UNIVERSITY OF PADUA

DEPARTMENT OF INDUSTRIAL ENGINEERING

Master Thesis in Environmental Engineering

An assessment of urban stormwater runoff influence on river water quality. A case study: Padua waterways.

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To Alessia and Giosuè.

“[…] world before us; an inexhaustible treasure, but for which […] we have eyes, yet see not, ears that hear not, and hearts that neither feel nor understand”

S.T. COLERIDGE, Biographia Literaria.

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1. ABSTRACT

By means of a mathematical model, the possible influence of urban stormwater runoff on the water quality of the hydraulic network of Padua city is assessed.
For this purpose, WEST 2014 of Mike by DHI is utilized.
The software allows for the graphical construction of the model, considering proper blocks that embody a pre-written numerical code able to mathematically represent the series of different processes occurring within the studied system.
The first step of the modelling procedure is the identification of the streams to be considered in the system definition; after that, the characterization of the studied area is performed in terms of water catchments, sewage network and land use.
The system is consequently re-created using the WEST software and a dynamic simulation of the rivers water quality is performed: the model results (i.e. time series of Biochemical Oxygen Demand and Ammonia Nitrogen concentrations) are compared to a set of available observations provided by ARPAV authority.
The results of the first simulation evidence the need of a proper calibration in order to improve the model fit to the observed data.
For this reason, the sensitivity analysis on the model is performed: it indicates that the calculated concentrations are particularly influenced by ecological and hydraulics parameters.
The Parameters Estimation of WEST 2014 allows for the model calibration, determining the set of parameters that minimizes the differences between calculated and measured data.
A total of 19 parameters is added to the experiment: due probably to this relevant number of terms and to the limited amount of observed data, even if an improvement of the model adaptation is achieved, the calibration process is not able to give a proper fitting.
In addition, because of the results sensitivity to the hydraulics of the system, it seems worth having a deeper knowledge of the sewage network characteristics, in order to better represent it with the WEST software.

In conclusion, the model results suggest that the urban stormwater runoff may have a possible influence on the rivers water quality of the system, but it is believed that an improvement of the sampling campaign for the water characterization should be needed, in order to have a greater number of data with higher sampling frequency to be used as comparison of the calculated concentration and to better analyze the model behavior.
In this way, it would be possible to have a wider picture of the behavior of the ecological system.

2. INTRODUCTION

The increasing interest of the public on the environmental issue has enhanced studies and analyses focused on the protection of the ecological resources.

Taking into consideration receiving water bodies like rivers and lakes, great attention is given to the possible causes of pollution coming from the surrounding environment: point and non-point sources.

Point inputs are continuous injection of substances, but they are normally easier to be managed with respect to the non-point ones, that are most of times not known and difficult to be controlled.

Urban stormwater runoff has being recognized as the major form of diffuse (non-point) source of contaminants for the water resource.

During storm events, several substances are washed out from roofs, roads, cultivated fields and many other surfaces by the rainwater, creating the so called runoff. This water deriving from the precipitation is partially collected by the sewage network and partly discharged directly into rivers and streams.

Consequently, it is reasonable to think that such contribution may have a certain influence on the water quality of the different receiving bodies. In other words, considering a river watershed, it is possible that the washout determines the release of several substances, including pollutants, that are discharged into the waterways and this contribution may alter the complex and delicate equilibrium of aquatic ecosystems.

Starting from these considerations, the purpose of the thesis is to evaluate the impact of such a process on the environment, taking into consideration the specific case of Padua's hydraulic network: by the use of proper mathematical models, the aim is to assess the influence of the urban stormwater runoff on the water quality of the streams that compose the network.

This is done with the use of a properly designed software: WEST 2014, of MIKE by DHI.

Such a tool is used to model and simulate rivers water quality by means of mathematical models, so that it is possible to give a simplified, but reliable representation of the reality.

With this instrument, a series of different processes are considered: rainfall and runoff generation, release of compounds from different land uses and runoff characterization, its collection into the sewage network (with possible combined sewer overflows), discharge of the runoff into the hydraulic network and the ecological processes taking place in the aquatic ecosystems.

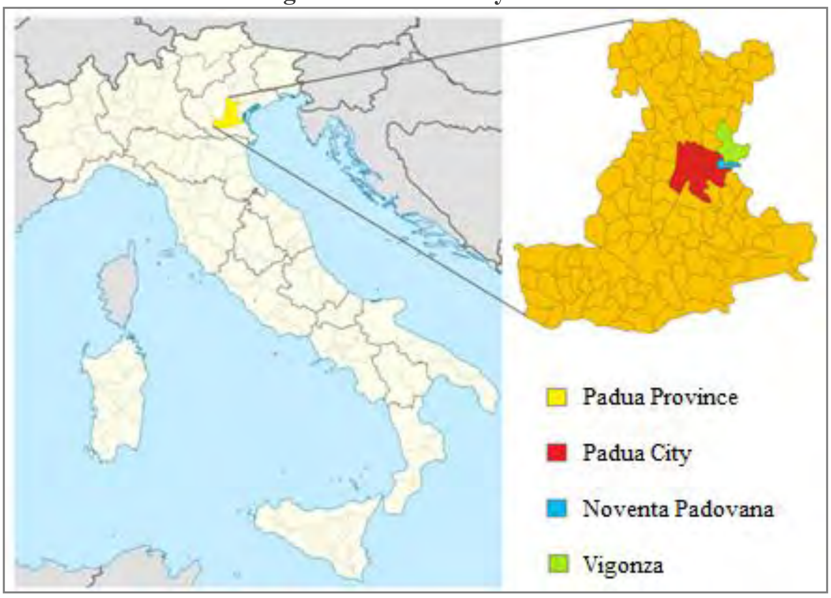
The results of the model are finally compared to available water quality measures for the rivers network.

The biggest problem encountered in this study is the lack of information: the models of the software library require quite a large amount of data, in terms of both parameters and input variables, in order to characterize the studied system, but they were not always available; for this reason, some assumptions and simplifications are taken and justified.
Furthermore, considering the water quality measures, it seems necessary to improve the observation campaign, in order to have a more detailed picture of the rivers conditions. One of the biggest limits of the study consists in the few data to be used as comparison with respect to the model results.

2.1 AREA DESCRIPTION

The hydraulic network of interest is a quite complicate system of rivers and channels, aimed to protect the urban area of Padua and surrounding towns from floods.
Its actual conformation is the result of a series of manmade activities meant to improve its efficiency and to adapt it to the enlargement of the city.
In particular, the streams belonging to the system develop their courses within three main municipalities: Padua city itself, Noventa Padovana and Vigonza (Fig. 2-1 and Fig. 2-2).

Figure 2-1 Case study area.



Padua is a city in the North-East of Italy, 20 km Westwards the Venice Lagoon.
Its surface is mainly flat and it covers about 9300 ha of urbanized area, surrounded by several small towns belonging to the same province.

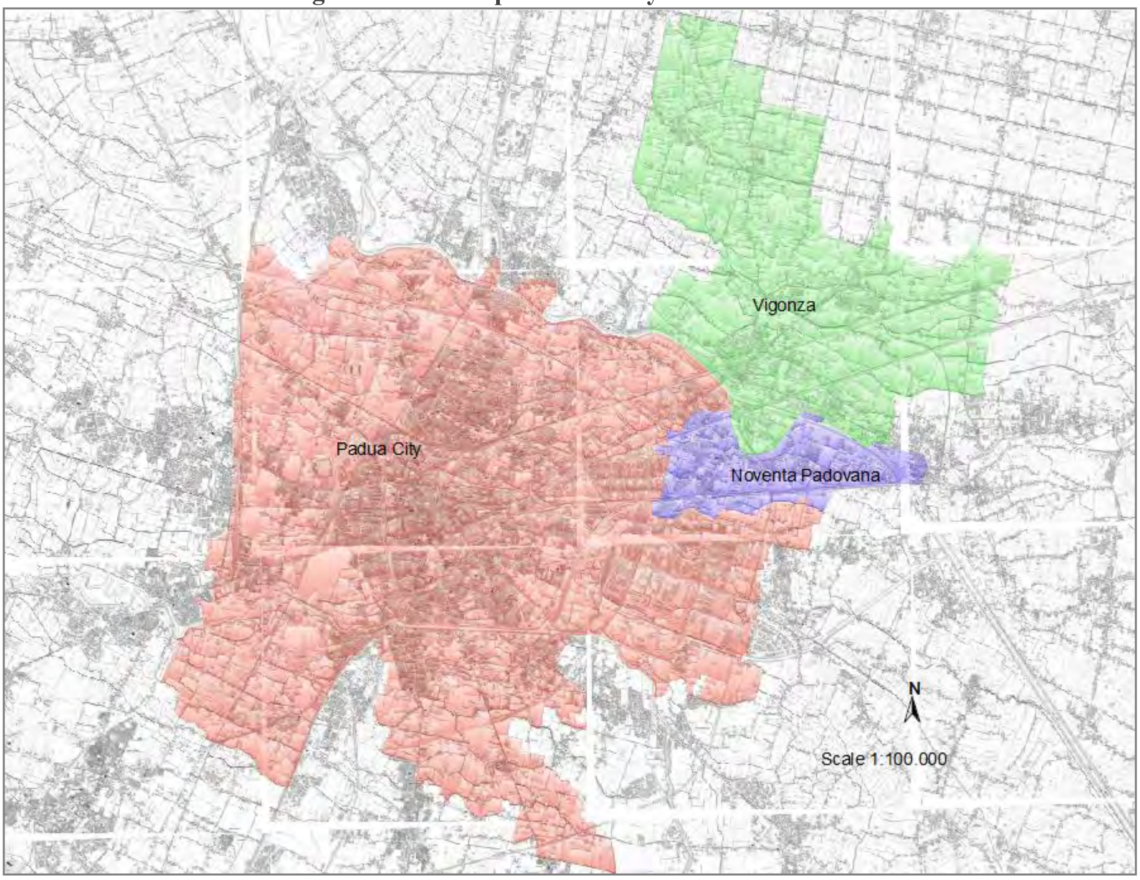
In particular, the city borders with:

- Cadoneghe, Limena, Vigodarzere, Villafranca Padovana on the North;
- Legnaro, Noventa Padovana, Saonara, Vigonovo, Vigonza on the East;
- Albignasego, Ponte San Nicolò on the South;
- Abano Terme, Rubano, Selvazzano Dentro on the West.

Noventa Padovana is a little municipality close to Padua city. It covers about 714 ha and it develops in a territory characterized by an altimetry going from 12 m.a.s.l. to 6 m.a.s.l., from West to East. The area is crossed by a great number of rivers, determining a complex hydraulic network that routes through fields destined to agricultural uses, residential areas and industrial sites.

Vigonza is another municipality not so far from Padua; it covers about 3400 ha and most of its surface is occupied by cultivated fields and residential areas. The territory is mainly flat, characterized by an average altitude is about 10 m.a.s.l., passing from 14 m.a.s.l. to a minimum of 5 m.a.s.l. .

Figure 2-2 Municipalities and hydraulic network.



2.1.1 POPULATION

Padua city is the third city of Veneto Region as regards the number of inhabitants.

In the first part of the 20th century, the town had been characterized by an important demographic increase, but this trend has changed from the 80's.

The other two municipalities of the study show a similar behavior in the past and this raise of population is still present nowadays.

Some details are presented in the following tables (Tab. 2-1), with indication of the reference source.

Table 2-1 Population from 2001 to 2010 for Padua city.

Year	Padua[1]	Noventa[2]	Vigonza[3]
2001	209290	8139	19479
2002	209621	8224	19849
2003	210536	8490	20157
2004	210821	9003	20421
2005	210985	9266	20677
2006	210301	9705	20880
2007	210173	10226	21208
2008	211936	10616	21419
2009	212989	10814	21879
2010	214198	10922	22075

2.1.2 CLIMATE

The area is characterized by a temperate climate, with cold winters, hot summers, and rainy springs and autumns.

This detail is important in order to evaluate in which part of the year the runoff is (or may be) impacting the water quality of the receiving bodies belonging to the hydraulic network.

Referring to the meteorological station of the Orto Botanico in Padua city, it is possible to obtain some useful data about the weather of the area. This station is owned by ARPAV[4], the public regional authority responsible for the management and protection of the environmental resources.

[1] Municipality of Padua - Elaborazione del Settore Programmazione Controllo e Statistica su dati dell'Anagrafe, 2013.
[2] UrbiStat, 2014.
[3] UrbiStat, 2014.
[4] ARPAV: Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto.

Some details about both temperature (minimum and maximum) and rainfall from 2001 to 2012 are presented in the following table (Tab.2-2).

Table 2-2 Climate information[5].

Year	Min Temperature (°C)	Max Temperature (°C)	Total Rainfall (mm)
2001	-4,8	35,6	801
2002	-4,9	35,9	1109
2003	-4,8	39,8	698
2004	-2,8	36,2	1101
2005	-4,8	34,9	1109
2006	-5,4	37	872
2007	-2,3	36,8	751
2008	-2,9	34,1	1264
2009	-7,9	35,1	1023
2010	-5,1	35,8	1350
2011	-2,8	37,5	672
2012	-6,6	36,9	735

[5] Kindly provided by ARPAV – Servizio Meteorologico di Teolo.

2.2 HYDRAULIC NETWORK

The three municipalities are sited between two very important rivers, that are Brenta and Bacchiglione.
Here following, a brief description of the two streams is provided.

2.2.1 BRENTA RIVER

Brenta is one of the most relevant national rivers and it is one of the biggest of Northern Italy.
It origins from the Lakes Caldonazzo (Trentino Alto Adige Region), at about 450 m.a.s.l. and it develops Eastwards until it reaches Veneto Region.
It is characterized by a watershed of 2280 km^2, of which about 1120 km^2 are in Veneto Region; this catchment is sited between those of Bacchiglione River (South-West), Adige (North-West) and Piave River (East).
Once Brenta enters Veneto Region, it flows through the provinces of Vicenza, Padua and Venice respectively, where it receives the flows of its most significant tributaries (as Cismon, Ceggio, Maso, Muson dei Sassi and Grigno rivers) before discharging in the Adriatic Sea.
It is connected to Bacchiglione River through an arm named channel Brentella: this stream, about 11 km long, is used to discharge part of Brenta flows directly into the other river, routing Southwards.
This is possible by the installment of an hydraulic support at Limena city, but it is closed in event of flood, so that it is avoided to add even more water to the hydraulic network of Padua in case of danger.
The Brenta catchment is presented in the following figure (Fig. 2-3), referring specifically to the area that develops in Veneto Region.
In addition, it is possible to see details about its boundaries and the location of ARPAV monitoring stations used to measure flows and water levels along its course.

Figure 2-3 Brenta catchment in Veneto Region[6].

2.2.2 Bacchiglione River

Bacchiglione River is another important stream of Northern Italy.

It is considered as a separate water body with respect to Brenta, since their direct connection occurs only when they are very close to the Sea (about 5 km far).

Bacchiglione River origins in Vicenza province (Veneto Region) from the connection of two streams named Bacchiglioncello and Leogra-Timonchio, respectively.

Its watershed has an extension of about 1940 km^2 and it develops across the provinces of Vicenza and Padua; the hydraulic network of this river is extremely complex, due to a great number of tributaries.

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[6] Edited from ARPAV, 2011.

Along its course, this important stream develops to reach Padua, giving rise to its complex hydraulic waterway.

Before entering the city, in the area named Bassanello, Bacchiglione river gets the contribute of the tributary channel Brentella, receiving water directly from Brenta river, and it partly discharges into another stream, named channel Battaglia, that flows Southwards.

Once in Padua, the Bacchiglione river is subdivided into two main channels: Canale Scaricatore and Tronco Maestro. The first one is used to take most of the flow of Bacchiglione out of the core of Padua, while the other stream enters the city to fuel internal channels.

At the end of its course, Bacchiglione river discharges into the Adriatic Sea, as Brenta does.

In the following figure (Fig. 2-4), the water catchment is represented.

In addition, it is possible to see the monitoring stations of ARPAV for the control of the streams.

Figure 2-4 Bacchiglione catchment in Veneto Region[7].

[7] Edited from ARPAV, 2011.

2.2.3 Padua hydraulic node

Bacchiglione river represents the first source of danger for the area under management, since it is frequently subjected to floods during large stormwater events.

The hydraulic arrangement of the city is composed of a set of different streams, connected to one another with gates, supports and water-scooping machines that work together in case of high flows: the basic principle is to reduce the main flow of the river, discharging it into different streams across the city.

Due to the developments and the structural changes of the city, this important network has been subject to modifications through the history, as shown in the figures below (Fig. 2-5and Fig. 2-6).

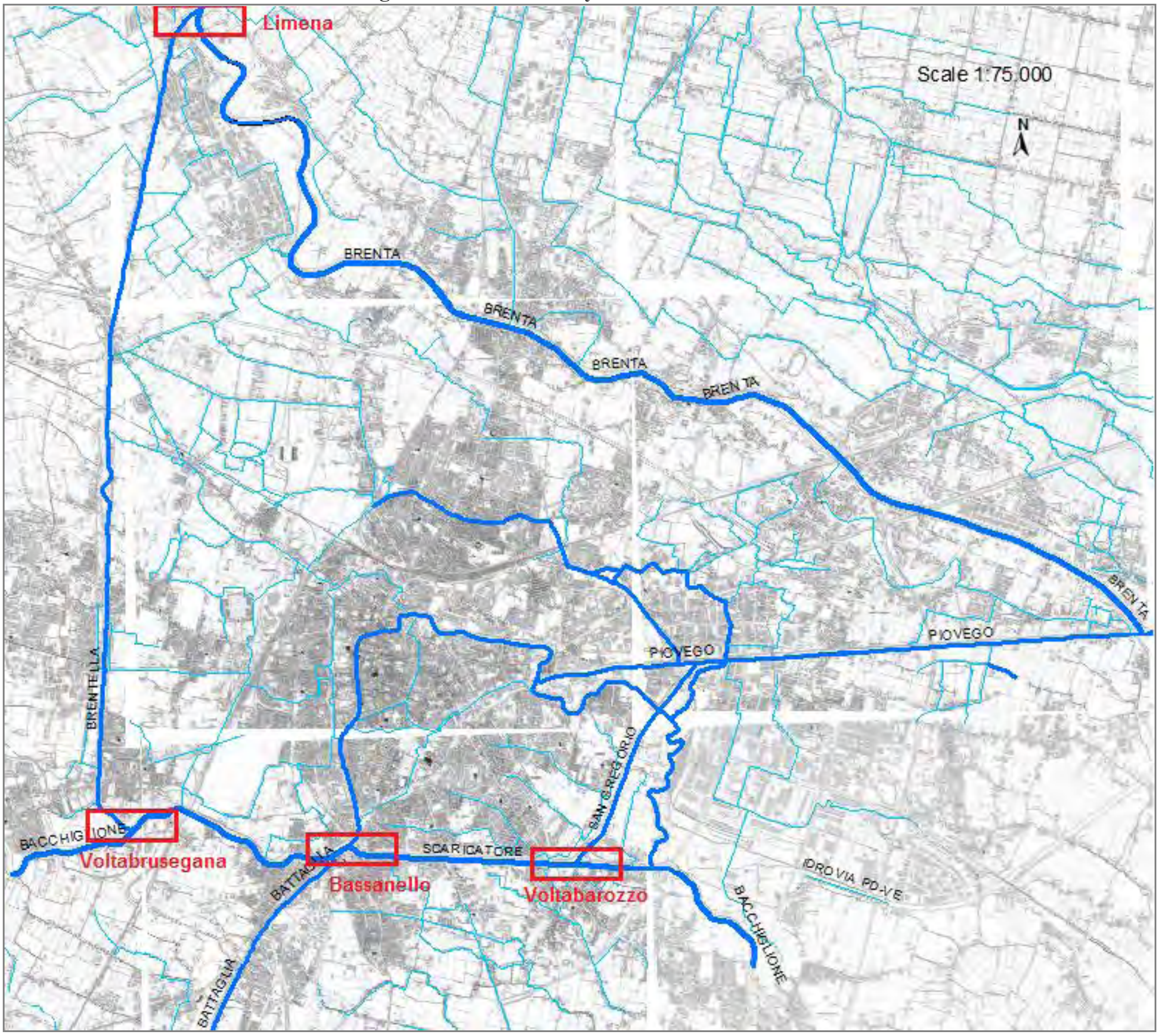
Figure 2-5 Structure of the hydraulic network in Medieval Time.

Figure 2-6 Structure of the hydraulic network in 1868.

In the following image (Fig. 2-7), a representation of the actual arrangement is given; in particular, some important elements are evidenced:

- Brenta river;
- Bacchiglione river;
- Piovego river.

Figure 2-2-7 Modern hydraulic network.



As it is possible to see, Padua city mainly develops between the first two streams and Piovego channel, being a connection between them, crosses the three considered municipalities.

In the picture, four localities are highlighted: Limena city, where Brenta discharges part of its flow into channel Brentella, Voltabrusegana, where it reaches Bacchiglione river, Bassanello and Voltabarozzo.

While Brenta river maintains its course Southwards after Limena, passing through Vigonza and Noventa Padovana, Bacchiglione river enters the city at Bassanello, where it is divided into three main streams:

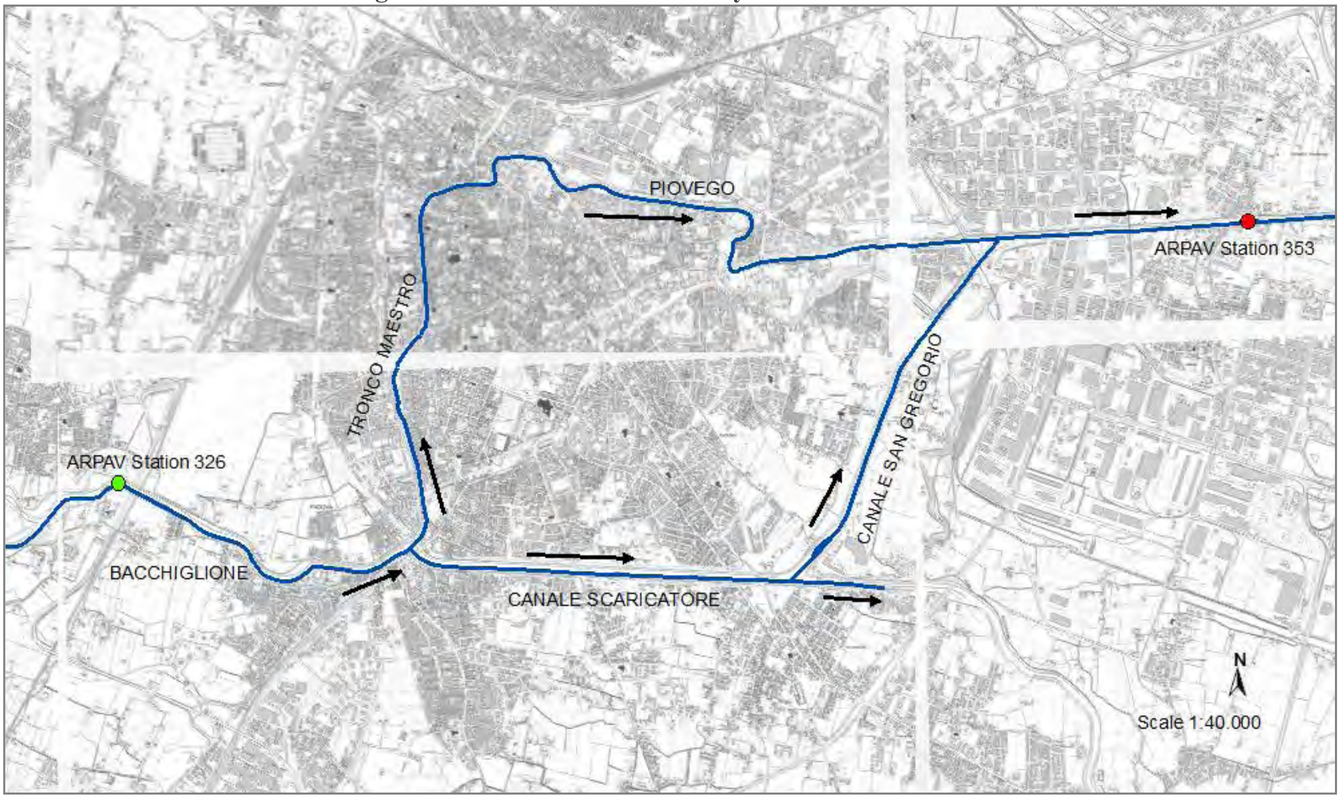
- Channel Battaglia, flowing Southwards,
- Canale Scaricatore, flowing Eastwards,
- Channel Tronco Maestro, flowing Northwards, to the core of Padua.

The last one turns its name in channel Piovego along its course into the city, while Canale Scaricatore is divided into two more streams at Voltabarozzo gate: Roncajette and San Gregorio channels. The first one exits Padua city and it sustains the main course of Bacchiglione river, flowing Eastwards to the Adriatic Sea, while the last one is a tributary of the channel Piovego and, together, their flows are taken to Noventa Padovana, where they join Brenta again.

In the following figure (Fig. 2-8) the flow directions are represented for each of the main streams that compose the hydraulic network.

In addition, the two stations used in this work where water quality measures are performed by ARPAV authority are evidenced: Station No. 326 along Bacchiglione river and Station No. 353 along Piovego channel.

Figure 2-8 Flow direction in the hydraulic network.



2.2.4 HYDRAULIC STRUCTURES

In order to regulate the flows of the streams belonging to the waterway, a complex system of structures is used. The hydraulic tools of the network have different functions[8]:

1. **Limena check dam**: placed in the Brenta river, it is used to determine the hydraulic jump that upstream allows the discharge in Brentella channel;
2. **Limena gated spillway**: placed in Brentella channel, it is used to discharge the flow from Brenta river into the Brentella channel itself. It is closed when floods occur;
3. **Gated Spillway for the input of channel Battaglia**: sited in channel Battaglia, it is used to discharge the flow from Bacchiglione river into the channel itself. It is closed when floods occur;
4. **Gated Spillway at "Ponte dei Cavai"**: used to discharge part of the flow of the Bacchiglione into the internal channels of Padua. This gates system is closed during flood events;
5. **Voltabarozzo gate**: used to maintain the difference of hydraulic level (about 7 m) between Scaricatore channel (before the gate) and the Roncajette channel (after the gate). The gates open completely during flood events to discharge the flow of Bacchiglione into the river downstream;
6. **Gated Spillway at Voltabarozzo**: used to discharge part of the flow of Scaricatore channel (about 1/3) into channel San Gregorio. In this way, it is possible to reduce the flow of Bacchiglione river, discharging it into Brenta river thanks to channel Piovego;
7. **Gated Spillway for San Gregorio channel**: used to protect the city of Padua from resurgence of Brenta flows. This structure is composed of a series of gates that close automatically during flood events;
8. **Gated Spillway at "Ca' Nordio"**: used to protect the internal channels of Padua city from resurgence of Roncajette flows. It is composed of a series of gates that close automatically during flood events;
9. **Gated Spillway at Noventa Padovana**: placed in Piovego river, it is used to maintain the hydraulic level difference between this stream and Brenta river, at their confluence. It is composed of a gate that is completely open during flood events, in order to discharge all the flow coming from the city into Brenta river;

[8] Acegas-Aps , 2011.

10. Gated Spillway at Stra: after the confluence of Piovego and Brenta rivers, a bottom sill is placed in the last one. It is used to maintain the hydraulic level upstream and it is composed of three gates that open completely during flood events;

11. Sant'Agostino check dam: used to regulate the hydraulic level for the internal channels of Padua;

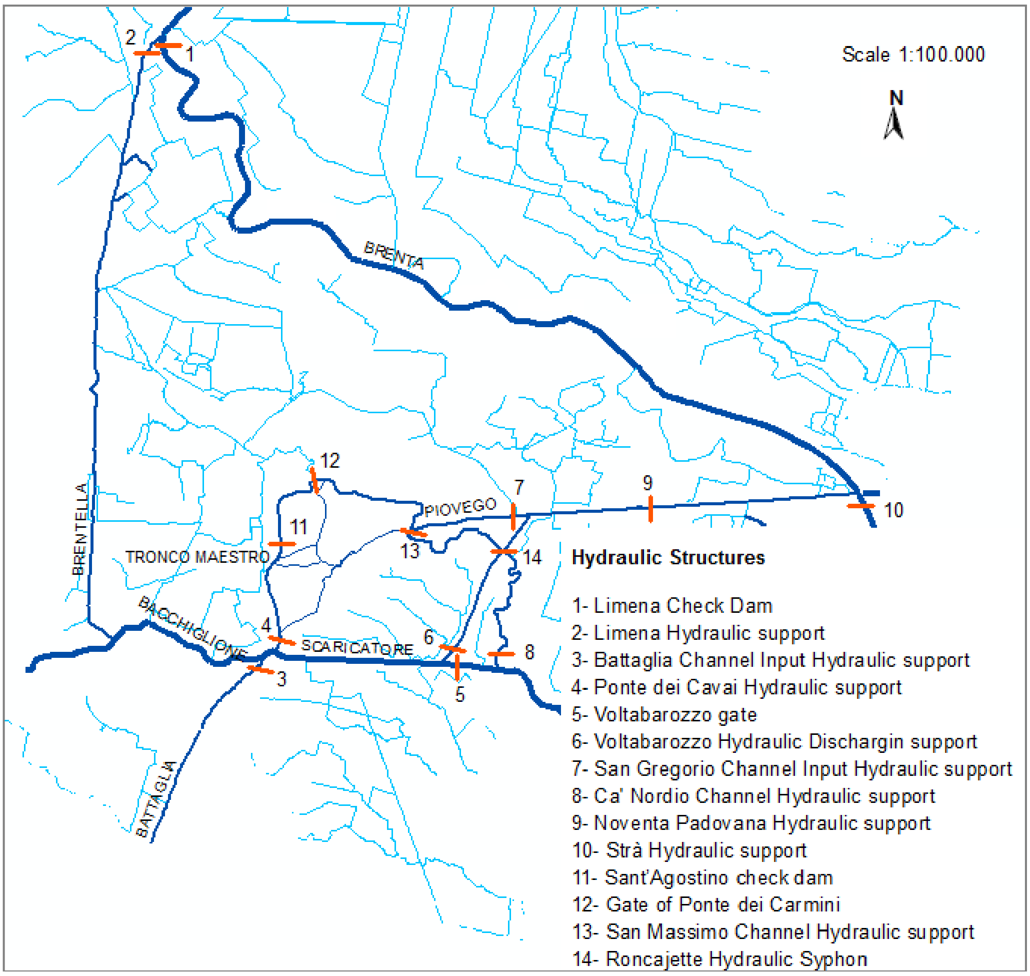
12. Gate of Carmini: used to regulate the flows of the channels in the core of Padua, this check dam collapsed in the late last century and it was no more reconstructed;

13. Gated Spillway of San Massimo: used to maintain the difference of hydraulic level between Piovego and Roncajette channels, it is composed of two gates;

14. Roncajette Siphon: used to guarantee the continuity of Roncajette below San Gregorio channel, so that the first one can continue its course. The structure is made of two ways (each cross section is 3.5 m x 2.5 m) and it is about 95 m long.

These structures are represented in the figure below (Fig. 2-9).

Figure 2-9 Hydraulic network with instruments for flows regulations.



A series of photos of the hydraulic network and some of its structures is presented below (from Fig. 2-10 to Fig. 2-15).

Figure 2-10 Specola Sant'Agostino.

Figure 2-11 San Massimo gate[9].

[9] Acegas-Aps, 2011.

Figure 2-12 Sewage release in Piovego channel.

Figure 2-13 Domestic use and pipe discharging to the Piovego cannel.

Figure 2-14 Piovego channel: river view[10].

Figure 2-15 Sant'Agostino check dam: downstream view.

[10] Thanks to the Association "Amissi del Piovego" that gave me the possibility to go by boat on Piovego river and take these photos.

2.3 RUNOFF

Runoff is a by-product of rainfall.

Considering a storm event on a closed system, the *hydrological balance* is a mathematical equation, based on the conservation of mass principle, able to describe the fate of the rainwater once it reaches the ground:

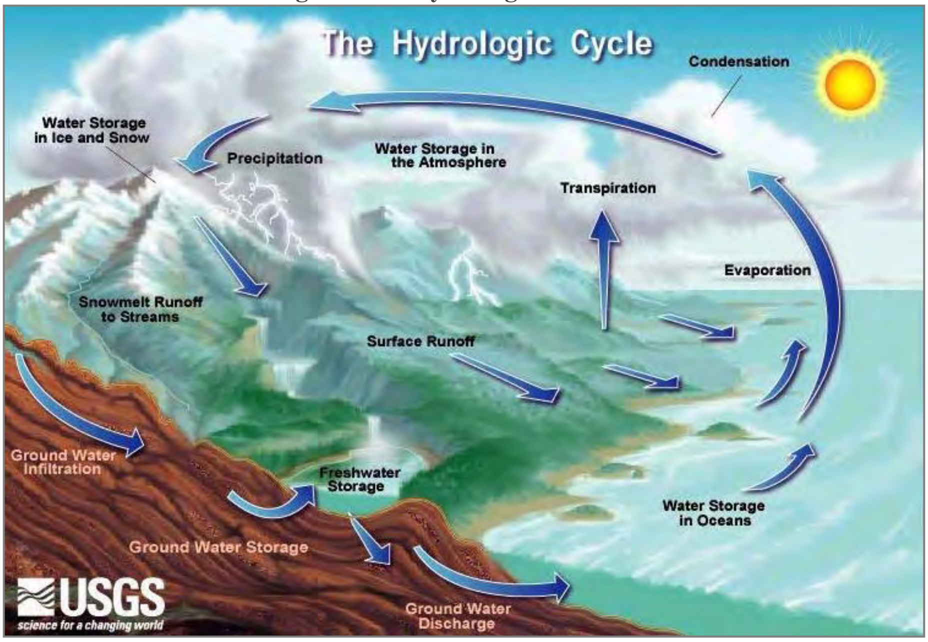
$$P = R + ET + S + I$$

Where:

- P = precipitation (mm);
- R = runoff (mm);
- ET = evapo-transpiration (mm);
- S = shallow infiltration (mm);
- I = deep infiltration (mm).

Any water entering the system during a rain event is transformed either into evaporated water, surface discharge or it is retained by the soil (infiltration), (Fig. 2-16).

Figure 2-16 Hydrological balance.

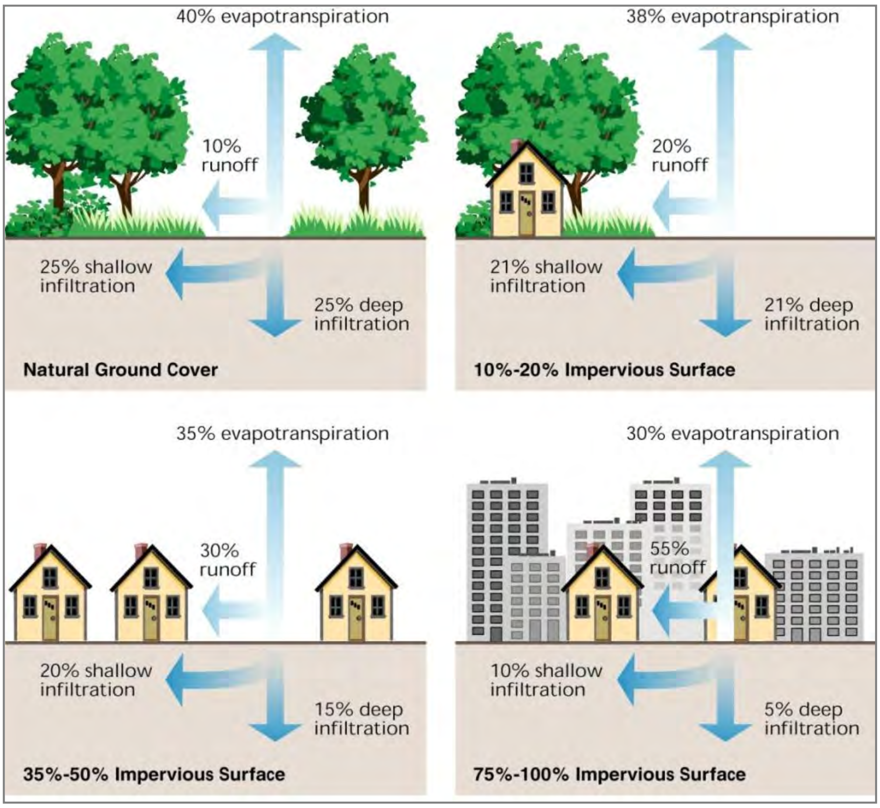


It is clear that the fate of storm water depends on the characteristics of the area, since it determines the fractions of water that infiltrates, evaporates or creates the runoff.

In particular, undeveloped areas are characterized by a low runoff generation potential, as they allow water to evaporate or to be retained by the soil. Only when the soil reaches its full capacity, the excess of water accumulates on the surface, determining the runoff.

On the contrary, the so called "*impervious surfaces*"[11] (such as roofs, roads, parking lots, sidewalks and pavements in general) prevent infiltration, due to their artificial conformation, and they enhance the runoff formation (Fig. 2-17).

Figure 2-17 Hydrological balance for different surfaces[12].



2.3.1 Runoff Generation

The stormwater runoff can be generated either by rainfall or by snow melting.

In general, the process that origins this surface flow is complex and, for some aspects, not fully understood yet.

Anyway, it is possible to identify two main processes that are supposed to govern the process:

- Infiltration excess overland flow: the velocity of the rainfall exceeds the velocity of infiltration into the ground, so the rainwater accumulates on the surface;
- Saturation excess overland flow: the soil is saturated, so no more water can be removed via infiltration and it is retained on the surface.

[11] Areas covered with impermeable materials, like concrete, asphalt, brick, and stone.
[12] http://atgeist.com/water/

When no infiltration nor saturation are possible because of an impervious cover, the amount of generated runoff increases.
The other phenomena able to influence the amount of runoff are[13]:

- Interception: part of the rainfall (about 1.2 – 1.8 mm) can be retained on vegetation surface until a small film is created. This portion depends on the kind of vegetation and on the characteristics of the precipitation (volume and intensity);
- Depression Storage: a portion of the rain water would naturally fill the depressed zones present in the surface; this water accumulates creating small ponds and it is generally lost by evaporation or infiltration;
- Infiltration: a part of the precipitation is removed by the downward movement of water within the soil. This process depends on several factors: soil type, permeability, vegetation cover, temperature and ancient moisture.

2.3.2 Typical parameters

Due to the complexity of runoff formation process, mathematical models would never be able to represent it completely. Nevertheless, the most important parameters that influence the runoff generation are:

- Rainfall: the amount of rainwater that is released on the catchment;
- Duration of the precipitation;
- Time of concentration: time needed for the watershed response to the rain event;
- Drainage area and land use: different kinds of surface respond in different way to the rainfall.

Since runoff is a by-product of the precipitation, this factor is actually the most important one between those already presented. In order to develop a robust model, a long series of data should be preferable: rainfall amount is used to evaluate the runoff produced by historical events into the area of study.
The duration of the rain event is also important, since this is necessary to understand how the precipitation is transformed into a flow that reaches the receiving bodies. This information is derived directly from the data about the precipitation.

[13] Novotny, 2002.

As concerns the time of concentration, this parameter is specific for the considered watershed and it must be evaluated case by case.
It is defined as the time needed by a catchment to get all the contributions coming from the rainfall through its outlet: the higher the time of concentration, the smaller the runoff rate.
The characteristics of the watershed are also influencing the response to a storm event: shape, slope, flow length, depressions and storage areas, soil cover and land use may alter significantly the runoff rate and its volume.
All these features are evaluated and presented in the dedicated sections of the model creation.

2.3.3 Characterization

Runoff role in surface water quality deterioration is known: stormwater runoff deriving from urban areas can hold several substances, potentially dangerous for the aquatic ecosystems of the receiving bodies.
Its generation, as far as its composition, depends on the features of the washed area: in other words, in relation to the land use, the stormwater would remove different kinds of contaminants from the washed surfaces.
For this reason, it is quite difficult to give atypical characterization of the runoff, since this aspect is related to each specific area: compounds and concentrations of pollutants depend on the degree of urbanization of the catchment.
Referring to the EPA's Nationwide Urban Runoff Program (NURP), developed between 1978 and 1983, the following substances are considered to be the main components of urban runoff:

- Total Suspended Solids (TSS)
- Biochemical Oxygen Demand (BOD)
- Chemical Oxygen Demand (COD)
- Total Phosphorus (TP)
- Soluble Phosphorus (SP)
- Total Kjeldahl Nitrogen (TKN)
- Nitrates and Nitrites (N)
- Microorganisms
- Total Copper (Cu)
- Total Lead (Pb)
- Total Zinc (Zn)

These pollutants are present as different compounds, depending on their physical and chemical characteristics, and also depending on the natural and human activities performed in the drainage area.

2.3.4 Pollution Sources

Considering the stormwater runoff characterization, a lot of different possible sources of contaminants are found within the urban areas.
Some examples are resumed in the following table (Tab. 2.3).

Table 2-3 Sources of Contaminants for Urban Stormwater Runoff[14].

Contaminants	Sources
Sediments	Streets, lawns, roads, construction activities, atmospheric deposition, drainage channel erosion
Pesticides and Herbicides	Residential lawns and gardens, roadsides, commercial and industrial areas, soil wash-off
Organic Material	Residential lawns and gardens, commercial areas, animal wastes
Metals	Cars, bridges, atmospheric deposition, industrial areas, soil erosion, corroding metal surfaces, combustion processes
Hydrocarbons	Roads, parking lots, vehicle maintenance areas, gas stations
Bacteria and Viruses	Lawns, roads, leaky sanitary sewer lines, sanitary sewer cross-connections, animal waste, septic systems
Nitrogen and Phosphorous	Lawn fertilizers, atmospheric deposition, automobile exhaust, soil erosion, animal waste, detergents

Impervious surfaces coverage can be used as an environmental indicator of the urbanization of the area: the contribute to runoff generation (and its possible influence on streams water quality) would be <u>increasing with the increasing of the imperviousness</u>.

Another way to represent the connection between substances and sources is presented in the table that follows (Tab. 2.4): the sources are linked with an “x” to the kind of substance they release in the runoff.

[14] Adapted from EPA, 1999.

Table 2-4 Pollutants sources and Constituents[15].

Pollutant source	Solids	Nutrients	Pathogens	Oxygen Demand	Metals	Oils	Organics
Soil erosion	x	x		x	x		
Fertilizers		x					
Human waste	x	x	x	x			
Animal waste	x	x	x	x			
Vehicle fluids	x		x	x	x	x	
Vehicle wear	x			x	x		
Household Chemicals	x	x		x	x	x	x
Industrial Processes	x	x		x	x	x	x
Paints					x	x	
Pesticides				x	x	x	

What presented above confirms the difficulty in the runoff characterization and it gives an idea about the great variety of compounds possible to be find in it.

When direct analysis on the runoff composition are not feasible or available, the most common practices[16] are to assume either a mean concentration of the desired compounds (as mg/l) or a mean release per unit surface for different land use (expressed as kg/y/ha), referring to studies available in the literature.

In the present work, an analysis of the area under management is performed in order to evaluate the influence of the land use on the runoff quality. In addition, the mean runoff characterization is assumed in relation to the degree of imperviousness of the urban surface.

Further details are presented in the section dedicated to the implemented software.

[15] Adapted from Shaver et al., 2007.

[16] Shaver et al., 2007.

2.3.5 RUNOFF MANAGEMENT

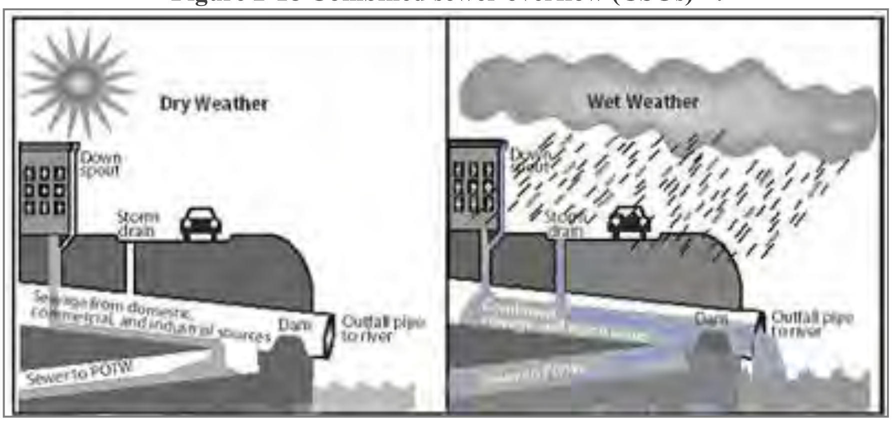
When the runoff forms before reaching a receiving body, it is considered one of the most important **non-point source** of pollutants: in urban areas it is a primary vector of contaminants since it is able to wash out substances from surfaces, and consequently to take them to rivers and streams.
The main way to handle stormwater runoff is to collect it into the sewer network.

In general, two kinds of installments are available:

- Separate sewer system, able to convey stormwater runoff and civil waste water in two different pipes. The rain water often discharged directly into receiving bodies, without previous treatment;
- Combined sewage system, aimed to collect stormwater and urban wastewater together. When large rain events take place, it may occur that the volume of the pipes is not sufficient for the collection of all the water. In this cases, the excess of untreated water (combination of stormwater and wastewater) can be discharged directly into streams and rivers, according to the Legislation: this kind of practice is known as "*Combined Sewer Overflow*" (CSOs).

CSOs are considered as possible diffuse sources of pollutants too, as far as stormwater runoff.
A representation is given in the following image (Fig. 2-18).

Figure 2-18 Combined sewer overflow (CSOs) [17].



During dry weather, the contribution that is collected by the sewage system is the wastewater from the domestic and civil uses, while, during storm events, the combined sewers are used also to receive and drain out the rain water. This determines an increase in the flow in the pipes of the network and it may cause the release into receiving water bodies.

[17] http://water.ky.gov/

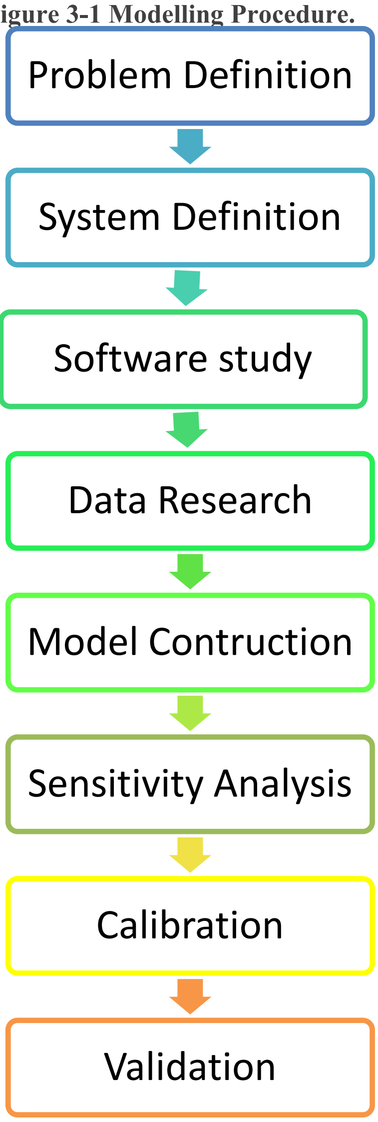
3. Modelling Procedure

The aim of the thesis is to utilize a series of mathematical models to evaluate the impact that the urban stormwater runoff of Padua city has on the water quality of the streams belonging to its hydraulic network.

In order to do this, it is worth to define the sequence of steps to be followed in the development of the project.

The next scheme can be useful for this purpose (Fig. 3-1).

Figure 3-1 Modelling Procedure.



The following chapters are specifically dedicated to the different steps of the given procedure.

4. MATERIALS AND METHODS

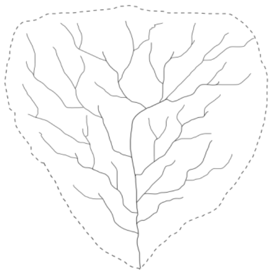
4.1 SYSTEM DEFINITION

Once the problem to be solved is identified, it is necessary to characterize the system, that is the area that will be modeled.

4.1.1 CATCHMENTS

By definition, a watershed is an area composed by streams able to collect, the water deriving from rain, snow melting and ice, and to drain it out to a single point considered as the exit of the basin itself: here the water is given to the main receiving body, like a river or a lake (Fig. 4-1).

Figure 4-1 Generic watershed.



The shape of a catchment depends on the waterways present in the area and it must be evaluated case by case.

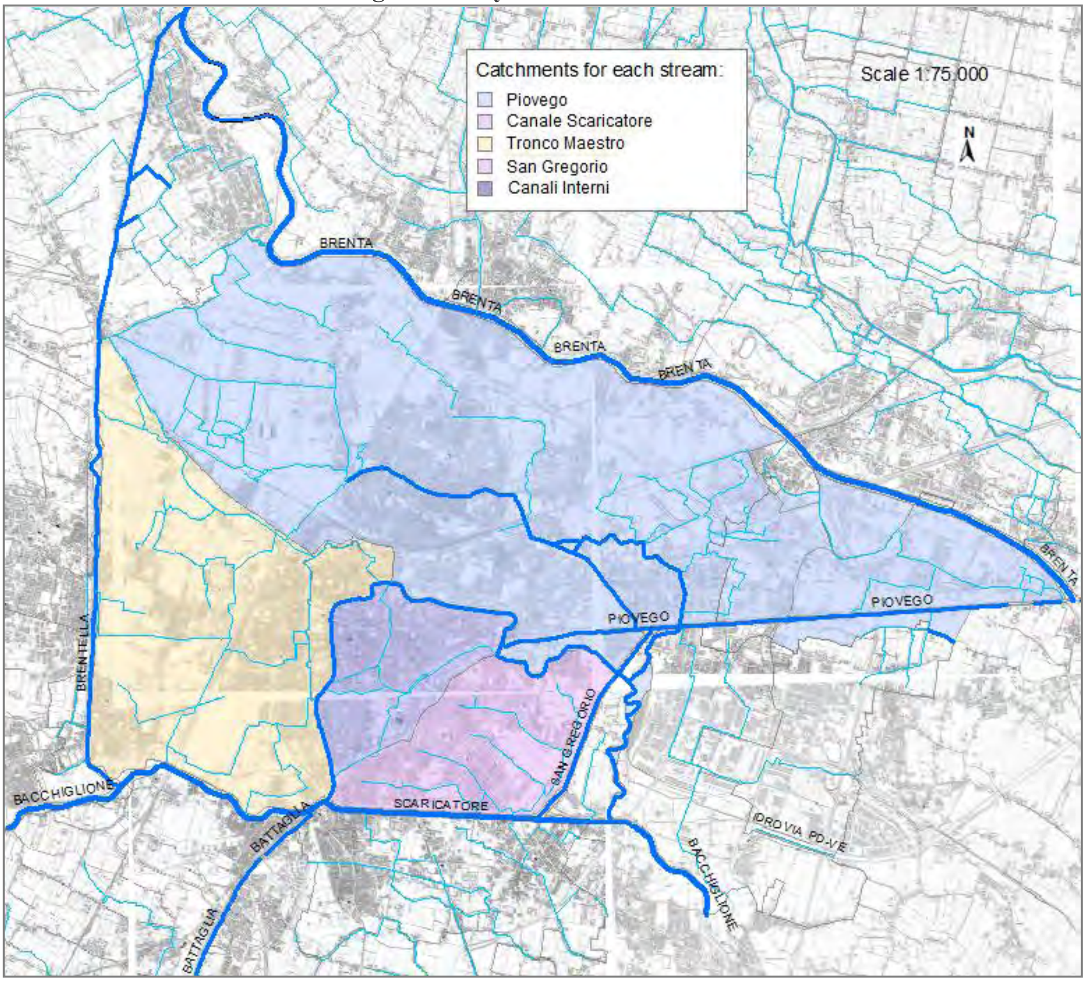
For this reason, even if the hydraulic network extends through Padua, Noventa Padovana and Vigonza, in the identification of the watersheds that contribute to the urban stormwater runoff generation it is necessary to take into consideration the entire area around these municipalities.

Thanks to the Veneto Region Database[18], that provides information about the territory, it was possible to find out information about the catchment basins of the waterway. The results are presented in the following figure (Fig. 4-2): it is possible to see that the catchment basin develops mainly within the area of Padua city; nevertheless, it is necessary to consider also most of the areas belonging to the municipality of Noventa Padovana and only a limited part of Vigonza.

As concerns the area that surrounds the three municipalities, it does not give any contribute to the definition of the water catchments for the hydraulic network of Padua city: consequently, it is not taken into account in the system definition.

[18] http://idt.regione.veneto.it/app/metacatalog/

Figure 4-2 Hydraulic Catchments.



4.1.2 LAND USES

Another important feature to be considered is the usage of the area under management: the land use determines not only the amount of runoff actually generated (or potentially generated), but it also contributes to its quality characteristics.

For this purpose, referring to the Veneto Region Database, it was possible to characterize the area under management in relation to the land use.

The further step is the description of each water basin in terms of land use and imperviousness degree, as described in detail in the dedicated section .

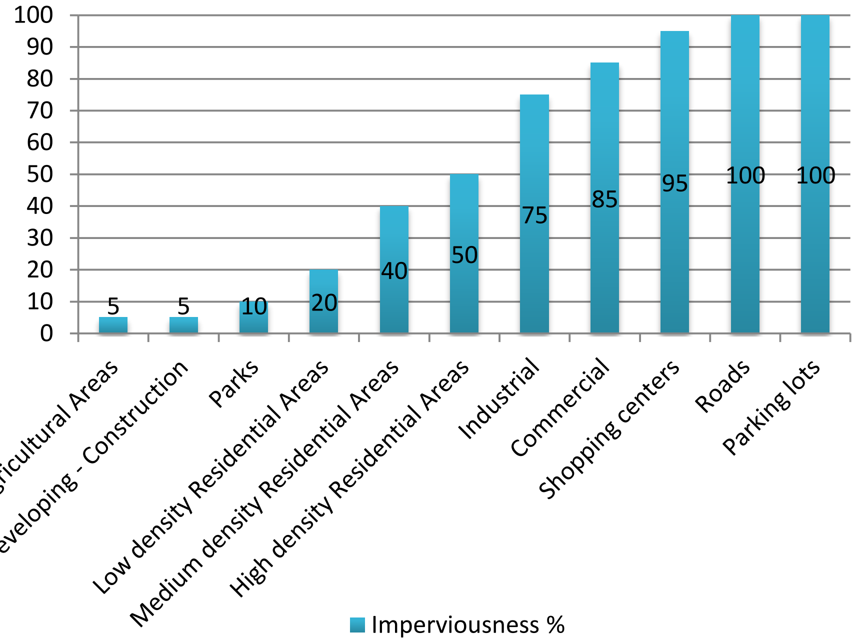
For simplicity, it is decided to consider only five classes of dominant land use: they are resumed in the following table (Tab. 4-1).

Table 4-1 Land use classes.

Land use	Examples
Impervious areas	Roads, parking lots, sidewalks, highways, airports, railways.
Agricultural areas	Fields, croplands, woods
Commercial and Industrial areas	Shopping centers, various factories
Green areas	Parks, gardens
Residential areas	Low, medium, high density areas

An important aspect of the land use is the rate of imperviousness to be related to each of the given classes: the figure that follows (Fig. 4-3) shows the mean percentage of imperviousness[19] for different surfaces in the urban areas.

Figure 4-3 Average imperviousness %.



As it can be seen, the degree of imperviousness increases passing from residential areas to roads and parking lots: this is due to the kind of materials used for their construction.

Different is for the agricultural areas, where the degree of imperviousness is minor or even negligible; as consequence, this kind of surfaces are supposed to determine a reduced runoff generation.

[19] Adapted from Arnold et al., 1996

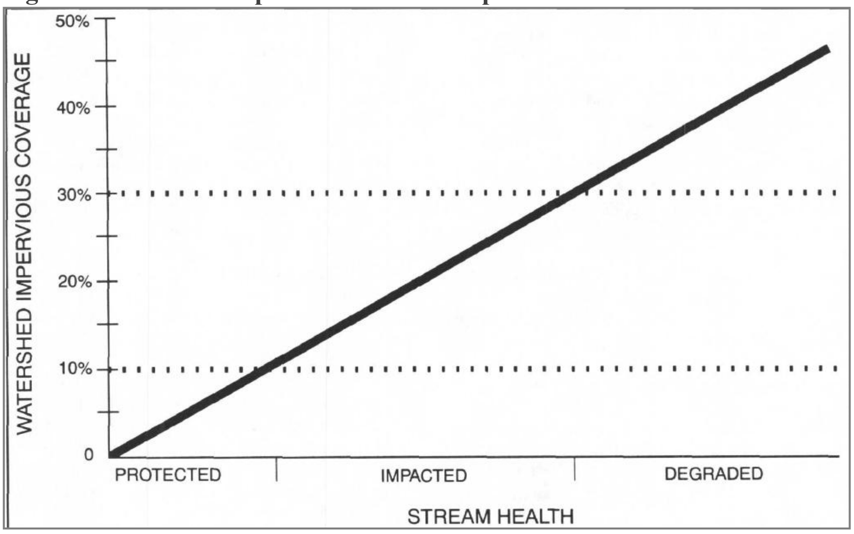
Nevertheless, they cannot be ignored in the study because of their contribution in terms of nutrients release: since Nitrogen and Phosphorous are two main components of fertilizers, these elements can be washed out by the rainfall and, even in small amounts, they can reach surface waters.
For this reason, cultivated fields represent another important source potentially impacting on the rivers water quality (Tab. 4-2).

Table 4-2 Qualitative contribute of pollutants for different land uses[20].

Water Quality parameter	Urban areas	Agricultural areas	Undeveloped areas
Nitrogen	Medium	Medium-High	Low
Phosphorous	Medium-High	Medium-High	Low
Herbicides	Medium	Medium-High	Low
Pesticides	Medium-High	Low-Medium	Very Low
Metals	High	Medium	Very Low
Toxic Organics	High	Medium	Very Low

The qualitative dependence between rate of imperviousness and rivers water quality is presented below (Fig. 4-4): the graphic confirms the primary role of the impervious coverage on the streams quality damage and runoff generation.

Figure 4-4 Relationship between urban imperviousness and rivers health[21].



Consequently, it is required to evaluate the degree of imperviousness of the watersheds in the area, in order to weight their runoff contribute and its composition, as illustrated in detail in the following sections, dedicated to the software description.

[20] Adapted from Shaver et al., 2007.
[21] Arnold et al., 1996.

In particular, for simplicity it is decided to work with the mean substances release from impervious surfaces only: this is done quantifying the fraction of imperviousness that characterizes the different areas that compose the catchment basins.

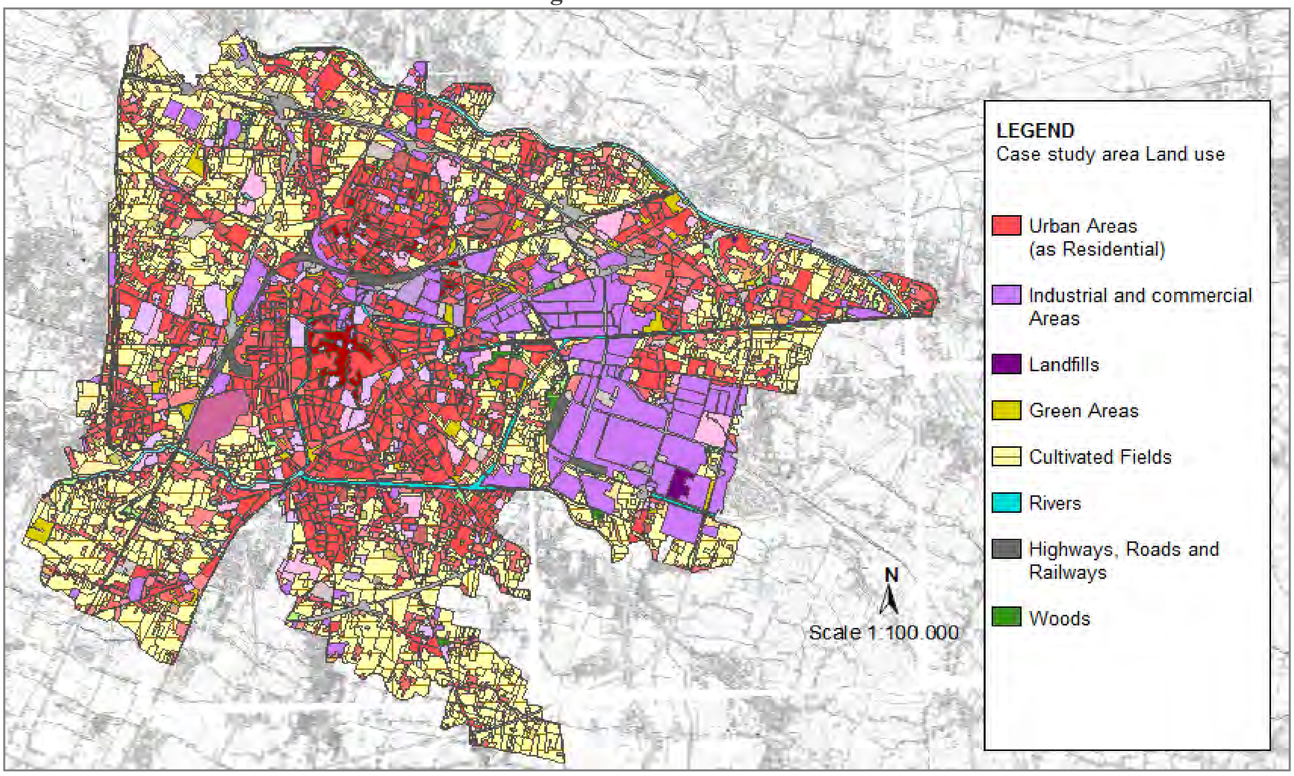
The next table presents the average characterization of urban stormwater runoff coming from impervious surfaces (Tab. 4-3).

Table 4-3 Impervious surfaces runoff characterization[22].

Ammonia NH_3 (mg/l)	Biochemical Oxygen Demand BOD (mg/l)	Chemical Oxygen Demand COD (mg/l)	Total Suspended Solids TSS (mg/l)	Runoff coefficient (adim)
0.30 – 1.7	4.2 – 11.9	21 – 100	43 – 99	0.9 – 1

In order to evaluate the imperviousness coverage of the studied areas, the land use is presented in the next figure (Fig. 4-5).

Figure 4-5 Land use.



Most of the area is destined to residential and productive uses (such as commercial and industrial sites). A great part of the surface is occupied by roads and other kinds of impervious surfaces, while the green areas are limited.

Also the agricultural areas represent a quite relevant portion of the territory, in the suburbs of the considered municipalities.

[22] Adapted from Shaver et al., 2007.

4.1.3 SEWAGE NETWORK

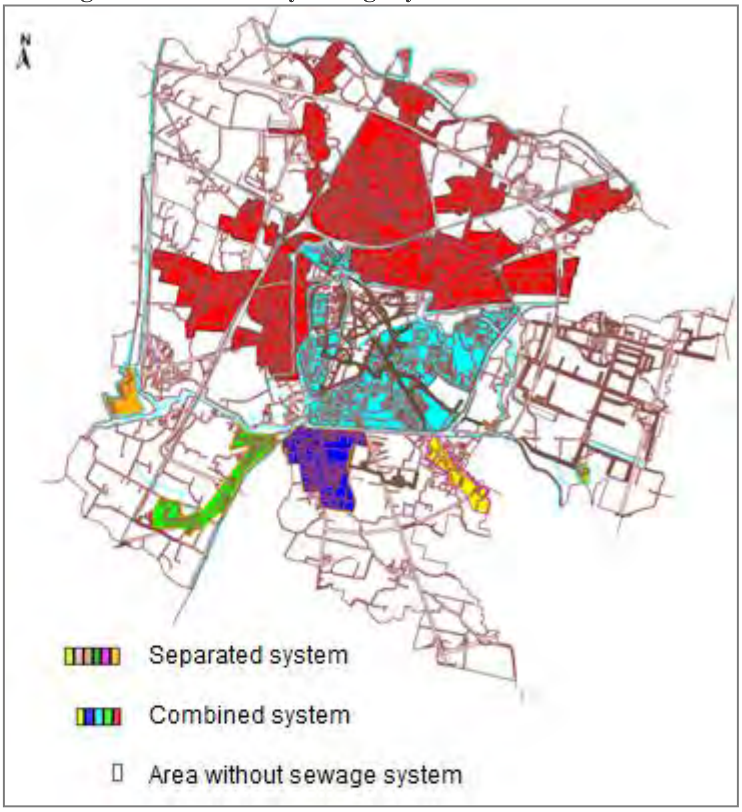
The sewage system represents the way runoff is partially collected and taken to receiving water bodies.

As stated before, there can be two different installments, i.e. separate and combined systems.

For the specific case study, the development of the network is complex and not homogeneous through the cities:

- the center of Padua city is served by both, separated and combined sewer (Fig.4-6);
- the area below Bacchiglione and Scaricatore channel is served by both systems too;
- the area above Piovego channel uses mainly a combined system;
- the industrial area of the city, below Piovego channel, is instead served by a separated system;
- Vigonza is characterized by a separate sewage system, so stormwater is collected into pipes that discharge their flows in surface receiving bodies, while civil wastewater is taken to WWTPs;
- Noventa Padovana is served by a combined system: no further details are available.

Figure 4-6 Padua city sewage system in 2002[23].



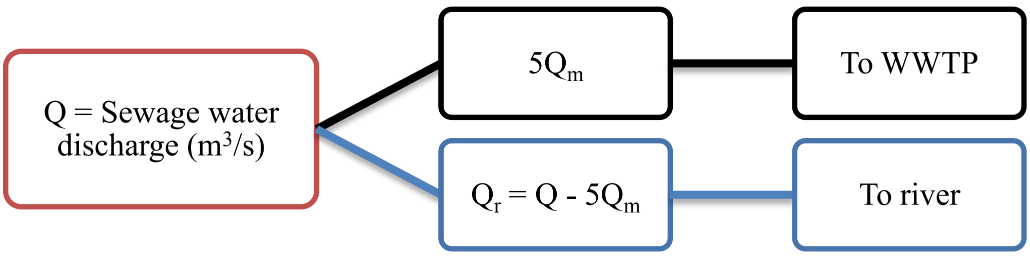
[23] Edited from ARPAV, 2002.

As a consequence, most of the runoff generated in the area is collected together with the civil wastewater: due to the physical limits of the pipes, this mixture is partly released into the hydraulic network by means of CSOs in case of extreme storm events.
In particular, since the sewage system of Noventa Padovana is not fully known, it is decided to assume the presence of one spillway discharging in Piovego river, to avoid neglecting the contribute that may come from this part of the model system.
Thanks to the help provided by Acegas-Aps, the enterprise responsible for the management of the sewage network in Padua, it was possible to localize the hydraulic installments present in the city and used for the discharge of the overflows.
This fact is important in order to characterize the external sources of pollution for the rivers system and for the definition of their water quality.

4.1.3.1 Sewage discharges

It is important to underline the fact that the discharge of sewage water into surface receiving bodies and the management of spillways are regulated by a proper set of legislations: in particular, the "Legge Galli" of 1994, together with D.P.C.M. 3/2006, states about the requirement of collecting the runoff water, since it contains pollutants deriving directly from urban surfaces wash off.
In addition, according to the Veneto Region legislation, the so called "Piano Di Tutela Delle Acque" with annex "A3-(Norme tecniche di attuazione)", defines the guidelines for the proper management of combined sewer during large stormwater events.
Specifically, in Art.33 it is stated that the minimum ratio between the combined sewage discharge during rain events and the average flow in dry periods must be equal to five.
This implies that discharges up to five times the average dry weather flow must be collected and taken to the wastewater treatment plant (WWTP), while the excess can be released directly into receiving water bodies (Fig. 4-7).

Figure 4-7 Sewage water management in large storm events.



Referring to the particular case study, the spillways installed along the course of the network have been designed in order to respect the given legislation, as specified by Acegas-Aps, responsible for the management of the sewage system of the city.

Details about the location and features of the spillways of the Northern part of Padua city are presented in the following table (Tab. 4-4).

Table 4-4 Spillways in Padua city[24].

Index	Location	Q_m [l/s]	5 Q_m [l/s]
1	Riviera Mugnai	0.7	3.5
2	Ponte San Leonardo	1.5	7.7
3	Via Rolando da Piazzola	1.2	6
4	V.Tolomei	0.7	3.5
5	Via Morgagni	6.7	33
6	Via Orus	3.8	18.8
7	Via Cornaro	1.1	5.6
8	Piazzale San Giovanni	3.5	17.7
9	Via Michele San micheli	1.0	5
10	Via Acquette	46	232
11	Via XX Settembre	3.4	17
12	Riviera A.Mussato	1.3	6
13	Riviera A.Mussato	3.7	18.6
14	Riviera A.Mussato	2.7	13.7
15	Via Raggio di sole	5.2	25.9
16	Via Palestro	4.2	21
17	Via Cristoforo Moro	1.7	8.6
18	Riviera Paleocapa	26	128
19	Riviera San Benedetto	0.5	2.3
20	Via Orto Botanico	0.2	1
21	Via Falconetto	1.0	4.8
22	P.le Mazzini	14	70
23	V.le Codalunga	5.6	28
24	Via Cernaia	34	170

Q_m (average dry weather flow, deriving from domestic uses) is calculated as follows:

$$Q_m = \frac{N \cdot d \cdot \varphi}{86400} = \left[\frac{l}{s}\right]$$

[24] Acegas-Aps.

- N = number of inhabitants served within the basin of the network (inh);
- d = mean daily water consumption per person (l/inh/d) from the reservoir;
- φ = fraction of the consumed water "d" that is taken to the sewage network (adim): it is set equal to 0.8.

The sewage network is designed in order to reduce the chance of having CSOs.
Nevertheless, the model will evaluate, depending on the rainfall, the possible release of sewage water into streams in relation to the physical characteristics of the sewage system itself.
This is done comparing the flow conveyed by the sewage network and the $5Q_m$ that can be taken, in each part of the system, to the WWTP.
Due to the great number of spillways present in Padua city (Tab. 4-4 and Fig. 4-8), it is decided to aggregate most of them, combining their contributes: this choice turns out to be helpful in the model definition, as it is presented in the dedicated section.

Figure 4-8 Spillways in Padua city[25].

Noventa Padovana is served by a combined system, but no extra information is available. For this reason, it seems worth not to neglect its potential runoff contribute (given by part of the Piovego catchment, after the connection with San Gregorio channel): it is assumed to work with a CSO characterized by a $5Q_m$ discharge equal to 0.25 m^3/s.
For the other two watersheds, a reference $5Q_m$ discharge of 0.43 m^3/s and 0.42 m^3/s respectively is chosen, so that their sum is equal to the total flows of the considered spillways (Tab. 4-5).

Table 4-5 CSOs location simplifications.

Index	Contributing Catchment	$5Q_m$ (m^3/s)
1	Tronco Maestro	0.43
2	Piovego (before San Gregorio)	0.42
3	Piovego (after San Gregorio)	0.25

[25] Google Maps (https://maps.google.it/).

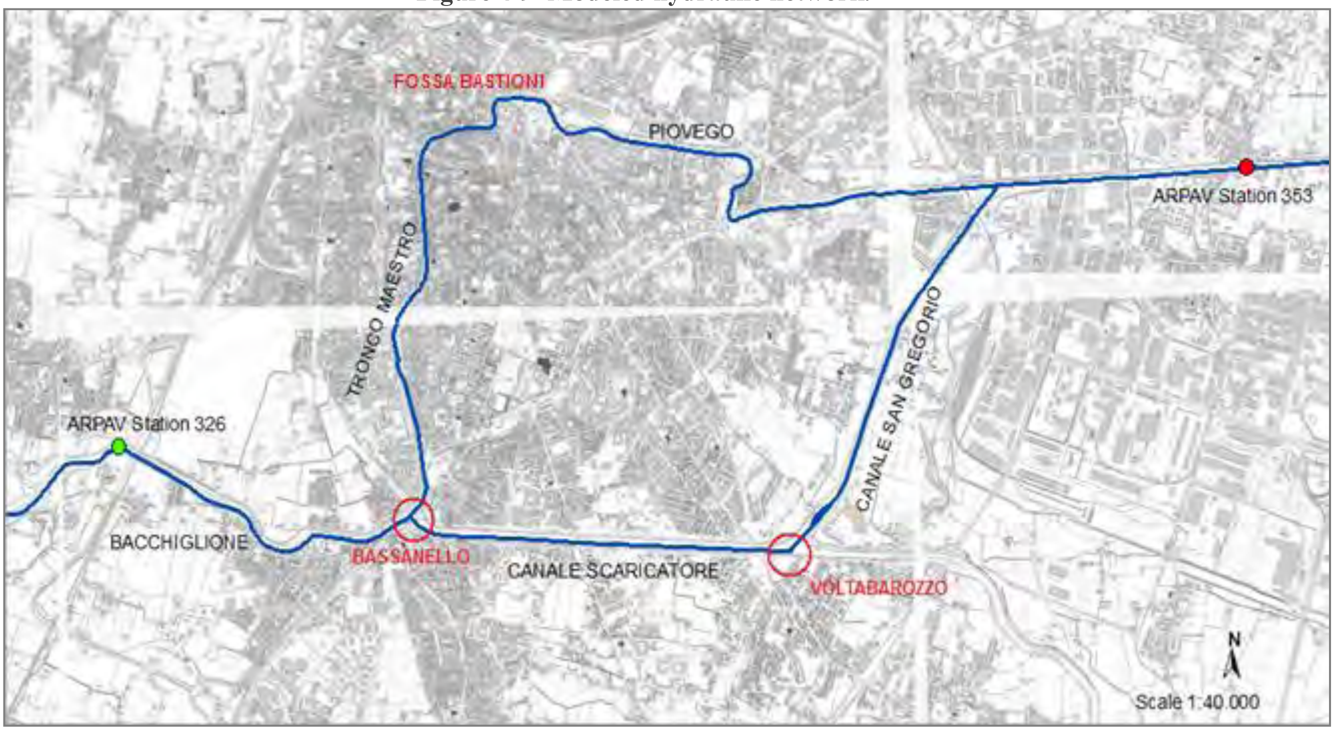
4.1.4 WATERWAYS

Developing a mathematical representation of the reality through a model, it is not possible to give a complete picture of a system; in particular, it is necessary to find a compromise between the purpose of the study, the available data and the complexity of the system to be analyzed.
In this case, three main limits have to be faced:

1. Few available information about the flows in the hydraulic network → the discharges of the rivers are measured only in one point of the network, that is the ARPAV station in Montegalda (see further details in the dedicated section that follows);
2. Few accessible data about the water quality for the streams belonging to the network → only two sites for measures are available: they are used as the boundaries of the system, as starting and end points;
3. A complex system of internal channels for Padua city.

In order to solve these limits, the water network chosen for the model is a simplification of the actual arrangement, as presented in the following figure (Fig. 4-9).

Figure 4-9 Modeled hydraulic network.



As it is possible to see, **the internal channels** of Padua city **are not taken directly into account**. The runoff from the city center is assumed to drain in Tronco Maestro (Northern and the Western part), in Canale Scaricatote (the Southern part) and San Gregorio (the Eastern side).

The streams considered separately in the model are:

- Bacchiglione river, from the ARPAV station No. 326 until it reaches Bassanello;
- Channel Scaricatore, until Voltabarozzo gate;
- Tronco Maestro;
- San Gregorio Channel;
- Piovego river, until ARPAV station No. 353.

In particular, considering the Piovego river, it is decided to subdivide its course in two parts: one developing from Tronco Maestro at Fossa Bastioni, until the connection with San Gregorio channel, and the other from the connection itself to the ARPAV station No. 353.

They are named "Piovego_In" and "Piovego_Out", respectively.

Some physical characteristics of the main rivers composing the network are resumed in the following table (Tab. 4-6).

Table 4-6 Waterways.

River	Length[26] (km)	Mean Width[27] (m)
Bacchiglione	2.5	≈ 57
Scaricatore	4	≈ 50
Tronco Maestro	6.1	≈ 25
San Gregorio	3.1	≈ 28
Piovego_In	2.1	≈ 25
Piovego_Out	5.7	≈ 28

[26] AcegasAps, 2011.
[27] Google Maps (maps.google.it).

4.2 MIKE BY DHI: WEST 2014

Thanks to the DHI Italy Group, it was possible to utilize a fully-working trial version of the WEST software, release 2014, and to exploit it for the construction of the mathematical models necessary to study the water quality of Padua's hydraulic network and the possible influence of urban stormwater runoff.

WEST 2014 gives the chance of implementing the new IUWS[28] Library: a suitable modelling tool specifically developed for the management of urban areas and the study of rainfall runoff.

This Library contains the instruments necessary to create a series of mathematical models able to consider the processes taking place in the urban areas, starting from the rainfall generation and ending up with the release of sewage water into the receiving bodies of a chosen network (with the so called Combined Sewer Overflows).

Moreover, the software can be used also to represent in a realistic way the different ecological processes that characterize the aquatic ecosystems and to assess the temporal behavior of their water quality.

Such an effort is possible by means of "blocks" used to represent the different parts of the urban system: once they are characterized in order to adapt them to the real case study, the different blocks are connected together to specify the links between processes and sub-systems, as well.

Each block contains a pre-written code made of a series of proper equations, variables and parameters, used to give a mathematical representation of the processes to be considered in the model construction.

It is also possible to perform those steps of the modelling procedure that are worth to improve the capabilities of the model itself, such as sensitivity and uncertainty analysis and calibration.

The WEST 2014 product specifically exploited in this work is WESTforOPTIMIZATION; once the system is recreated, it gives the possibility of performing:

- steady-state simulation;
- dynamic simulation;
- local or global sensitivity;
- parameters estimation;
- uncertainty analysis.

For further details, it is possible to refer to the WEST software guide[29].

[28] Vezzaro et al., 2014. IUWS: "Integrated modelling of Urban Water Systems".

4.2.1 WEST SIMULATIONS

The experiments utilized in this work are:

1. Steady-state Simulation;
2. Dynamic Simulation;
3. Global Sensitivity Analysis;
4. Parameters Estimation.

At the end, the Validation of the model is performed too.

Steady-state Simulation. WEST 2014 allows to study the system running the model until the stationary conditions are reached: then, they are used as "realistic" initial conditions for the dynamic simulation.
This is possible using a properly designed set of input data and running the model for a sufficiently long time period in order to arrive at the steady-state.
By definition, a system is considered to be in stationary conditions when the temporal variation of its state variables is equal to zero.
Consequently, the forcing functions also have to be constant in time: for this reason, it is possible to run the model with constant input values and to reach the wanted steady-state.

Dynamic Simulation. This experiments is used to evaluate the behavior of a system with respect to time, since the steady-state is a simplified, but clearly unrealistic condition.
The simulation is performed setting the initial values of the state variables to the final results of the steady-state analysis (automatically done by the software) and using input data no longer constant, but, on the contrary, deriving from temporal measurements and observations.
In particular, the experiment determines the state-trajectories of an ODE based model[30], by using different possible solvers, such as the VODE[31] and RK4ASC ones.

Global Sensitivity Analysis (GSA). The experiment is aimed to determine those parameters, input variables or initial conditions which are able to influence the model results the most.
For this purpose, WEST 2014 runs the model several times, each time using a different set of parameters, input variables and initial conditions (chosen by the user to evaluate their influence on the model).

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[29] WEST User Guide. Tool Used Guide.
[30] ODE: Ordinary Differential Equations.
[31] Brown et al., 1989.

These combinations are generated by means of the Monte Carlo Simulation and the Latin Hypercube Sampling solver: in this way, it is possible to ensure an equal and uniform sampling in the parameters hyperspace.
The main idea is to discover the relationship between parameters and outputs using randomly generated combinations of values and to run the model for each of them: in this way, the calculated outputs are independent to one another and related only to the specified parameters.
In particular, after these multiple runs, the Linear Regression between parameters values and output variables is computed: the identification of the most influencing terms is done by means of specific sensitivity functions, as explained in the dedicated section that follows.

Parameters Estimation. Once the sensitivity of the model is assessed, it is necessary to calibrate the most influencing parameters.
This is done, most of all, to solve the problem of the uncertainty connected to their preliminary estimation.
WEST 2014, thanks to the Parameters Estimation virtual experiment, allows to find out those values of a specified set of terms, that minimize a particular deviation function, chosen by the user.
For this reason, it is necessary to provide to the software the measured data, used as comparison with the model results in the minimization process.

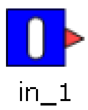
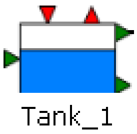
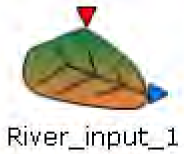
Further details are presented in the dedicated sections of these analyses.
In addition, it is worth to refer to the software user guide[32].

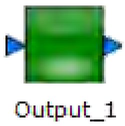
[32] WEST User Guide. Tool Used Guide.

4.2.2 WEST BLOCKS

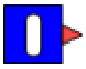
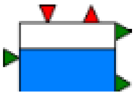
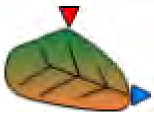
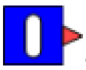
As presented before, the WEST software allows the model construction by using a series of "blocks" representing different parts of the system to be studied and embodying sets of a pre-written mathematical code. Here, a quick picture of the utilized blocks is given (Tab. 4-7). For each element, the required input and output variables is presented, with specification of the function within the system.

Table 4-7 WEST 2014 Block Editor elements.

Block Name	Icon	Function	Input Variables	Output Variables
Input		Define and supply the input variables required in the model	– Rainfall – Air Temperature – Solar Radiation – River Flow Velocity – BOD and NH4 concentration at the beginning of the system	None
Catchment		Determine the runoff generation, its characterization and collection in the sewage system	– Rainfall	– Sewage water produced within the catchment
Tank		Represent the final part of the sewage network; this block defines the amount of wastewater that is released into water bodies by CSOs with extreme storm events	– Sewage water produced within the catchment	– Sewage Overflow to the CSO and Valve-flow to be taken to the WWTP
CSOs		Transform the sewage output into a river input. Define the possible releases of combined sewage into receiving bodies	– Overflow from the Tank	– Sewage discharge to the river
River input		Define the input for the river, as flow velocity and discharge	– River flow velocity (m/s)	– River flow (m^3/s)
River		Represent the ecological system	– River input (as flow and water quality) – Sewage discharge during CSOs.	– Output mass fluxes for different compounds (such as NH4, BOD, TSS, …)

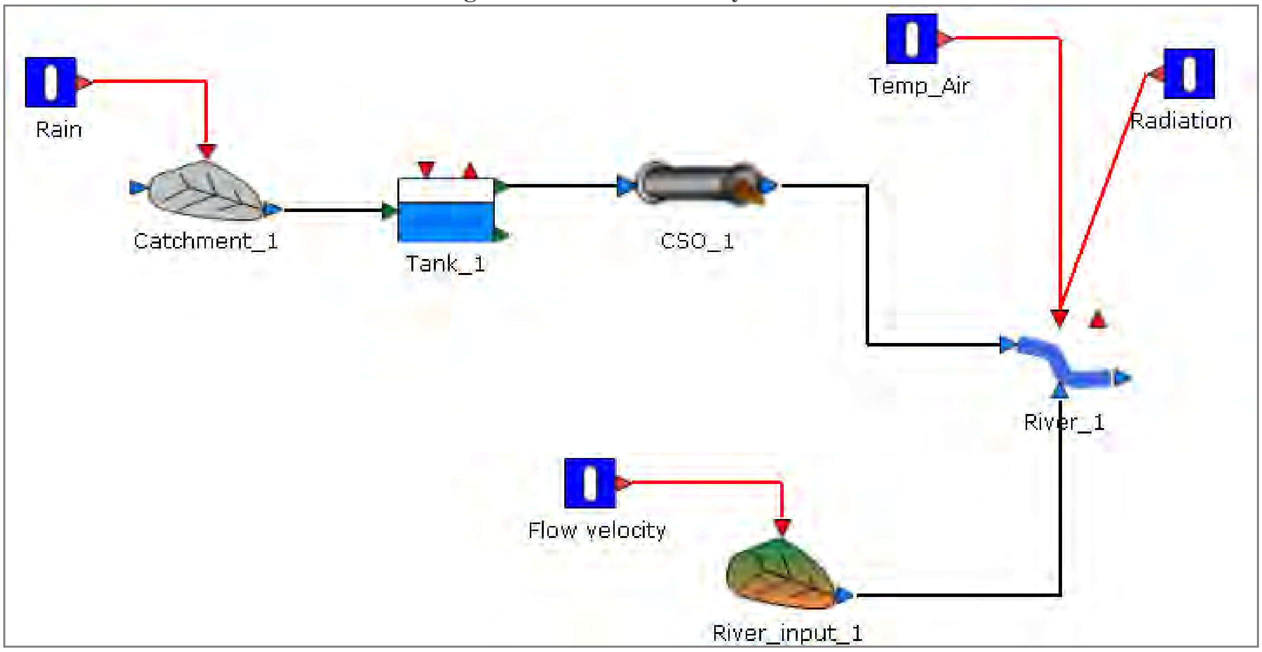
Flow splitter		Subdivide the outflow of a river into two or more parts	– River flow – Control fraction	– Rivers flows
Flow Combiner		Connect the flows of two (or more) rivers into one way only	– Rivers flows	– River flow
Connector		Transform mass flows (g/d) of a river output into concentrations (g/m^3)	– River output (given as mass flows)	– Substances Concentrations

The basic system that can be created is composed of:

- an input object  used to add the rainfall as external data;
- a catchment  that simulates the runoff generation and its characterization, in relation to the features of the drainage area;
- a tank  that represents the combined sewage network;
- a CSO element  that simulates the overflow events;
- a river input  that receives the information about the flow velocity and the discharge at the starting point of the stream;
- three input  of external data: river flow, air temperature and solar radiation;
- a river stretch  to represent the water ecosystem.

These blocks provide the basic structure necessary to build up the model for an urban area and its hydraulic network (Fig. 4-10).

Figure 4-10 Basic urban system[33].



Considering the present work, no wastewater treatment plants are added since those present in the chosen area do not to discharge into the streams considered in the study.

The following step is the representation of the studied system using the WEST software, as presented in the dedicated section that follows.

[33] WEST 2014, Mike by DHI.

4.2.3 MODEL DATA

Due to the complexity of the system, a great amount of information is required in order to develop a suitable mathematical model with the WEST software.

Nevertheless, dealing with ecological systems, it is not always easy to find (or obtain) all the data necessary in the procedure: the reason is mainly that what should be observed does not always correspond to what is actually measured and, consequently, available.

For this reason, when data were missing or not sufficient, some assumptions and simplifications are taken and justified.

The main required data are resumed in the following table (Tab. 4-8).

Table 4-8 Data used with WEST model.

Data	Source
Climate	• Rainfall (mm) - 5 minutes time scale • Air Temperature (°C) - 15 minutes time scale • Solar Radiation (W/m^2) - 15 minutes time scale (ARPAV[34])
Land use	• Land activity destinations • Imperviousness fraction (http://idt.regione.veneto.it/app/metacatalog/)
Stream flow and Water Quality	• Water flow (m^3/s) - 30 minutes time scale • Hydrometric level (m) - 30 minutes time scale • Flow velocity (m/s) - 30 minutes time scale (ARPAV)
Sewage Management	• Combined sewage spillways characteristics (Acegas-APS)

4.2.3.1 Rainfall

Since runoff is a by-product of precipitation, this is the fundamental information needed in the thesis. Data are provide by ARPAV and they refer to the measurements taken at the meteorological station of Orto Botanico, sited in Padua, between 2005 and 2010: the used temporal scale for rainfall measurements is 5 minutes.

Such a short temporal scale is chosen because:

[34] Kindly provided by: Centro Meteorologico di Teolo, Dipartimento Regionale per la Sicurezza del Territorio, Servizio Idrologico Regionale.

- considering small basins, the runoff generation is a fast process (it can take minutes or hours), so daily precipitation, for instance, seems to be a not sufficiently detailed data;
- higher temporal scales are also characterized by an higher level of uncertainty.

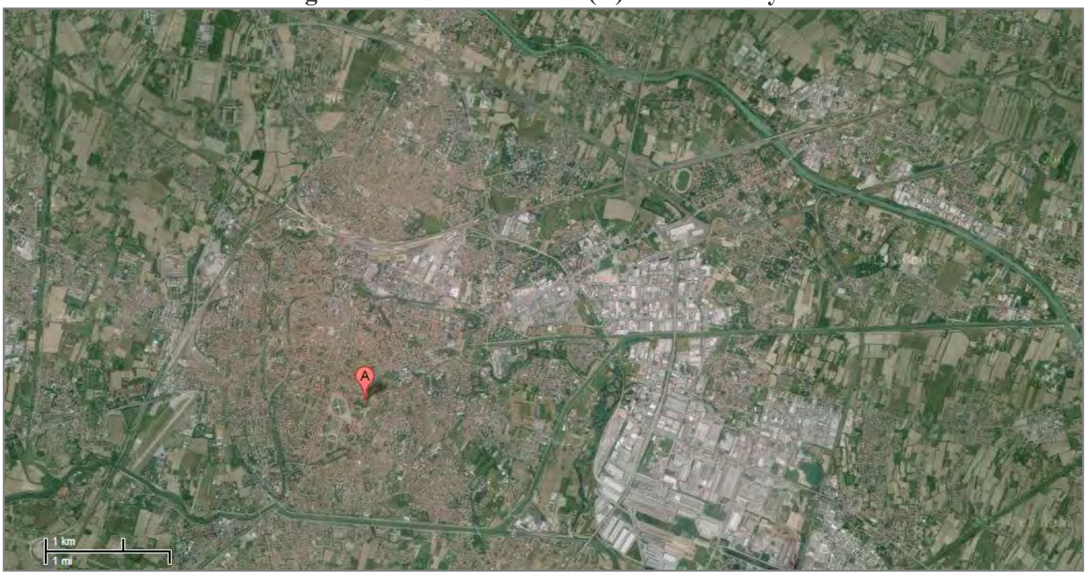
Available data are expressed in millimeters (mm) and a small extract of the entire series is given in the following table (Tab. 4-9).

Table 4-9 Example Rainfall data[35].

Date	Hour	Rainfall (mm)
08/11/2003	15.30	0.4
08/11/2003	15.35	0.6
08/11/2003	15.40	1.0
08/11/2003	15.45	0.4
08/11/2003	15.50	0.4
08/11/2003	15.55	1.2
08/11/2003	16.00	1.6
08/11/2003	16.05	1.0

In the following figure (Fig. 4-11), the location of the chosen meteorological station is presented.

Figure 4-11 Orto Botanico (A) in Padua city[36].



[35] Kindly provided by ARPAV, Centro Meteorologico di Teolo.
[36] Google Maps (google.maps.it)

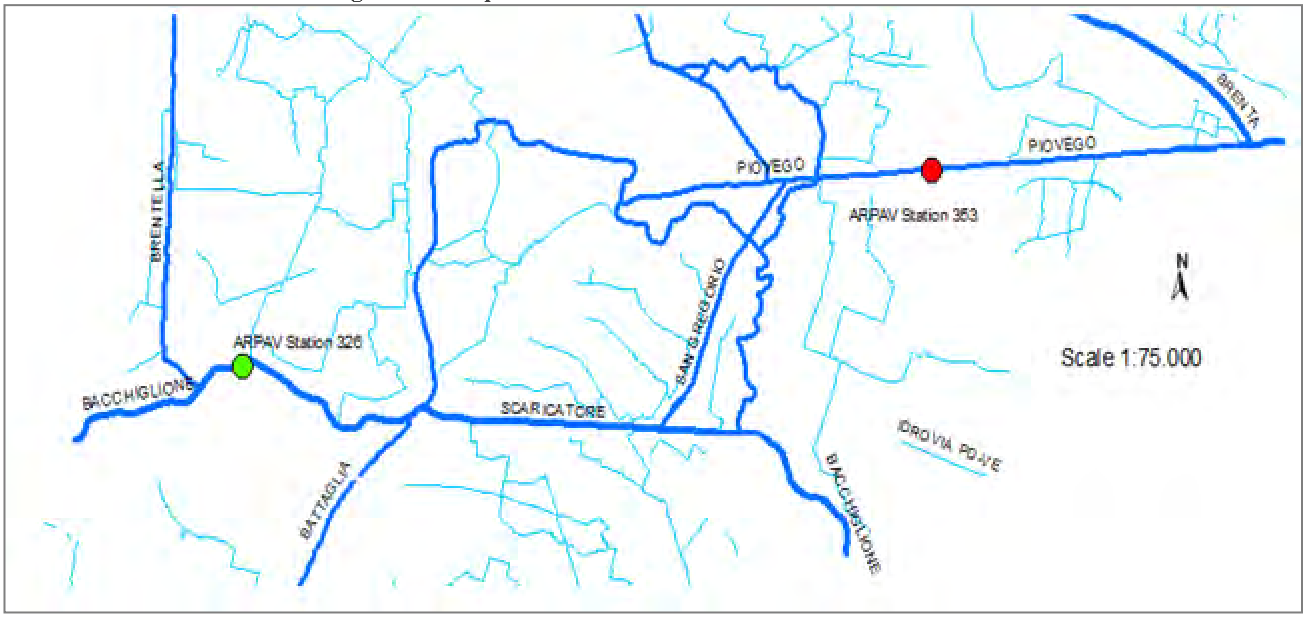
4.2.3.2 Water quality

In order to evaluate the impact of urban runoff, it is decided to consider two points of the hydraulic network where data about water quality analysis are available: one is sited at the beginning of the waterway, before Bacchiglione River enters Padua (station No. 326) and the other is placed downstream in channel Piovego (station No. 353), before it reaches Brenta River (Fig. 4-12).

Knowing the water characterization in these two points, upstream and downstream the network, it is possible to assess if an injection due to the urban contribute, as runoff and sewage, together with the natural processes occurring in the streams, can explain the differences in concentration that actually occur between the two locations (Tab. 4-11).

In particular, the utilized data refer to the period from 2005 to 2010.

Figure 4-12 Upstream and downstream monitored sites.



Data available for the station No. 326 are used in order to characterize the rivers network at the beginning of its course.

In particular, using the WEST software with the IUWS Library, it is possible to exploit such information to set the river stretch features: for this reason, these data are required as input.

An example of characterization is presented in the following table (Tab. 4-10): the first column contains the date when the analysis was performed, while the others give the concentrations of some compounds actually measured in water quality controls.

Table 4-10 Input values[37].

Date	NH_4	NO_3	NO_2	Total N	PO_4	Total P	BOD
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
15/01/2003	0.3	4.29	0.07	4.66	0.09	0	2
19/02/2003	0.26	4.07	0.05	4.4	0.12	0	2
19/03/2003	0.23	9.71	0.09	11	0.06	0	2
02/04/2003	0.19	2.94	0.09	3.6	0.07	0	2
21/05/2003	0.15	2.94	0.13	6.3	0.03	0	3
25/06/2003	0.05	2.24	0.13	3.4	0.09	0	2
23/07/2003	0.02	1.17	0.04	4	0.27	0	6
20/08/2003	0.05	1.76	0.05	3.8	0.16	0	2

Considering the present work, it is decided to focus the attention on:

- **Ammonia Nitrogen** (NH4);
- **Biochemical Oxygen Demand** (BOD).

The choice is done, most of all, to match the software capabilities, the available data and the compounds relevance for rivers water quality.
The following table is useful to compare the upstream and downstream water characterizations in terms of the chosen substances (Tab. 4-11).

Table 4-11 An example of water quality comparison: upstream and downstream.

UPSTREAM (station no. 326)			DOWNSTREAM (station no. 353)		
Sampling Date	NH4 mg/l	BOD mg/l	Sampling Date	NH4 mg/l	BOD mg/l
06/03/2006	<0,02	2	13/03/2006	0.07	1
03/04/2006	0.04	2	10/04/2006	<0,02	1
08/05/2006	0.08	6	22/05/2006	0.06	2
05/06/2006	0.05	1	26/06/2006	0.05	1
10/07/2006	0.18	2	10/07/2006	0.21	2
07/08/2006	0.03	1	17/08/2006	0.12	2

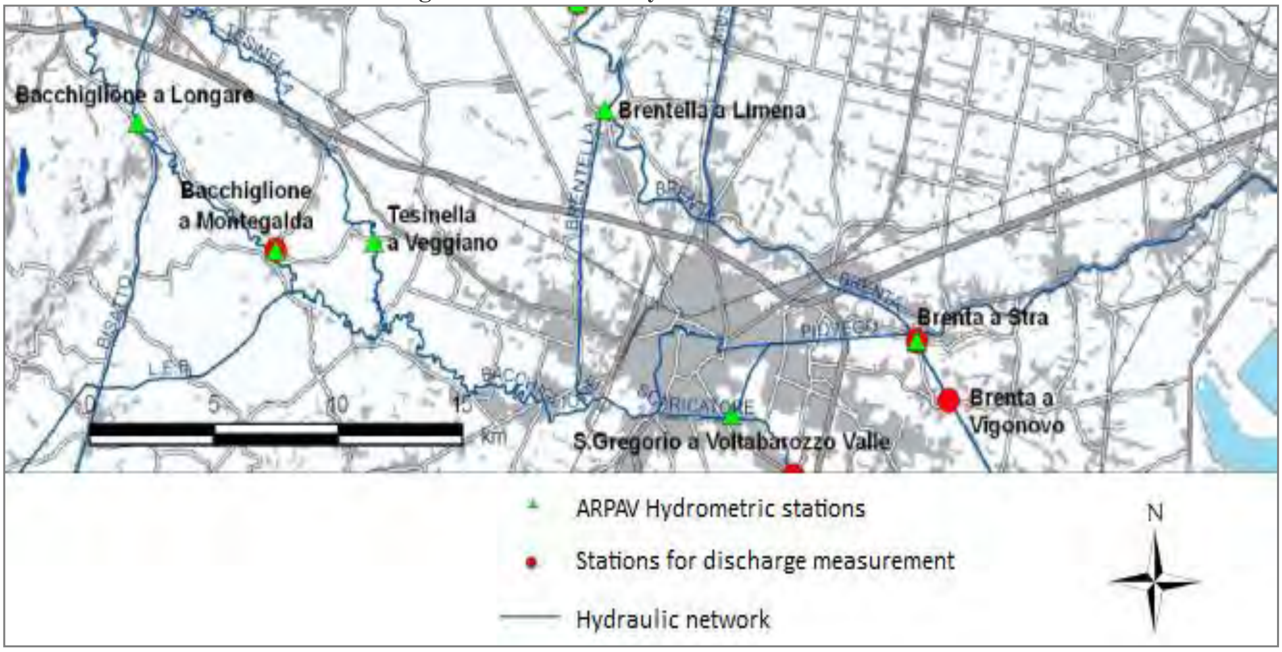
As it is possible to see , the water quality in the two locations is different: the aim of the model is to try, at least, to explain the causes of these two characterizations in terms of urban runoff influence.

[37] Kindly provided by ARPAV, Dipartimento Regionale per la Sicurezza del Territorio.

4.2.3.3 River flows

Another important required information is the flow that characterizes the rivers of the network.
In particular, one input required by the WEST software is the velocity of the water: for this purpose, useful data are obtained thanks to measurements performed by ARPAV[38] in Montegalda (Fig. 4-13).
This is a town in Vicenza province, where river Bacchiglione is subject to direct and constant analysis in terms of discharges and hydrometric levels.
It represents also the closest available measurement station with respect to Padua.

Figure 4-13 ARPAV hydrometric stations[39].



The monitoring sites surrounding Padua City are limited: in particular, it is not possible to have direct information about the flows and the water levels at the starting point of the chosen system (water quality station No. 326).
In addition, Bacchiglione river is subject to both flow injections and discharges before entering the city, but no detailed data are available.
Consequently, it is decided to use the information available from Montegalda station about the flow and the hydrometric level to characterize the system, neglecting the other injections and discharges along Bacchiglione river before reaching Padua.
Together with the few observations about water characterization, this is one of the biggest problems to be faced in the model construction.

[38] ARPAV, Servizio Idrologico Regionale.
[39] Adapted from ARPAV, 2010.

In Montegalda, the hydraulic observations are carried out by means of tele-hydrometers on a bridge (Fig. 4-14, right) and with the use of an hydrometric rod (Fig. 4-14, left).

Figure 4-14 Montegalda station[40].

An extract of the data supplied by ARPAV, referring to the period from 2005 to 2010, is given in the following table (Tab. 4-12): the date of the measurements is given in the first column, while the others contain the hour of the measurements, the values of the water levels and water flows, respectively.

Table 4-12 Bacchiglione at Montegalda: discharge and hydrometric level.

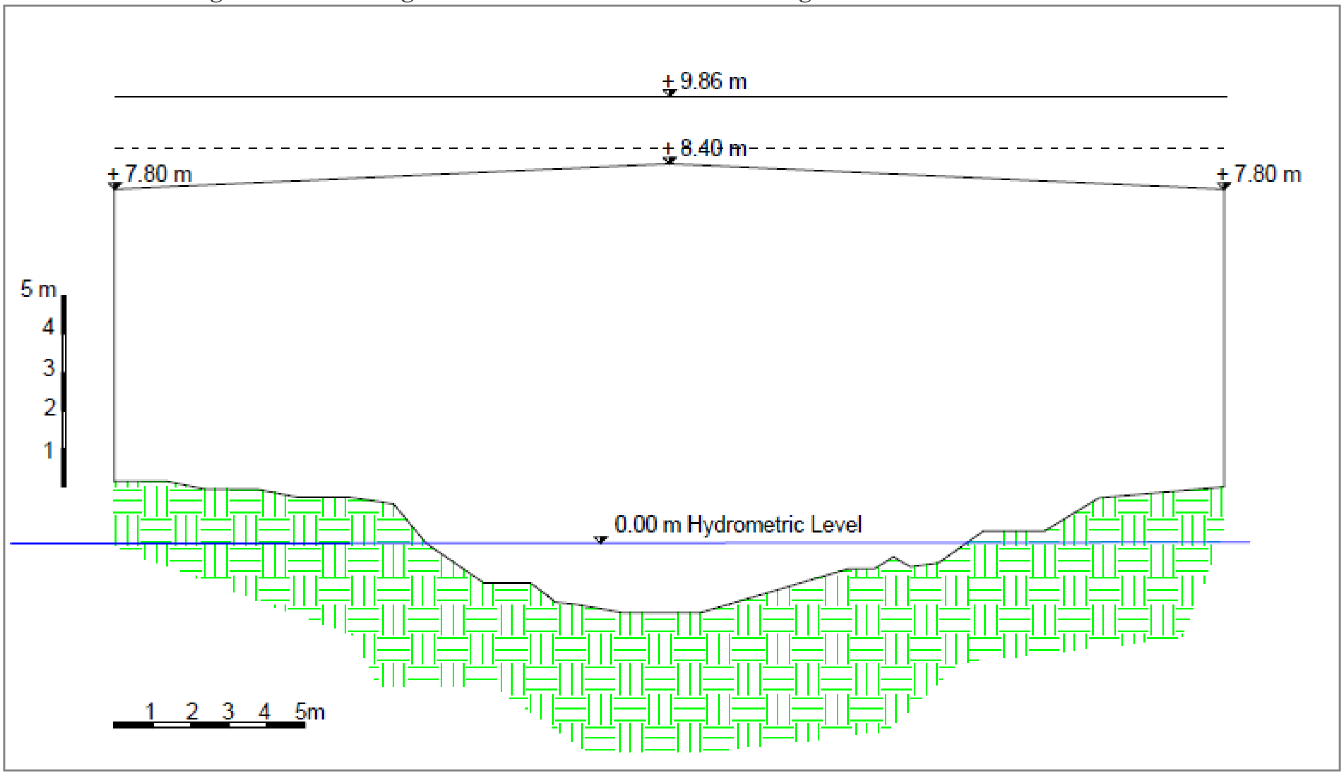
Date	Hour	h (m)	Q (m^3/s)
21/11/2010	21.00	3.1	169.04
21/11/2010	21.30	3.23	175.93
21/11/2010	22.00	3.42	186.06
21/11/2010	22.30	3.56	193.55
21/11/2010	23.00	3.66	198.92
21/11/2010	23.30	3.82	207.54
22/11/2010	0.00	3.93	213.48
22/11/2010	0.30	4.07	221.06

This table refers to the extreme event of November 2010.
In particular, it is possible to see that the temporal scale for available measurements is of 30 minutes.

[40] ARPAV, 2006.

It seems worth to underline that the value of the water level is measured with respect to a fixed reference (*hydrometric zero*): in the following image (Fig. 4-15), the cross section of the stream is presented, with indication of the *zero*.

Figure 4-15 Bacchiglione River cross section at Montegalda. Downstream view[41].



From the discharge value (m^3/s) and the water level (m) resulting from direct measures, it is then possible to get the velocity (m/d) by considering the cross section of the stream.

Another important information required for the model construction is the <u>water depth of Bacchiglione river in the town of Longare</u>: here the measure of the hydrometric level is performed and the observed values are used as reference to decide when to close the hydraulic structures of Padua city, in case of floods[42].
For this reason, data about the water depth in Longare[43] (referring to the same period, from 2005 to 2010) are used as input of the model, as presented in the following sections.

[41] Adapted from ARPAV, 2006.
[42] According to Genio Civile of Padua: the public regional authority responsible for the management of the hydraulic network.
[43] Kindly provided by ARPAV, Dipartimento Regionale per la Sicurezza del Territorio.

4.2.3.4 Land use and Imperviousness

Another important information about the territory is its activity destination, useful in order to have an idea about the tendency of a watershed to generate runoff.

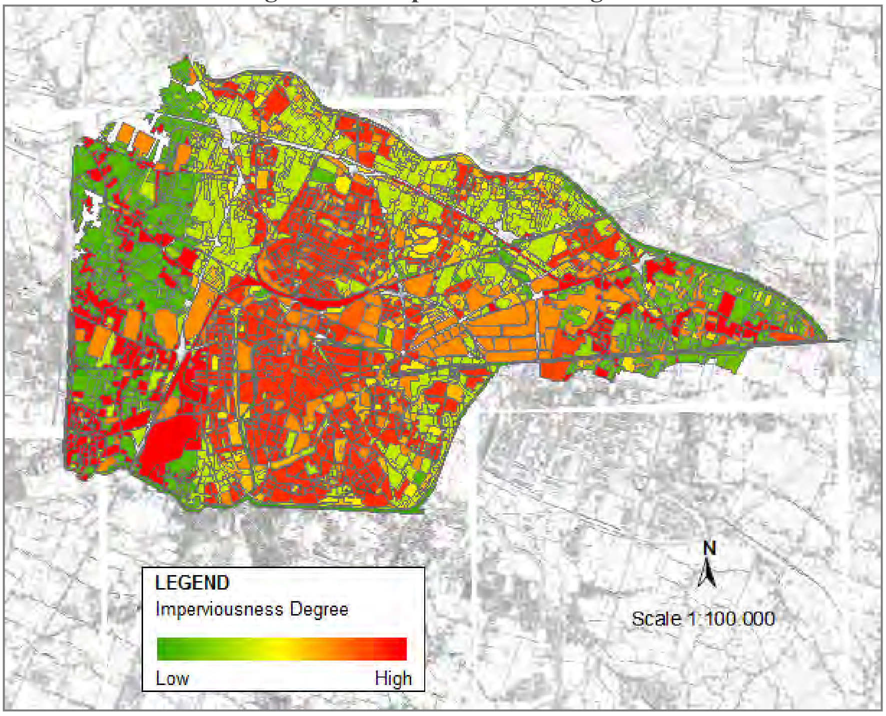
Referring to the Database of Veneto Region, it is possible to find the needed information about the topic (see also Paragraph 4.1.2) .

Once the land use is obtained, it is decided to consider the imperviousness degree of the catchments surfaces: the highest the degree, the highest the capability to give runoff.

For this purpose, a proper level of imperviousness (ranging from 0 to 1) is associated to each land use of the areas that compose the watersheds (refer also to Fig. 4-2).

A qualitative result is presented in the following image (Fig. 4-16).

Figure 4-16 Imperviousness degree.

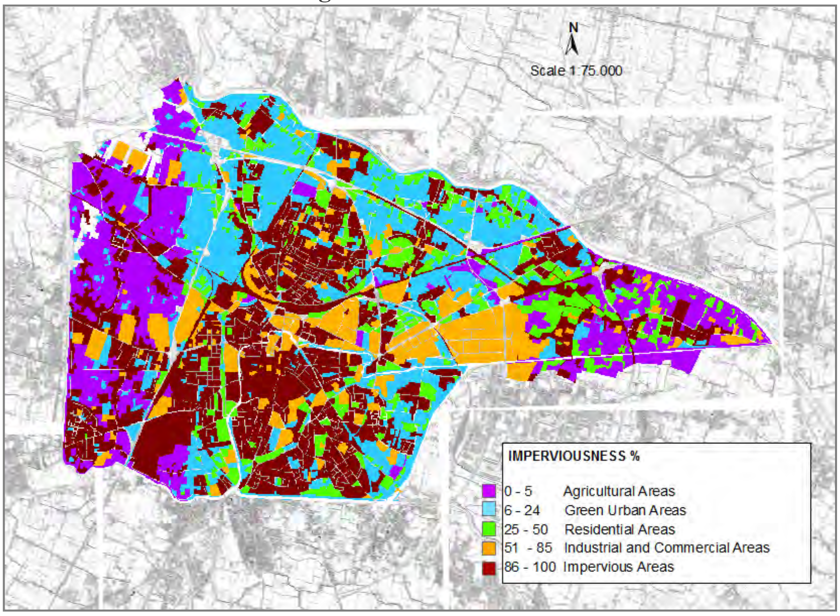


Looking at the previous picture, these considerations can be done:

- the center of Padua city shows the highest degree of imperviousness (red surfaces);
- the surrounding area, especially the East part of Padua municipality where industries are present, has an high rate of imperviousness too (orange surfaces);
- Noventa Padovana and Vigonza are mostly covered by low imperviousness degree surfaces, such as cultivated fields and green areas;
- the West side of Padua city is destined, most of all, to agricultural uses;
- a not negligible part of the considered territory is covered with impervious surfaces.

As already said, for simplicity it is decided to consider only five main classes of land use: agricultural areas, green areas, residential areas, industrial and commercial areas, and impervious areas. By means of a GIS software, the various kinds of land uses are aggregated into the chosen ones: the figure that follows (Fig. 4-17) gives the subdivision in relation to 5 land uses and their relative percentage of imperviousness.

Figure 4-17 Land use.



Considering the WEST software, it is required to characterize each water basin in terms of pervious and impervious coverage, in order to evaluate the runoff generation.

Consequently, it is necessary to calculated the average imperviousness fraction for all the considered catchments: it is given as a weighted mean of the degrees of imperviousness of the different areas that compose a watershed.

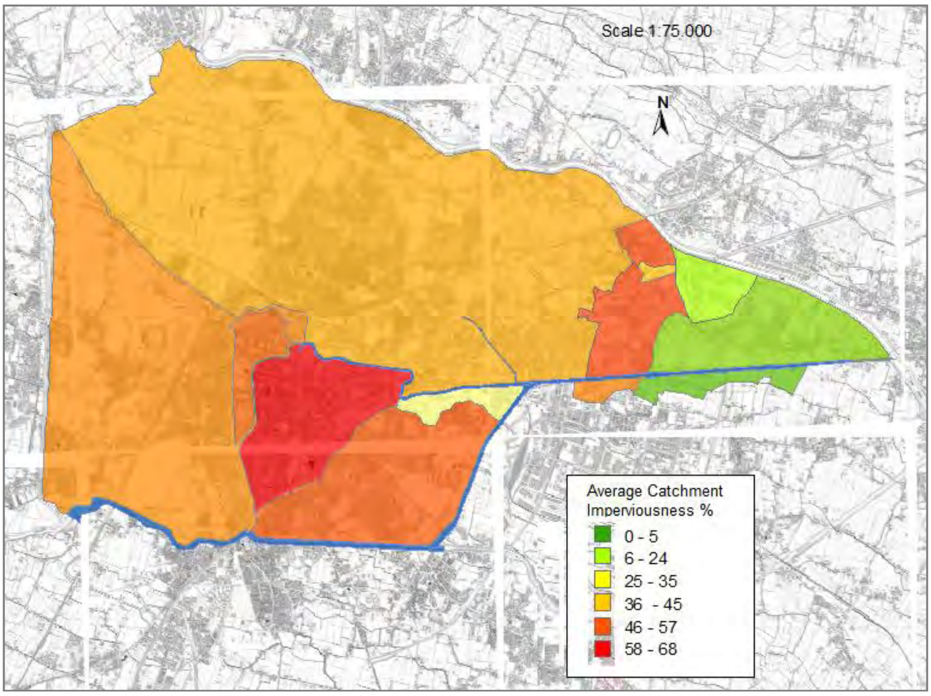
$$F_{Imp,j} = \frac{\sum d_{Imp,i} \cdot A_i}{\sum A_i} = \frac{\sum d_{Imp,i} \cdot A_i}{A_{Tot}}$$

Where:

- $F_{Imp,j}$ = Imperviousness fraction (from 0 to 1) for the jth catchment;
- A_i = ith sub-area that compose the basin (ha);
- A_{Tot} = total area of the catchment (ha);
- $d_{Imp,i}$ = degree of imperviousness for ith area (adimensional).

The results are presented in the next figure (Fig. 4-18).

Figure 4-18 Basins average imperviousness percentage.



As it is possible to see, the main contribute is given by the center of Padua city (where average imperviousness degree reaches values of 58-68%).

Anyway, in the model, only some of the presented basins are considered for the runoff generation.

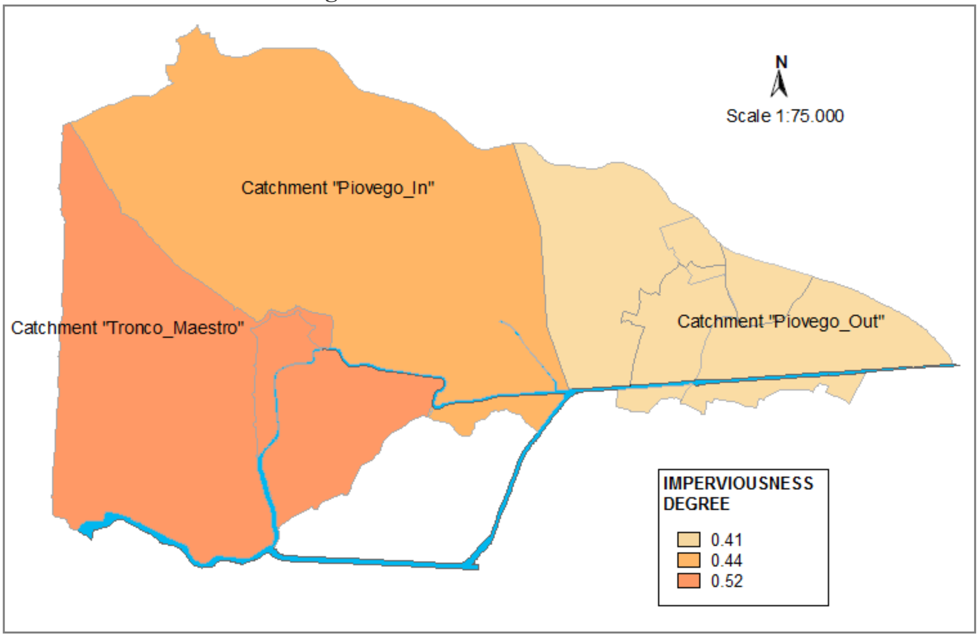
The reasons are, mainly :

1. There are no (known) spillways discharging in Scaricatore and in San Gregorio channels: due to the capabilities of the WEST software, a catchment is to be added to the model only if there is the possibility to release the generated runoff into receiving water bodies via combined sewage spillways;
2. The CSO installments of Padua city center (red basin) and those of the West side (orange basin on the left) are aggregated together as a unique contribute. This is possible because it is assumed that the rainfall is spatially constant;
3. Since no details are available about Noventa Padovana sewage system, the catchments present in that area are not neglected in the runoff generation process.

So, three macro-watersheds are considered, as presented in the figure that follows (Fig. 4-19):

1. **Tronco Maestro**;
2. **Piovego_In**, obtained considering the watershed on the North, until it reaches the connection of San Gregorio channel with Piovego river;
3. **Piovego_Out**, composed by those basins discharging in Piovego river after its connection with San Gregorio channel.

Figure 4-19 WEST model basins.



The features of the considered basins are resumed below (Tab. 4-13):

Table 4-13 WEST catchments imperviousness.

Catchment	Total Surface (ha)	Imperviousness Fraction
Tronco Maestro	1836	0.52
Piovego_In	2199	0.44
Piovego_Out	1516	0.41

4.2.3.5 Sewage discharge

It may be quite difficult to have detailed information about the punctual release of sewage water into surface receiving bodies.

Considering the specific case study, the only data available refer to the population that lives in the three Municipalities and the characteristics of the spillways discharging along the hydraulic network of Padua city.

Due to the lack of further details, it is decided to consider that each catchment of the model is characterized by the presence of one spillway only, able to discharge a maximum contribute that is set to be the sum of those actually present in the considered area.

In each watershed, a system of Tank and CSO blocks is added to release the generated runoff into the proper stream of the network. A brief summary is presented in the following table (Tab. 4-14).

Table 4-14 Sewage system characterization with WEST 2014.

Element	**Catchment Tronco Maestro**	**Catchment Piovego_In**	**Catchment Piovego_Out**
Tank Max_Volume (m^3)	10	10	10
Tank Min_Volume (m^3)	1	1	1
Max Outflow (m^3/s)	1	1	1
Max Valve flow (m^3/s)	0.43	0.42	0.25
Tank Pipe Height (m)	0.6	0.6	0.6
BOD in sewage (mg/l)	60	60	60
COD in sewage (mg/l)	120	120	120
NH4 in sewage (mg/l)	3.2	3.2	3.2

In relation to the fixed settings of the sewage systems, the model is able to determine, depending on the rainfall, the portion of diluted sewage water taken to the rivers of the considered hydraulic network.

4.3 MATHEMATICAL MODEL

In order to combine the available information about water quality and the capabilities of the software, it is decided to model **Ammonia Nitrogen** and **Biochemical Oxygen Demand** for the period **2005-2010**.

In particular, the choice of this time stage is done because the flow discharge measurements for Bacchiglione river are existing only from 2005.

As already said, the aim of the model is to give a simplified picture of the water quality along the river network, considering the physical, chemical and biological processes taking place within the aquatic environment.

Great remark is given to the urban stormwater runoff influence on the streams water quality: for this purpose, the model results are compared with the known water characterization for the ARPAV station No. 353, downstream of the system.

4.3.1 PROCESSES AND EQUATIONS

The goal of this section is the identification and the description of the ecological processes considered in the model: it is possible to recognize them by looking at the software code.

Referring to a river block, the ecological processes of interest are:

- Nitrification;
- Biological degradation;
- Reaeration;
- Settling;
- Oxygen Consumption.

Since it is decided to focus the attention of Ammonia Nitrogen (NH4) and Biochemical Oxygen Demand (BOD), their concentrations represent the two **state variables** of the problem.

Their **forcing functions** are, respectively:

NH4	**BOD**
− Temperature	− Temperature
− Dissolved Oxygen	− Dissolved Oxygen
− Input water quality	− Input water quality
− Runoff input	− Runoff input
− Sediments release	− Sediments Oxygen Demand (SOD)

For both state variables, the conceptual diagrams are presented in the figures that follow (Fig. 4-20 and Fig. 4-21).

Figure 4-20 Ammonia Nitrogen Conceptual diagram.

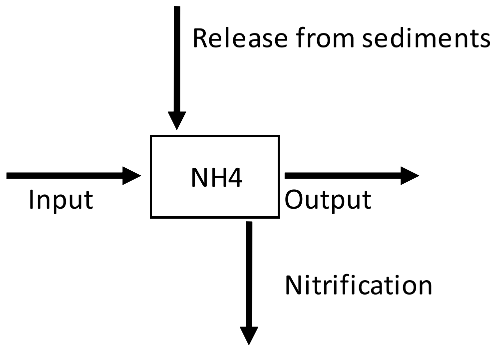
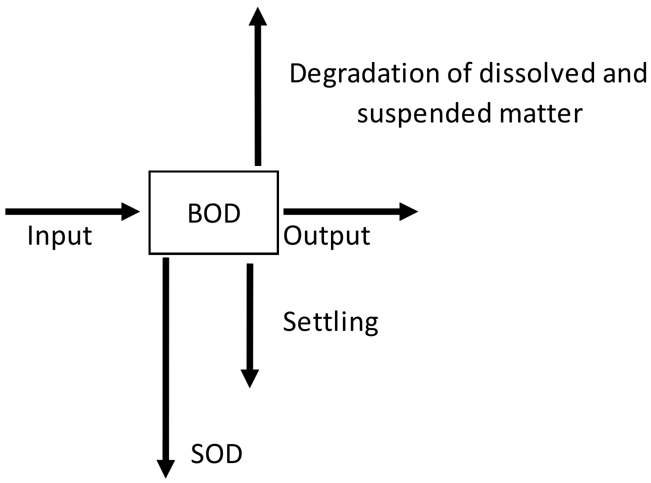


Figure 4-21 BOD Conceptual diagram.



Nitrification. This process is a two steps oxidation performed by aerobic bacteria and it is represented by the following chemical reactions:

$$NH_4 + 2O_2 \rightarrow NO_2 + 2H_2O$$

$$NO_2 + \frac{1}{2}O_2 \rightarrow NO_3$$

The first step is carried out by Nitrosomonas which are aerobic and autotrophic bacteria; the second one, instead, is performed by Nitrobacter bacteria, that are aerobic and heterotrops.
The kinetics of this process is determined by the first step because it is the slowest between the two. Considering the mathematical model, nitrification is represented with the following equation:

$$M_{NH4} = \left(- C_{NH4} \cdot Knit \cdot (TKnit)^{(Tw-20)} \cdot \frac{C_{O2}}{(C_{O2} + KNO2)} + \frac{SNH4}{d} \right) \cdot V$$

$$T_w = \frac{T_{air} + (T_{ref} - T_{air})}{T_{par}}$$

Where:

- M_{NH4} = Ammonia Nitrogen mass flux [g/d];
- $Knit$ = nitrification rate, set to 0.2 [1/d];
- C_{NH4} = actual Ammonia Nitrogen concentration [g/m^3];
- $TKnit$ = nitrification temperature coefficient, set to 1.06 [adim];
- C_{O2} = actual Oxygen concentration at T_w [g/m^3];
- $KNO2$ = Monod O_2 constant for nitrification, set to 3 [g/m^3];
- $SNH4$ = Diffuse source NH_4, from sediments [g/m^2/d];
- T_w = water temperature [°C];
- T_{air} = air temperature [°C];
- T_{ref} = reference temperature, set to 15 °C;
- T_{par} = temperature, set to 3 °C;
- d = water depth [m];
- V = river water volume[m^3].

The nitrification is modeled as a first order decay $[- C_{NH4} \cdot Knit]$, in which the minus sign stands for a consumption. The temperature dependence is expressed by the Arrhenius exponential model $\left[(TKnit)^{(Tw - 20)}\right]$, while the dependence on the dissolved oxygen content is represented by a Monod kinetics $\left[\frac{C_{O2}}{(C_{O2} + KNO2)}\right]$. Sediments contribution is modeled considering a mean daily release per unit of sediment surface and its effect is weighted with the water depth: the deepest the river, the lowest the impact of this input on the water quality $\left[\frac{SNH4}{d}\right]$.

BOD decay. Biochemical Oxygen Demand (BOD) is subjected to degradation performed by aerobic bacteria and it is common to refer to this process in terms of [mgO_2/l] required by microorganisms to oxidize the organic substance.
The mathematical equations used in the model are:

$$BODox = (- Kd1 \cdot C_{BOD1} - Kd2 \cdot C_{BOD2}) \cdot (TKd)^{(Tw-20)} \cdot \frac{C_{O2}}{(C_{O2} + KO2)}$$

$$BOD = C_{BOD1} + C_{BOD1\,p} + C_{BOD2} + C_{BOD2\,p}$$

$$M_{BOD1} = \left(- Kd_1 \cdot C_{BOD1} \cdot (TKd)^{(Tw-20)} \cdot \frac{C_{O2}}{(C_{O2} + KO2)} + \frac{SBOD1}{d}\right) \cdot V$$

$$M_{BOD1p} = \left(- VS1 - Kd_1 \cdot (TKd)^{(Tw-20)} \cdot \frac{C_{O2}}{(C_{O2} + KO2)}\right) \cdot C_{BOD1} \cdot V$$

$$M_{BOD2} = \left(- Kd_2 \cdot C_{BOD2} \cdot (TKd)^{(Tw-20)} \cdot \frac{C_{O2}}{(C_{O2} + KO2)} + \frac{SBOD2}{d}\right) \cdot V$$

$$M_{BOD2p} = \left(- VS2 - Kd_2 \cdot (TKd)^{(Tw-20)} \cdot \frac{C_{O2}}{(C_{O2} + KO2)}\right) \cdot C_{BOD2} \cdot V$$

$$M_{BODs} = \left(Vs1 \cdot C_{BOD1\,p} + Vs2 \cdot C_{BOD2\,p} + SODT\right) \cdot V$$

Where:

- $BODox$ = Oxidized BOD [g/m^3/d];
- BOD = total BOD concentration in the river [g/m^3];
- $BOD1, BOD2, BOD1p, BOD2p$ = BOD concentration [g/m^3];
- M_{BODi} = BOD mass flux for the ith component [g/d];
- $M_{BODi\,p}$ = particulate BOD flux for the ith component [g/d];
- M_{BODs} = BOD mass flux for sediments [g/m/d];
- Kd_i = BOD decay rate for the ith component, 0.4 – 0.6 [1/d];
- VSi = BOD sedimentation term for the ith component, 10 – 50 [1/d];
- C_{BODi} = actual BOD concentration for the ith component [g/m^3];
- $C_{BODi\,p}$ = actual particulate BOD concentration for the ith component [g/m^3];
- TKd = BOD temperature coefficient, set to 1.05 [adim];
- C_{O2} = actual Oxygen concentration at T_w [g/m^3];
- $KO2$ = Monod O_2 constant for BOD decay, set to 2 [g/m^3];
- $SBODi$ = diffuse source of BOD from sediments [g/m^2/d];
- $SODT$ = Sediments Oxygen Demand for BOD oxidation [g/m^2/d];
- d = water depth [m];
- V = river water volume[m^3].

The BOD oxidation is modeled as a first order decay [$- Kd2 \cdot C_{BOD2}$], with the minus sign that represents a consumption.

The temperature dependence is expressed, as for Ammonia Nitrogen, with the Arrhenius exponential model and the oxygen content dependence is modeled with the Monod kinetics.

Diffuse sources of BOD coming from sediments are also considered, using a mean daily release per surface of sediments and this contribute is weighted with the water depth.

The particulate BOD removal is represented by two combined processes: settling and oxidation. The first one is modeled fixing a settling velocity, that multiplies the actual particulate BOD concentration.

Reaeration. This process is the result of a different concentration of Oxygen between air and water. Due to this difference, there is an Oxygen exchange from air to water (or vice versa) until the same concentration is reached in both phases.
In particular, the equations used in the model are:

$$REAR = \left(\frac{KLT}{d}\right) \cdot (CS - C_{O2})$$

$$CS = 14.652 - 0.41022 \cdot T_w + 0.007991 \cdot {T_w}^2 - 0.000077774 \cdot {T_w}^3$$

$$C_{O2} = \frac{\mathrm{M_{O2}}}{V}$$

$$KLT = KL20 \cdot (TKL)^{(Tw - 20)}$$

$$KL20 = VKL \cdot \left(\frac{v_w}{3600 \cdot 24}\right)^{0.67} \cdot (d)^{-0.85}$$

Where:

- REAR = reaeration [g/m^3/d];
- CS = Oxygen concentration at saturation [g/m^3];
- C_{O2} = actual Oxygen concentration at T_w [g/m^3];
- $KL20$ = mass transfer at 20°C [m/d];
- KLT = mass transfer at T_w [m/d];
- VKL = reaeration velocity coefficient, set to 3.2 [m/d];
- v_w = water velocity [m/s];
- d = water depth [m];
- TKL = temperature coefficient for mass transfer, set to 1.02 [adim.];
- $\mathrm{M_{O2}}$= Dissolved Oxygen mass [g].

The reaeration, at the given temperature, depends directly on the difference in Oxygen concentration between the saturation and the actual conditions represented with $(CS - C_{O2})$.
In particular, the REAR term can be considered as a daily mass exchange, per water volume unit.
The saturation concentration CS is calculated considering distilled water with the Elmore and Hayes polynomial equation, while the temperature dependence of the process is represented by the Arrhenius exponential model.

In addition, the process depends on the water depth and the flow velocity: shallow rivers are characterized by a faster reaeration with respect to deep rivers. Same consideration can be done considering streams having an high water velocity, as evidenced in the previous equations.

Settling. This process is the removal of matter from the water column, because of the weight of the particles. In particular, it is used in the model of the BOD removal, given as the product of a settling velocity and the particulate matter concentration $[Vs \cdot C_{BOD\,p}]$.

Oxygen consumption. Oxygen is very important, since it enters in the natural cycle of many other elements. For this reason, Oxygen consumption and production are related to a very wide set of different processes able to influence its amount as dissolved gas into a water body.
The necessary equations are given below.

$$Nitrif = -\left(4.57\,\frac{\text{gO2}}{\text{gNH4}}\right) \cdot K_{nit} \cdot C_{NH4} \cdot (TKnit)^{(Tw-20)} \cdot \frac{C_{O2}}{(C_{O2} + KNO2)}$$

$$SedO2 = \left(-\frac{SOD}{d}\right) \cdot (TSOD)^{(Tw-20)} \cdot \frac{C_{O2}}{(C_{O2} + KSO2)}$$

$$SODT = -C_{BODs} \cdot KBODs \cdot (TSOD)^{(Tw-20)} \cdot \frac{C_{O2}}{(C_{O2} + KSO2)}$$

$$RivO2 = (REAR + PO2M + SedO2 + BODox + Nitrif + SODT) \cdot V$$

Where:

- $Nitrif$ = Oxygen consumption for nitrification [g/m^3/d];
- $SedO2$ = Oxygen consumption from sediments [g/m^3/d];
- SOD = Sediments Oxygen Demand, set to 5 [g/m^2/d];
- $TSOD$ = temperature coefficient for Sediments Oxygen Demand, set to 1.08 [adim];
- $KSO2$ = Monod O_2 constant on sediment oxygen demand, set to 2 [g/m^3];
- $PO2M$ = net oxygen production/consumption Macrophytes [g/m^3/d];
- $RivO2$ = Oxygen content [g/d].

In the previous equations, the minus sign again stands for a consumption, while a plus represent a production of Oxygen within the river body.

For further details, refer to the WEST software code.

4.3.2 MODEL PARAMETERS

As presented in the previous section, the model variables depend on a large number of parameters. Most of times, anyway, it is not possible to have an exact value for all of them, suitable or specific for the actual case study: consequently, it is frequent practice to assume them, referring to the literature.

Here following, a summary of the most important model parameters is presented (Tab. 4-15).

Table 4-15 Model parameters.

Processes and blocks	**Parameter name**	**Parameter value**	**Literature reference**
Nitrification	Nitrification rate	Knit = 0.2 1/d	Jørgenses, Bendoricchio (2001).
	Nitrification temperature coefficient	TKnit = 1.06	Jørgenses, Bendoricchio (2001).
Biological degradation	Decay rate	Kd1 = 0.4 1/d	WEST 2014
	Decay temperature coefficient	TKd = 1.05	Jørgenses, Bendoricchio (2001).
Runoff characterization	Ammonia from impervious surfaces	ConcImp(NH4_sew) = 5 mg/l	Assumed from Lee, Bang (2000).
	Soluble COD from impervious surfaces	ConcImp(COD_sol) = 20 mg/l	Assumed from Lee, Bang (2000).
	Particulate COD from impervious surfaces	ConcImp(COD_part) = 39 mg/l	Assumed from Lee, Bang (2000).
Runoff generation	Reservoirs constant	k = 0.02083 d	Best guess
CSO	BOD concentration in CSO	BOD_CSO = 60 mg/l	Best guess
	COD concentration in CSO	COD_CSO = 120 mg/l	Best guess
	NH4 concentration in CSO	NH4_CSO = 3.2 mg/l	WEST 2014
Tank	Maximum Outflow	Q_max = 1 m^3/s	Based on Spillways characterization, (Acegas- APS).
	Outflow from Valve	Q_valve = 0.25 – 0.43 m^3/s	
	Maximum Volume	V_Max = 1 m^3	
	Minimum Volume	V_Min = 1 m^3	
	Final pipe dimension	PipeHeight = 0.6 m	

Since these parameters have been assumed, their value is affected by an uncertainty that can influence the model outputs and, consequently, it may be necessary to test their influence on the model results, as described in the dedicated section.

4.3.3 GRAPHICAL REPRESENTATION OF THE SYSTEM

Referring to the present work, the main difficulty is to recreate a system that properly represents the complex structure of the hydraulic network of Padua city.

The chosen arrangement is presented in the following figure (Fig. 4-22).

It is composed of a first river input block (named "Bacchiglione_input") and used to characterize the Bacchiglione river (represented by a proper river block, "Bacchiglione") in terms of water quality and flows.

In particular, the water quality data used as input are those coming from the ARPAV station No. 326, while data about the flows are those referring to Montegalda measurements.

It is worth to underline that the "Bacchiglione" river block represents, consequently, the part of Bacchiglione river extending between the ARPAV station and locality Bassanello: here, the river enters Padua and it divides its flows into two ways, Tronco Maestro and Canale Scaricatore.

For this reason, a first flow splitter is placed at the end of the first river block and it is connected to a controller unit: in this way, it is possible to control the flow released from Bacchiglione in the two streams (each one represented with a proper river block) in case of floods: when the hydraulic level at Longare city (given as input with the input block named "Longare_water_level") reaches and overcomes a value of 1.80 m, the controller impose to the flow splitter to close the way to "Tronco_Maestro" and to discharge all the flow in the "Canale_Scaricatore"; otherwise, the flows to "Tronco_Maestro" are set to be 1/3 of those of Bacchiglione river.

Another flow splitter is added at the end of "Canale_Scaricatore" river block: it represents the hydraulic gates system of Voltabarozzo and San Gregorio.

As the other one, this splitter is connected to a water level controller, in order to close the gates when the hydrometric level of Longare is equal or higher than 1.80 m.

In these conditions, all the flows coming from "Canale_Scaricatore" are discharged through Voltabarozzo gates and no flows go to the "San_Gregorio" channel.

Otherwise, a fixed fraction of 1/3 is set to be released in the last stream, while the remaining fraction leaves the systems through Voltabarozzo hydraulic system.

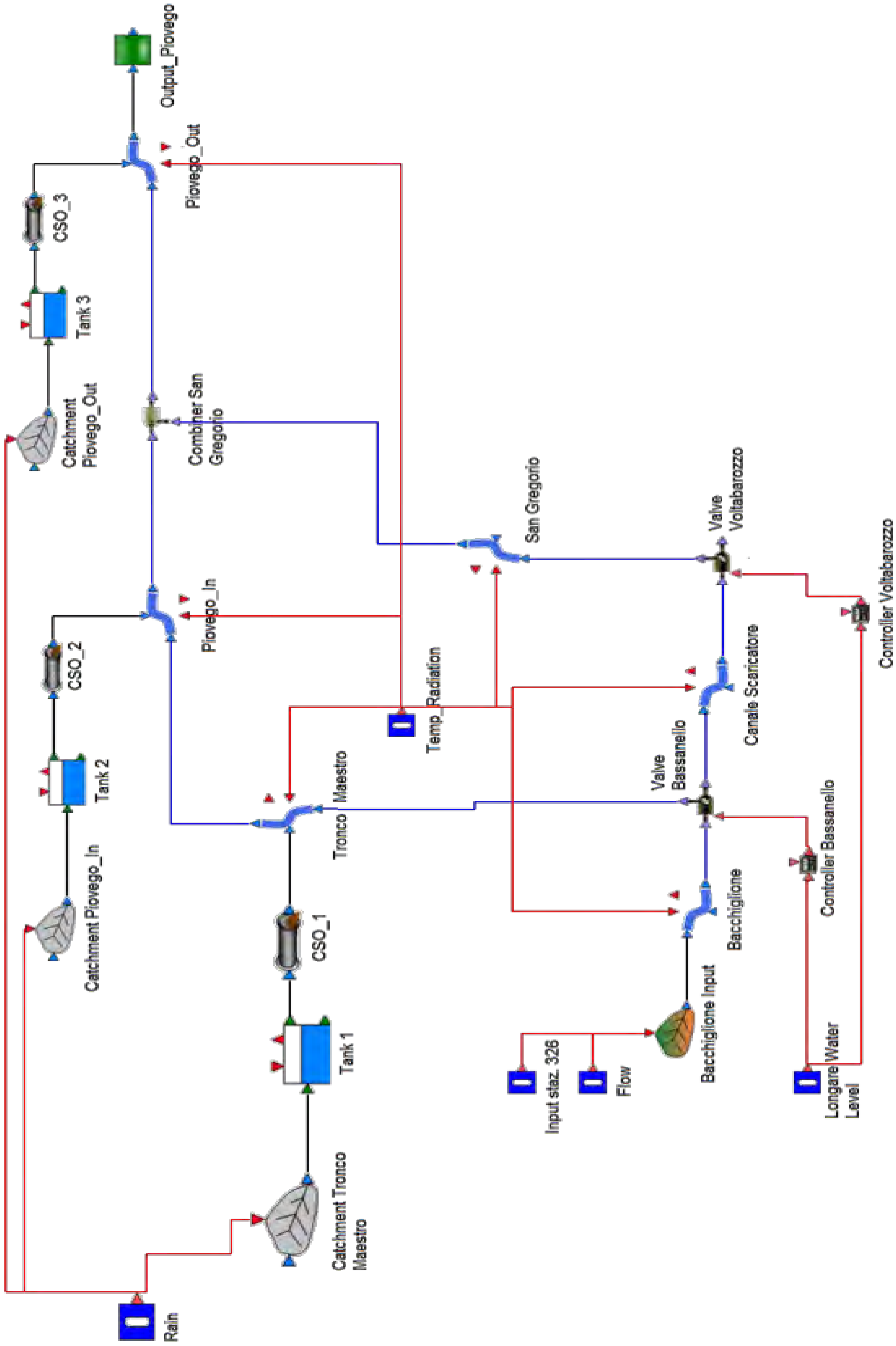
"Tronco_Maestro" river block receives as input the flows (and the relative water characterization) coming from the Bacchiglione river at Bassanello; in addition, it receives also the sewage contribute during large stormwater events from its own hydraulic catchment ("Catchment_TM").
For this reason, a system of tank and CSO blocks is added and connected, in this order, to the catchment itself; when the fixed characteristics of the combined network are insufficient to manage the sewage water, a portion of this wastewater is released into "Tronco_Maestro": the amount, according to the legislation, it set to be the flow exceeding five times the dry weather flow of the network.
This particular set of structures (and block) is used to represent the spillways located along the course of the rivers in the city.
Something similar is done for "Piovego_In" river block: it represents the portion of Piovego stream developing within the city, before the conjunction with San Gregorio channel.
This stream has its own watershed ("Catchment_Piovego_In") and two specific tank and CSO blocks to consider the runoff discharge into the river in case of large stormwater events.
"Piovego_In" receives its flows from "Tronco_Maestro" and it discharges in the "Piovego_Out" river block: to do this, a two flow combiner block is added, in order to collect together the flows of "Piovego_In" and "San_Gregorio" streams.
Another input for the last river block is represented by the sewage release coming from the "Catchment_Piovego_Out": also in this case, a system of Tank and CSO blocks is added to represent the spillways along the river course.

At the end of the system, a converter is added to transform the output fluxes (g/d), coming from the "Piovego_Out" river block, into output concentrations (g/m^3): they are the model variables to be compared with the available water quality measurements taken on Piovego river by ARPAV.

The necessary data (and the relative input blocks) to be added from external files are:

- Rainfall, with 5 minutes temporal scale, (mm);
- Water level, with 30 minutes time scale, (m);
- Flow and river water velocity, with 30 minutes time scale, (m^3/s) and (m/s), respectively;
- Temperature and Radiation, with 15 minutes temporal scale, (°C) and (W/m^2), respectively;
- Input water quality for Bacchiglione river, in terms of NH4 and BOD concentrations, expressed in (mg/L);
- Output water quality for Piovego river, in terms of NH4 and BOD concentrations, expressed in (mg/L).

Figure 4-22 Graphical construction of the model.



5. RESULTS AND DISCUSSION

WEST 2014 is used to compute the output concentrations of ammonia nitrogen (NH4) and Biochemical Oxygen Demand (BOD) for the considered system (Fig. 4-22).

These values, expressed as g/m^3, are consequently compared with the water quality data available for the ARPAV Station No. 353, sited on Piovego river, as indicated in the previous chapters: the aim is to try to represent as well as possible the water quality of the measurement site.

For this purpose, these experiments are taken:

- Steady-state and dynamic simulations for data of 2005;
- Global Sensitivity Analysis for the dynamic simulation of 2005;
- Parameters Estimation for the dynamic simulation of 2005;
- Steady-state and dynamic simulations for data of 2006;
- Steady-state and dynamic simulations for data of 2007;
- Steady-state and dynamic simulations for data of 2008
- Steady-state and dynamic simulations for data of 2010.

In particular, it is decided to build up the model and to calibrate it on the basis of 2005 data because it was one of the reference years having the highest number of observations for the water quality characterization of the system.

Data referring to the period 2006-2010 are used in the validation phase, at the end of the modelling procedure.

This is done in order to test the model behavior with a set of data independent from those exploited during the calibration.

5.1 STEADY STATE SIMULATION

The first step of the modelling procedure is represented by the stationary analysis: the model runs for a 100 days simulation, in order to take the system to the steady-state.

For this reason, a proper set of input data is used: these data are the measurements taken in the first 20 days of the simulated year, for all the available information: Bacchiglione river hydrometric levels, flows and water characterization, air temperature, solar radiation and rainfall.

In this way, the model runs using input values that are changing only for the first 20 days of the simulation and then they stay constant.

The steady-state is an unrealistic condition for a system: the simulation is performed only to use the end-state situation as plausible initial condition for the dynamic simulation.

In the following figures (Fig. 5-1 and 5-2), the modeled concentrations for NH4 and BOD are presented: the simulated outputs are represented with a blue curve, while the observed data are shown as orange circles.

The concentrations are calculated at the exit of the system, so provided by the "Output_Piovego" converter block, as shown in the graphical representation.

Figure 5-1 NH4 - 2005 steady-state simulation.

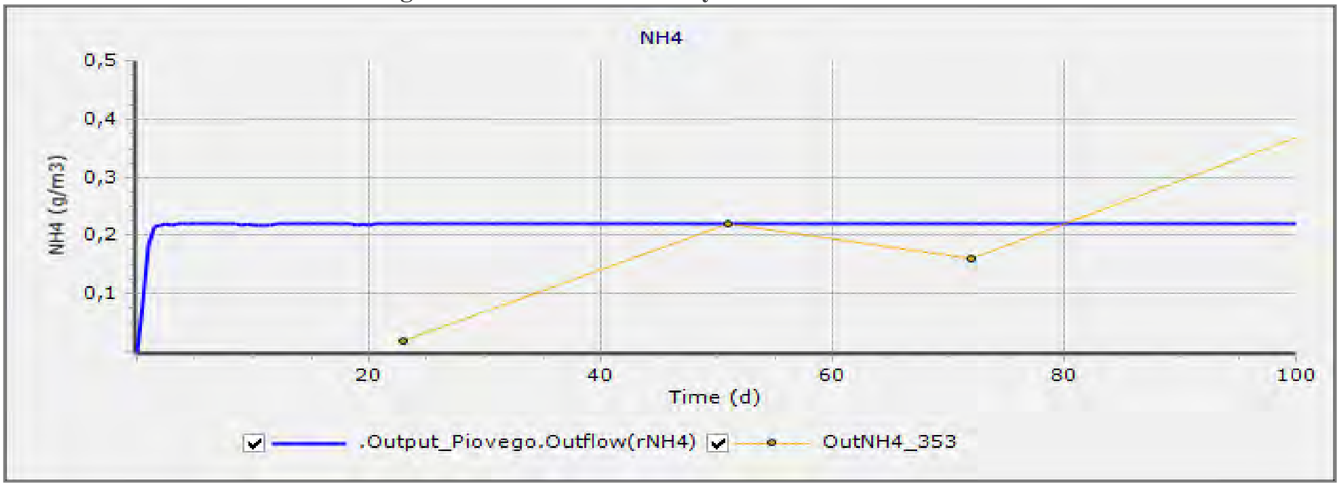
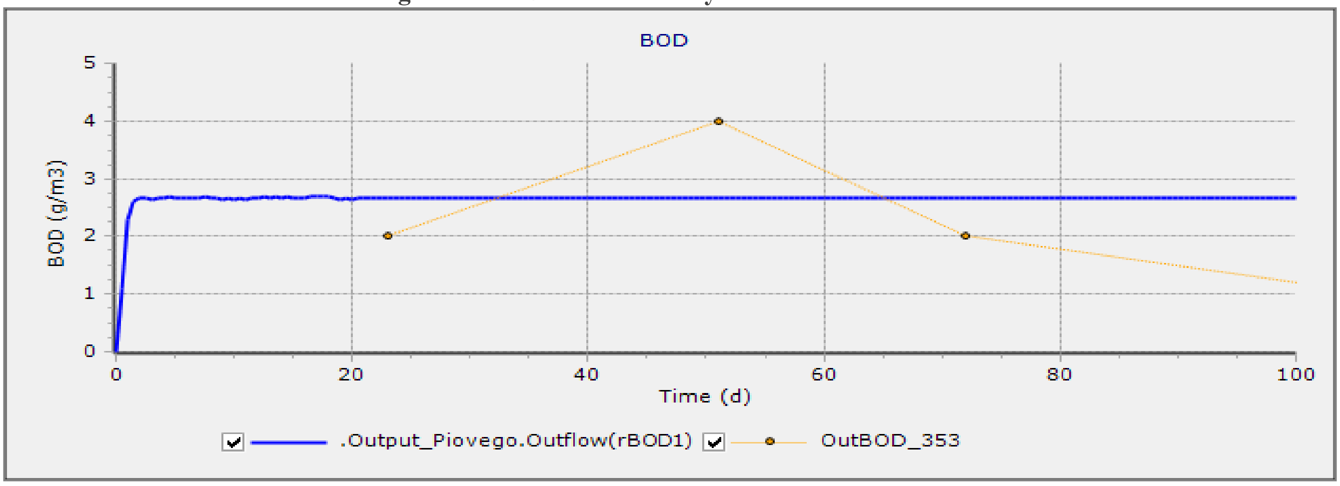


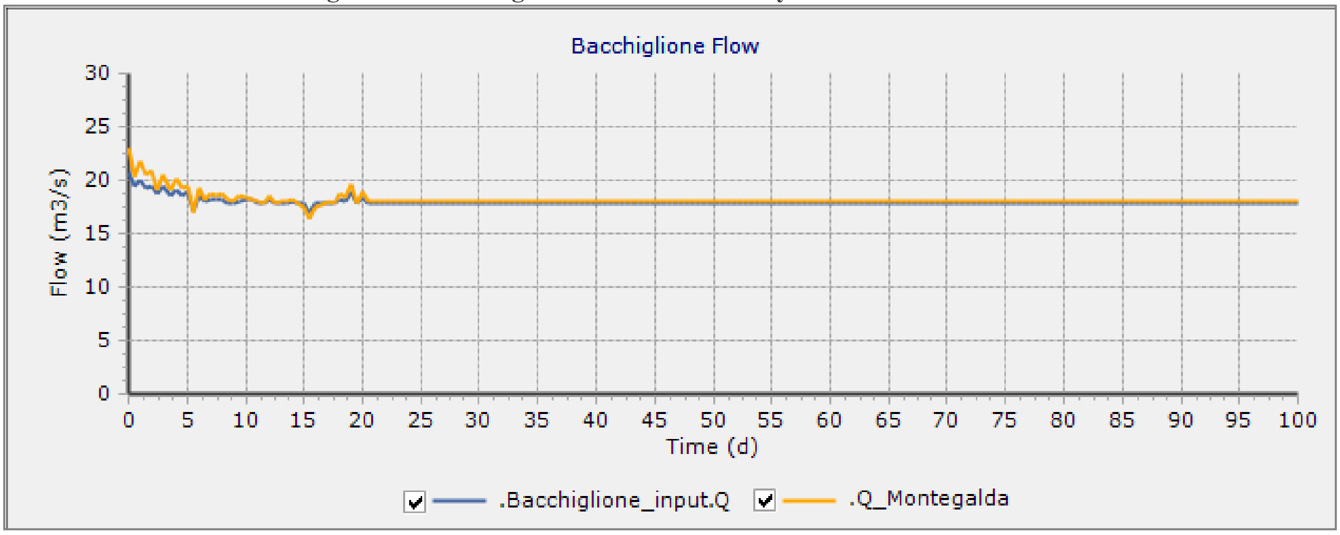
Figure 5-2 BOD - 2005 steady-state simulation.



As it is possible to see, the steady-state analysis is not able to represent the behavior of the water quality, for both concentrations. This was fairly predictable due to the unrealistic conditions described by such a simulation.

In the next figure, the representation of the Bacchiglione flows is given: for the first 20 days of the simulation the input data are varying (orange curve) and, consequently, also the modeled flow (blue curve). Once the input discharge is kept constant, the stationary condition is reached.

Figure 5-3 Bacchiglione flow - 2005 steady-state simulation.



5.2 Dynamic simulation

Considering the different processes taking place in the environment, their time dependence is soon recognized.

For this reason, in order to give a more realistic representation of the studied system, a 365 days dynamic simulation is performed.

With respect to the steady-state analysis, a different set of data is used referring to Bacchiglione river hydrometric levels, flows and water characterization, air temperature, solar radiation and rainfall in 2005: in this specific case, in fact, the input variables are no longer constant, so the simulation is taken using the actual available measured data for all the 365 days.

The following figures are useful to evaluate the behavior of the model (Fig. 5-4 and Fig. 5-5).

The calculated concentrations (given as g/m^3) of Biochemical Oxygen Demand and Ammonia Nitrogen are represented by a blue curve, while the observed data are represented by orange circles.

Figure 5-4 NH4 - 2005 dynamic simulation.

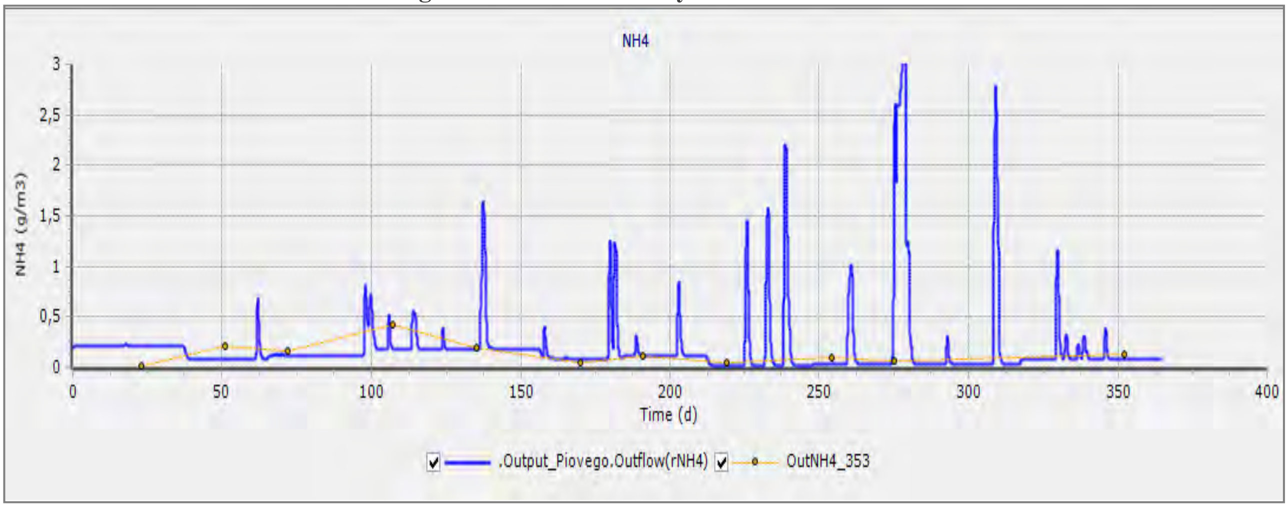
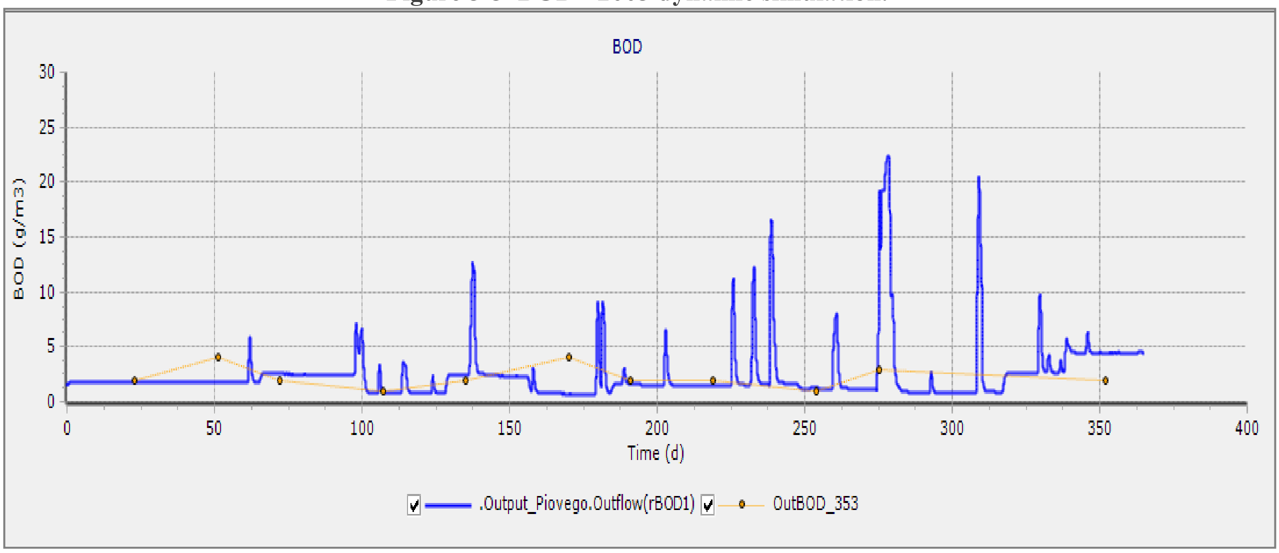
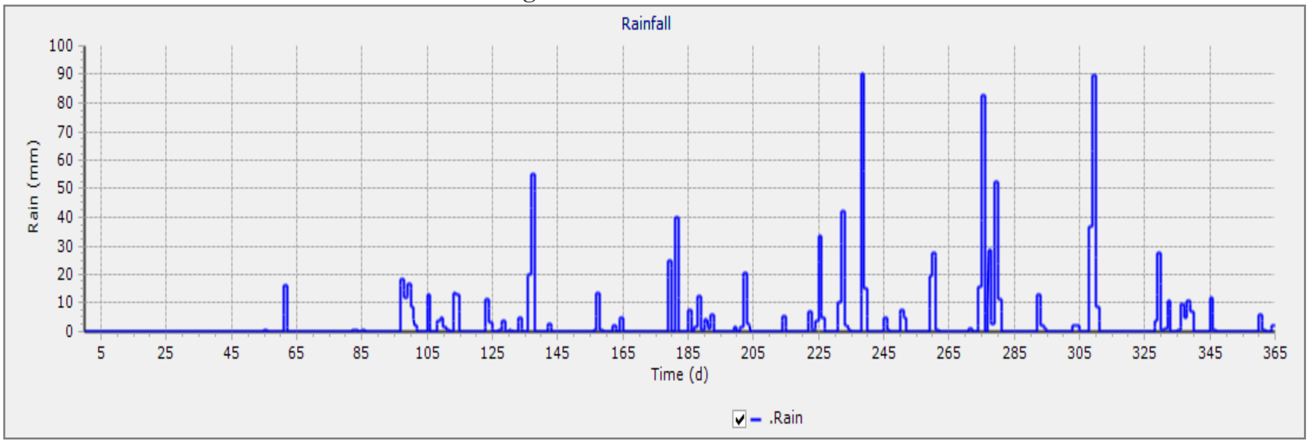


Figure 5-5 BOD - 2005 dynamic simulation.



As it is possible to see from the previous figures, the dynamic simulation gives a more detailed picture of the system with respect to the steady-state analysis: for instance, the relationship between the water quality and the precipitation is clearly evidenced (Fig. 5-6).

Figure 5-6 Rainfall 2005.



The rainfall peaks are present also in the NH4 and BOD temporal variation, but with a certain delay: this is the time needed by the different water basins to respond to the storm events.
Considering Ammonia Nitrogen, the model seems to fit reasonably to the measured values, except for a couple of data in the initial part of the simulation, while the calculated Biochemical Oxygen Demand seems to have some difficulties in the fit, mostly at the beginning and at the end of the simulation.

It is also evident that the available observed data are too limited to be able to do a good comparison with the modeled values.
In particular, it seems that the water quality measurements are taken in periods when no rainfall occurs on the studied area: in this way, it is not possible neither to judge the goodness of the representation given by the modeled peaks, nor to calibrate them with the proper accuracy. More frequent measurements of water quality would be needed to do this and assess the impact of urban runoff on river water quality.

In order to better study the behavior of the model, it is decided to compare directly the observed concentrations with the corresponding calculated ones (from Fig. 5-7 to Fig. 5-10): the first figure shows that, most of times, the calculated concentration of Ammonia Nitrogen is an underestimation of the given measurements.
When a perfect fitting is achieved, the points should be aligned along the 1:1 black line. This is not always true considering the image above, meaning that a further improvement of the model, as concerns NH4, could be necessary.

This is particularly evident also in the next image (Fig. 5-8), where both calculated concentrations (blue asterisks) and observed values (green dots) are plotted with respect to time.

Figure 5-7 NH4 modeled - NH4 observed concentrations – 2005.

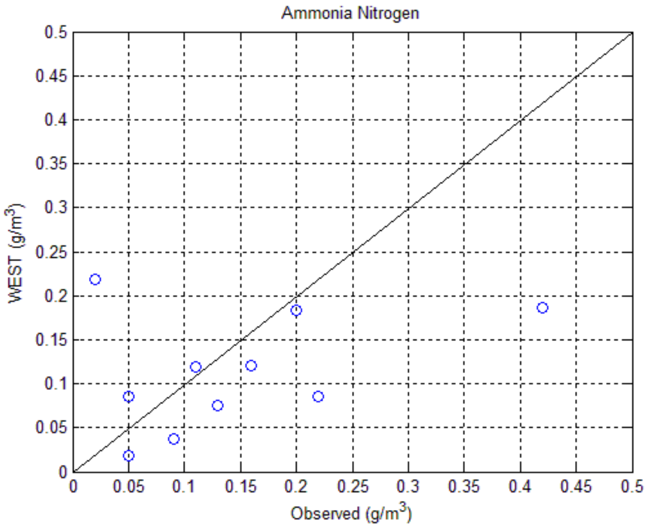
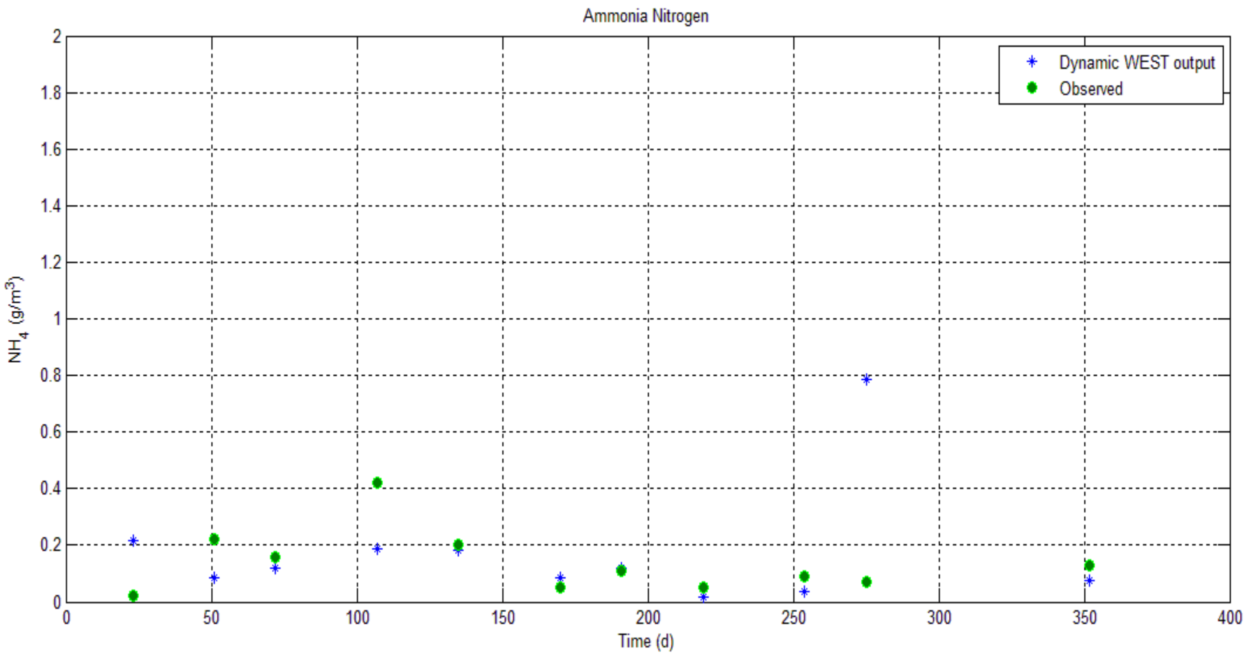


Figure 5-8 NH4 temporal distribution of observed and calculated concentrations – 2005.



In the following table (Tab. 5-1), the summary of the observed and calculated concentrations for Ammonia Nitrogen with the dynamic simulation is given.

Table 5-1 NH4 concentrations – 2005 dynamic simulation.

Observed (g/m^3)	Modeled (g/m^3)
0.02	0.218
0.22	0.085
0.16	0.12
0.42	0.187
0.20	0.183
0.05	0.086
0.11	0.119
0.05	0.018
0.09	0.037
0.07	0.787
0.13	0.076

The previous data can be used to evaluate the goodness of the model adaptation to the observed data calculating the Nash-Sutcliffe Efficiency (E).

This term is given as:

$$E_{NH4} = 1 - \frac{\sum(Q_{oi} - Q_i)^2}{\sum(Q_{oi} - Q_o)^2} = -3.98$$

Where:

- Q_{oi} = observed concentration at ith measurement (g/m^3);
- Q_o = mean of observed concentrations, equal to 0.14 (g/m^3);
- Q_i = modeled concentration at ith measurement (g/m^3).

Considering Ammonia Nitrogen result for the dynamic simulation, the Nash-Sutcliffe Efficiency states that the model representation is worse than the mean value of the observed concentrations: in other words, the capabilities of the model must be improved.
Something similar is done also to evaluate the performance of the model in relation to the BOD content characterization (Fig. 5-9 and Fig. 5-10).

In the first figure, the calculated concentrations are plotted with respect to the observed ones and represented by blue circles.

The second image, instead, gives the comparison of the model results and the reference concentrations, with respect to time.

Figure 5-9 BOD modeled - BOD observed concentrations.

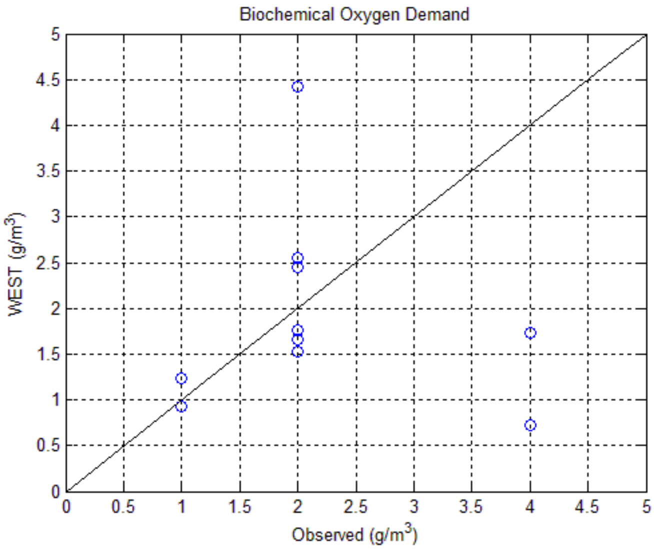
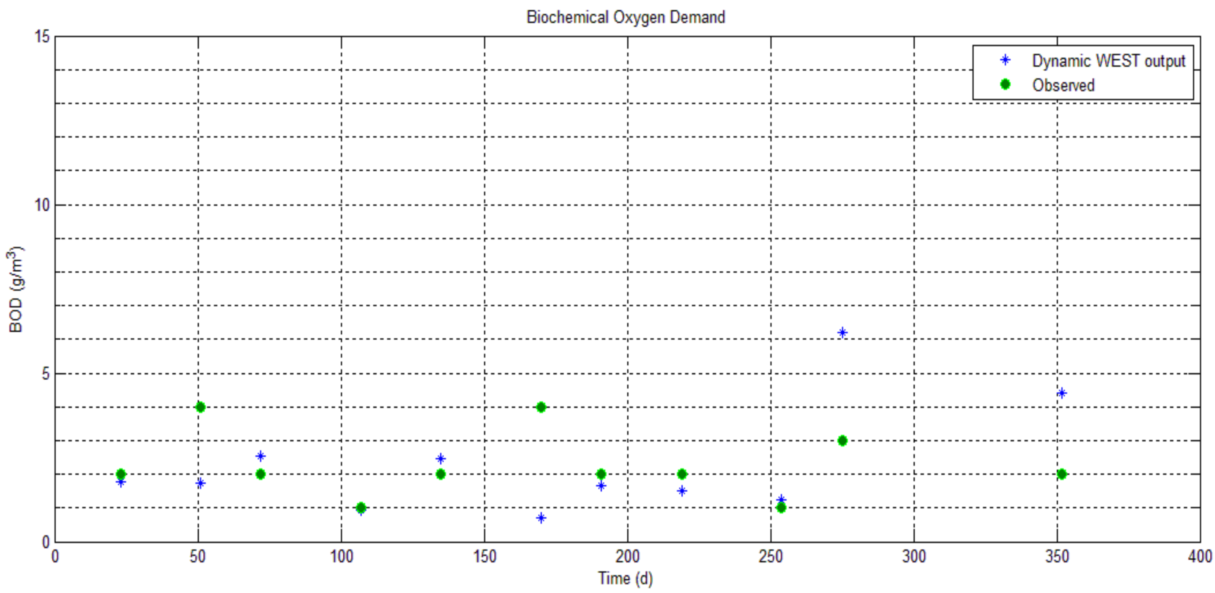


Figure 5-10 BOD temporal distribution of observed and calculated concentrations – 2005.



The previous images show that the model, in most cases, gives an underestimation of the observed data.

Looking at the following table (Tab. 5-2), it is possible to identify a limit of the measurements used as reference concentrations: the available values are all integer numbers.

It is believed that this fact can influence the proper comparison with the model results, in particular in graphics like the one in Fig. 5-9, where the behavior of the cloud is studied.

Table 5-2 BOD concentrations – 2005 dynamic simulation.

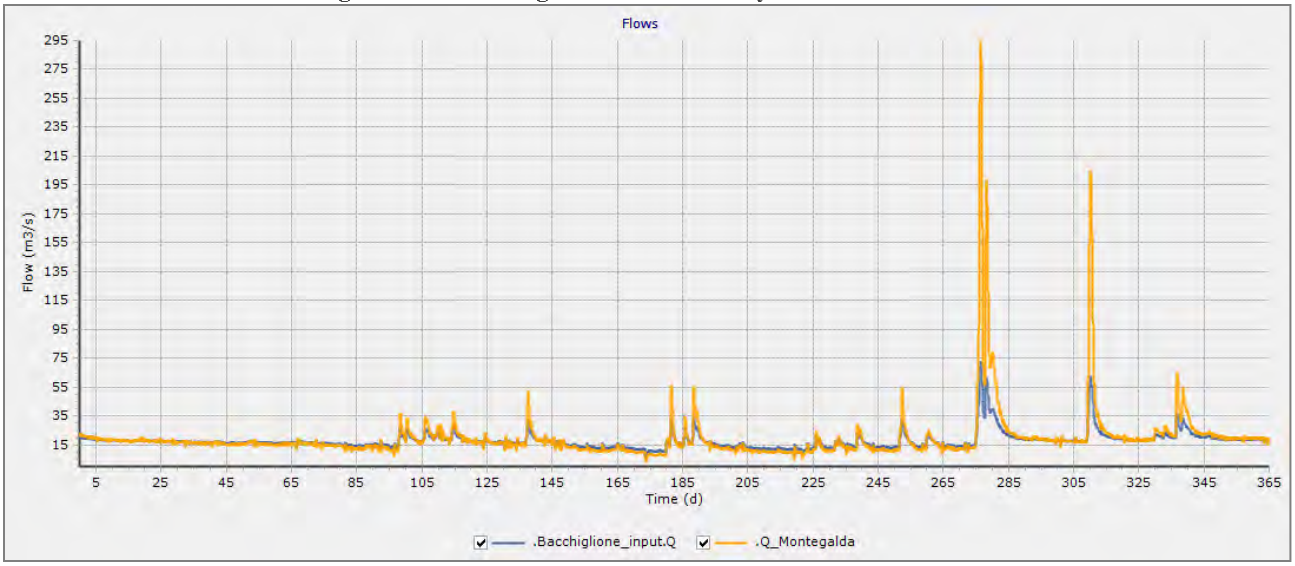
Observed (g/m^3)	Modeled (g/m^3)
2	1.764
4	1.738
2	2.556
1	0.926
2	2.449
4	0.724
2	1.654
2	1.525
1	1.242
3	6.218
2	4.426

Also in this case it is possible to calculate the Nash-Sutcliffe Efficiency, that is equal to $E_{BOD} = -2.25$. This means that the BOD representation with the model is, also in this case, worse than the mean of the observed concentrations: consequently, the model performance needs to be improved.

The following figure (Fig. 5-11), instead, gives the comparison between the measures flows for Bacchiglione river at Montegalda station (orange curve) and the modeled flows for the first river stretch (blue curve).

It is evident that the model is able to properly represent the discharges, except for the extraordinary events at the end of the simulation: between days 270 and 310 there are two series of peaks that are underestimated by the model.

Figure 5-11 Bacchiglione flow - 2005 dynamic simulation.



5.3 SENSITIVITY ANALYSIS

According to the modelling procedure, it is necessary to evaluate the influence that the different parameters have on the calculated outputs.

Focusing the attention on the water quality, it is decided to estimate the sensitivity of both Ammonia Nitrogen and BOD modeled concentrations of Piovego river in relation to the parameters used to represent the ecological processes taking place in the aquatic ecosystem.

Moreover, the runoff influence is assessed too: the sensitivity of the model to the mean releases of Ammonia Nitrogen from urban surfaces is performed, together with the parameters used to represent the runoff generation phenomenon.

In particular, it is decided to implement a global sensitivity analysis (GSA) for the specified variables (in bold, as follows), with respect to the given terms:

Piovego_Out NH4 concentration

- Nitrification Rate (Knit);
- Nitrification Temperature coefficient (TKnit);

Piovego_Out BOD concentration

- BOD Decay Rate (Kd1);
- Decay Temperature Coefficient (TKd);

Piovego_Out NH4 and BOD concentrations

- Bacchiglione river flow velocity;
- Reservoir constant (k);
- Linearity exponent (m).

The Global Sensitivity Analysis is performed using the Monte Carlo simulation[44]: this experiment consists in running the model several times in dynamic conditions, using for each run a different combination of parameters, input variables or initial conditions.

These sets of values are generated in a random way, by means of the Monte Carlo analysis solver, named Latin Hypercube Sampling (LHS): it ensures an equal and homogeneous sampling within the parameters hyperspace, with respect to a fixed distribution (as uniform, Gaussian or exponential).

In this manner, the output variables of one run are independent from those of the others, so it is possible to evaluate their correlation with the chosen terms.

[44] Claeys, 2008.

In particular, after all simulations, the Linear Regression is performed between parameters and output variables, in order to identify the most influencing terms on the model results.
For this purpose, WEST 2014 allows the calculation of the Upper Percentile (fixed at 95%) for the output variables of each model run and the evaluation of the Linear Correlation Coefficient (LCC) with the chosen parameters (input variables or initial conditions).
The LCC is an adimensional term, ranging between -1 and 1: a value equal to 0 does not imply that no correlation is present between the considered parameters and variables, but, on the contrary, it means that the relationship is not linear. The closest the value to 1, the strongest the direct linear dependency: an increase of one parameter determines the increase of the variable. Same idea with an LCC close to -1, but in this case the linear relationship turns out to be indirect, meaning that the increase of one parameter causes the decrease of the variable.
In particular, the model is considered to be sensitive to those terms having the highest LCC.
In this case, it is decided to carry out separate GSAs for each parameters set, so that a total of seven analyses are performed:

1. Nitrification Rate GSA;
2. Nitrification Temperature coefficient GSA;
3. BOD Decay Rate GSA;
4. BOD Decay Temperature Coefficient GSA;
5. Bacchiglione river flow velocity GSA;
6. Reservoir constant GSA;
7. Linearity exponent GSA.

In this way, it seems possible to have a wider evaluation of the influence that a single set of parameters determine on the model outputs.

5.3.1 Nitrification Rate GSA

Here following, the results of the first sensitivity analysis are presented.
The parameters taken into account in this experiments are the Nitrification rates (Knit) of the six river stretches of the model.
In particular, it is decided to choose an uniform distribution to be used with the LHS; for this reason, it is necessary to fix the lower and upper bounds of possible values for the chosen parameters.

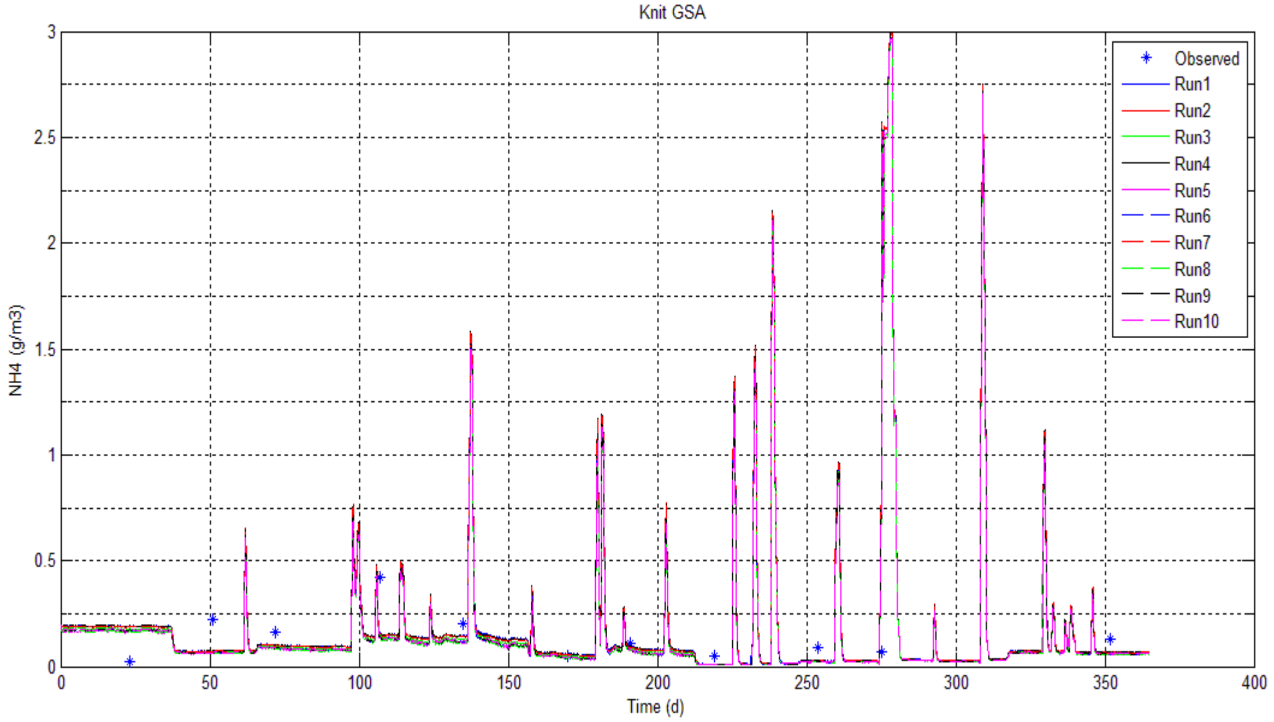
Specifically, the Knit can vary between 0.1 – 2 1/d [45].

The following table (Tab. 5-3) presents the parameters values used for the sensitivity analysis, while the model outputs for each run are given in the figures below (from Fig. 5-12 to Fig. 5-14); the observed values are represented too (blue asterisks).

Table 5-3 Knit GSA parameters.

Run	Bacchiglione Knit	Canale Scaricatore Knit	Piovego_in Knit	Piovego_out Knit	San Gregorio Knit	Tronco Maestro Knit
1	0.701	0.211	1.488	1.262	0.116	0.103
2	0.206	1.104	1.036	0.278	0.839	1.939
3	0.202	0.440	1.245	1.224	0.798	1.520
4	0.430	1.298	0.579	0.687	0.443	1.091
5	1.785	0.784	1.116	1.681	0.403	1.931
6	0.780	1.540	0.667	1.023	1.821	1.955
7	0.938	1.066	1.900	0.350	0.670	0.973
8	0.112	1.502	1.203	1.967	0.802	1.576
9	0.682	1.214	0.609	1.583	1.450	1.239
10	0.366	1.363	1.706	1.925	0.825	0.310

Figure 5-12 Knit GSA runs comparison.



[45] Jørgensen et al., 2001.

The model turns out to be sensitive to the Nitrification Rate (Knit) and this is even more evident when no rainfall occurs: in these periods, in fact, the different curves of the NH4 output can be seen clearly in the graphic.

This is shown also in the other figures that follow (Fig. 5-13 and Fig. 5-14): the results of the 10 runs are divided in two different charts, to better evaluate the model behavior.

A possible explanation for this dependency is that, during storm events, the residence time within the hydraulic network is reduced (increased flow and water velocity of the rivers) due the injection of urban runoff. Consequently, the time available for physical, chemical and biological processes to act decreases, so the nitrification rate loses part of its influence on the model output.

Figure 5-13 Knit GSA runs 1 to 5.

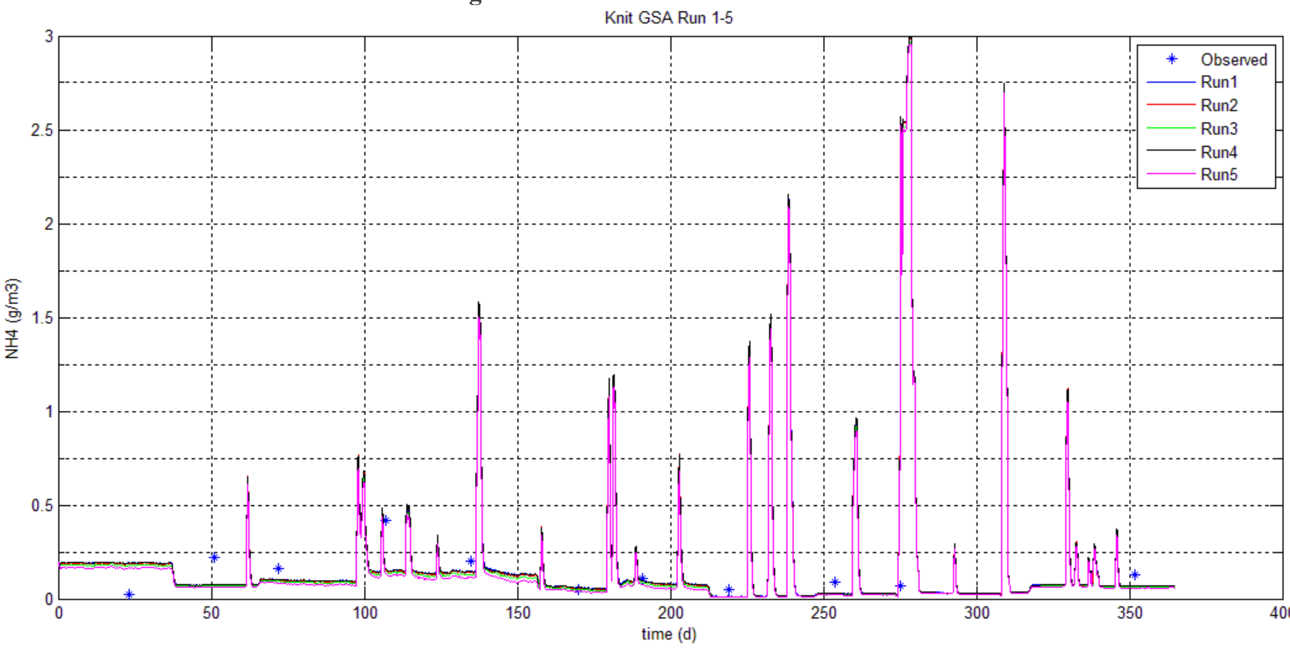
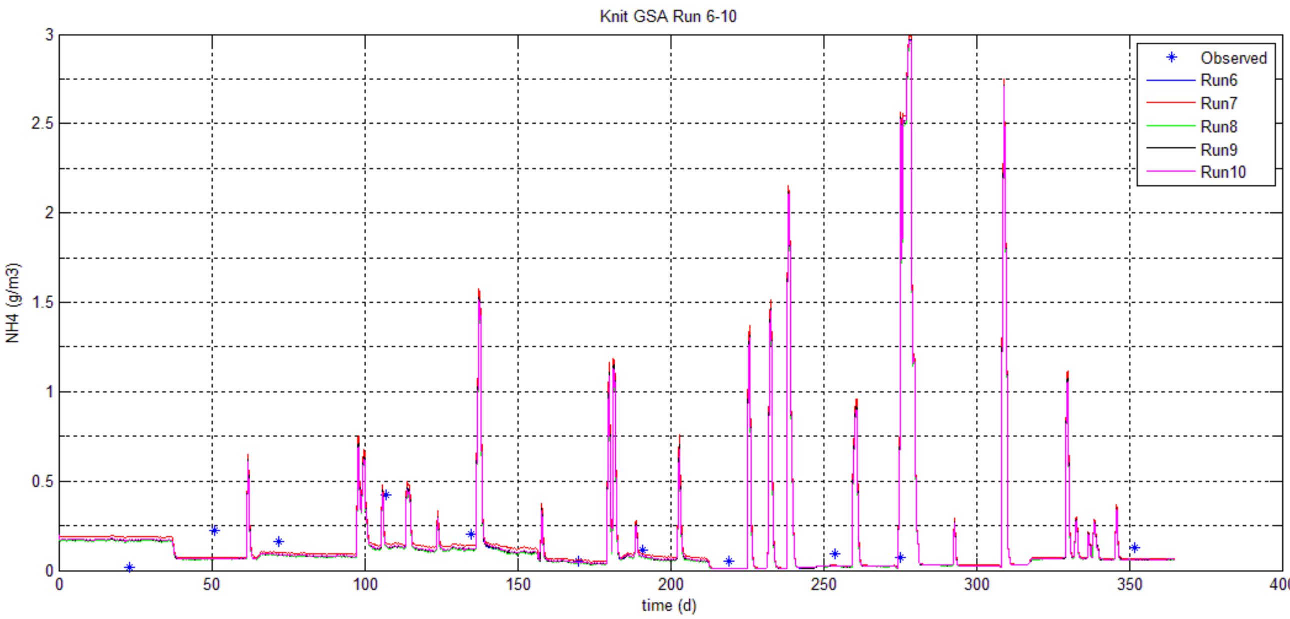
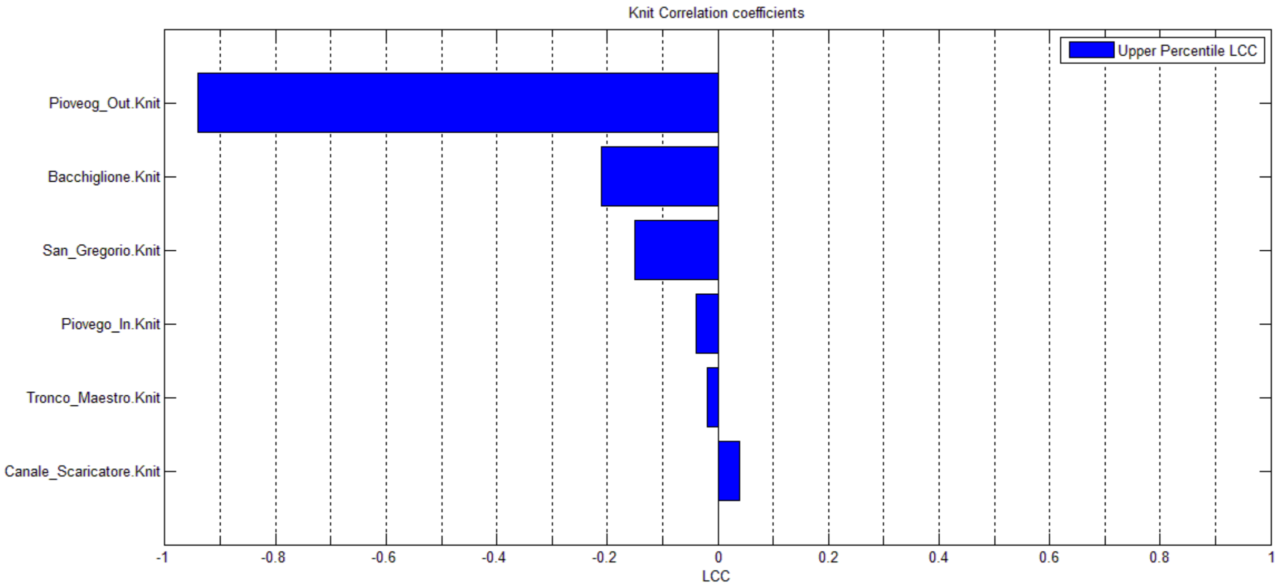


Figure 5-14 Knit GSA runs 6 to 10.



The following step of the analysis is the identification of those parameters that influence the NH4 concentration the most: for this purpose, it is useful to study the results of the Linear Regression performed between the parameters values and the outputs.
First, the Upper Percentile (95%) is calculated for the modeled concentrations of each run and then the relationship with the different parameters is assessed by means of the Linear Correlation Coefficient: the highest the LCC (as absolute value), the highest the linear dependency output variable-parameter, the highest the influence of the parameter itself on the model results (Fig. 5-15) and (Tab. 5-4).

Figure 5-15 LCC for Ammonia Nitrogen and Knit.



The highest influence is given by the Nitrification rate Knit of the final part of Piovego river ("Piovego_Out" river block), having an LCC equal to -0.94: the negative sign means that increasing the value of this parameter, the output concentration of Ammonia Nitrogen decreases.
In other words, there is a inverse dependency between the parameter and the output variable.

This strong dependency of the output concentration was fairly predictable for two reasons:

1. The "Piovego_Out" river block is the closest one to the output of the system, so it is able to primarily influence the final concentration of NH4;
2. The Ammonia Nitrogen concentration is determined with a first order decay representation of Nitrification; this implies that the NH4 amount is written as $M_{NH4} = f(-Knit)$, as presented before in the dedicated section (paragraph 4.3.1).

Consequently, it is decided to add the Piovego_Out Nitrification rate to the parameters to be calibrated. Further details are presented in the following sections.

Table 5-4 Linear Correlation Coefficient: Knit GSA.

Parameter	LCC
Canale Scaricatore Knit	0.04
Tronco Maestro Knit	-0.02
Piovego_in Knit	-0.04
San Gregorio Knit	-0.15
Bacchiglione Knit	-0.21
Piovego_out Knit	-0.94

5.3.2 NITRIFICATION TEMPERATURE COEFFICIENT GSA

Another possible set of parameters that may influence the Ammonia Nitrogen output is represented by the Nitrification temperature coefficients (identified as TKnit).

As already done for the Nitrification rate, a Global Sensitivity Analysis is performed for the temperature coefficients of the six river stretches of the model. In particular, it is decided to choose again an uniform distribution to be used with the Latin Hypercube Sampling; the interval of possible variation for the parameters is 1 – 1.1 [46].

The following table (Tab. 5-5) presents the parameters combinations used for the sensitivity analysis.

Table 5-5 TKnit GSA parameters.

Run	Bacchiglione TKnit	Canale Scaricatore TKnit	Piovego_in TKnit	Piovego_out TKnit	San Gregorio TKnit	Tronco Maestro TKnit
1	1.032	1.006	1.073	1.061	1.001	1.000
2	1.006	1.053	1.049	1.009	1.039	1.097
3	1.005	1.018	1.060	1.059	1.037	1.075
4	1.017	1.063	1.025	1.031	1.018	1.052
5	1.089	1.036	1.053	1.083	1.016	1.096
6	1.036	1.076	1.030	1.049	1.091	1.098
7	1.044	1.051	1.095	1.013	1.030	1.046
8	1.001	1.074	1.058	1.098	1.037	1.078
9	1.031	1.059	1.027	1.078	1.071	1.060
10	1.014	1.066	1.085	1.096	1.038	1.011

46 Jørgensen et al., 2001.

The model outputs for each run are given in the figures below (from Fig. 5-16 to Fig. 5-18); the observed values are represented too (blue asterisks).

As it is possible to see, the Ammonia Nitrogen concentration does not seem to be sensitive to the variation of the Nitrification Temperature coefficient TKnit: the curves representing the output concentration for each simulation run cannot be distinguished from one another.

Consequently, the final results of the 10 shots are similar; in other words, the changes in TKnit values do not determine relevant changes in the model outputs.

This is even more evident when studying separately the results of this GSA (Fig. 5-17 and Fig. 5-18).

Figure 5-16 TKnit GSA runs comparison.

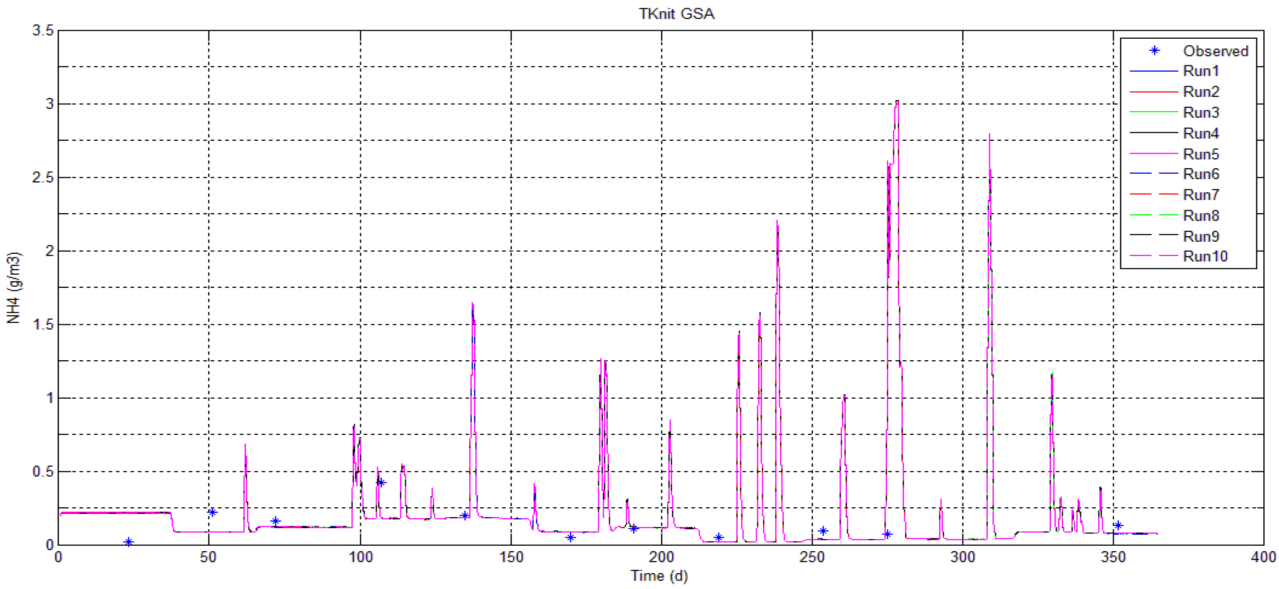


Figure 5-17 TKnit GSA runs 1 to 5.

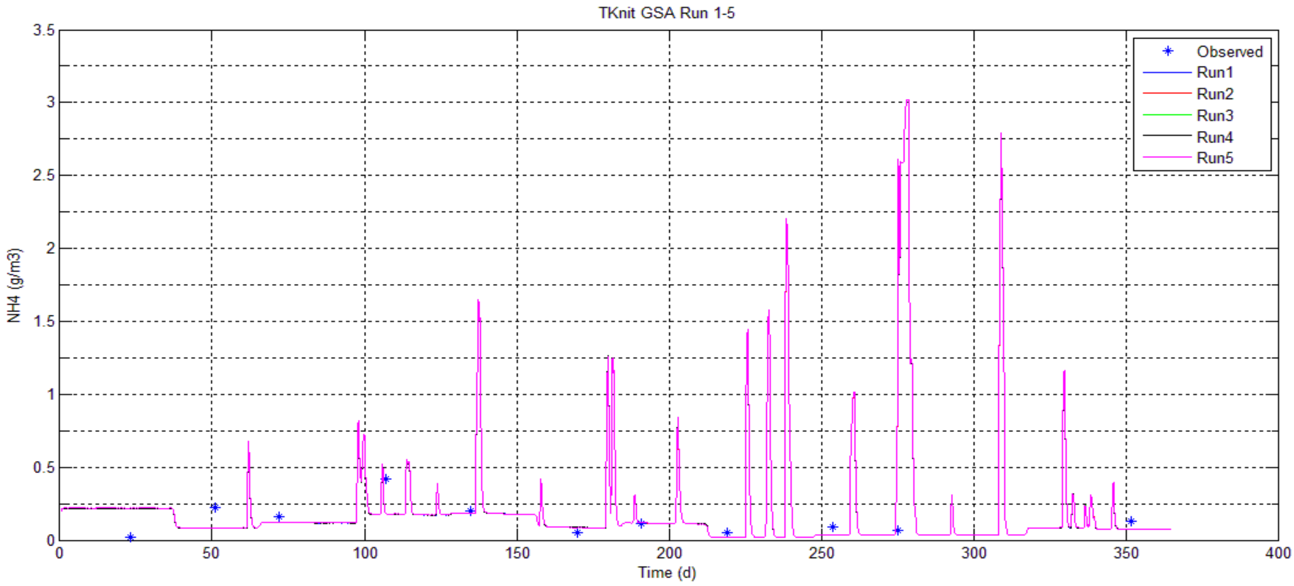
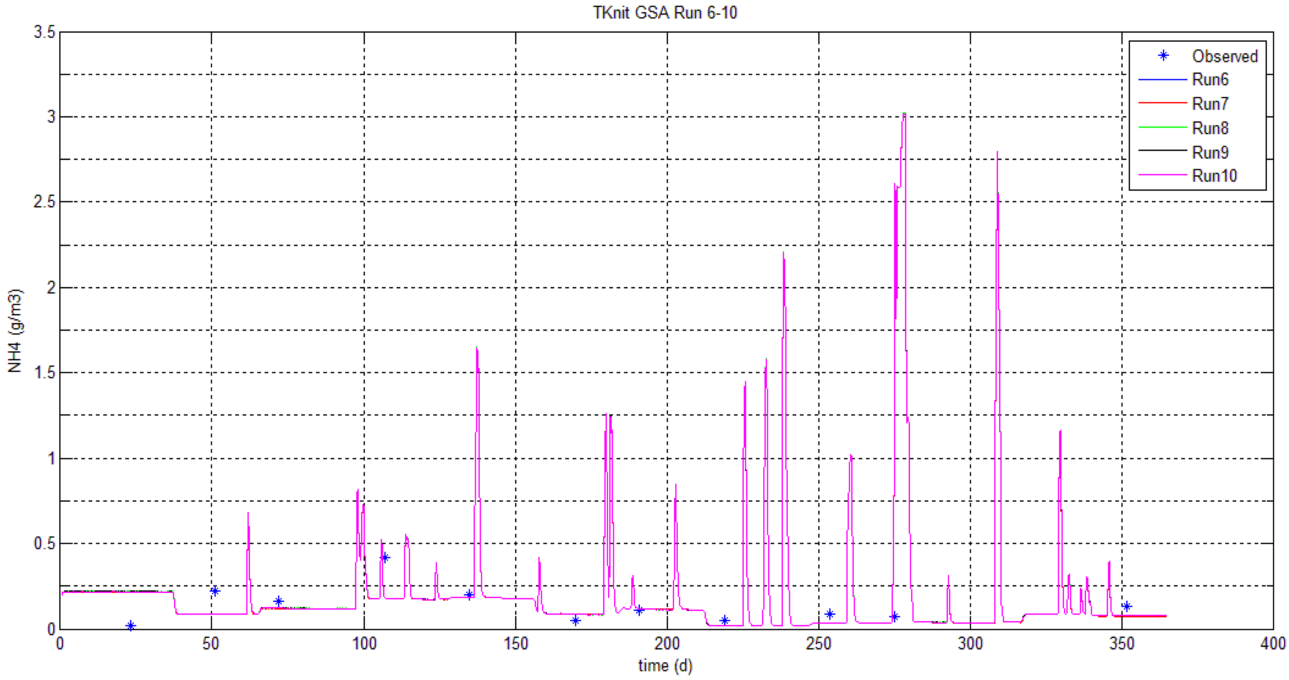


Figure 5-18 TKnit GSA runs 6 to 10.



At the end of the analysis, it is possible to evaluate the correlation between the chosen parameters and the output Ammonia Nitrogen concentration. This is done performing Linear Regression and evaluating the Linear Correlation Coefficient (LCC) between the different TKnit and the modeled concentration.

Results are presented below (Fig. 5-19 and Tab. 5-6).

Figure 5-19 LCC for Ammonia Nitrogen and TKnit.

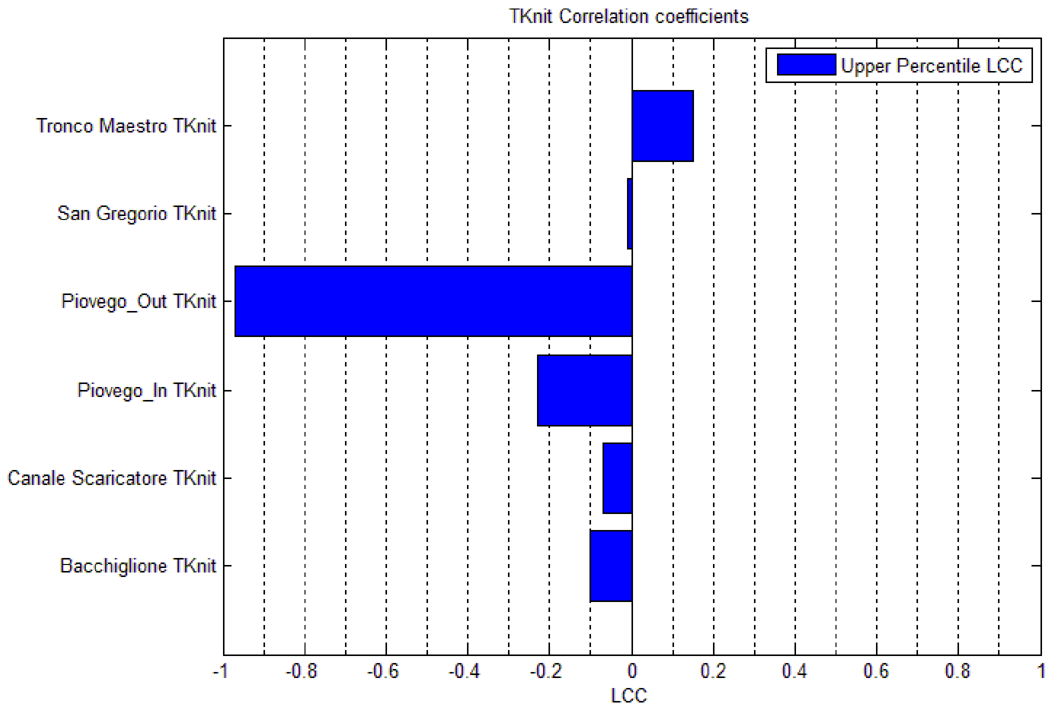


Table 5-6 Linear Correlation Coefficient: TKnit GSA.

Parameter	LCC
Bacchiglione TKnit	-0.10
Canale Scaricatore TKnit	-0.07
Piovego_in TKnit	-0.23
Piovego_out TKnit	-0.97
San Gregorio TKnit	-0.01
Tronco Maestro TKnit	0.15

The strongest correlation is found for the “Piovego_out” river block: the LCC for its Nitrification Temperature Coefficient and the modeled Ammonia concentration is equal to -0.97. The negative sign, again, states that an increase of the TKnit determines the decrease of the output variable.
The overall result of this Global Sensitivity Analysis is that the considered Nitrification Temperature Coefficients seems to have a limited influence on the model results; it is decided, anyway, to add the “Piovego_Out” TKnit to the calibration process, since it is the one showing the highest absolute value of the correlation coefficient.

5.3.3 BOD Decay Rate GSA

As presented before, the state variables of the model are two: Ammonia Nitrogen and Biochemical Oxygen Demand concentrations out of the system (i.e., the effluent of “Piovego_Out” river block).
The previous sections deal with the sensitivity analysis for the first variable; the same experiment is taken to evaluate the influence of some ecological parameters on the Biochemical Oxygen Demand concentration given by the model.
In particular, here following the results of the Global Sensitivity Analysis performed for the BOD decay rate coefficient of the six river stretches are presented.
It is decided to choose again an uniform distribution to be used with the Latin Hypercube Sampling and to divide the analysis in two different parts: the first one uses an interval[47] of possible variation for the parameters equal to (0.2 – 1) 1/d, while the second allows sampling within (1 – 2) 1/d.
This choice is done in order to have a wider picture of the dependency of the output variable on the degradation rate coefficient (identified as Kd).
The following table (Tab. 5-7) presents the parameters combinations used for the two analyses.

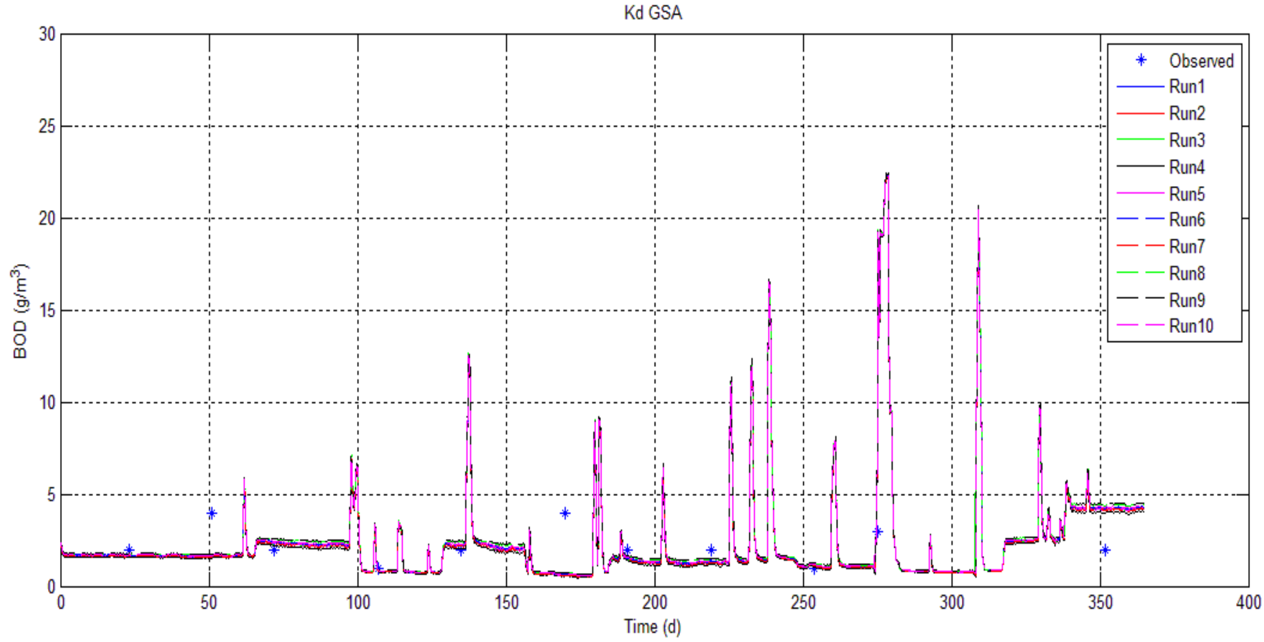
[47] Reichert et al., 2001.

Table 5-7 Kd GSA parameters.

Part 1						
Run	**Bacchiglione Kd**	**Canale Scaricatore Kd**	**Piovego_in Kd**	**Piovego_out Kd**	**San Gregorio Kd**	**Tronco Maestro Kd**
1	0.45	0.50	0.22	0.64	0.30	0.85
2	0.49	0.91	0.41	0.48	0.73	0.91
3	0.61	0.91	0.97	0.88	0.41	0.21
4	0.86	0.64	0.48	0.97	0.75	0.74
5	0.32	0.29	0.61	0.73	0.89	0.71
6	0.89	0.24	0.83	0.51	0.55	0.52
7	0.74	0.57	0.65	0.68	0.85	0.56
8	0.46	0.96	0.26	0.31	0.20	0.70
9	0.56	0.41	0.57	0.20	0.51	0.48
10	0.29	0.56	0.56	0.41	0.39	0.97
Part 2						
Run	**Bacchiglione Kd**	**Canale Scaricatore Kd**	**Piovego_in Kd**	**Piovego_out Kd**	**San Gregorio Kd**	**Tronco Maestro Kd**
1	1.34	1.78	1.57	1.86	1.55	1.76
2	1.85	1.09	1.43	1.06	1.31	1.29
3	1.20	1.37	1.14	1.58	1.79	1.70
4	1.58	1.93	1.86	1.69	1.15	1.90
5	1.84	1.36	1.60	1.50	1.35	1.27
6	1.34	1.57	1.33	1.86	1.76	1.28
7	1.50	1.71	1.49	1.25	1.23	1.48
8	1.71	1.90	1.60	1.38	1.83	1.39
9	1.73	1.89	1.50	1.89	1.00	1.60
10	1.27	1.53	1.44	1.75	1.94	1.71

In the following figures (from Fig. 5-20 to Fig. 5-22), the results of the analyses are presented; in addition, also the observed data for BOD concentration of Piovego river are plotted (blue asterisks).

Figure 5-20 Kd 1st GSA runs comparison.



The dependency of the BOD concentration on the Decay rate Kd is evident in the previous figure, where the curves corresponding to the outputs of the different runs can be seen clearly.

This means that a variation of the Kd value determines relevant variations in the modeled concentration of BOD: in particular, such a behavior is even more relevant when no rainfall occur.

This is seen also in the following figures, where the results of the 10 runs are represented separately.

Figure 5-21 Kd 1st GSA runs 1 to 5.

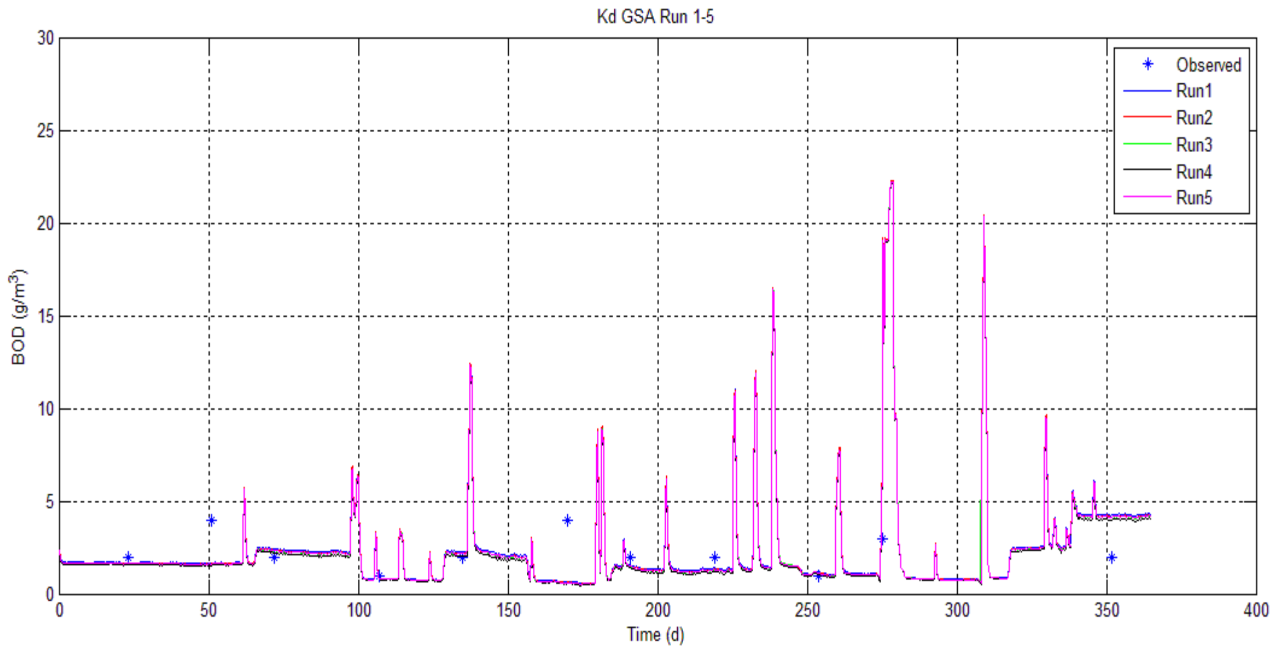
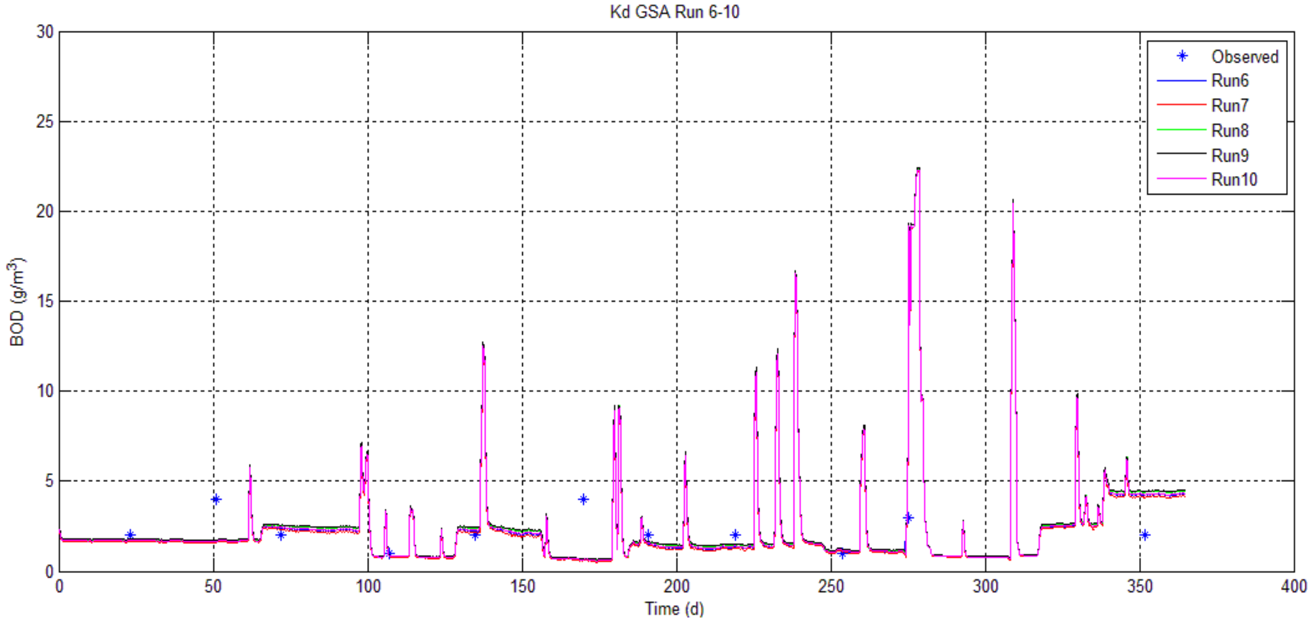


Figure 5-22 Kd 1st GSA runs 6 to 10.



In order to identify the most influencing parameters, it is decided to evaluate the Linear Correlation Coefficient (LCC) of the Upper Percentile (set to 95%) of the calculated outputs for each run with respect to the six parameters.

The results are presented below (Fig. 5-23, Fig. 5-24 and Tab. 5-8).

Figure 5-23 LCC for BOD and Kd - 1st GSA.

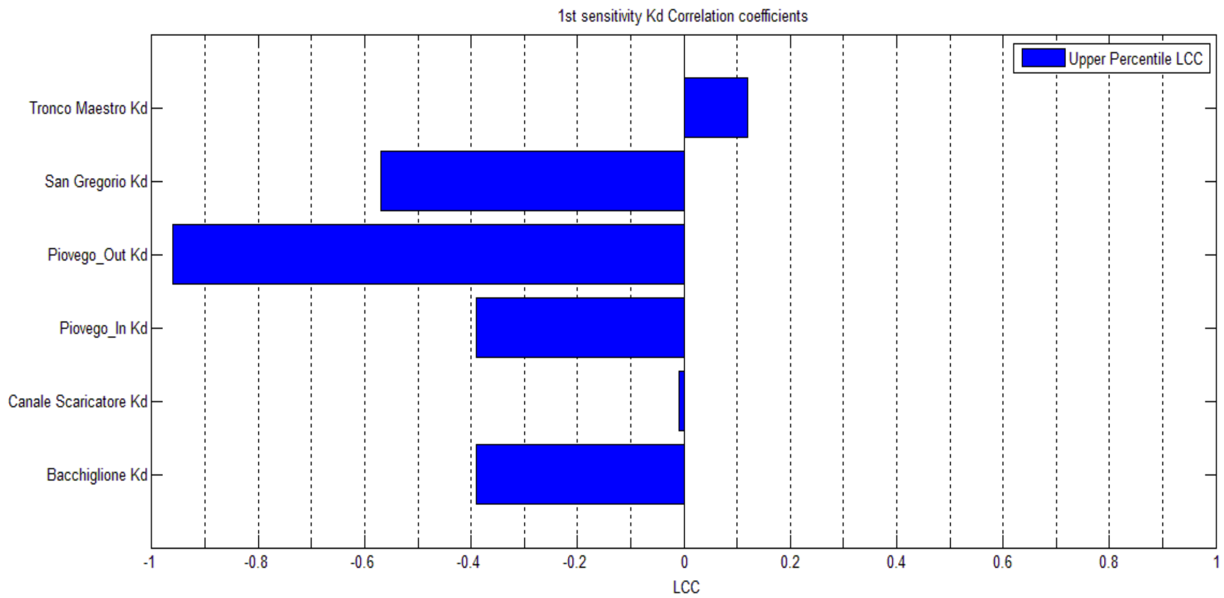
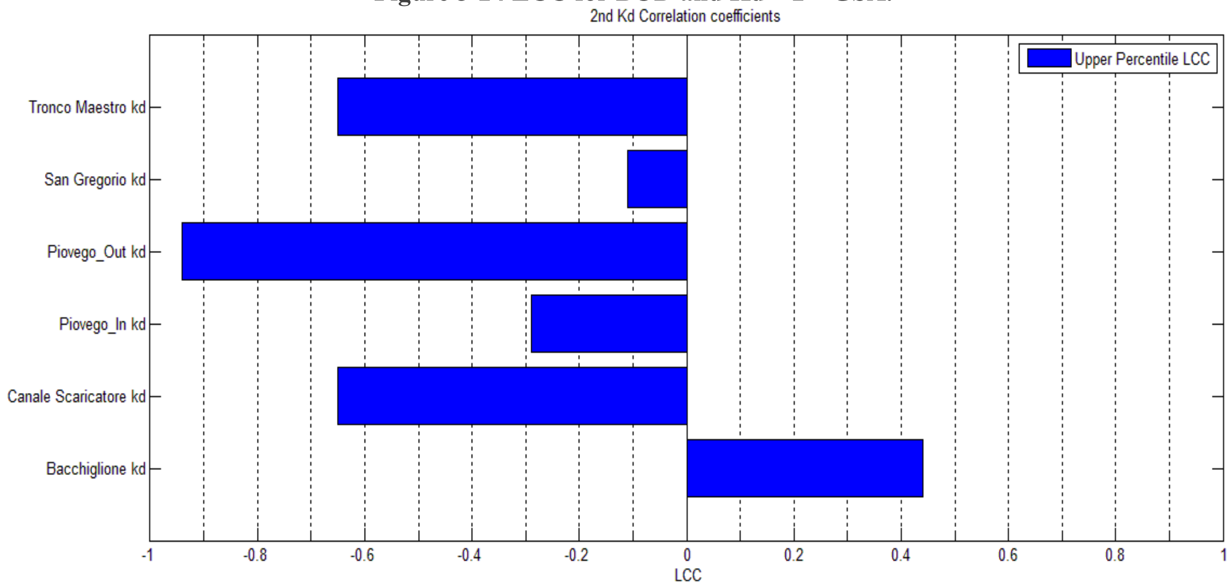


Figure 5-24 LCC for BOD and Kd – 2nd GSA.



The first sensitivity analysis on the BOD Decay rate shows the importance of this parameter on the calculated BOD concentration.

In particular, the most influencing rates are those belonging to three river stretches present in the system: “San Gregorio” and “Piovego_Out” river blocks.

Something different results from the 2nd Global Sensitivity Analysis (Fig. 5-24): “Piovego_Out” Kd shows again the highest linear correlation with the BOD output, together with “Tronco Maestro” Kd, “Canale Scaricatore” Kd and “Bacchiglione Kd”.

With the second part of the analysis, the correlation between the calculated concentrations and “Canale Scaricatore” Kd increases, giving rise to a strongest negative linear dependency; in addition, the LCC of “Bacchiglione” Kd increases and it becomes positive (Tab. 5-8).

Table 5-8 Linear Correlation Coefficient: Kd GSA.

Parameter	**Part 1 - LCC**	**Part 2 - LCC**
Bacchiglione Kd	-0.39	0.44
Canale Scaricatore Kd	-0.01	-0.65
Piovego_in Kd	-0.39	-0.29
Piovego_out Kd	-0.96	-0.94
San Gregorio Kd	-0.57	-0.11
Tronco Maestro Kd	0.12	-0.65

Consequenlty, it is decided to calibrate the following BOD Decay rates: “Tronco_Maestro” Kd, “Piovego_Out” Kd, “Canale_Scaricatore” Kd and “Bacchiglione” Kd.

In the following figures, the results of the second GSA on the decay rates are presented (from Fig. 5-25 to Fig. 5-27).

The model sensitivity to the chosen parameters is evident because the curves of the different runs can be seen distinctly from one another, as in the first part of the analysis.

Figure 5-25 Kd 2nd GSA runs comparison.

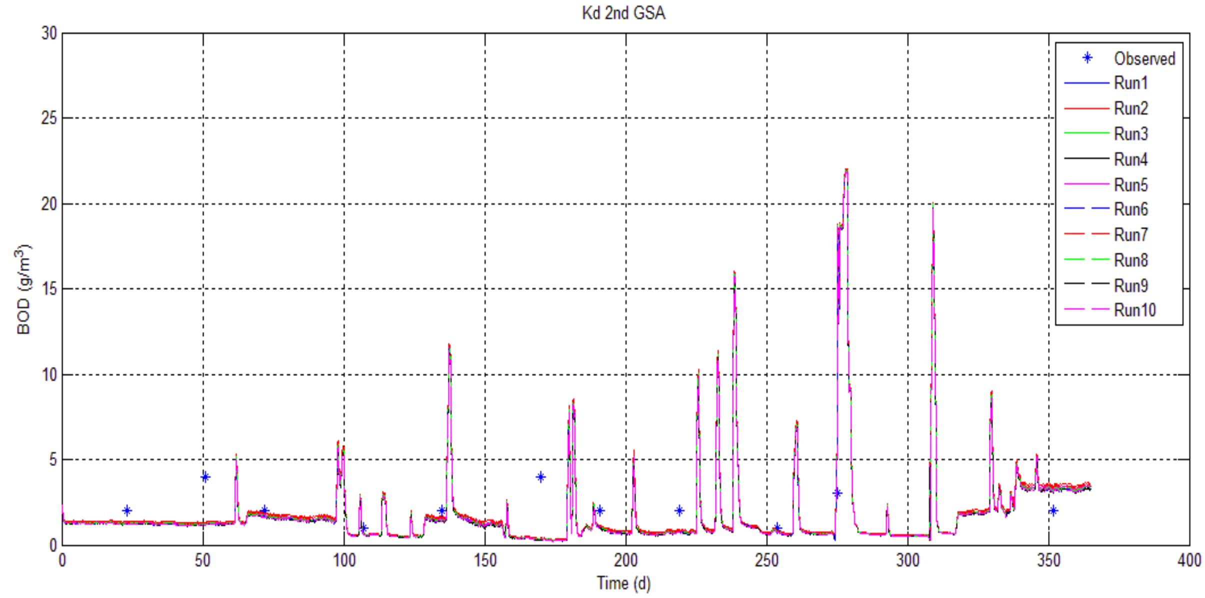


Figure 5-26 Kd 2nd GSA runs 1 to 5.

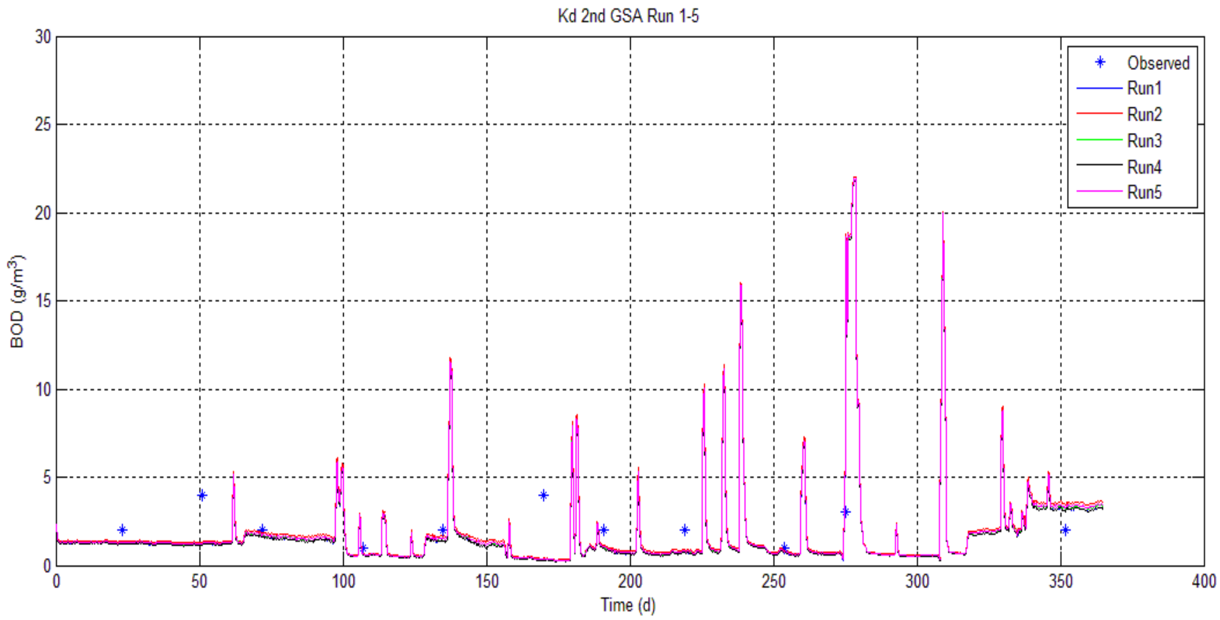
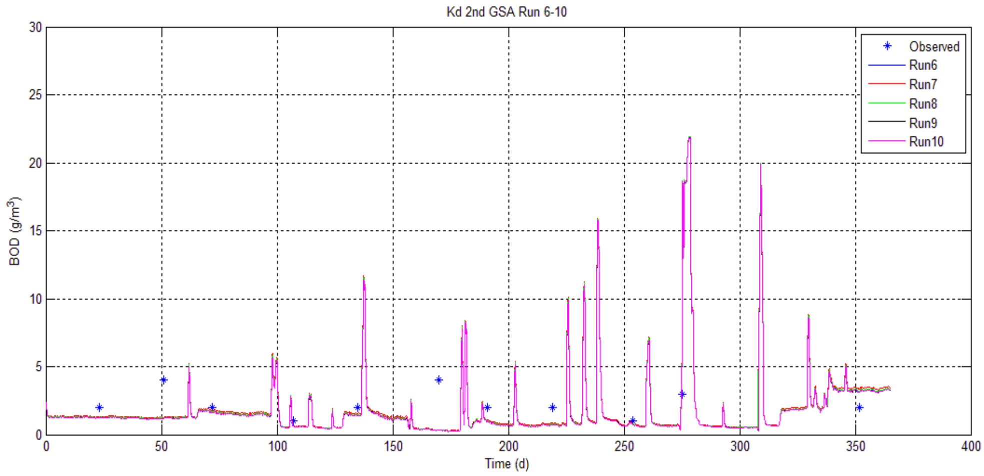


Figure 5-27 Kd 2nd GSA runs 6 to 10.



5.3.4 BOD Temperature Coefficient GSA

Another ecological parameter is added to the sensitivity analysis: the BOD decay temperature coefficient Tkd (adimensional).

Also in this case, the sensitivity parameters are the coefficients of the six river stretches belonging to the system.

In particular, it is decided to perform a 10 runs analysis, choosing an uniform distribution of the parameters values for the Latin Hypercube Sampling: the range is (1 – 1.1)[48].

The following table (Tab. 5-9) presents the parameters combinations used for the two analyses.

Table 5-9 TKd GSA parameters.

Run	Bacchiglione TKd	Canale Scaricatore TKd	Piovego_in TKd	Piovego_out TKd	San Gregorio TKd	Tronco Maestro TKd
1	1.031	1.038	1.002	1.055	1.012	1.081
2	1.036	1.089	1.026	1.035	1.066	1.089
3	1.052	1.088	1.097	1.084	1.026	1.001
4	1.082	1.056	1.035	1.096	1.069	1.068
5	1.015	1.011	1.052	1.066	1.086	1.064
6	1.086	1.006	1.079	1.039	1.044	1.040
7	1.068	1.046	1.056	1.060	1.082	1.045
8	1.033	1.095	1.008	1.013	1.001	1.062
9	1.045	1.026	1.046	1.000	1.039	1.035
10	1.011	1.045	1.045	1.026	1.024	1.096

48 Jørgensen et al., 2001.

The results are plotted in the following figures (from Fig. 5-28 to Fig. 5-30): it is possible to see that the model is sensitive to the changes of the parameters values.

The curves corresponding to the runs are different from one another, in particular during those periods when no rainfall occurs at the beginning and at the end of the simulations.

This fact, again, is probably due to the actual influence of the stormwater arriving to the receiving bodies during precipitations: it increases the flow velocity of the streams, reducing the residence time of the water (and, consequently, of the different substances) within the system.

For this reason, the ecological processes have a smaller time to be performed and to influence the water quality.

Figure 5-28 TKd GSA runs comparison.

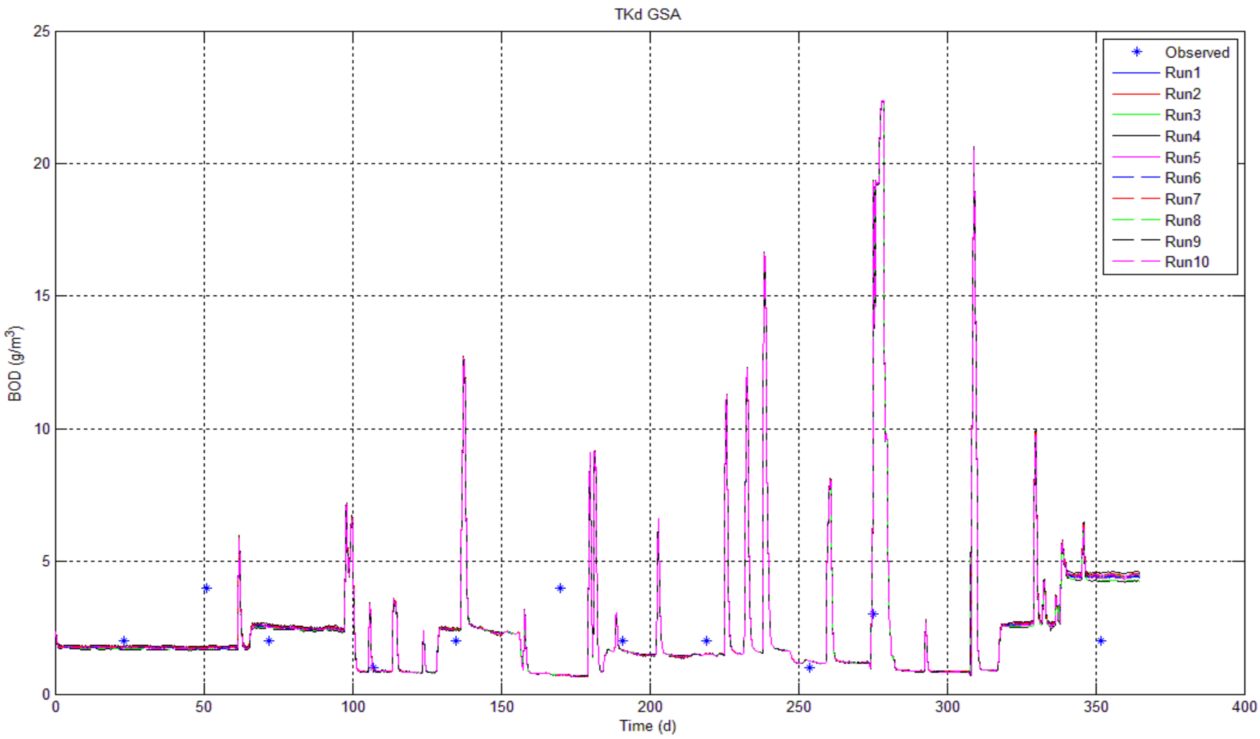


Figure 5-29 TKd GSA runs 1 to 5.

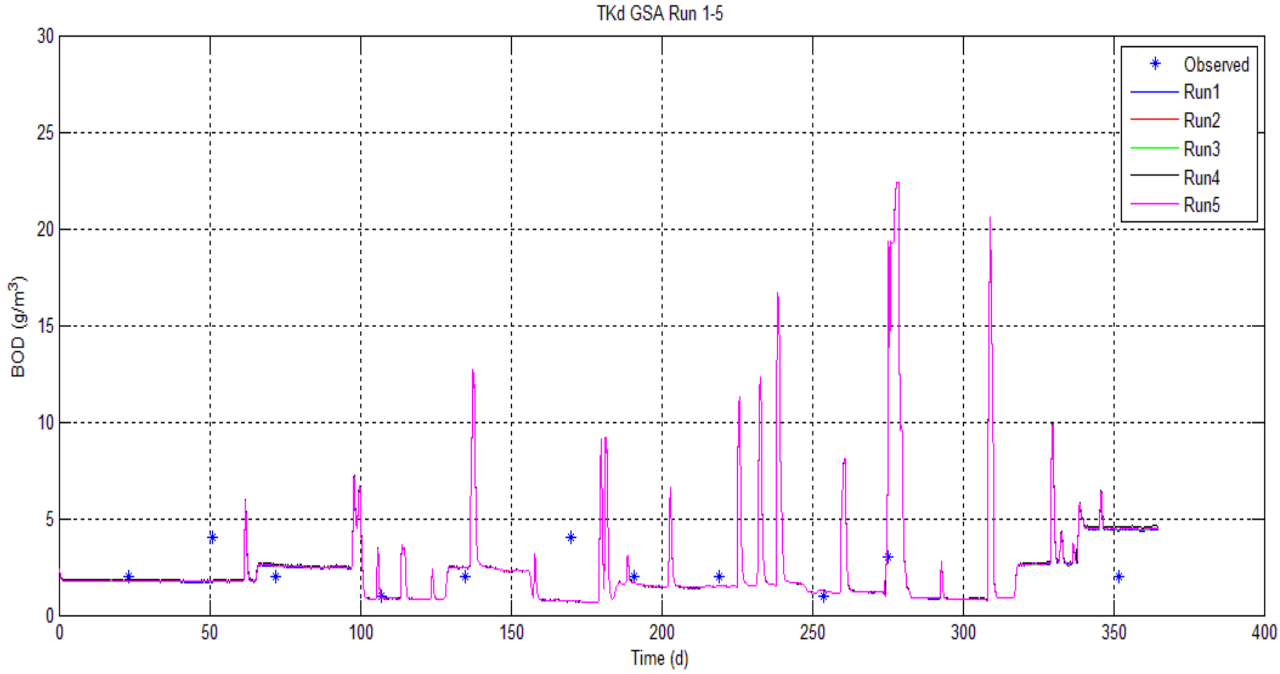
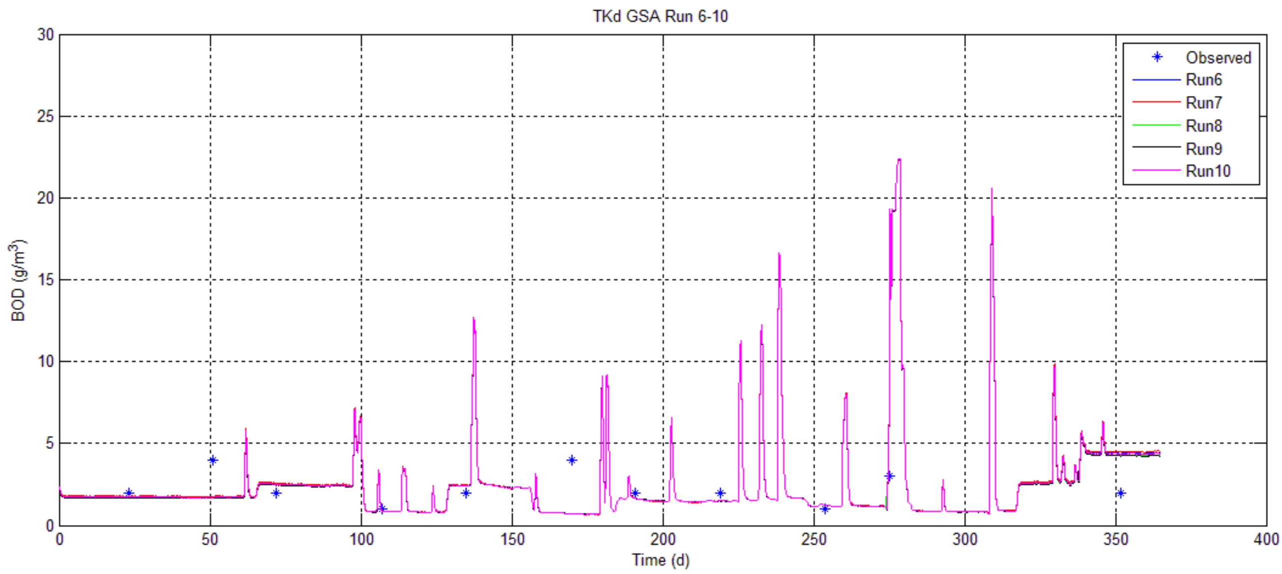


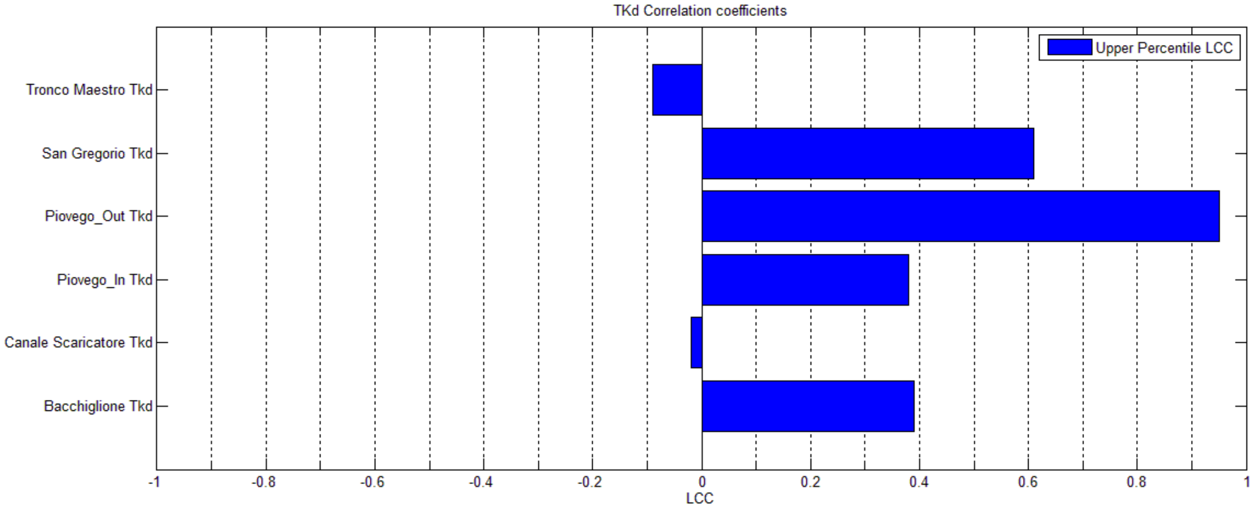
Figure 5-30 TKd GSA runs 6 to 10.



In order to identify the most influencing BOD temperature coefficients, the Linear Regression between the calculated BOD concentration and the parameters is performed during the GSA.

In particular, the Linear Correlation Coefficient (LCC) is calculated between the studied parameters and the model outputs: the results are presented below (Fig. 5-31) and (Tab.5-10).

Figure 5-31 LCC for BOD and TKd GSA.



In this case, the model seems to be sensitive, most of all, to the TKd of "Piovego_Out" and "San Gregorio" river blocks and, for this reason, it is decided to consider them during the calibration phase.

Both of the coefficients show a direct relationship with the final BOD concentration: this implies that, increasing the temperature coefficient, the biodegradation capabilities improve.

As for the other analyzed parameters, the final part of the modeled systems ("Piovego_Out") determines an high influence on the results.

Table 5-10 Linear Correlation Coefficient: TKd GSA.

Parameter	LCC
Bacchiglione Kd	0.39
Canale Scaricatore Kd	-0.02
Piovego_in Kd	0.38
Piovego_out Kd	0.95
San Gregorio Kd	0.61
Tronco Maestro Kd	-0.09

5.3.5 RESERVOIRS CONSTANT GSA

Once the sensitivity to ecological parameters is studied, it is decided to consider those parameters that may influence the hydraulics of the system.

Here following, the results of the Global Sensitivity Analysis performed on the reservoir constants K are presented.

This parameter is used to determine the flow exiting a catchment once a storm event occurs; in particular, it transforms the rain water volume into a discharge.

The flow is obtained representing the watersheds as a series of three tanks, discharging one into the other that follows.

In this specific case, the dependency between the tank volume and the released flow is supposed to be: $Q = (V/k)^{1/m}$, where V is the volume (m^3), Q is the flow (m^3/d), k is the reservoir constant (d) and m is the exponent, set to 1 if linearity is supposed.

Since the runoff generation of the entire system is to be evaluated, the GSA is performed involving the reservoir constant of all the three basins considered in the modeled: "Catchment_Tronco_Maestro", "Catchment_Piovego_In" and "Catchment_Piovego_Out" blocks. In particular, it is decided to vary the set parameters within the range (0.02 – 5) days and their values are generated by means of the Latin Hypercube Sampling solver, as usual.

The values used for each model run in the experiment are resumed in the following table (Tab. 5-11).

Table 5-11 K GSA parameters.

RunNo	Catchment Piovego_in k	Catchment Piovego_out k	Catchment Tronco Maestro k
1	1.57	2.71	3.34
2	2.62	3.41	1.12
3	2.56	2.86	0.75
4	4.90	3.99	4.24
5	1.27	3.68	3.27
6	4.86	3.56	0.75
7	0.77	0.14	4.50
8	3.96	4.71	1.32
9	3.90	4.93	0.09
10	2.92	3.58	4.87

Considering this specific sensitivity analysis, it is decided to evaluate the effect of the reservoir constant K on both the modeled concentrations: the results for Ammonia Nitrogen and BOD concentrations are presentment below (Fig. 5-32 and Fig. 5-33).

In particular, the influence of the parameters changes are seen only in correspondence of the model peaks: this means that the effects of the reservoir constants are predominant when rainfall occurs. This was quite predictable, due to the role of such parameters in the runoff generation.

Figure 5-32 Reservoir constant K GSA runs for BOD.

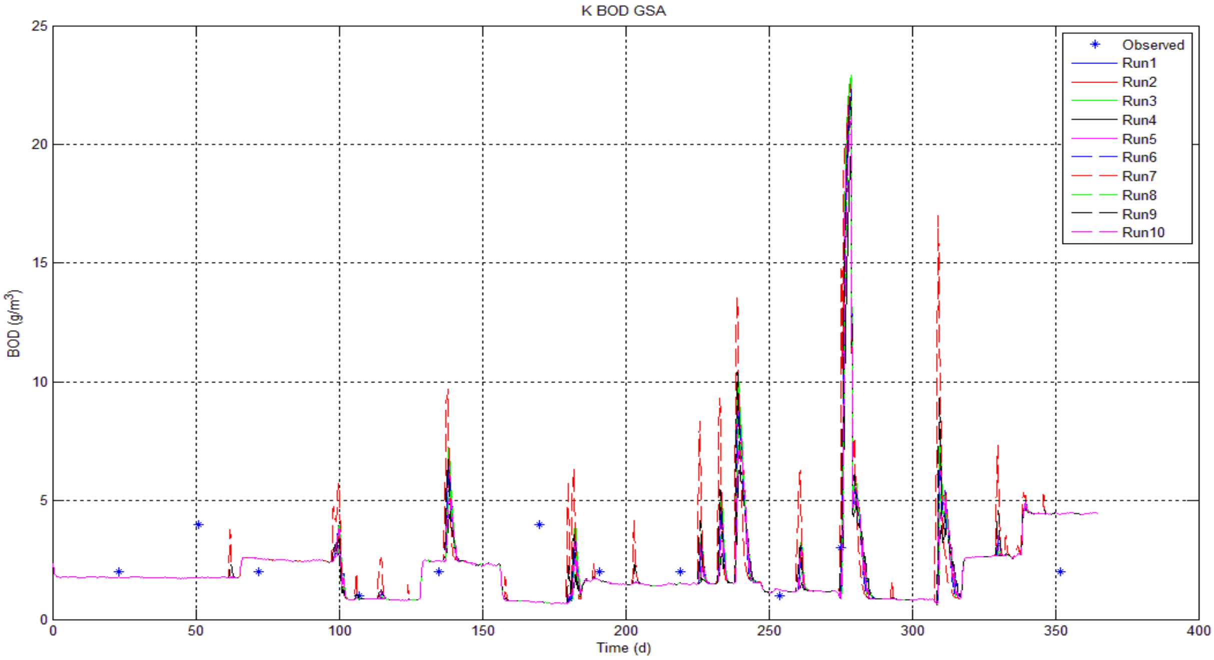
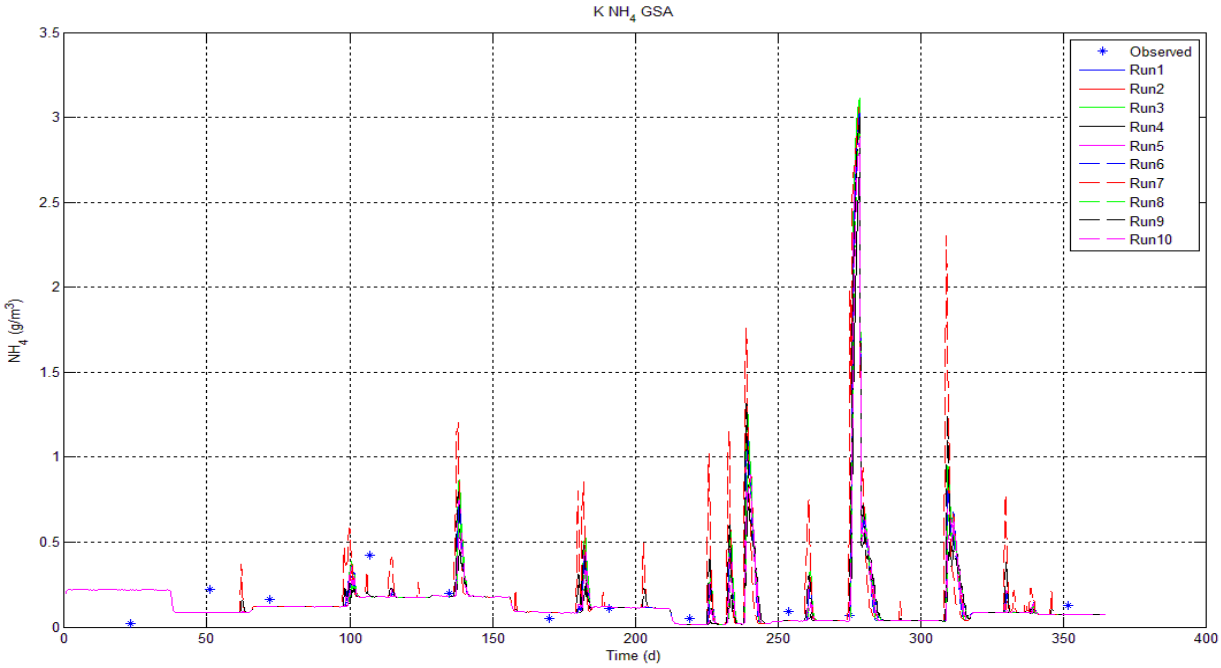


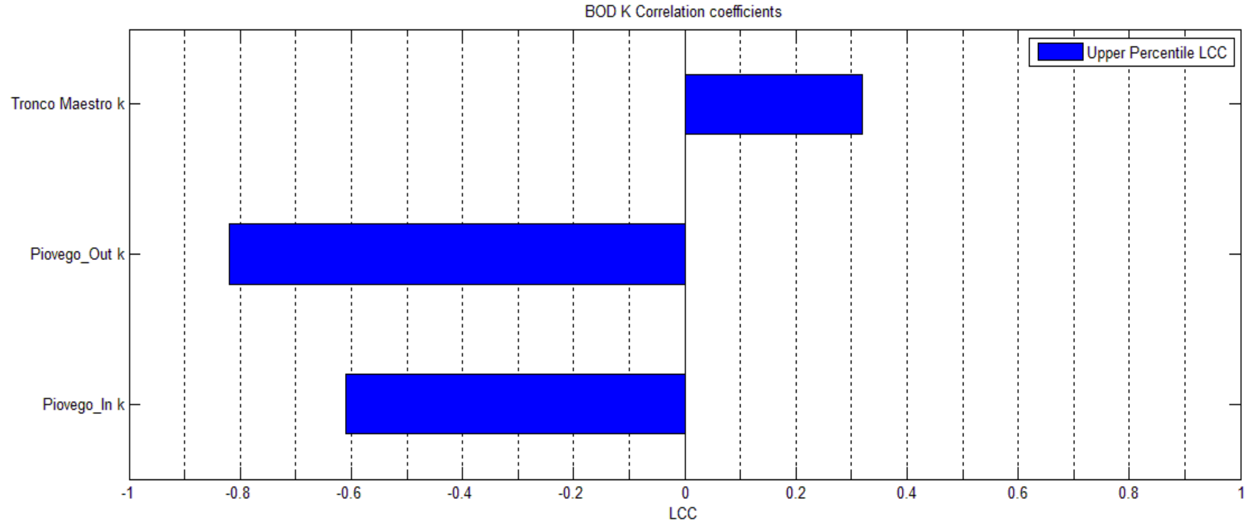
Figure 5-33 Reservoir constant K GSA runs for NH4.



It is also worth to calculate the Linear Correlation coefficient between the Upper Percentile of the calculated concentration and the different parameters used in the GSA.

Results are presented in the figures and table that follow (Fig. 5-34, Fig. 5-35 and Tab. 5-12).

Figure 5-34 Reservoir constant K GSA LCC for BOD.



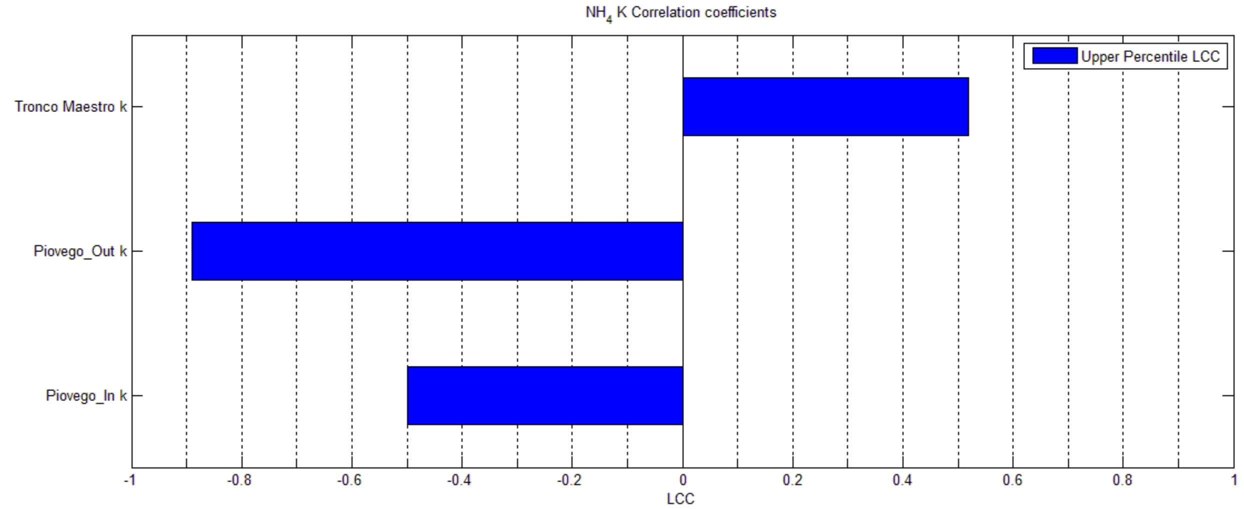
The results show that the BOD seems to be sensitive, most of all, to the reservoir costants of two catchments: "Catchment_Piovego_Out" and "Catchment_Piovego_In" blocks.

This implies that their runoff generation, in terms of released discharge, is much more impactive on the water quality than the supply coming from the other basin.

The reason may be that the two basins discharge their runoff contribution directly in the final part of the waterway, so they can have a greater influence on the model results, due to their actual position.

Besides that, the dependency between the output and the parameter is direct for the "Catchment_Tronco_Maestro", while it is inverse for the "Catchment_Piovego_Out" and "Catchment_Piovego_In".

Figure 5-35 Reservoir constant K GSA LCC for NH4.



Considering Ammonia Nitrogen, all the chosen parameters show a certain influence on the model results; in particular, "Catchment_Piovego_Out" reservoir constant have the highest absolute value of the LCC, "Catchment_Piovego_In" decreases its inverse Linear Correlation Coefficient with respect to BOD analysis and "Catchment_Tronco_Maestro" increases its pressure on the model results.
Due to this behaviors, it is decided to consider all the parameters in the calibration step.
The values of the Linear Correlation Coefficients are resumed in the following table (Tab. 5-12).

Table 5-12 Linear Correlation Coefficient: K GSA.

Parameter	**NH4 LCC**	**BOD LCC**
Catchment Piovego_In k	-0.50	-0.61
Catchment Piovego_Out k	-0.89	-0.82
Catchment Tronco Maestro k	0.52	0.32

5.3.6 LINEARITY EXPONENT GSA

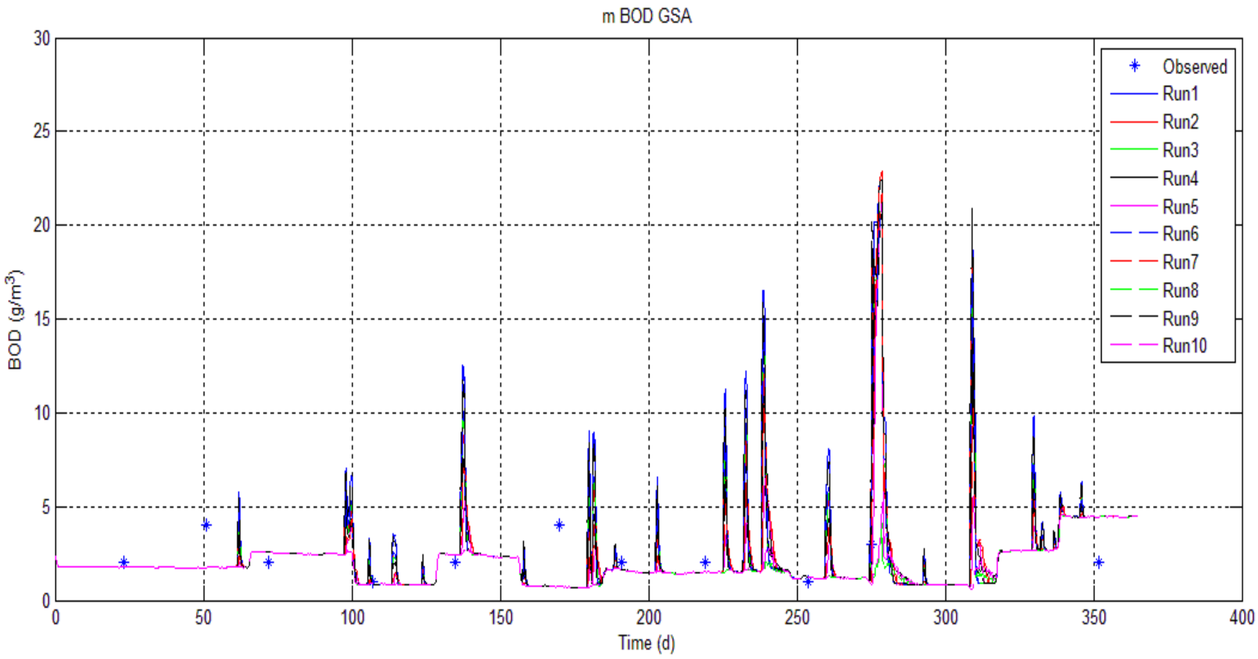
Another important parameter to be studied in order to evaluate the hydraulics of the system is the exponent used for the reservoir model that transforms the rainwater volume in discharge.
As presented in the previous section, the first assumption is to work with a series of three tanks discharging one into the other that follows, in which the volume and the outflow are linked by a linear relationship.
Nevertheless, the linearity may be a too strong simplification of the process and so, in WEST 2014 it is possible to set the value of the exponent representing the dependency between tank volume V (m^3) and discharge Q (m^3/d): $Q = (V/k)^{1/m}$, where k is the reservoir constant (d) and m the adimensional exponent.
For this reason, it is decided to evaluate the influence of such a parameter on the model results, in terms of BOD and NH4 concentration at the end of the system.
In the next table (Tab. 5-13), the set of values used for the GSA is presented: in particular, the exponent can vary within the range (0.6 – 2) and its values are generated by means of the Latin Hypercube Sampling solver, as done for the other GSA experiments.

Some graphics are also added, as follows (Fig. 5-36 and Fig. 5-37): for both the modeled compounds, the concentration (g/m^3) calculated at each run are plotted with respect to time.

Table 5-13 Reservoir constant m GSA parameters.

Run	Catchment Piovego_in m	Catchment Piovego_out m	Catchment Tronco Maestro m
1	1.03	1.13	0.63
2	1.37	0.77	1.74
3	1.10	1.84	0.96
4	1.09	1.52	1.84
5	1.32	1.83	1.95
6	1.78	0.97	0.61
7	1.75	1.38	1.09
8	1.95	1.56	1.55
9	0.81	0.75	1.32
10	1.53	1.81	1.49

Figure 5-36 Exponent m GSA runs for BOD.

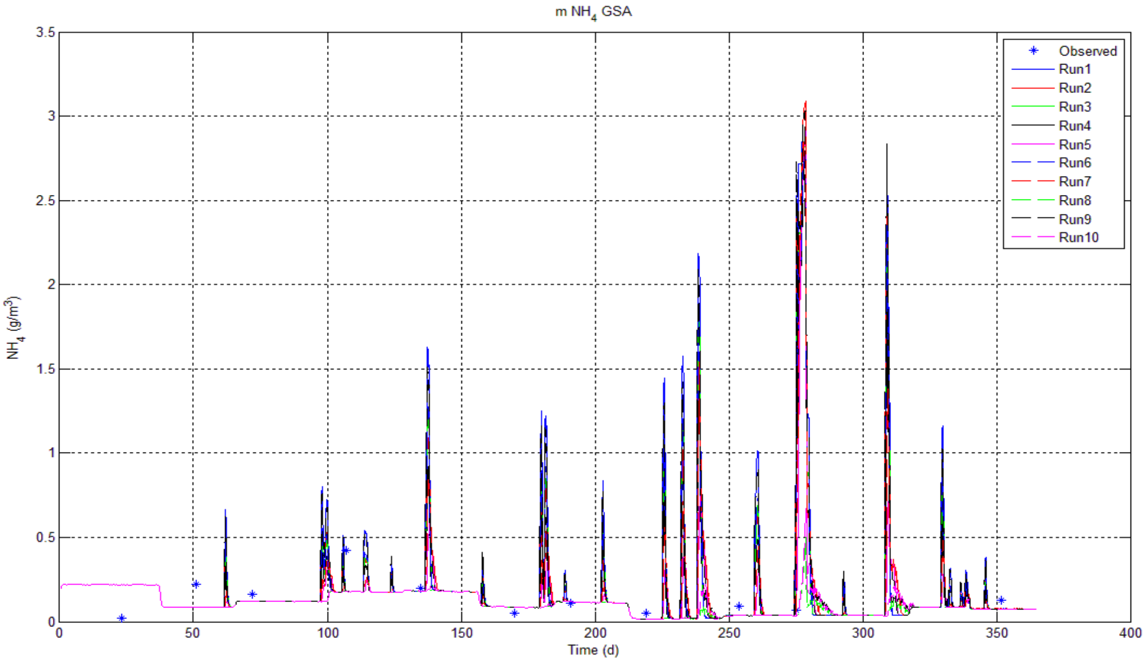


The previous picture shows the effect of the exponent variation on the concentration of BOD at the end of the system.

It is evident that the model is sensitive to the considered parameter and this can be assessed by looking at the peaks: during stormwater events, the behavior of the different curves changes from one run to another.

A similar consideration can be done for the Ammonia Nitrogen, as presented below, in the following image.

Figure 5-37 Exponent m GSA runs for NH4.



As for BOD, the Ammonia Nitrogen dependency on the exponent is evident in correspondence of the peaks.

This was expected, since this parameter is used to model the catchments response to a precipitation: in other words, the exponent does not affect the calculated concentrations when no rain occurs.

It is useful to plot the Linear Correlation Coefficient for each parameter taken into consideration: as usual, it is calculated between the Upper Percentile of the modeled concentrations and the parameters involved into the GSA.

The results are presented below (Fig. 5-38, Fig. 5-39 and Tab. 5-14).

Figure 5-38 Exponent m GSA LCC for BOD.

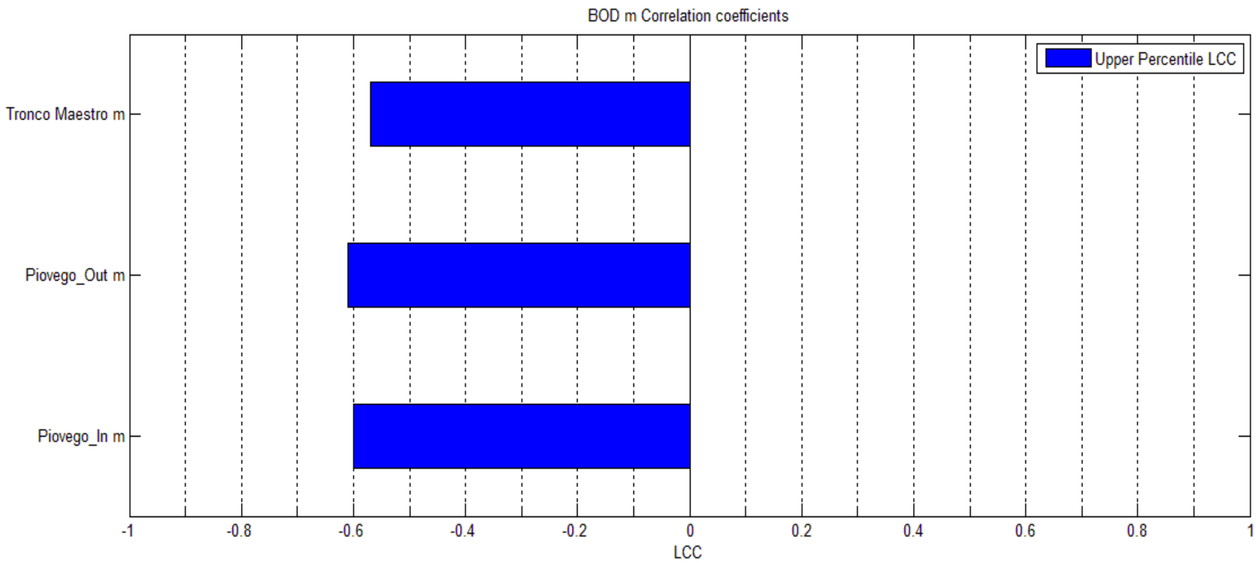
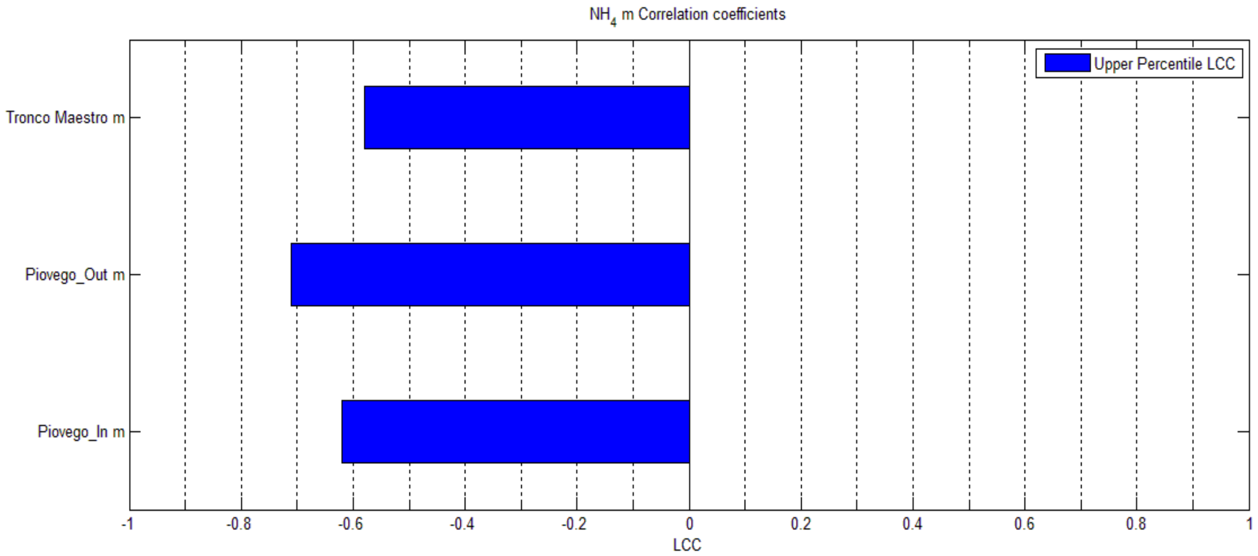


Figure 5-39 Exponent m GSA LCC for NH4.



All the considered parameters seem to have a certain correlation with the model outputs: for this reason, it is decided to consider all of them in the calibration.

In general, it can be seen that the calculated LCC are all negative: this implies that the relationship between exponent and water quality is inverse.

Such a dependency was fairly predictable because of the mathematical formulation of the flow discharge calculation: since it is $Q = (V/k)^{1/m}$, a reduction of the exponent causes it to increase when V/k is greater than 1.

In the following table (Tab. 5-14), the Linear Correlation Coefficients are presented: they are calculated between the Upper Percentile (by default set to 95%) of the modeled concentrations and the studied exponent m.

“Catchment_Piovego_Out” is still the basin having the strongest correlation with the model results.

Table 5-14 Linear Correlation Coefficient: m GSA.

Parameter	BOD LCC	NH4 LCC
Catchment Piovego_in m	-0.60	-0.62
Catchment Piovego_out m	-0.61	-0.71
Catchment Tronco Maestro m	-0.57	-0.58

5.3.7 Flow Velocity GSA

In order to better analyze the hydraulics of the chosen system, it is decided to evaluate the influence of the river flow velocity on the modeled concentrations of BOD and NH4: as defined before, it is given as input variable to characterize the "Bacchiglione" river block.
In this case, it is decided to perform a Global Sensitivity Analysis with 15 runs: the flow velocity is generated through the Latin Hypercube Sampling solver within the interval (0.3 – 1.5) m/s.
In the following table (Tab. 5-15), the values are resumed.

Table 5-15 River flow velocity GSA.

Run	Input Flow Velocity (m/s)
1	0.67
2	1.28
3	0.44
4	1.34
5	1.29
6	0.80
7	0.85
8	1.11
9	0.52
10	0.42
11	1.20
12	1.33
13	0.30
14	1.24
15	0.81

The output concentrations are presented below (Fig. 5-40 and Fig- 5-41) for each model run of the analysis.
As it is possible to see, the influence of the flow velocity is meaningless: the changes determined on the calculated concentrations by the variation of the flow velocity are very small.
Consequently, the model does not seem to be sensitive to this input value which is not, therefore, calibrated.

Figure 5-40 Flow velocity GSA runs for BOD.

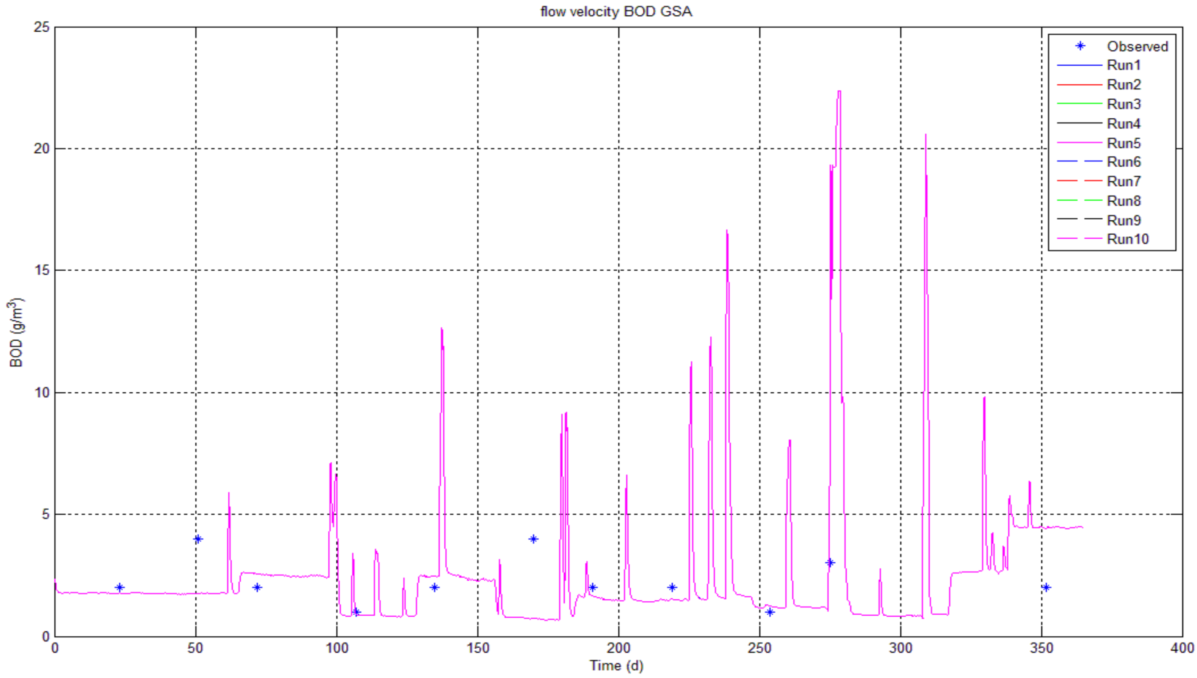
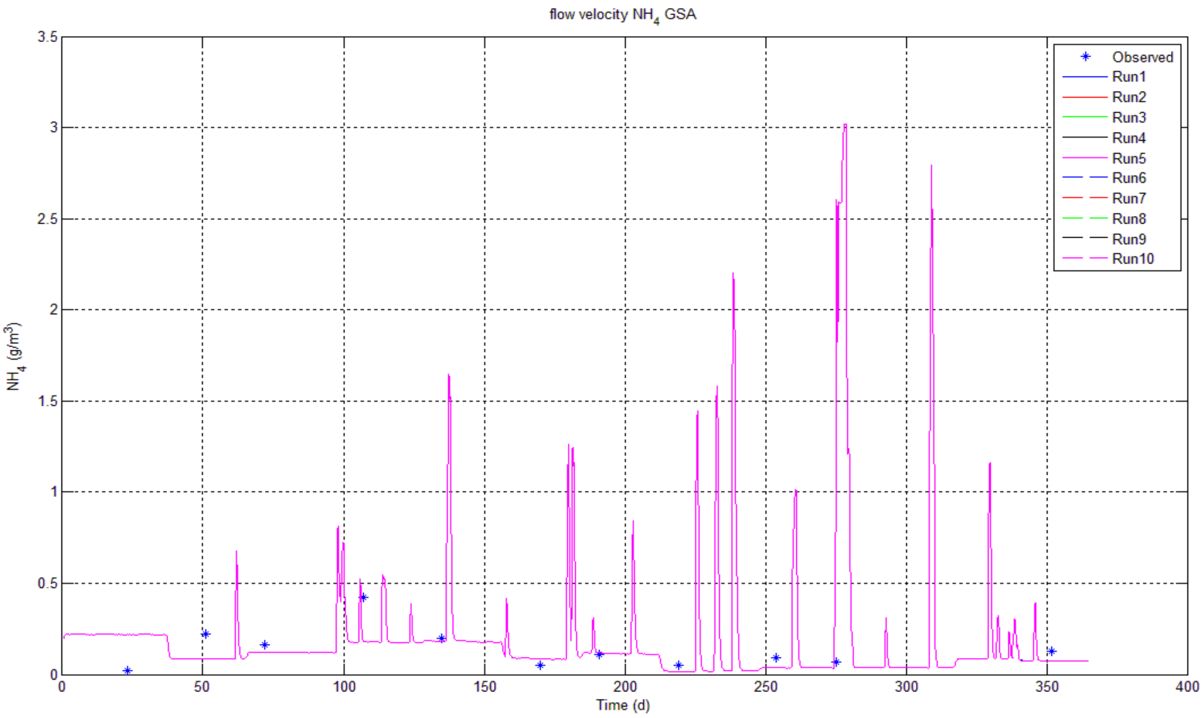


Figure 5-41 Flow velocity GSA runs for NH4.



5.3.8 Sensitivity Analysis Discussion

This section gives a summary of the Global Sensitivity Analysis.
In particular, a brief discussion for each considered parameter is presented.

Nitrification Rate, Knit. Its influence is evident when no rainfall occurs on the considered catchments (refer to Fig. 5-12): during a precipitation, the water supply coming from the different basins and reaching the hydraulic network determines a reduction of the residence time into the rivers system, so that the nitrifying bacteria have a lower time to act on the available Ammonia Nitrogen.
This fact can be confirmed comparing the half time of the Nitrification rate Knit used during the GSA to the average residence time within the network: by definition, the half time (t_{nit12}) is calculated as $t_{nit\,12} = \ln(2)/(Knit)$, and it can be used as a representation of the rate of the biological process.
The residence time within the system is calculated as $t_{res} = L_{max}/v_m \cong 0.42\ d$, where L_{max} is the maximum length of the rivers system and v_m is the average flow velocity of "Bacchiglione" river block.
Whenever the residence time is considerably lower than the half time, the Nitrification has not enough time to be performed significantly and affect the water quality: in the following table (Tab. 5-16), the calculated half times are resumed; in red, those that are greater than the average residence time of the system.

Table 5-16 Residence time for each Knit of the 10 runs GSA.

Run	Bacchiglione $t_{nit\,12}$	Canale Scaricatore $t_{nit\,12}$	Piovego_in $t_{nit\,12}$	Piovego_out $t_{nit\,12}$	San Gregorio $t_{nit\,12}$	Tronco Maestro $t_{nit\,12}$
1	0.99	3.29	0.47	0.55	5.99	6.71
2	3.37	0.63	0.67	2.49	0.83	0.36
3	3.43	1.57	0.56	0.57	0.87	0.46
4	1.61	0.53	1.20	1.01	1.56	0.64
5	0.39	0.88	0.62	0.41	1.72	0.36
6	0.89	0.45	1.04	0.68	0.38	0.35
7	0.74	0.65	0.36	1.98	1.03	0.71
8	6.16	0.46	0.58	0.35	0.86	0.44
9	1.02	0.57	1.14	0.44	0.48	0.56
10	1.89	0.51	0.41	0.36	0.84	2.24

As it is possible to see from the given table, in most cases the Nitrification half time is higher than the residence time, therefore the process cannot completely act on the Ammonia Nitrogen and this is confirmed by the low influence of the Nitrification Rate on the NH4 calculated concentration when stormwater events occur in the case study area.
In particular, the nitrification rate of the "Piovego_Out" river block shows the higher Linear Correlation Coefficient (absolute value) with the modeled concentration of Ammonia Nitrogen: consequently, it seems to be the most impacting parameter and it is decided to consider it in the calibration process.

Nitrification Temperature Coefficient, Tknit. Referring to Fig. 5-16, it is possible to see that the influence of this parameter on the calculated concentration of Ammonia Nitrogen is meaningless. Due to its small range of variation (that is (1 – 1.1)), the Nitrification Temperature Coefficient TKnit does not affect the model output that much. Only the TKnit of "Piovego_Out" river stretch is added to the calibration process.

BOD Decay Rate, Kd. In order to better investigate the influence of this parameter on the model results, it is decided to split the sensitivity analysis in two parts, using two different intervals for the Latin Hypercube Sampling: both of the analyses evidence the important influence of the parameter on the calculated concentration of BOD at the end of the system. In particular, the second study shows a more relevant variation of the model outputs with respect to the parameters changes (Fig. 5-20 and Fig. 5-25), meaning that the calculated concentrations are more sensitive to variations of the BOD decay rate within the range (1 – 2) 1/d.
In particular, the effect of the parameter on the results is evident, as for the Nitrification Rate Knit, when no rainfall occurs: the runoff contribute and the enlarged river flow discharge determine the reduction of the residence time into the rivers system, causing the biological degradation to have a lower time to act and influence the final BOD concentration.
As for the Knit, it is possible to compare the residence time that characterizes the system to the biodegradation half time $t_{BOD\ 12}$ that is given as $t_{BOD\,12} = ln2/(Kd)$: when ($t_{BOD\ 12} > t_{RES}$), the biodegradation has not enough time to be performed and to affect significantly the final BOD concentration.
The calculated values of the half time, for each Kd used in the Global Sensitivity Analysis, are presented in the following table (Tab. 5-17): in red, those values that are greater than the residence time.

Table 5-17 Residence time for each Kd of the first 10 runs GSA.

Part 1						
Run	Bacchiglione $t_{BOD\ 12}$	Canale Scaricatore $t_{BOD\ 12}$	Piovego_in $t_{BOD\ 12}$	Piovego_out $t_{BOD\ 12}$	San Gregorio $t_{BOD\ 12}$	Tronco Maestro $t_{BOD\ 12}$
1	1.55	1.38	3.21	1.08	2.33	0.82
2	1.43	0.76	1.70	1.44	0.95	0.76
3	1.13	0.77	0.71	0.79	1.69	3.34
4	0.81	1.08	1.44	0.71	0.92	0.93
5	2.18	2.40	1.13	0.95	0.78	0.98
6	0.78	2.84	0.83	1.35	1.25	1.33
7	0.93	1.22	1.07	1.02	0.81	1.23
8	1.49	0.72	2.66	2.26	3.39	0.99
9	1.24	1.70	1.22	3.42	1.36	1.45
10	2.43	1.24	1.24	1.69	1.76	0.72
Part 2						
Run	Bacchiglione $t_{BOD\ 12}$	Canale Scaricatore $t_{BOD\ 12}$	Piovego_in $t_{BOD\ 12}$	Piovego_out $t_{BOD\ 12}$	San Gregorio $t_{BOD\ 12}$	Tronco Maestro $t_{BOD\ 12}$
1	0.52	0.39	0.44	0.37	0.45	0.39
2	0.37	0.64	0.49	0.65	0.53	0.54
3	0.58	0.51	0.61	0.44	0.39	0.41
4	0.44	0.36	0.37	0.41	0.60	0.37
5	0.38	0.51	0.43	0.46	0.51	0.55
6	0.52	0.44	0.52	0.37	0.39	0.54
7	0.46	0.40	0.47	0.56	0.57	0.47
8	0.41	0.36	0.43	0.50	0.38	0.50
9	0.40	0.37	0.46	0.37	0.69	0.43
10	0.54	0.45	0.48	0.40	0.36	0.40

Decay Temperature Coefficient, TKd. Considering the Fig. 5-28, it is possible to see that the influence of this parameter on the output of Biochemical Oxygen Demand is not so relevant: apart from the beginning and the end of the simulations, the curves representing the BOD concentration are not affected that much by the TKd changes.
Due to its narrow variation interval (between 1 and 1.1), this parameter seems to have a limited influence on the model.
Looking at the calculated Linear Correlation Coefficients, it is decided to add only the "Piovego_Out" and "San Gregorio" river blocks coefficients to the calibration.

Reservoir Coefficient, K. This parameter is used to evaluate the sensitivity of the model to the hydraulics of the system: in particular, it is used to characterize the response of a catchment to the rainfall.
Referring to Fig. 5-32 and Fig. 5-33, it is possible to see that it influences the calculated concentrations of both BOD and Ammonia Nitrogen only during stormwater events, in fact it modifies the peaks of the outputs.
For these considerations and since the values for this parameters are guessed at the beginning of the model construction, it is decided to add the reservoir constants of all the three considered basins to the calibration process.

Reservoir Exponent, m. In order to evaluate the influence of the exponent on the final concentrations of both BOD and Ammonia Nitrogen, it is worth to consider the Fig. 5-36 and Fig. 5-37: as expected, the effect of such a parameter is seen only in the peaks of the modeled concentrations, since it is used to represent the hydraulic response of a basin to the rainfall.
Considering the Linear Correlation Coefficient, all the exponents show a quite important inverse correlation with the calculated outputs.
Again, the "Catchment_Piovego_Out" is the one having the highest absolute value of the LCC: this may be due to its position, since it discharges its runoff contribution directly in the final part of the system.
Anyway, due to their relevant correlation coefficients, it is decided to consider all the exponents in the calibration process.

Flow Velocity. One of the input data used to characterize the starting point of the system is the water velocity of the Bacchiglione river: this information is obtained by a simplification of the river cross section and by direct measures of flow discharges and hydrometric levels in the station of Montegalda.

Due to the uncertainty connected, most of all, to the simplification of the cross section, it is decided to evaluate the influence of this data on the model result.

Referring to Fig. 5-40 and Fig. 5-41, it is possible to see that changes in the flow velocity do not give relevant changes in the calculated concentrations.

This is confirmed also by the calculation of the Linear Correlation Coefficient, that results very low (equal to -0.18 for the BOD concentration and to 0.18 for the Ammonia Nitrogen one).

The reason may be that, due to the hydraulic installments placed along the network and the river discharges subdivisions, the velocity of the initial part of the system is not able to affect the model in order to give significant effects on the concentrations at the end of the network.

Consequently, it is decided to neglect this data from the model calibration.

5.4 MODEL CALIBRATION

This step of the modelling procedure is aimed to improve the performance of the model, in order to better fit and represent the observed data.

Thanks to the results of the Global Sensitivity Analysis, it is possible to decide which parameters are worth to be calibrated.

Considering WEST 2014, the calibration is done exploiting the Parameters Estimation virtual experiment: the software performs a series of model runs using different sets of automatically generated parameters (chosen by the user), in order to minimize a specific deviation function, calculated with respect to the model output and a set of observed data.

The values of the parameters are generated directly by the software, sampling within a given range that can be set by the user for each term considered in the analysis.

In this case, it is decided to work with the same model variables considered so far, that are the BOD and Ammonia Nitrogen concentrations at the exit of the system: they are calculated during each model run with the set of generated parameters and then compared with the observed values.

The function to be minimized is the relative squared mean difference:

$$MD = \sqrt{\frac{\sum_{i=1}^{n} w_i \cdot \left(\frac{y_i - \dot{y}_i}{y_i}\right)^2}{\sum_{i=1}^{n} w_i}}$$

Where:

- MD = Relative mean difference;
- y_i = simulated value at time t_i (in this case, BOD or NH4 concentrations, g/m^3);
- $\dot{y}_i$ = observed value at time t_i;
- w_i = weight (adim);
- n = total number of available observed values (here, n = 11 for both, BOD and NH4 concentrations).

For each reference value (the observed concentration), it is possible to set the weight w_i to be used in the calculation of the mean difference: in this way, the different observed values would have a different importance in the minimization process.

In this case, it is decided to use the same weight for all the measured values, so that all of them have the same relevance: $w_i = 1$ for i=1, …, n.

As consequence, the mean difference is simplified to: $MD = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{y_i - \dot{y}_i}{y_i}\right)^2}{n}}$.

The aim of the Parameter Estimation is to find the set of parameters that gives the model output y_i, calculated at time t_i, as close as possible to the observed value $\dot{y}_i$, measured at the same time t_i. According to WEST 2014, the best run is the one presenting the lowest Objective Value (ObjValue), that is the average of the calculated relative mean difference of BOD and the relative mean difference of Ammonia Nitrogen.

5.4.1 First Calibration

During the first execution of the Parameter Estimation experiment, the software performed a series of 113 runs: at this stage, the value of the calculated mean difference was stable around 0.65, with no relevant improvements with respect the previous steps, so it was decided to stop the analysis. The mean difference was about 0.7 at the beginning of the calibration.

The parameters to be calibrated and the first results are resumed in the following table (Tab. 5-18).

Table 5-18 Calibrated parameters.

Parameter Name	Initial value	Calibrated value
BacchiglioneKd1	0.2	0.268
BacchiglioneKnit	0.2	0.2
Canale_Scaricatore Kd1	0.4	0.342
Canale_Scaricatore Knit	0.2	0.2
Catchment_Piovego_in k	0.042	3.0
Catchment_Piovego_in m	1	1.464
Catchment_Piovego_out k	0.042	0.039
Catchment_Piovego_out m	1	1.460
Catchment_TM k	0.042	0.038
Catchment_TM m	1	1
Piovego_in Knit	0.2	0.223
Piovego_out Kd1	0.4	0.391
Piovego_out Knit	0.2	0.182
Piovego_out TKd	1	1
Piovego_out TKnit	1	1
San_Gregorio Knit	0.2	0.218
San_Gregorio TKd	1	1
Tronco_Maestro Kd1	0.4	0.4
Tronco_Maestro Knit	0.2	0.224

Once the experiment is complete, it seems worth to evaluate the Nash-Sutcliffe Efficiency for the model results with the calibrated parameters:

$$E_{NH4} = 1 - \frac{\sum(\dot{y}_i - y_i)^2}{\sum(\dot{y}_i - \dot{y})^2} = -3.29$$

$$E_{BOD} = -1.87$$

Where ẏ is the mean value of the observed data.

Comparing the previous efficiencies to those calculated before the calibration, it is possible to see that their values are still both negative, but their module is reduced by 17.3% and 16.9% respectively, meaning that the capability of the model to adapt to the measured data has been improved by the calibration process.

Since it is $|E_{BOD}| < |E_{NH4}|$, the BOD fit is better than the one of Ammonia Nitrogen.

However, both efficiencies are far from 0, meaning that the representation given by the calculated concentrations is worse than the averages of the observed data.

As a consequence, the efficiencies suggest that the model still needs to be improved.

This consideration is confirmed also calculating two error measures as the MAPE (Mean Absolute Percentage Error) and the RMSE (Root-Mean Squared Error):

$$MAPE = \frac{100}{n} \cdot \sum \left| \frac{\dot{y}_i - y_i}{\dot{y}_i} \right|$$

$$RMSE = \frac{1}{n} \cdot \sqrt{\sum \left(\frac{\dot{y}_i - y_i}{\dot{y}_i} \right)^2}$$

The results are presented in the table below (Tab. 5-19).

Table 5-19 MAPE and RMSE.

	BOD	**NH4**
MAPE	43 %	209 %
RMSE	0.55	4.08

When a perfect fit is achieved, the MAPE and the RMSE are equal to zero.

Considering the Ammonia Nitrogen, the errors confirm the limited capability of the calculated concentrations to adapt to the observed data.

Lower values are found for the BOD, but in both cases an improvement is needed.

The calibrated concentrations are graphically presented in the following figures (Fig. 5-42 and Fig. 5-43): the observed values are represented by green circles, the model outputs of the first dynamic simulation are the red curves, while the blue ones represent the simulated concentrations at the end of the calibration experiment.

Figure 5-42 BOD concentration with calibrated parameters.

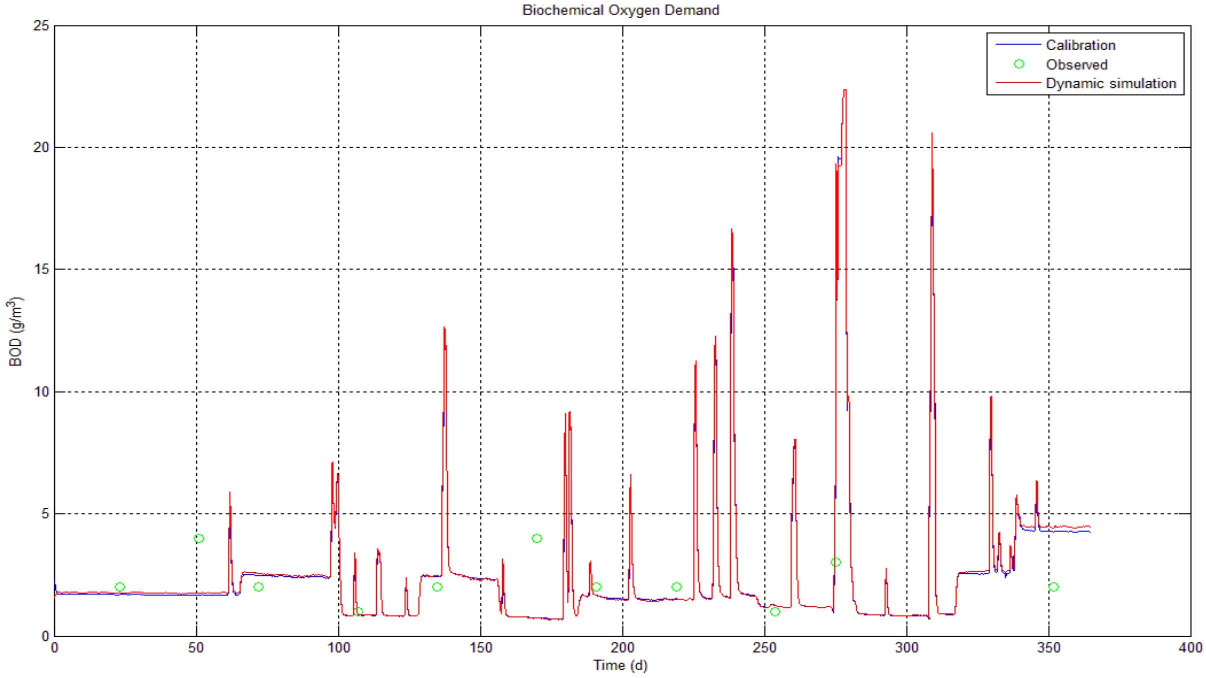
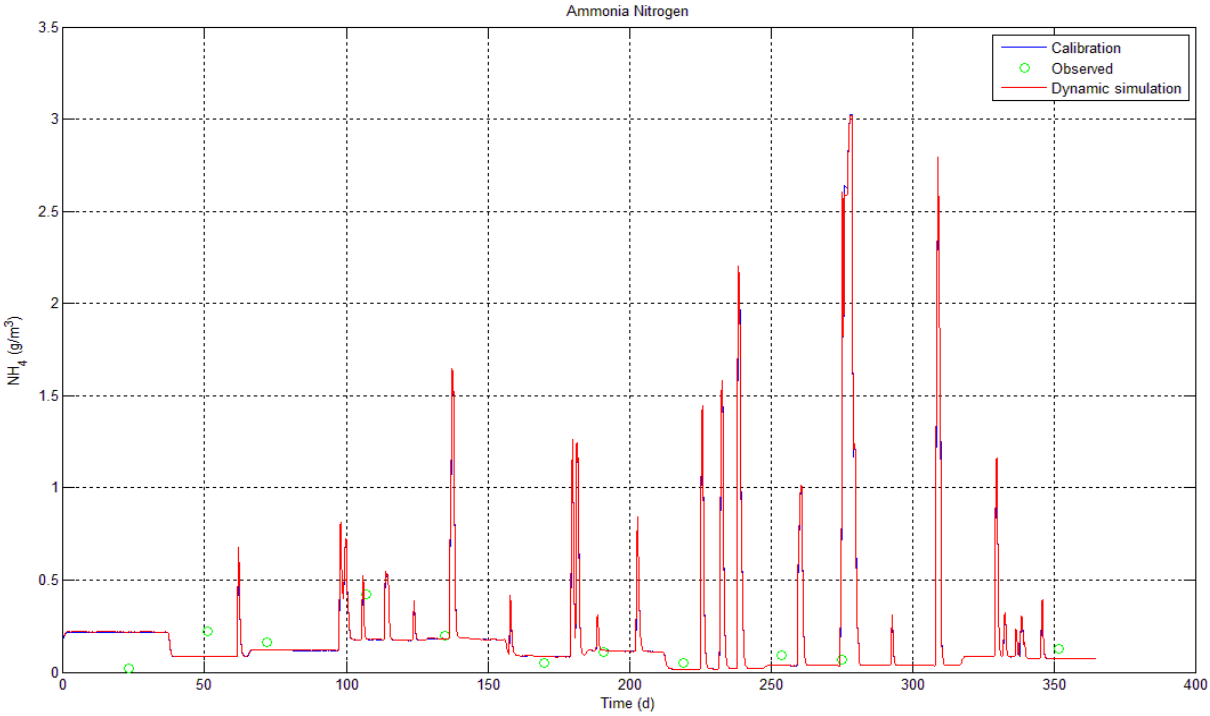


Figure 5-43 NH4 concentration with calibrated parameters.



As it is possible to see, the calibration influence on the model results is limited.

Considering the BOD concentration, two effects are evident: first, the Parameters Estimation experiment is able to lower the curves (see the blue line with respect to the red one) and second, it reduces the peaks.

These effects were predictable because of the parameters used in the experiment: in the sensitivity analysis, the BOD decay rate Kd turned out to influence the output concentration only when no rain occurs, so it lowers the flat parts of the curve.
On the other hand, the exponent m and the reservoir constant k control the hydraulics of the system, so they influence the peaks of the model since they are related to the runoff generation consequent to storm water events.
In general, after this experiment, it seems that the model adaptation for BOD is not improved that much.

Contrary to Biochemical Oxygen Demand, the effects of the calibration on the Ammonia Nitrogen are even less significant.
As it is possible to see above, the flat parts of the curves are not (evidently) influenced by the parameters calibration, while there are some limited differences concerning the peaks.
This result is unexpected: considering the sensitivity analysis, the Nitrification rates showed an important influence on the Ammonia Nitrogen concentration, as for the linearity exponent and the reservoir constant.
The results of the first calibration are resumed in the following table (Tab. 5-20).

Table 5-20 Observed concentrations and Model results.

Observed BOD (g/m^3)	**Calculated BOD (g/m^3)**	**Observed NH4 (g/m^3)**	**Calculated NH4 (g/m^3)**
2	1.689	0.02	0.214
4	1.665	0.22	0.083
2	2.474	0.16	0.119
1	0.906	0.42	0.184
2	2.430	0.2	0.181
4	0.746	0.05	0.086
2	1.658	0.11	0.119
2	1.520	0.05	0.018
1	1.250	0.09	0.037
3	5.675	0.07	0.720
2	4.256	0.13	0.075

As presented in the previous table, the Biochemical Oxygen Demand seems to be able to better represent the measured data with respect to the Ammonia Nitrogen (as shown by the value of the MAPE calculated before).

In the following figures (Fig. 5-44 and Fig. 5-45), a comparison between the observed and the simulated values is presented: the green circles represent the measured concentrations, the blue asterisks are the calculated concentrations at the end of the calibration, while the red asterisks are the model results of the first dynamic simulation.

Looking at the charts, it is possible to see that the effects of the calibration are evident only for a couple of data of both concentrations, while the global effect on the calculated data is not so relevant.

Figure 5-44 BOD results comparison.

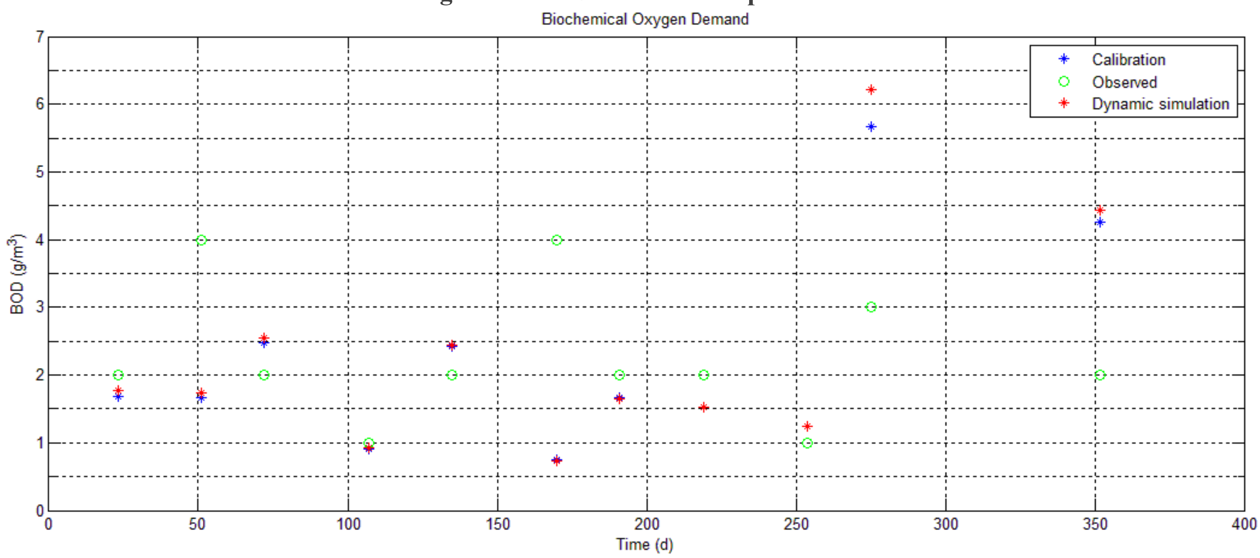
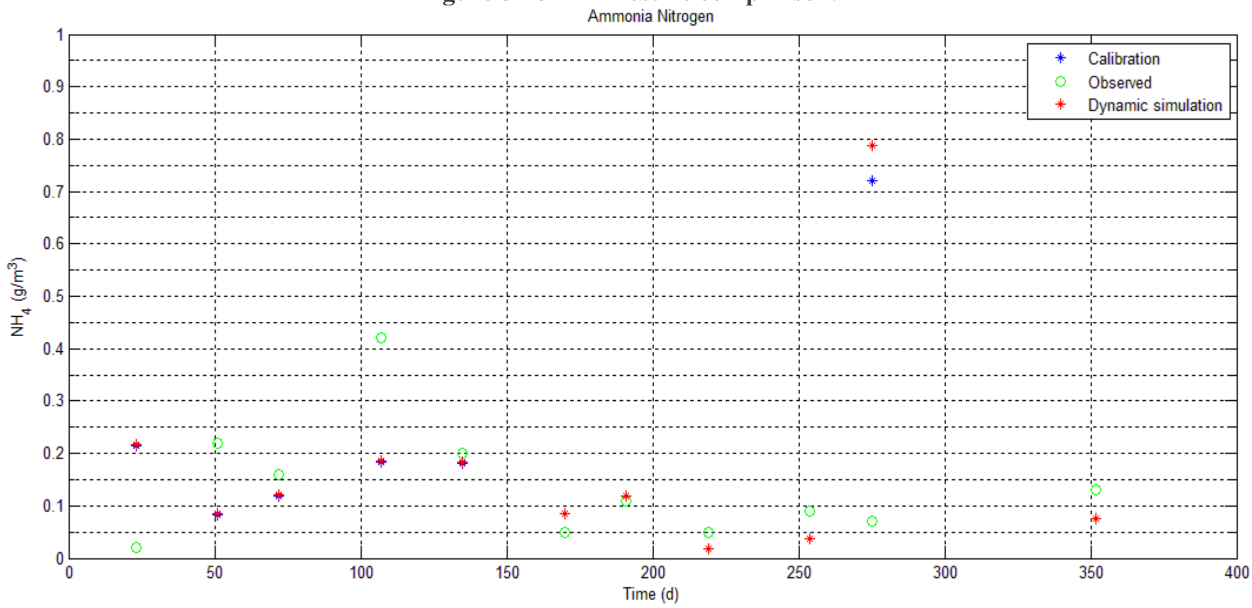


Figure 5-45 NH4 results comparison.



The following figures (Fig. 5-46 and Fig. 5-47) give a direct comparison between the calculated and the observed values: as for the initial dynamic simulation, the model seems to be an underestimation of the available measurements.

This is particularly evident considering the Ammonia Nitrogen plot, because most of the circles are below the black line.

Since the perfect fitting is reached when the blue circles are placed along the black line, also the figures below suggest the necessity of a model improvement with a further calibration.

Figure 5-46 Calculated BOD compared with Observed BOD: first calibration results.

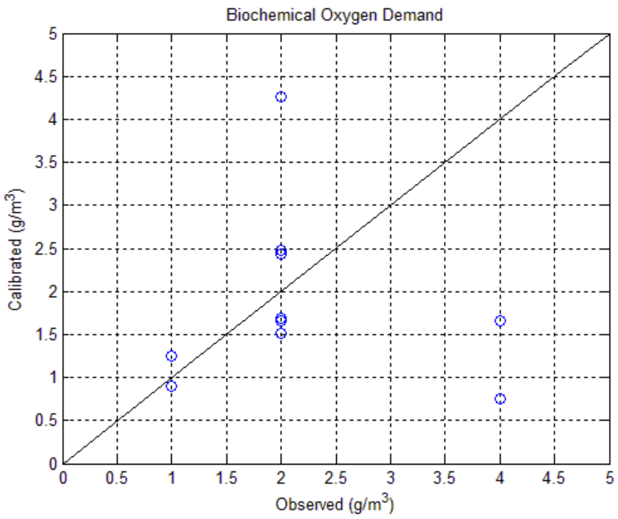
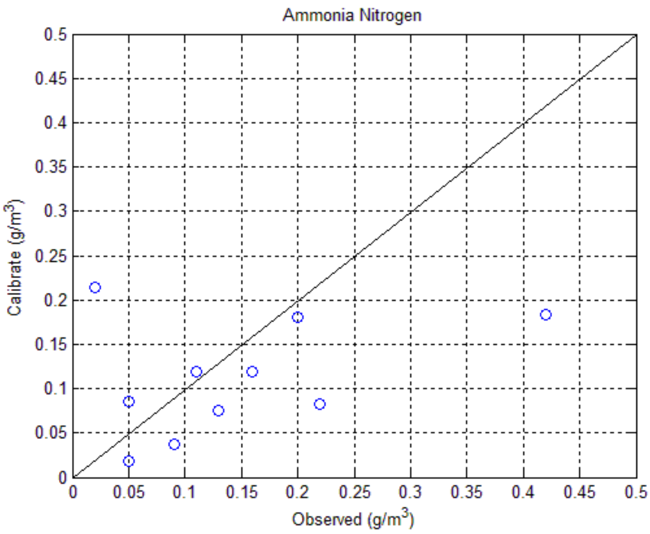


Figure 5-47 Calculated NH4 compared with Observed NH4: first calibration results.



5.4.2 SECOND CALIBRATION

Once the first step of the Parameters Estimation is over, a second one is performed in order to try to improve the model adaptation to the observed values.
In particular, it is decided to start the new experiment with some of the calibrated values resulting from the previous analysis and to enlarge the intervals where the software can generate the parameters used for each run: this is done to give to the software a wider range for the values generation.
As done before, the minimization function is the relative mean difference: after 80 runs, its value was stable around 0.60, so it was decided to stop the analysis.
In particular, the relative mean difference (adimensional) of Ammonia Nitrogen is equal to 0.077, while for BOD it is about 1.127: this suggests that the calculated concentration of the first compound has a better adaption to the observed data, with respect to the second one.
The results are resumed in the following table (Tab. 5-21).

Table 5-21 Second calibration results.

Parameter Name	**Initial value**	**Calibrated value**
BacchiglioneKd1	0.268	0.2684
BacchiglioneKnit	0.2	0.1986
Canale_Scaricatore Kd1	0.342	0.3422
Canale_Scaricatore Knit	0.2	0.2260
Catchment_Piovego_in k	3.0	3.1200
Catchment_Piovego_in m	1.464	1.4638
Catchment_Piovego_out k	0.039	0.0394
Catchment_Piovego_out m	1.460	1.1430
Catchment_TM k	0.038	0.0393
Catchment_TM m	1	1
Piovego_in Knit	0.223	0.2189
Piovego_out Kd1	0.391	0.4156
Piovego_out Knit	0.182	0.1821
Piovego_out TKd	1	1
Piovego_out TKnit	1	1
San_Gregorio Knit	0.218	0.2274
San_Gregorio TKd	1	1.0210
Tronco_Maestro Kd1	0.4	0.3956
Tronco_Maestro Knit	0.224	0.2210

Also in this case, it is decided to evaluate the Nash-Sutcliffe Efficiency for the model results with the calibrated parameters: $E_{NH4} = 0.021$ and $E_{BOD} = -1.62$.

The previous calculations show that the efficiency has been evidently improved for Ammonia Nitrogen, with respect to the first calibration: its value, in fact, is now greater than zero.
This means that the representation given by the model is a little better than the one given by the average value of the observed concentrations.
Considering the Biochemical Oxygen Demand, the second calibration gives a small improvement to the efficiency, that passes from -1.87 to 1.62.
However, the model fit to the observed data can still be advanced with a further calibration.
Also in this case, it seems worth to calculate some error measures, used to evaluate the goodness of the model adaptation (Tab. 5-22):

Table 5-22 MAPE and RMSE.

	BOD	**NH4**
MAPE	42%	129%
RMSE	0.53	2.98

Referring to Tab. 5-19, the second calibration decreases the error terms for both the calculated concentrations, coherently with what stated by the Nash-Sutcliff efficiencies.
The calculated concentrations with the newly calibrated parameters are resumed in the following table (Tab. 5-23).

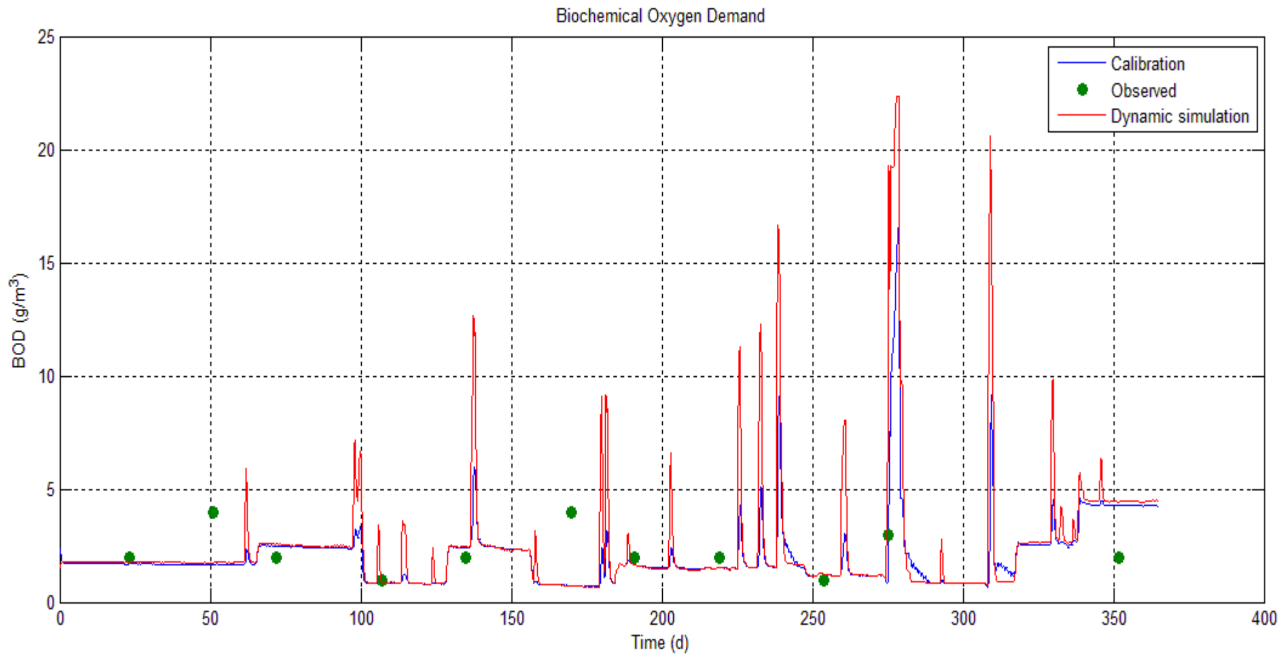
Table 5-23 Observed concentrations and Model results.

Observed BOD (g/m^3)	**Calculated BOD (g/m^3)**	**Observed NH4 (g/m^3)**	**Calculated NH4 (g/m^3)**
2	1.688	0.02	0.215
4	1.664	0.22	0.084
2	2.471	0.16	0.120
1	0.886	0.42	0.182
2	2.428	0.2	0.182
4	0.744	0.05	0.086
2	1.654	0.11	0.119
2	1.518	0.05	0.018
1	1.248	0.09	0.037
3	0.841	0.07	0.032
2	4.251	0.13	0.075

Making a comparison with the calculated values resumed in Tab. 5-20, it is possible to see that the changes determined by the second calibration to the model output are quite small, except for some cases in which, for both BOD and Ammonia Nitrogen, the fit is drastically improved.
See, for example, the 10th observed value for NH4: with the first calibration, the calculated concentration was 0.72 g/m^3, while the observation is equal to 0.07 g/m^3.
Thus the model gave an overestimation of 10 times; after the second calibration, the output is about 0.03 g/m^3; this evident change in the gives its contribute to the model improvement.

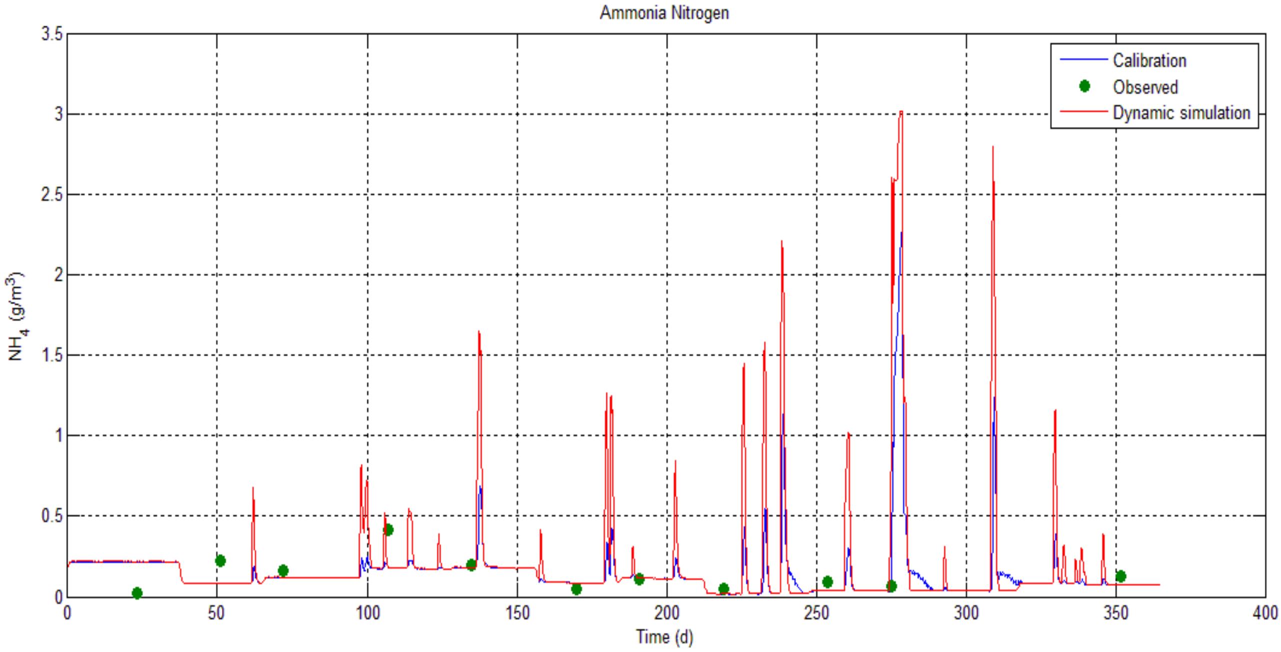
The results of the second Parameters Estimation experiment are presented in the following figures (Fig. 5-48 and Fig. 5-49), where the calculated concentrations are plotted with respect to time, making a comparison between the initial dynamic simulation (red curve), the second calibration results (blue curve) and the available observations (green dots).

Figure 5-48 BOD concentration with calibrated parameters.



As it is possible to see, the second experiment is able to lower the curve of the calculated BOD concentration and, most of all, it is able to reduce the peaks due to the rainfall runoff contribution to the river network.
This reduction is due to the calibration of the parameters that influence the hydraulics of the system, such as the reservoir constants k; it is also evident, anyway, that the changes occurred to the “flat” parts of the output representation are still unable to match all the observed values.
This is particularly evident at the beginning of the simulation.

Figure 5-49 NH4 concentration with calibrated parameters.



Referring to the Ammonia Nitrogen, it is possible to see that the model, after the second calibration, is still unable to fit the observed data at the beginning of the simulation.

In addition, as for the Biochemical Oxygen Demand, the peaks are reduced because of the calibration on the reservoir constants, but, in some cases (4^{th} observed data, from the left), this determines a worse adaptation to the observed references.

Another consideration that can be done about the calibration is that the changes in the ecological parameters (as the Nitrification and Decay rates) are not able, for both the concentrations, to consistently vary the “flat” parts of the curves.

On the contrary, small variations of the catchment reservoir constants determine a sensitive change in the curves peaks.

This may suggest that the model is primarily sensitive to the hydraulics of the system, rather than to the ecological parameters. Also, these findings suggest that, in the dry periods. some processes controlling the variations of the water quality of the hydraulic network of the city (see, for instance, the oscillations in ammonia at the beginning of the simulation) are not included in the model. Examples include not authorized sewage discharges into the rivers network and the internal channels of Padua city centre that are not directly considered in the model simulation.

In order to better investigate this behavior, it is decided to perform a third Parameters Estimation experiment, changing the initial values of the linearity exponents to evaluate the influence on the calculated concentrations and the overall model efficiency.

In the following figures (Fig. 5-50 and Fig. 5-51), the comparison between the observed data (green circles) and the calibrated ones (blue asterisks) is presented.

As it is possible to see, the Ammonia Nitrogen adaptation to the observed data is better than that of BOD.

Figure 5-50 Calculated BOD compared with Observed BOD: second calibration results.

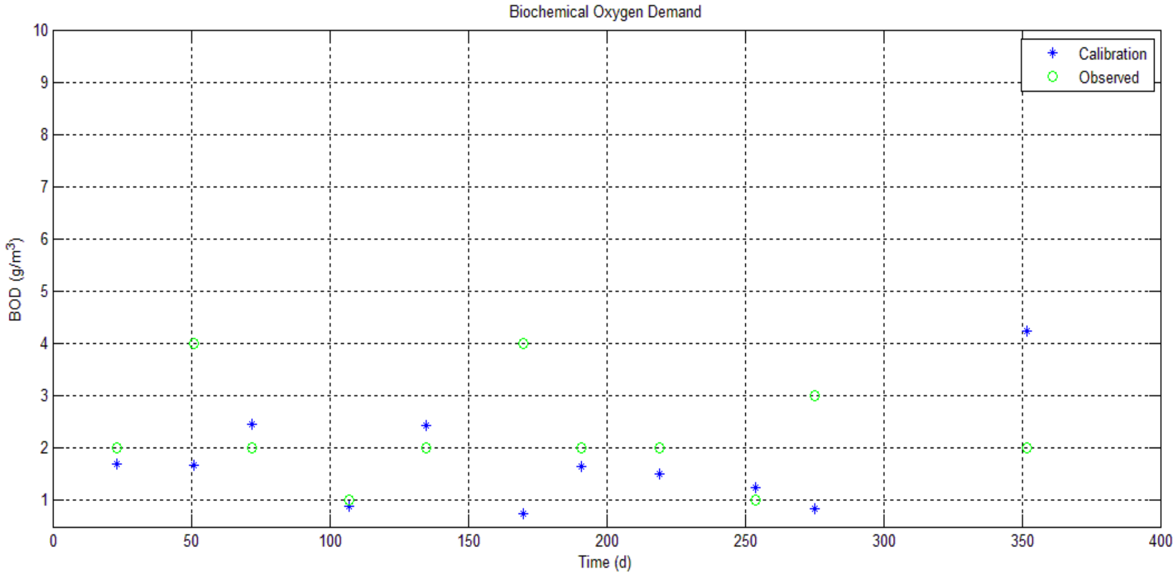
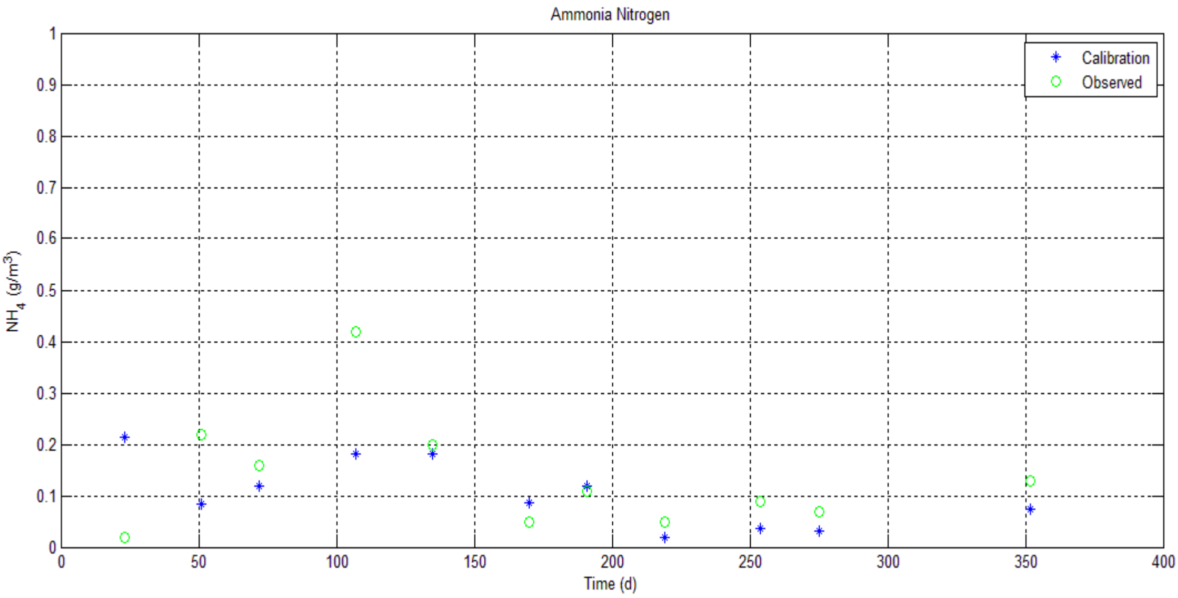


Figure 5-51 Calculated NH4 compared with Observed NH4: second calibration results.



5.4.3 THIRD CALIBRATION

As stated before, it is decided to better evaluate the sensitivity of the model to the hydraulic parameters considered in the calibration.

For this purpose, a third experiment is performed, setting the initial value to be used for the linearity exponent to a value different from 1 (the default value used so far).

In addition, due to the small changes occurred to the BOD decay rates and BOD temperature coefficients, it is decided to modify also their initial value.

The is due to the calibration process procedure: the initial value set by the modeler is the starting point used by WEST 2014 to automatically generate the values (for each parameter) to be utilized in the different runs of the estimation.

Furthermore, the variations applied by the software to the parameters values is very small from run to run: as consequence, to calibrate parameters having a “bad” initial value, it is necessary a very long experiment. In the following table (Tab. 5- 24), the initial and calibrated values are resumed.

Table 5-24 Third calibration results.

Parameter Name	Initial value	Calibrated value
BacchiglioneKd1	3.1200	3.124
BacchiglioneKnit	0.1990	0.202
Canale_Scaricatore Kd1	0.3450	0.3459
Canale_Scaricatore Knit	0.2280	0.224
Catchment_Piovego_in k	3.1500	3.142
Catchment_Piovego_in m	1.4660	1.469
Catchment_Piovego_out k	0.0398	0.0498
Catchment_Piovego_out m	1.13	1.118
Catchment_TM k	0.0397	0.0378
Catchment_TM m	1.1220	1.1220
Piovego_in Knit	0.2177	0.2168
Piovego_out Kd1	0.4156	0.4182
Piovego_out Knit	0.1821	0.1821
Piovego_out TKd	1	1.011
Piovego_out TKnit	1	1
San_Gregorio Knit	0.2274	0.2281
San_Gregorio TKd	1.021	1.026
Tronco_Maestro Kd1	0.3956	0.3932
Tronco_Maestro Knit	0.2200	0.2273

After this calibration, the Objective Value (average mean difference) is stable around 0.516; in particular, considering NH4 the mean difference is 0.0986, while for the BOD it is 0.934.
With respect to the previous step, the adaptation capability of Ammonia Nitrogen seems to be decreases, while the one of BOD has been improved: this is confirmed calculating the Nash-Sutcliffe Efficiencies, that are equal to -0.87 and -1.23, respectively.

Analyzing the different runs of the calibration, it is seen that:

- BOD and NH4 efficiencies increase when "Catchment_Piovego_Out" reservoir constant k, "Catchment_Piovego_in" reservoir constant and "Catchment_Piovego_in" linearity exponent m increase;
- BOD efficiencies decreases when "Catchment_Piovego_Out" linearity exponent m, "Catchment_Tronco_Maestro" reservoir constant and "Catchment_Tronco_Maestro" linearity exponent increase.

Due to these considerations, it is decided to run a final calibration step, using as initial values for the Ammonia Nitrogen parameters those resulting from the second calibration; considering BOD, instead, the initial values are equal to those resulting from the present step.

5.4.4 FOURTH CALIBRATION

The last step of the Parameters Estimation experiment is aimed to try to improve the model adaptation to the observed data.
The calculated average mean difference between the two variables was stable around 0.51 after 117 runs, so it was decided to stop the analysis.
In particular, the mean difference for BOD results to be equal to 0.92 (still consistently high), while for the Ammonia Nitrogen it is equal to 0.099.
Comparing this first information to the minimization functions calculated during the second calibration, it is clear that the final experiment gives an improvement to the BOD adaptation only.
This can be confirmed by the Nash-Sutcliffe efficiencies and the error measures for the two outputs (Tab. 5-25):

$$E_{NH4} = -0.61$$

$$E_{BOD} = -1.23$$

Table 5-25 MAPE and RMSE.

	BOD	NH4
MAPE	34%	164%
RMSE	0.47	3.28

The previous calculations evidence what suggested before: the calibration determines an improvement for the BOD model adaptation, but not for the Ammonia Nitrogen.

In particular, the Nash-Sutcliffe efficiency for the NH4 is positive after the second calibration, whereas, in this case, it decreases becoming negative.
Considering the Biochemical Oxygen Demand, the efficiency is still negative, but it is better than those of the previous calibrations.
Also the MAPE and the RMSE are reduced for the BOD, while they increase for the NH4.
In the following table (Tab. 5-26), the initial values and the calibrated ones are resumed.

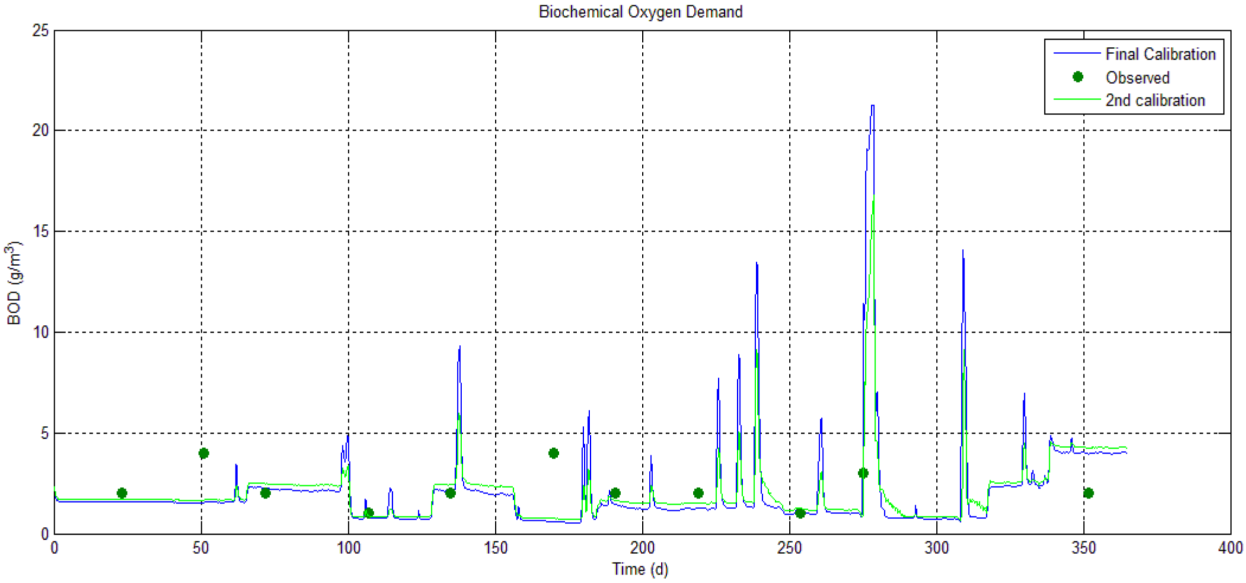
Table 5-26 Final calibration results.

Parameter Name	Initial value	Calibrated value
Bacchiglione Kd1	3.124	3.12679
Bacchiglione Knit	0.1986	0.19162
Canale_Scaricatore Kd1	0.3459	0.34861
Canale_Scaricatore Knit	0.226	0.22864
Catchment_Piovego_in k	3.142	3.14257
Catchment_Piovego_in m	1.469	1.47180
Catchment_Piovego_out k	0.0498	0.05092
Catchment_Piovego_out m	1.122	1.12477
Catchment_TM k	0.0378	0.03647
Catchment_TM m	1.118	1.11657
Piovego_in Knit	0.2189	0.21897
Piovego_out Kd1	0.4182	0.42093
Piovego_out Knit	0.1821	0.18466
Piovego_out TKd	1.011	1.00984
Piovego_out TKnit	1	1.10000
San_Gregorio Knit	0.2274	0.22771
San_Gregorio TKd	1.026	1.02519
Tronco_Maestro Kd1	0.3932	0.39592
Tronco_Maestro Knit	0.221	0.21902

In the following figures (Fig. 5-52 and Fig. 5-53), the results of the calibration are presented: in particular, it is decided to make a comparison to the model concentrations resulting from the second Parameters Estimation experiment.

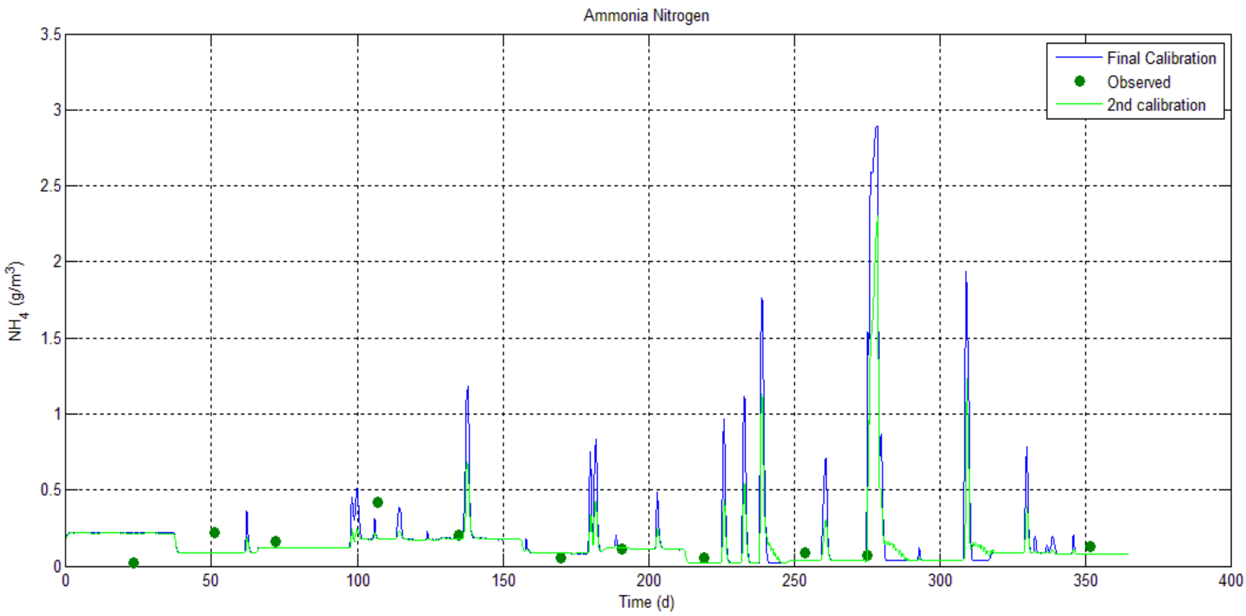
The green dots represent the observed data, the blue curves are the output concentrations resulting from the last calibration, while, in green, those of the second one.

Figure 5-52 BOD concentration with calibrated parameters.



As it possible to see, the effects on the model adaptation determined by the final calibration are quite evident. In particular, the last experiment is able to influence the peaks of the curves (coherently with the changes of the hydraulic parameters) and it is able to lower the "flat" parts.

Figure 5-53 NH4 concentration with calibrated parameters.



Considering the Ammonia Nitrogen, the final calibration does not seem to given relevant changes in the model results, except for the peaks, that are enlarged with respect to the second experiment. The variations occurred to the "flat" parts of the curves are not so evident, as for BOD.

Nevertheless, the calculated efficiencies point out that the second calibration gives a better representation of the observed values with respect to the final one.
This can be confirmed also by looking at the following figures (Fig. 5-54 and Fig. 5-55), where the comparison between the single reference concentrations are presented: the green circles are the measured data, the red asterisks represent the results of the second calibration, while blue asterisks represent those of the final calibration.

Figure 5-54 Calculated BOD compared with Observed BOD.

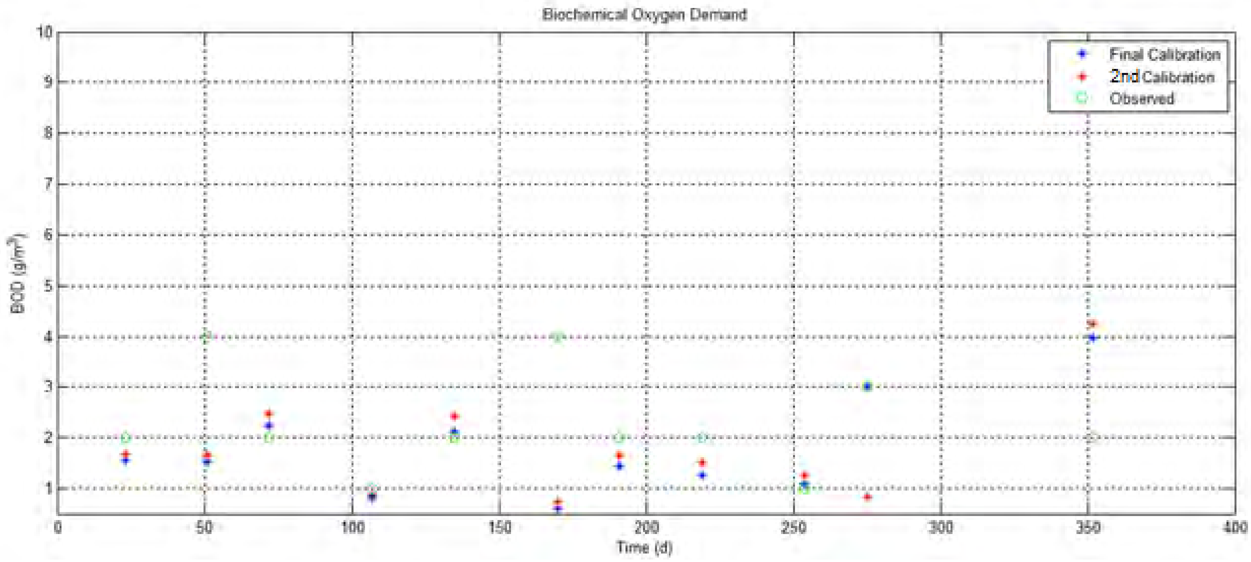
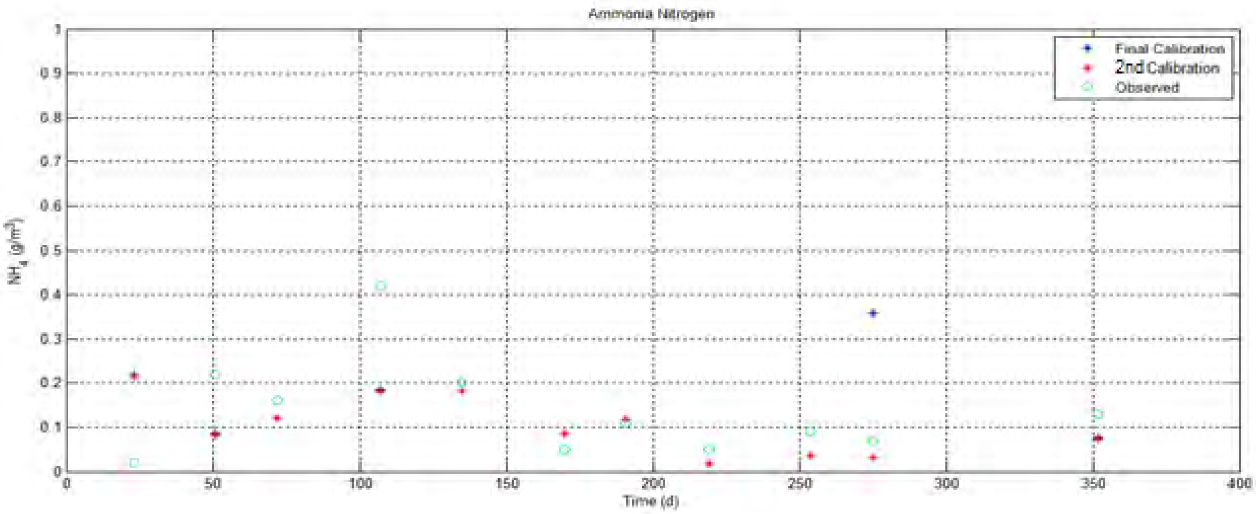


Figure 5-55 Calculated NH4 compared with Observed NH4.



The changes given by the final calibration to the model results are quite evident for the Biochemical Oxygen Demand, while they are small for the Ammonia Nitrogen.

In particular, see the 10th observed value (observation at day 275): it is the only clearly different result in the two calibrations and it is able to influence the final efficiency of the model in a consistent way.

The Nash-Sutcliffe Efficiency, in fact, passes from 0.02 of the second calibration to -0.61 of the fourth one.

In the following table (Tab. 5-27), the calculated concentrations are presented, compared to the observations.

Table 5-27 Observed concentrations and Model results.

Observed BOD (g/m^3)	Calculated BOD (g/m^3)	Observed NH4 (g/m^3)	Calculated NH4 (g/m^3)
2	1.570	0.02	0.220
4	1.535	0.22	0.085
2	2.242	0.16	0.122
1	0.817	0.42	0.184
2	2.125	0.2	0.183
4	0.594	0.05	0.085
2	1.452	0.11	0.119
2	1.262	0.05	0.018
1	1.097	0.09	0.037
3	3.009	0.07	0.358
2	3.960	0.13	0.076

In conclusion, these considerations can be done about the calibration phase:

- Referring to the system characterization, the available input observed data are only 11: this implies that the external forcings, in terms of water quality measures, are probably to limited to properly set the starting point of the system and this fact mostly influences the model results;
- The limited number of observations to be used as comparison to the model results influence the goodness of the Estimation experiment;
- The great number of parameters to be calibrated also influence the results of the experiment, since it is difficult to determine the set of 19 values that optimizes both calculations, of BOD and NH4 given by the model;

- The important influence of the hydraulics of the system on the model results is confirmed also in the calibration processes; instead, biological processes appear to influence in a weaker manner the effect of runoff and, in general, the water quality in the system.

5.5 VALIDATION

Once the calibration is complete, the final step of the modelling procedure is the validation: this phase is useful to have a more detailed picture of the model behavior, since it is tested on a completely independent set of data with respect to those exploited for the Parameters Estimation experiment.

It is decided to run the model using the parameters resulting from the second calibration, since it is the only giving a positive Nash-Sutcliffe efficiency for Ammonia Nitrogen.

The following analyses are performed:

- Steady-state and dynamic simulations on data of year 2006;
- Steady-state and dynamic simulations on data of year 2007;
- Steady-state and dynamic simulations on data of year 2008;
- Steady-state and dynamic simulations on data of year 2010;

The results of the simulations are presented below (from Fig. 6-1 to Fig. 6-11): the calculated concentrations (Biochemical Oxygen Demand or Ammonia Nitrogen) are represented by a blue curve, while the observed data are shown by the orange dots.

Figure 5-56 BOD 2006 dynamic simulation.

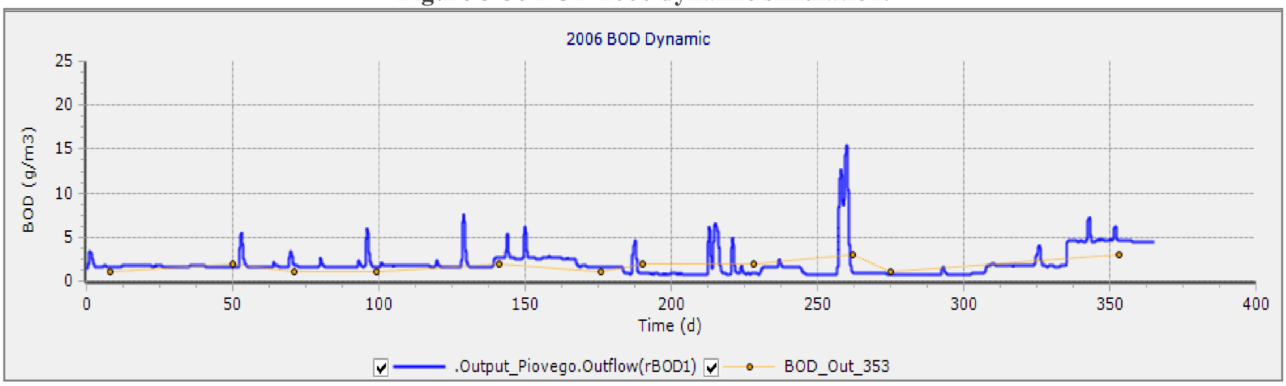
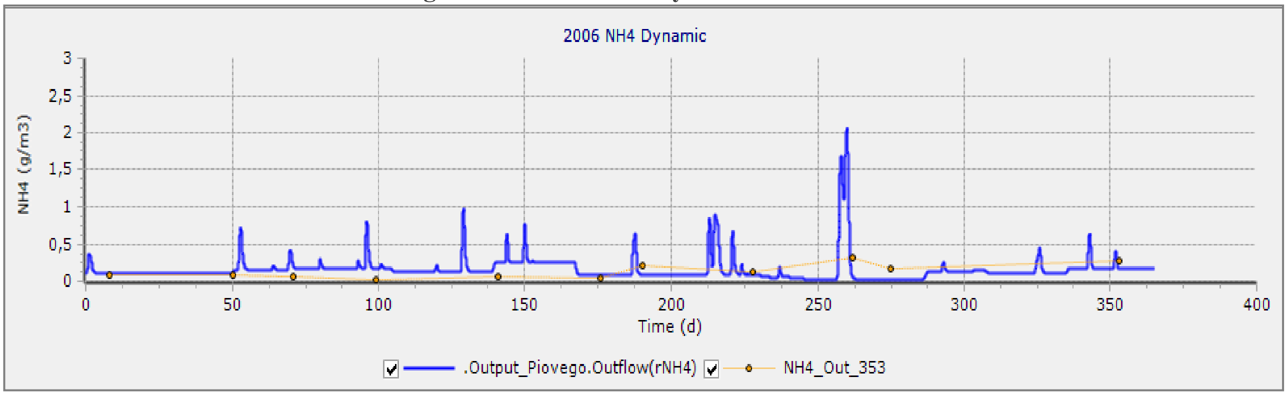


Figure 5-57 NH4 2006 dynamic simulation.



Referring to the previous figures, the difficulties of the model in the adaptation to the observed data is confirmed: Ammonia Nitrogen adaptation should be improved, in particular at the beginning of the simulation, while Biochemical Oxygen Demand gives a better representation of the measured data.

As it is possible to see, the limited number of available observations makes it hard to compare the global behavior of the model to the actual water quality of the system. More frequent sampling is needed to properly characterize the water quality peaks and validate the model predictions; this is important because according to the model runoff-driven peaks could represent an important fraction of BOD and, especially, NH4 flowing through the system over the whole year.

Another dynamic simulation is performed, considering data for year 2007: as presented below, the Biochemical Oxygen Demand adapts properly to the observations in the central part of the simulation, while some difficulties are found at the beginning (between day 50 and 60) and at the end, around day 300.

This may be caused by the limited number of observations used as input to characterize the system: an input data is provided for day 275 and another one for day 315. Within this time interval, the WEST software keeps the input as constant and this may consequently affect the output result.

Figure 5-58 BOD 2007 dynamic simulation.

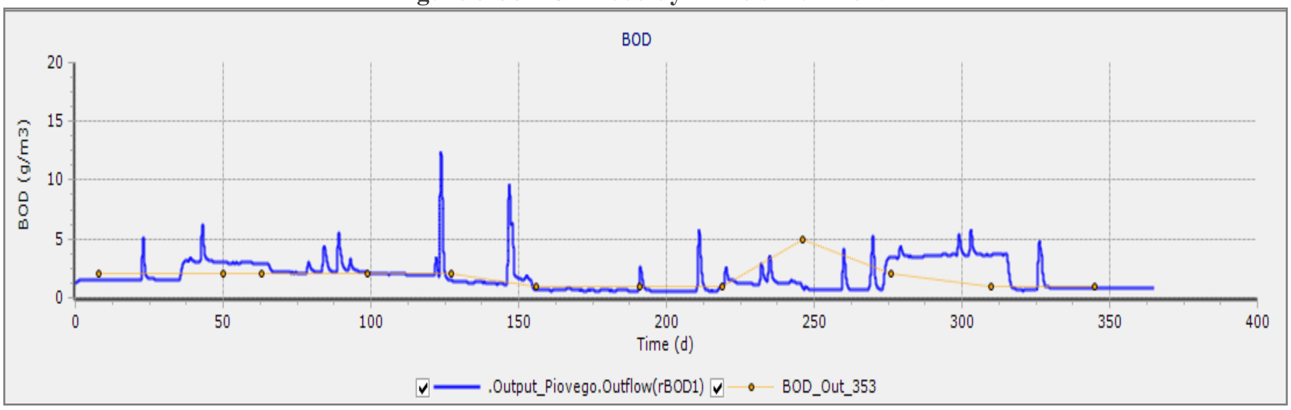
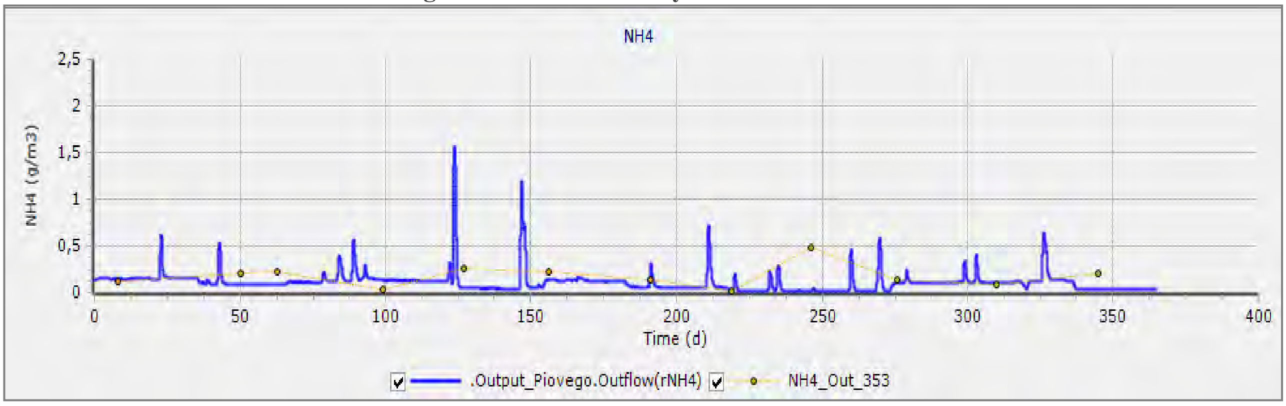


Figure 5-59 NH4 2007 dynamic simulation.



Referring to the previous image, Ammonia Nitrogen shows a good adaptation only to some of the observed data.At the beginning of the simulation, the representation of the model does not fit the measurements, while it improves in the central and ending part of the run.
Passing to the simulation of 2008, the figure below shows that the calculated BOD seems to be close to the observed data, except for a couple of points.

It is also possible to see that the data used to evaluate the adaptation of the model are only 6 for the entire 2008: as consequence, it is difficult to evaluate the goodness of the results with an observation in two months of simulation. Something similar occurs with NH4 (Fig. 6-6).

Figure 5-60 BOD 2008 dynamic simulation.

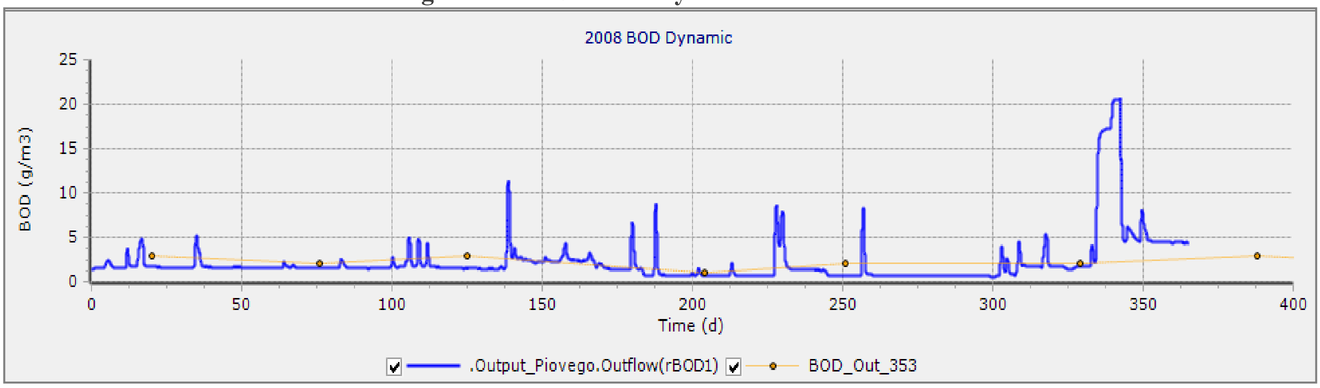
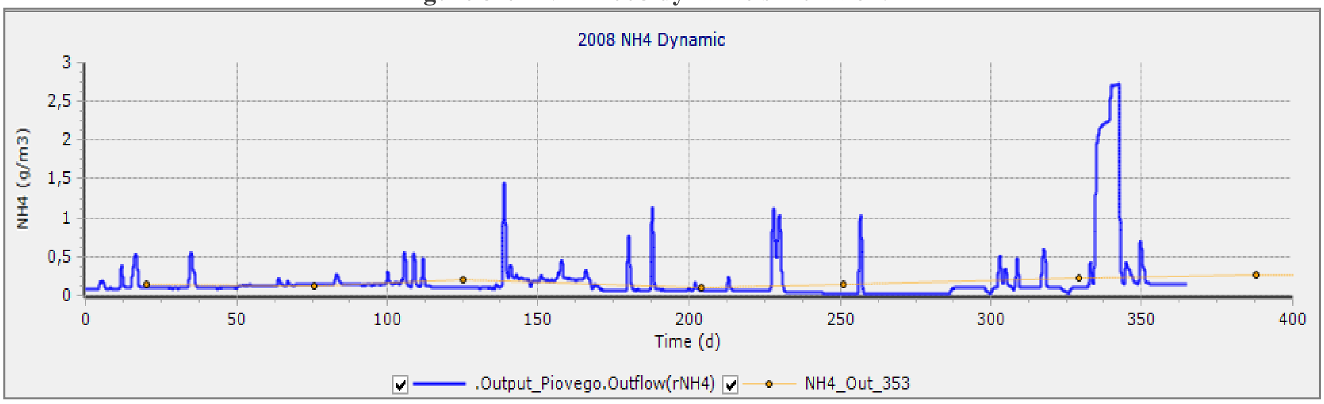


Figure 5-61 NH4 2008 dynamic simulation.



Another set of simulations is taken for 2010: the calculated concentrations of BOD and Ammonia Nitrogen resulting from the dynamic simulation and the rainfall that characterizes the year are presented in the following figures (from Fig. 6-7 to Fig. 6-9).

Figure 5-62 Rainfall, year 2010.

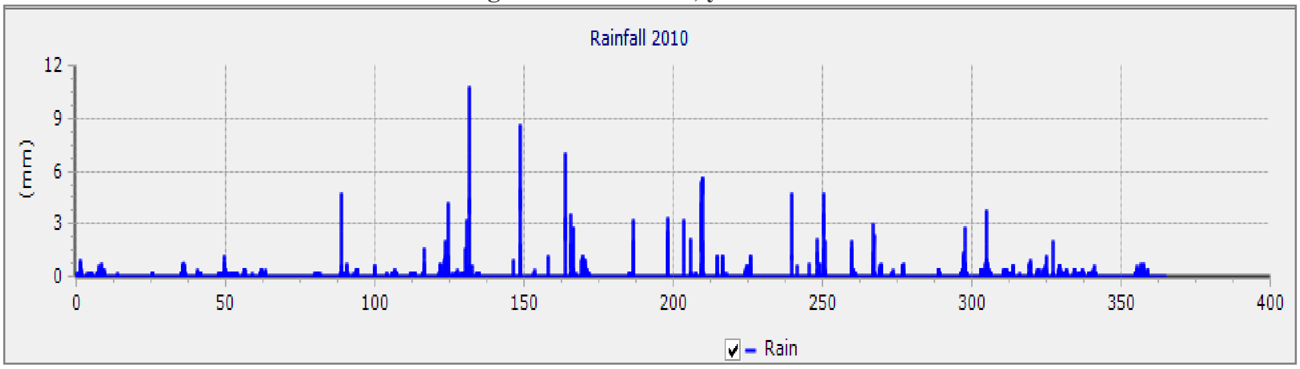


Figure 5-63 BOD 2010 dynamic simulation.

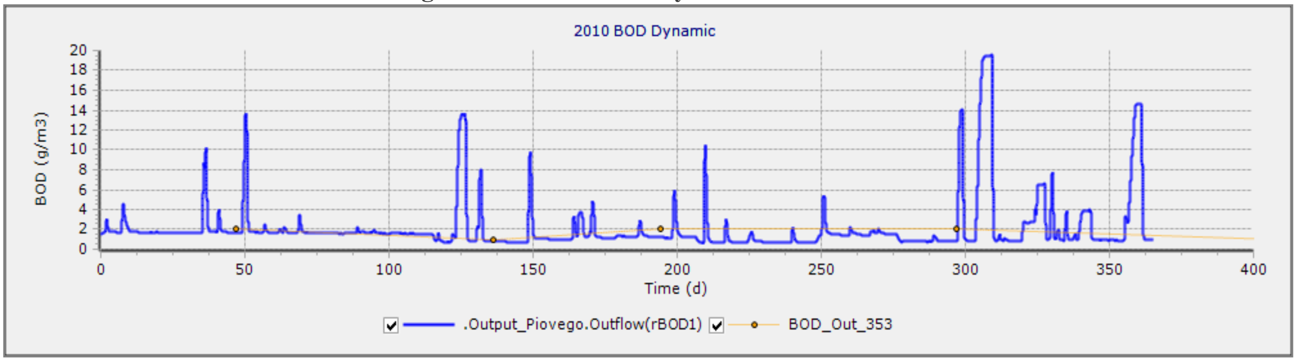
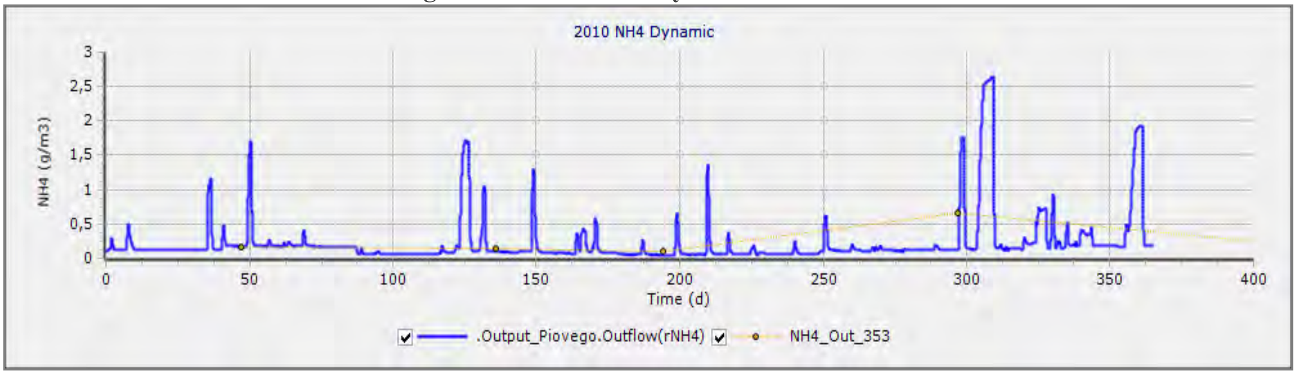


Figure 5-64 NH4 2010 dynamic simulation.



Considering the figures above, the model seems able to fit the observed data.

It is also evident the limit of the previous simulation: only 4 measurements are available, so it is difficult to do a consistent comparison of the results.

This confirms what stated before, that is the need of a greater number of observations to evaluate the capabilities of the model.

With such a limited amount of data, it is not possible to assess the actual influence of the urban runoff on the water quality of the network, even if the model fit the observations.

Consequently, it is decided to run the model neglecting the runoff contribution, so setting the system to consider only the ecological processes taking place in the rivers network.
The results are compared with the available measured data about the water quality of Piovego river, at the end of the system: in this way, it is possible to evaluate the model fit to the observations without the runoff contribute (Fig. 6-10 and Fig. 6-11).

Figure 5-65 BOD 2005 dynamic simulation with no runoff contribution.

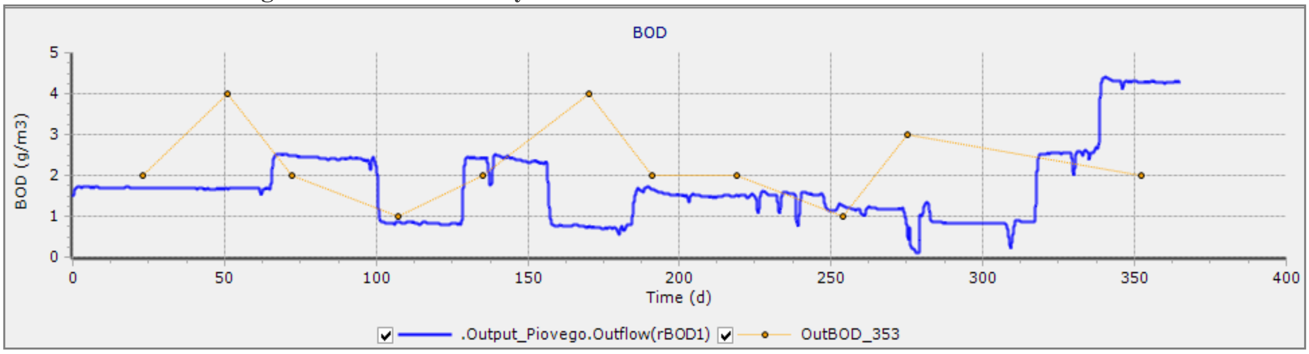
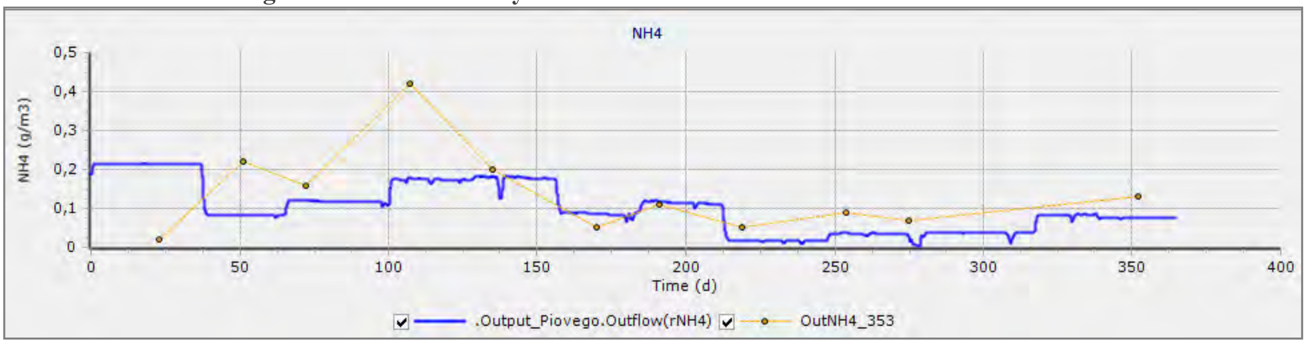


Figure 5-66 NH4 2005 dynamic simulation with no runoff contribution.



The model is not able to fit all the observed data, but, in some cases, there is a good correspondence between measured and calculated concentrations.
This seems to confirm the influence of a limited set of observations to be used as comparison with the model results and, most of all, the importance of a larger number of input data to characterize the starting point of the system (as it is possible to see, the model behavior is a series of stairs due to the fact that the software keeps the input constant until a new one is provided).

6. CONCLUSIONS

At the end of this work, some considerations can be done, according to the results of the different steps of the modelling procedure.

Input water quality characterization. One of the biggest problems found in this work is the limited amount of water quality data used for the characterization of the starting point of the system: referring to the years considered for the simulations, the available measurements taken at Station No. 326 are, at maximum, 11 per year (i.e., about 1 per month).
WEST 2014 uses correctly these data for the system characterization, but these values are kept constant until a new one is provided.
As consequence, it is not possible to represent properly the real dynamics of the rivers network.
This fact seems to have another effect, due to the actual behavior of the model: the calculated outputs do not show relevant variations, with respect to the water characterization of the starting point of the system, when no rainfall occurs. Therefore, if the observed input concentrations are quite different from the measured ones at the output, the model is not able to fit the last ones.
In addition, the runoff generation is recognized to be a fast process in small basins like those of the study. For this reason, such a low-frequency sampling effort for the water quality data is not sufficiently detailed to assess (completely) the relevance of this diffuse source of pollution for the hydraulic network.
Consequently, in order to have a wider picture of the system, it seems worth to improve the sampling campaign.

Output water quality characterization. Another important problem is related to the low number of available data to be used as comparison with the model.
The considered period for the model simulations ranges between 2005 and 2010: from 2005 to 2007, the accessible data are about 11 per year, while, from 2008 to 2010 they are only 4 or 6 per year.
Having an observation per month, it is difficult to state whether or not the model results between two measured data are good and realistic or not.
As a consequence, it is not only difficult to give a good representation of the real behavior of the system, but it is also complicated to obtain consistent results from the calibration step because the reference values are too few.
In this sense, it seems that the software capabilities are limited by the low amount of available data: in order to improve the study of such a delicate possible source of pollution, as runoff, these

considerations confirm the need of having a more frequent sampling campaign of the rivers water quality in terms of number of data.

Calibration results. Some difficulties are found during the model calibration, since the Parameter Estimation virtual experiment is not able to reach a good adaptation of the model to the observed data. The explanations can be two:

- It is difficult to calibrate a yearly simulation on the basis of 11 measurements only. In particular, since the water quality measurements are probably carried out when no rainfall occurs (see Fig. 5-4 and Fig. 5-5), the peaks of the modeled concentrations cannot be properly calibrated since no reference data are available;
- The number of parameters added to the calibration process is quite relevant and, for this reason, the software may need a greater time to reach the desired adaptation.

Model parameters. WEST 2014 needs a consistent amount of parameters to build up the mathematical model.
Most of times, it is not possible to know the exact value of these terms for the specific case study, so it is reasonably assumed referring to the literature.
Nevertheless, this determines the inevitable addition of uncertainty to the model and may influence the final results.
In particular, it seems necessary to better investigate:

- the sewage network, since its physical and operational characteristics represent a crucial part of the system for the model construction, for the runoff collection and for its release into the streams;
- the runoff characterization, in fact the Ammonia Nitrogen content is fixed, in terms of concentration (mg/l) from impervious surfaces, starting from literature studies and analyses. As consequence, also these assumed parameters can actually influence the model results and the adaptation to the observed data.

This is confirmed by the results of the sensitivity analysis: it is evident that the calculated concentrations are quite sensitive to the hydraulics of the system, so the characterization of the catchments and the relative sewage system may have a great impact on the model outputs.
In addition, it is necessary to underline that the pollutants contribution coming from the environment surrounding the waterway is extremely complex and, therefore, not fully comprehensible.

In other words, there are several different processes, accidents, events of any kind that may determine a sudden release of contaminants into the rivers network, so a model cannot represent all the episodes that are actually impacting the water quality.

In conclusion, the results state that the urban stormwater runoff may actually have an important influence on the water quality of the considered rivers network.

Nevertheless, in order to be sure of this impact, it seems necessary to collect a greater number of observations to get a more consistent comparison of the model results.

This is a key indication for future management and sampling strategies.

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