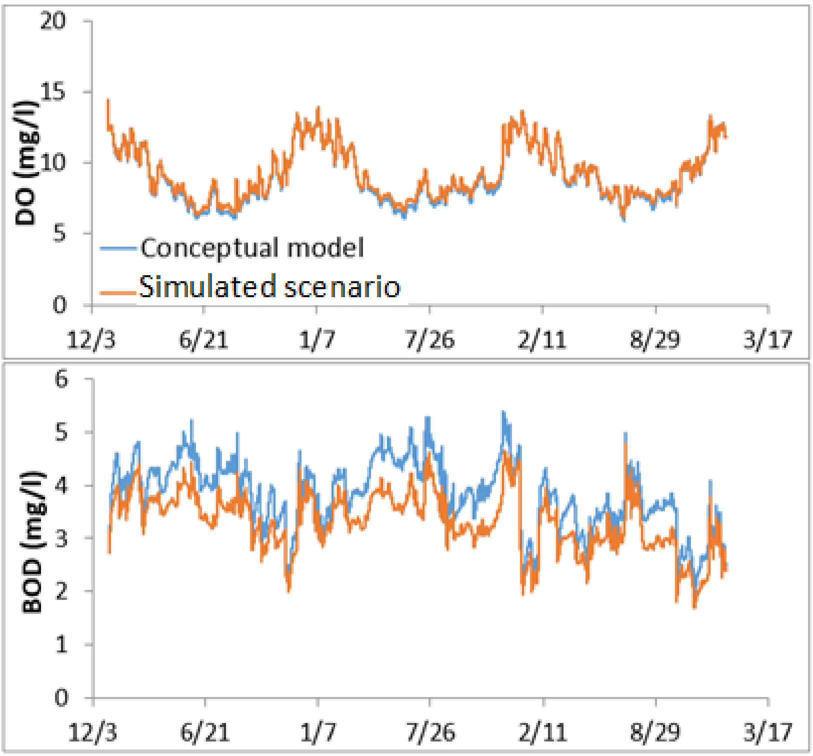



**Figure 23. Results of the scenario 4, for reach 10**



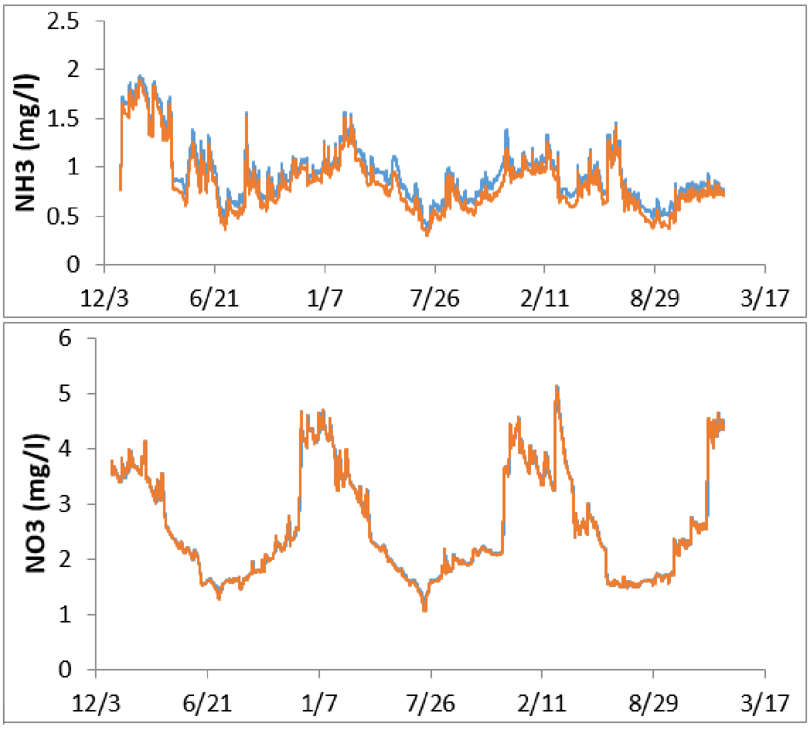



**Figure 24. Results of the scenario 4, for reach 16**

The maximum variation, in both reaches, are represented in this table:

| Reach | DO (%) | $NO_3$ (%) | $NH_3$ (%) | BOD (%) |
|---|---|---|---|---|
| 10 | +9.72 | -8.46 | -24.36 | -23.69 |
| 16 | +8.07 | -8.64 | -24.23 | -22.63 |

**Table 15. Maximum variation, in percentage, between the current situation and scenario 4**

In the last scenario, only the domestic type of pollutant load is modified. In this case, BOD levels decrease by almost 24% and DO levels increase by almost 10%. This reduction in the BOD levels is due to the decrease of organic matter from urban effluents. The reason why BOD decreases and DO increases is explained in section 7.2.2. For both parameters and reaches, the threshold is exceeded.

In this case, the percent change for $NO_3$ is lower than for $NH_3$. Standards for $NO_3$ are exceeded in both reaches, during the summer and at one of the peaks. The maximum values of this parameter are 5.34 mg/l in the reach 10 and 5.12 mg/l in the reach 16. On the other hand, values of $NH_3$ experiment a decrease of around 25%.

### 7.2.5. Results for scenario 5

Results for reach 1 is shown in the following Figures:

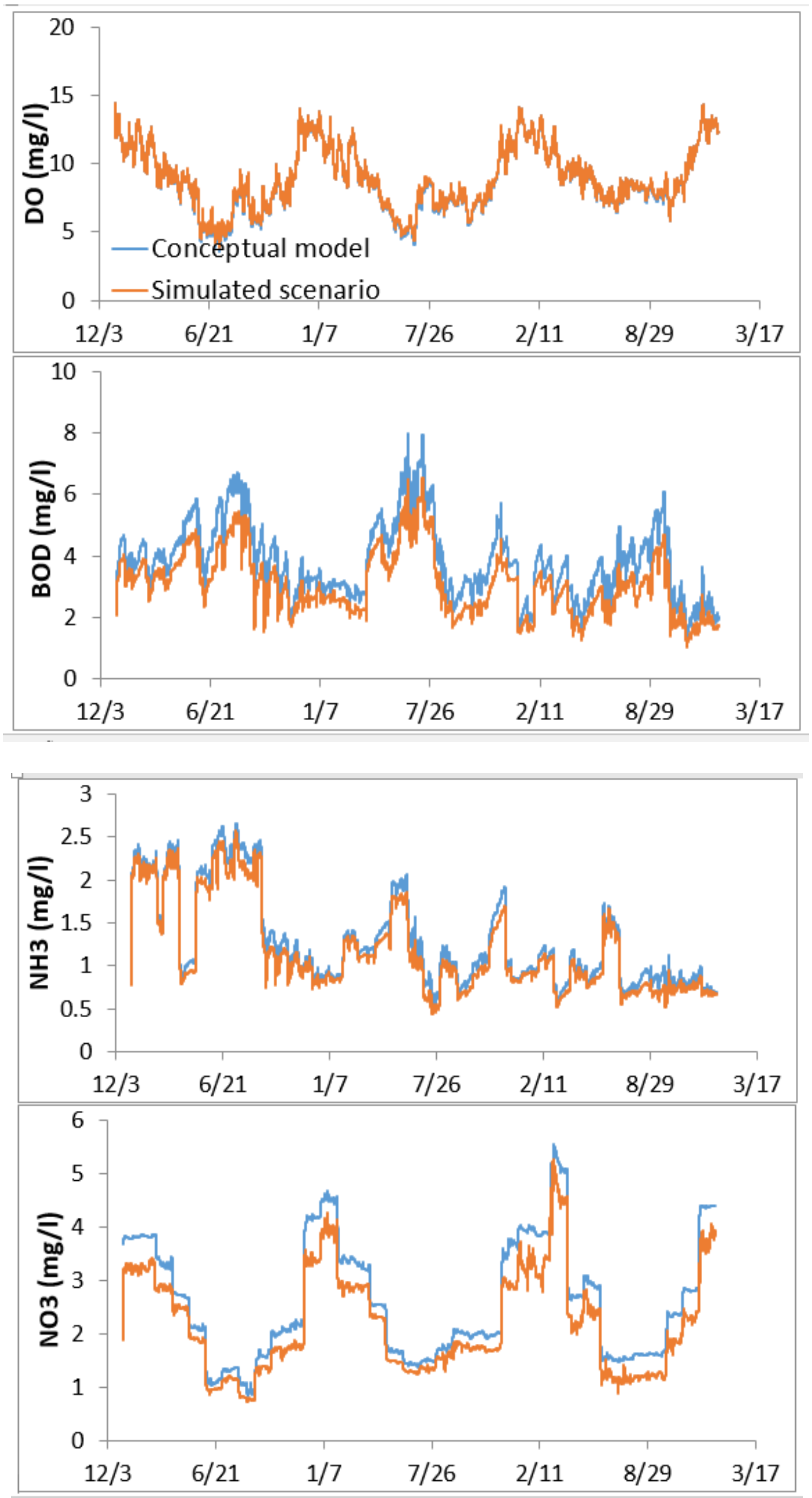



**Figure 25. Results of the scenario 5, for reach 1**

The maximum variation, in both reaches, are represented in this table:

| Reach | DO (%) | $NO_3$ (%) | $NH_3$ (%) | BOD (%) |
|---|---|---|---|---|
| 1 | +9.7 | -27.59 | -24.1 | -30.2 |

**Table 16. Maximum variation, in percentage, between the current situation and scenario 5**

In this case, both the DO and the BOD experiment a major improvement. Especially the BOD, where it is reduced up to 30% in some points. With these measures, in the first station, it is achieved that all parameters are kept below 6 mg/l, that is, a good water quality is achieved. In addition, in the case of BOD it is achieved to avoid many peaks that occurred in the simulation of the current situation.

Regarding $NO_3$ and $NH_3$, both results improve. In the case of $NO_3$ a reduction of up to 27.59% is achieved and in $NH_3$, a reduction of 24.1%. These are satisfactory results, since it is possible to comply with all the proposed standards.

# 8. Conclusions and further works

## 8.1. Conclusions

In this chapter of the paper we intend to make a synthesis of the complete study, as well as reach a series of conclusions.

This report is about an analysis of the water quality of the Dender River. For this, a diagnosis of the current situation of the river in question has been made first. Secondly, a water quality model has been developed.

The diagnosis of the current situation is based on the analysis of the flow regime of the river, the quality of its water and the characterization of its discharges. The pressures suffered by the studied river sections are due to the contaminating load that the urban effluents discharge. Numerous discharges are not cleared or deficient.

It is also noted that given the numerous discharges and river flows between two quality stations, it is not possible to evaluate the effects of all discharges on the water quality of the river studied. Furthermore, the distance between the quality stations should be shorter.

The calibration process of the model was performed using quality data provided by the VMM. The following parameters are calibrated: $BOD_5$, DO, $NO_3$ and $NH_3$.

Once the model has been constructed and calibrated, it has been used to simulate future scenarios. The simulated scenarios are 5, and correspond to the implementation of different measures. What is asked by a higher order is that in these measures, the concentration of the pollutant load of the effluents is reduced by half. Thus, a remarkable improvement of the quality of the water in the studied river is obtained. Based on these results, the two most beneficial scenarios for the river are chosen: scenario number 3 and number 5 are those chosen in this report, since they are the ones that produce the best and the biggest changes in the system.

On the other hand, from the implemented measures, these conclusions can be drawn:

- The reduction of pollutant load in effluents from the WWTP does not generate a relevant change.
- In contrast, the reduction of contaminant concentration in agricultural and domestic effluents does generate a great change.
- As for the variables, the most difficult change to achieve is the increase in DO. The easiest way to get this is by decreasing the pollutant load of the domestic effluent.
- On the contrary, the other variables vary in one form or another depending on the flow or pollutant load of the modified boundary.

## 8.2. Further works

As possible improvements in the monitoring of the water quality of the system studied and further works, the following possibilities are posed:

- Extension of the network of quality stations, to have a larger network, with more points to control.
- The study can be extended by modelling the phosphorus levels in the system
- Due to the presence of industries, heavy metal pollution challenges the water quality in the basin. Heavy metal pollution modelling can be undertaken in the future.
- The sediment processes on the water quality in the basin may be further studied.

To finish, the model is especially a tool for decision making, and in the future, it will have to be updated with new data and used to simulate new scenarios with different environmental measures and constraints.

The author of the report

Laura Ramón Marco

Valencia, September 2017

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# APPENDICES

## APPENDIX A: List of boundaries and correspondent reaches

| Boundary ID number | Name | Reach affected |
|---|---|---|
| 1 | BELLEBEEK_12800 | 23 |
| 2 | DENDER_0 | 1 |
| 3 | DENDER_1300 | 1 |
| 4 | DENDER_4300 | 2 |
| 5 | DENDER_14500 | 7 |
| 6 | DENDER_20100 | 9 |
| 7 | DENDER_21000 | 9 |
| 8 | DENDER_32000 | 15 |
| 9 | DENDER_35000 | 16 |
| 10 | DENDER_49866 | 19 |
| 11 | MARK_20800 | 20 |
| 12 | MOLENBEEK_G_0 | 21 |
| 13 | MOLENBEEK_G_942 | 21 |
| 14 | MOLENBEEK2_16400 | 25 |
| 15 | WOLFPUTBEEK_0 | 22 |
| 16 | WOLFPUTBEEK_1400 | 22 |
| 17 | BELLEBEEK_12800_AGRI | 23 |
| 18 | BELLEBEEK_12800_DOM | 23 |
| 19 | BELLEBEEK_12805_17100_AGRI_RES23 | 23 |
| 20 | BELLEBEEK_12805_17100_AGRI_RES24 | 24 |
| 21 | BELLEBEEK_12805_17100_DOM_RES23 | 23 |
| 22 | BELLEBEEK_12805_17100_DOM_RES24 | 24 |
| 23 | BELLEBEEK_12810_IND | 23 |
| 24 | BELLEBEEK_12810_STP | 23 |
| 25 | BELLEBEEK_12830_U_WWTP448 | 23 |
| 26 | BELLEBEEK_17100_WWTP | 24 |
| 27 | DENDER_0_14140_AGRI_RES1 | 1 |
| 28 | DENDER_0_14140_AGRI_RES2 | 2 |
| 29 | DENDER_0_14140_AGRI_RES3 | 3 |
| 30 | DENDER_0_14140_AGRI_RES4 | 4 |
| 31 | DENDER_0_14140_AGRI_RES5 | 5 |
| 32 | DENDER_0_14140_AGRI_RES6 | 6 |
| 33 | DENDER_0_14140_DOM_RES1 | 1 |
| 34 | DENDER_0_14140_DOM_RES2 | 2 |
| 35 | DENDER_0_14140_DOM_RES3 | 3 |
| 36 | DENDER_0_14140_DOM_RES4 | 4 |
| 37 | DENDER_0_14140_DOM_RES5 | 5 |
| 38 | DENDER_0_14140_DOM_RES6 | 6 |

| | | |
|---|---|---|
| 39 | DENDER_0_DOM | 1 |
| 40 | DENDER_5975_WWTP | 4 |
| 41 | DENDER_13864_WWTP | 6 |
| 42 | DENDER_14120_WWTP | 7 |
| 43 | DENDER_14140_21720_AGRI_RES7 | 7 |
| 44 | DENDER_14140_21720_AGRI_RES8 | 8 |
| 45 | DENDER_14140_21720_AGRI_RES9 | 9 |
| 46 | DENDER_14140_21720_DOM_RES7 | 7 |
| 47 | DENDER_14140_21720_DOM_RES8 | 8 |
| 48 | DENDER_14140_21720_DOM_RES9 | 9 |
| 49 | DENDER_14140_AGRI | 7 |
| 50 | DENDER_14140_DOM | 7 |
| 51 | DENDER_14140_STP | 7 |
| 52 | DENDER_14140_WWTP | 7 |
| 53 | DENDER_19245_WWTP | 9 |
| 54 | DENDER_21700_WWTP | 10 |
| 55 | DENDER_21720_36085_AGRI_RES10 | 10 |
| 56 | DENDER_21720_36085_AGRI_RES11 | 11 |
| 57 | DENDER_21720_36085_AGRI_RES12 | 12 |
| 58 | DENDER_21720_36085_AGRI_RES13 | 13 |
| 59 | DENDER_21720_36085_AGRI_RES14 | 14 |
| 60 | DENDER_21720_36085_AGRI_RES15 | 15 |
| 61 | DENDER_21720_36085_AGRI_RES16 | 16 |
| 62 | DENDER_21720_36085_DOM_RES10 | 10 |
| 63 | DENDER_21720_36085_DOM_RES11 | 11 |
| 64 | DENDER_21720_36085_DOM_RES12 | 12 |
| 65 | DENDER_21720_36085_DOM_RES13 | 13 |
| 66 | DENDER_21720_36085_DOM_RES14 | 14 |
| 67 | DENDER_21720_36085_DOM_RES15 | 15 |
| 68 | DENDER_21720_36085_DOM_RES16 | 16 |
| 69 | DENDER_21720_STP | 10 |
| 70 | DENDER_23350_IND | 10 |
| 71 | DENDER_29500_IND | 14 |
| 72 | DENDER_32830_IND | 15 |
| 73 | DENDER_35200_IND | 16 |
| 74 | DENDER_36085_49800_AGRI_RES17 | 17 |
| 75 | DENDER_36085_49800_AGRI_RES18 | 18 |
| 76 | DENDER_36085_49800_AGRI_RES19 | 19 |
| 77 | DENDER_36085_49800_DOM_RES17 | 17 |
| 78 | DENDER_36085_49800_DOM_RES18 | 18 |
| 79 | DENDER_36085_49800_DOM_RES19 | 19 |
| 80 | DENDER_36085_AGRI | 17 |

| | | |
|---|---|---|
| 81 | DENDER_36085_DOM | 17 |
| 82 | DENDER_36085_IND | 17 |
| 83 | DENDER_36085_STP | 17 |
| 84 | DENDER_42500_IND | 18 |
| 85 | DENDER_42500_IND1 | 18 |
| 86 | DENDER_44650_AGRI | 19 |
| 87 | DENDER_44650_DOM | 19 |
| 88 | DENDER_44650_WWTP | 19 |
| 89 | DENDER_45810_WWTP | 19 |
| 90 | DENDER_45960_IND | 19 |
| 91 | DENDER_45960_IND1 | 19 |
| 92 | DENDER_45960_IND2 | 19 |
| 93 | DENDER_45960_IND3 | 19 |
| 94 | DENDER_46400_IND | 19 |
| 95 | MARK_20800_AGRI | 20 |
| 96 | MARK_20800_DOM | 20 |
| 97 | MARK_20820_STP | 20 |
| 98 | MARK_20830_U_WWTPP222 | 20 |
| 99 | MARK_24500_DOM | 20 |
| 100 | MARK_24500_STP | 20 |
| 101 | MARK_24500_WWTP | 20 |
| 102 | MOLENBEEK2_16400_AGRI | 25 |
| 103 | MOLENBEEK2_16400_DOM | 25 |
| 104 | MOLENBEEK2_16420_STP | 25 |
| 105 | MOLENBEEK2_16430_U_WWTP | 25 |
| 106 | MOLENBEEK-G_0_AGRI | 21 |
| 107 | MOLENBEEK-G_0_DOM | 21 |
| 108 | MOLENBEEK-G_0_IND | 21 |
| 109 | MOLENBEEK-G_15_STP | 21 |
| 110 | WOLFPUTBEEK_0_AGRI | 22 |
| 111 | WOLFPUTBEEK_0_DOM | 22 |
| 112 | WOLFPUTBEEK_15_IND | 22 |
| 113 | WOLFPUTBEEK_20_STP | 22 |

**Table A-1. Number of boundaries, reach and tributary affected**

## APPENDIX B: Model calibration and validation results

The graphs show the results for calibration and validation in the model. The vertical axis of the graph shows the parameter to be calibrated or validated, while the horizontal axis represents the date in MM/DD format.

Model calibration results 2010-2011

- Reach 1

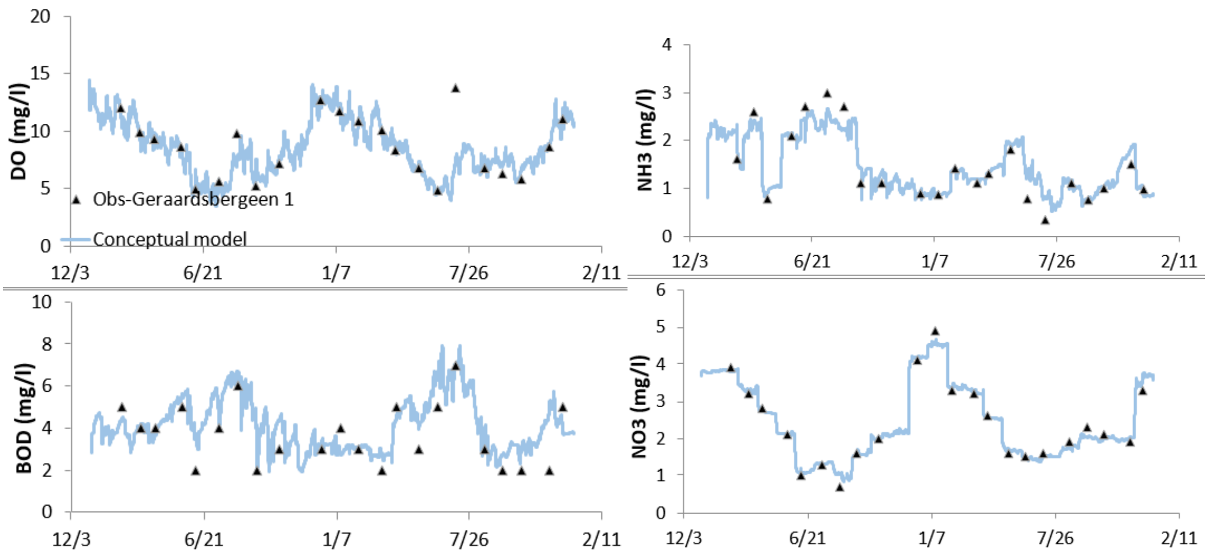


**Figure B-1. Calibration for reach 1**

- Reach 5

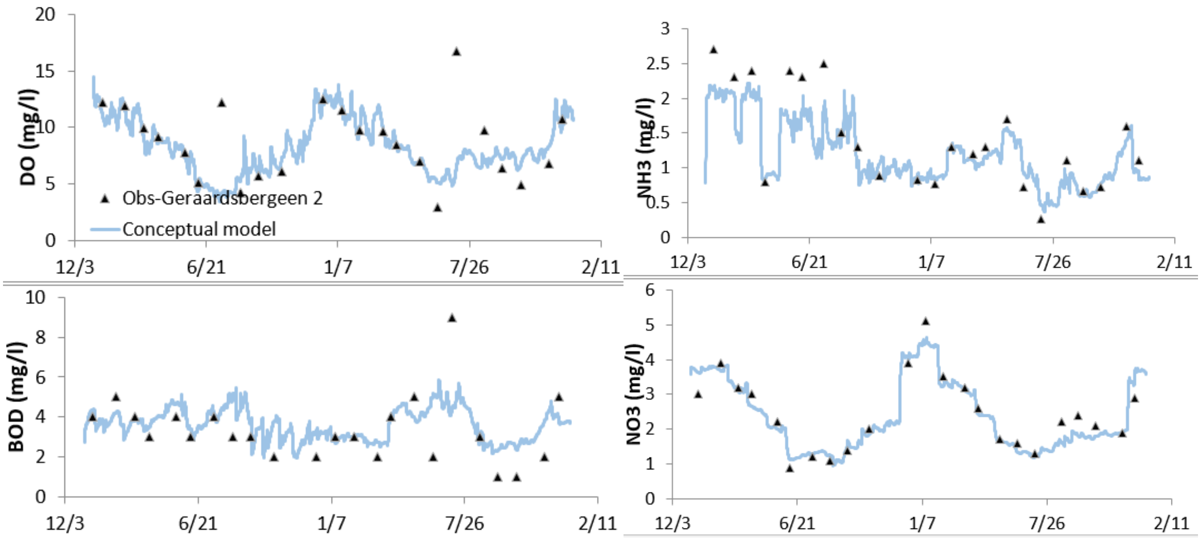


**Figure B-2. Calibration for reach 5**

- Reach 6

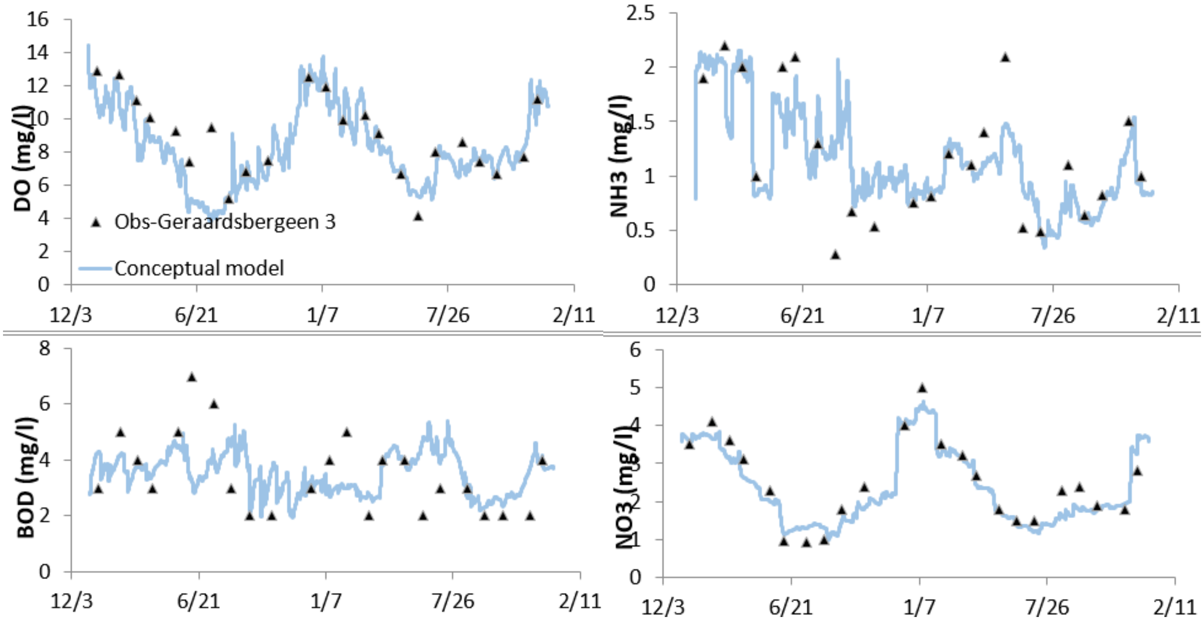


**Figure B-3. Calibration for reach 6**

- Reach 8

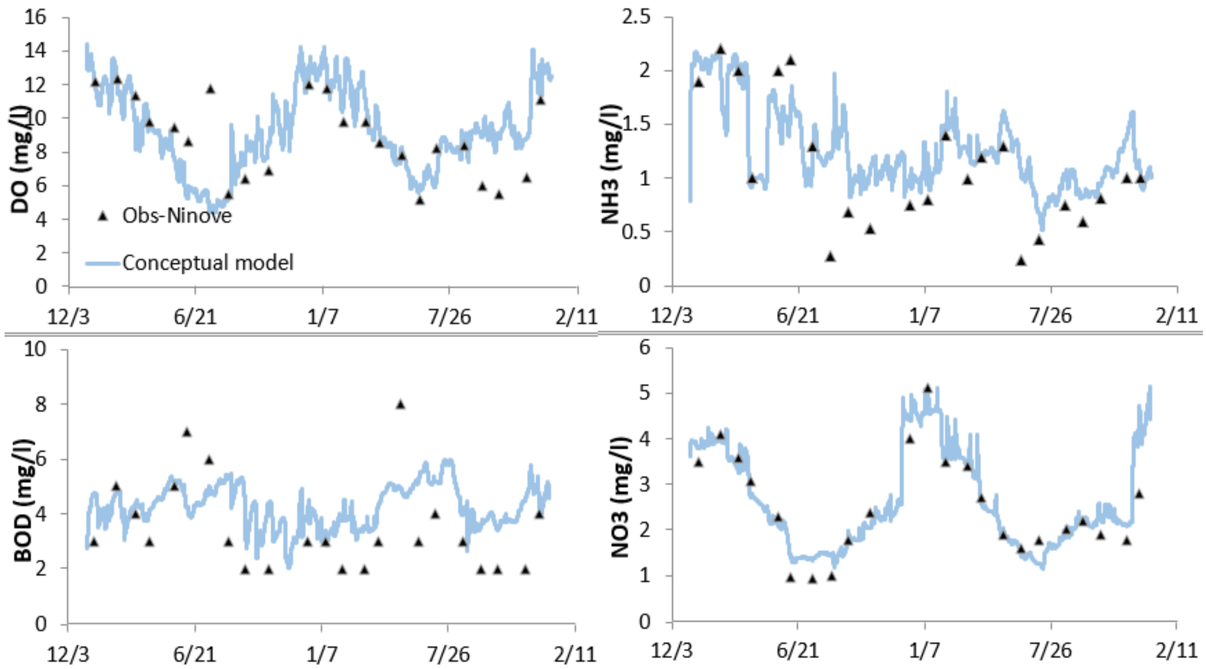


**Figure B-4. Calibration for reach 8**

- Reach 16

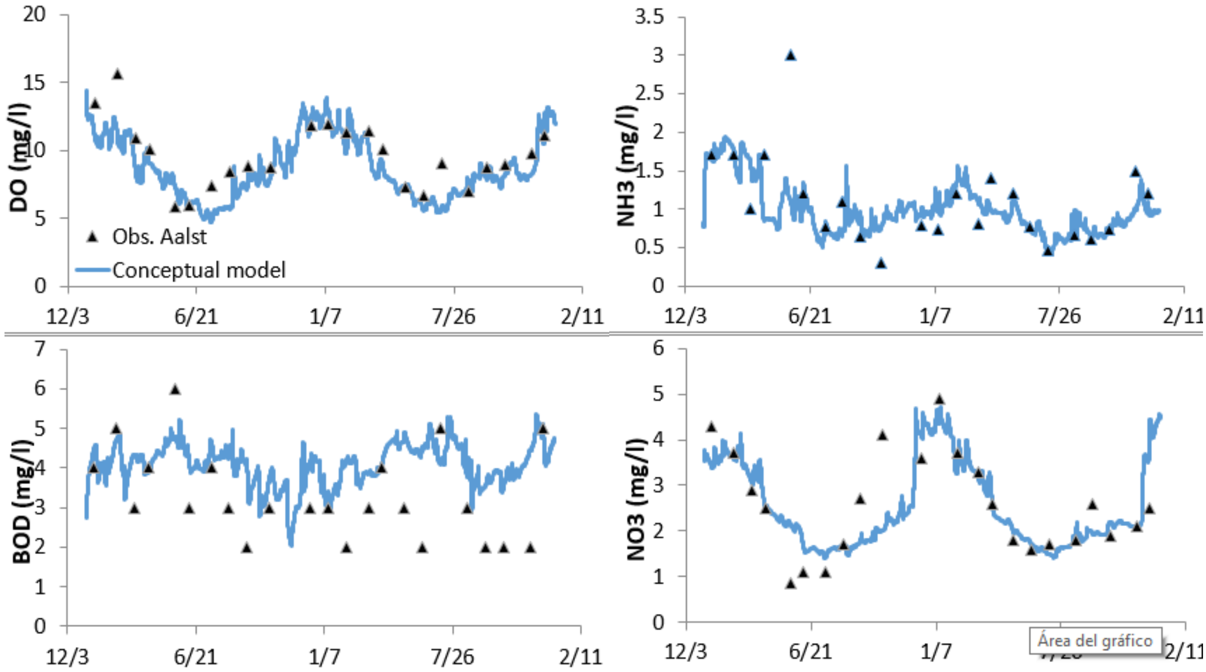


**Figure B-5. Calibration for reach 16**

Model validation results 2010-2012

- Reach 1

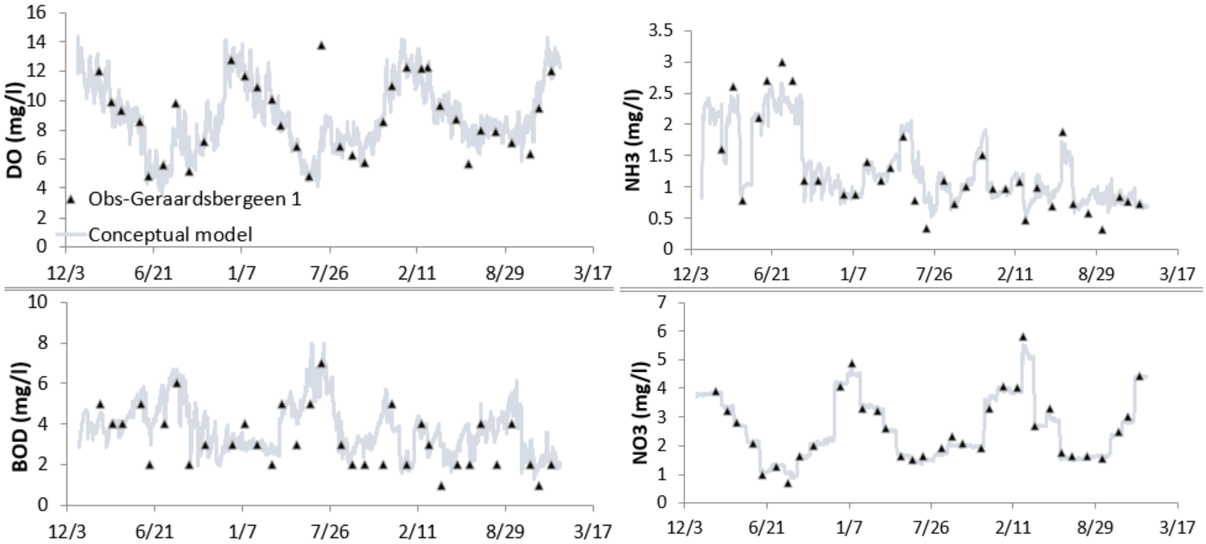


**Figure B-6. Validation for reach 1**

- Reach 5

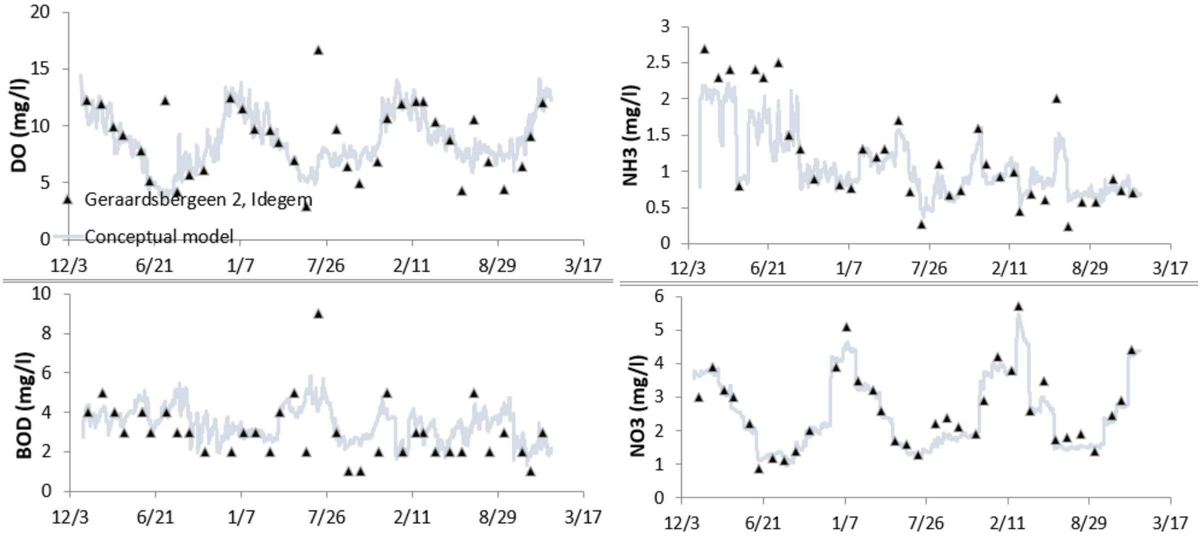


**Figure B-7. Validation for reach 5**

- Reach 6

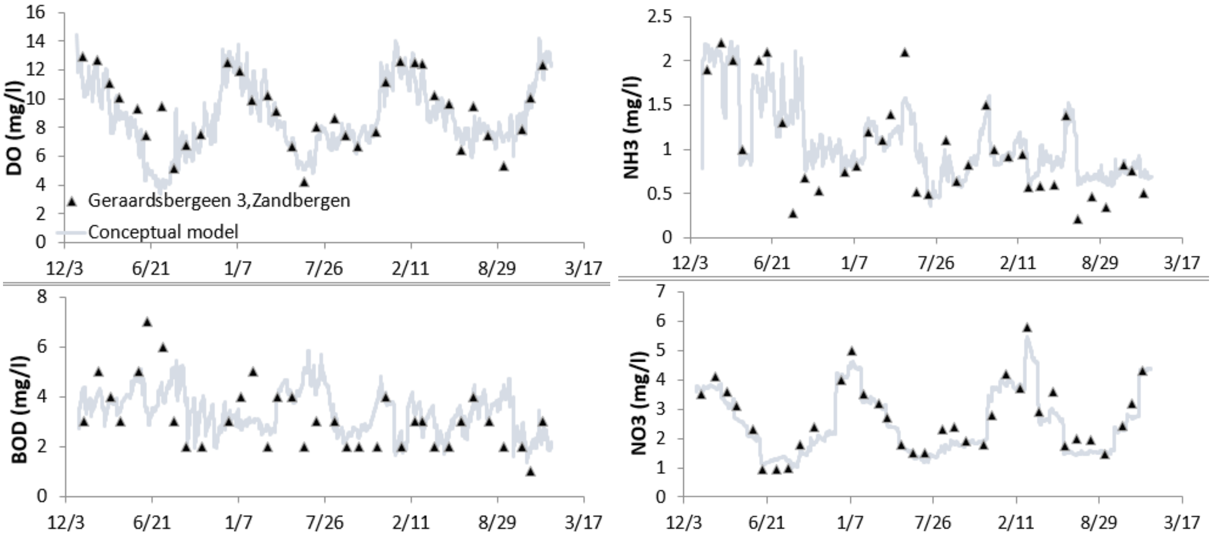


**Figure B-8. Validation for reach 6**

- Reach 8

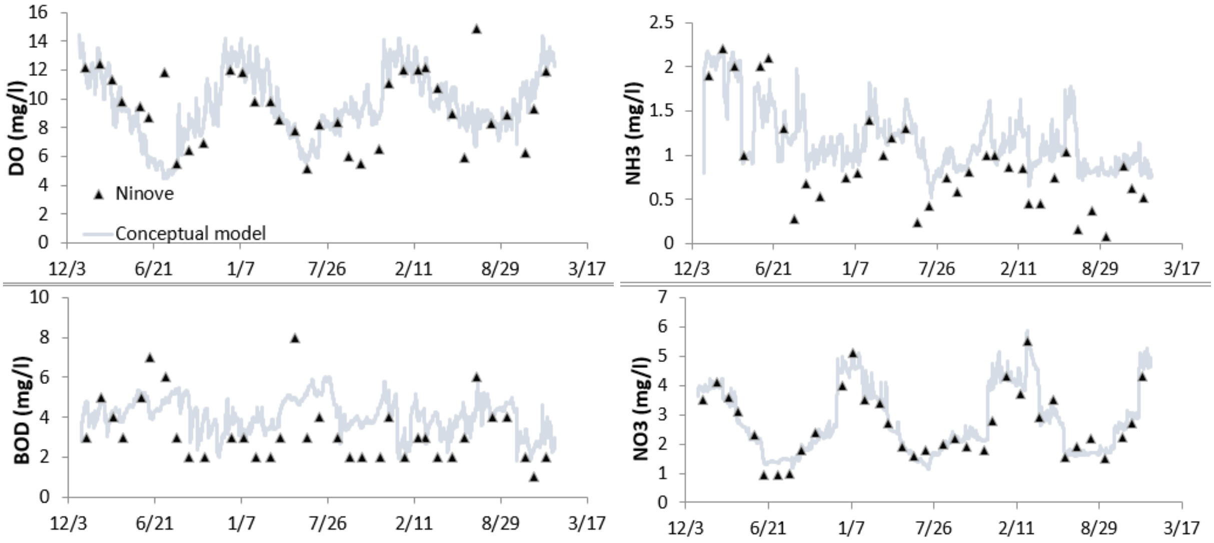


**Figure B-9. Validation for reach 8**

- Reach 16

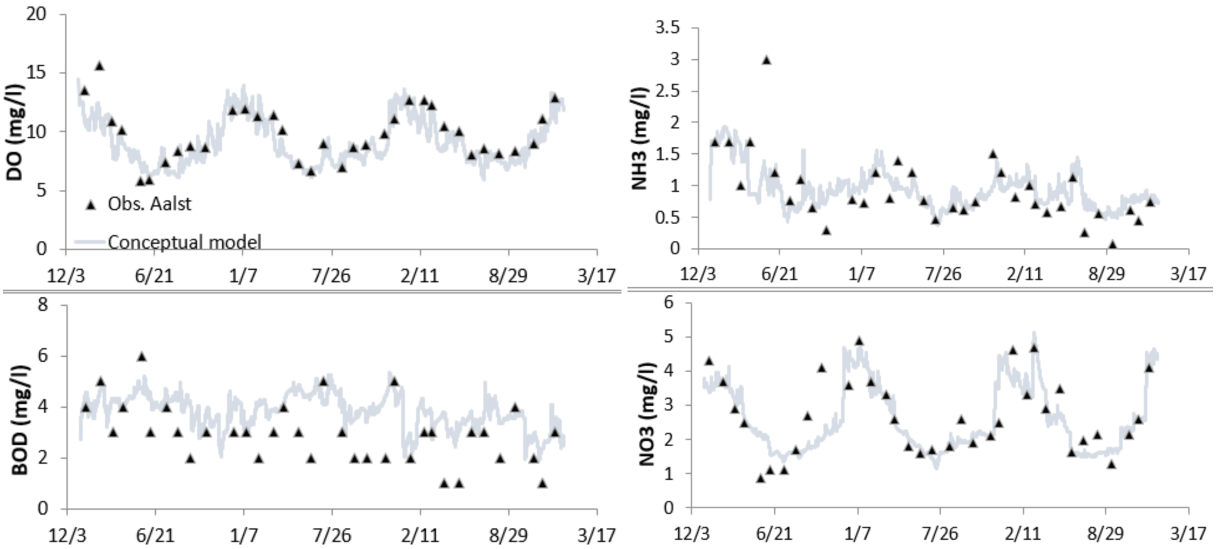


**Figure B-10. Validation for reach 16**