# Chapter 2
# Case Studies

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## 2.1 Introduction

As discussed in Chap. 1, this book presents a wide scope of research that combines multiple disciplines (as hydraulic and water quality modelling, data science, control, supervision, fault diagnosis) applied to the drinking-water systems. All the research presented and the book itself is oriented to the application of these methodologies. Thus, each chapter includes a section of simulation and results on real network models and data. These case studies are available because during the last two decades the authors have maintained a close collaboration with practitioners. This collaboration has helped in the design of the projects, the supervision of the decisions and finally the validation of the results. The experience of working for and with those who carry out the daily management of the system in study inspired this book as well. Hopefully, those readers who are working with water systems will appreciate the applicability of the approaches proposed. On the other hand, the examples help the understanding of the often complex methodologies presented. The research has been presented in international forums through conferences and journals, as shown in the references. This international exposure has guaranteed novelty and improvement beyond the state of the art. Nevertheless, due to the proximity, most of the techniques have been developed using case studies provided by the Catalan water companies and authorities. This regional focus in the applications provides homogeneity to the book. Besides which methodology fits in each kind of network is highlighted.

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## 2.2 Case Studies

The water supply system in Catalonia takes most of the water from two main river basins. Ebro river basin is managed by the Confederación Hidrográfica del Ebro (CHE) [2] as this river flows through other regions of Spain. The authors joined CHE in projects related to the river supervision [9]. This research on open channel systems, as stated before, is beyond the scope of this book. The other river basins are managed by the regional state holder Agència Catalana de l'Aigua (ACA) [1]. These river basins are called internal basins and they provide water to the Barcelona area (3.2 million people). Most of the water (around 80 %) that supplies the Barcelona metropolitan area (217000 $m^3$ in 2015) is surface water coming from rivers Ter and Llobregat. The rest comes from underground water, except for periods of water shortage, when a desalination plant provides up to 5 % of the water consumption. The use of desalinated water shows how critical water supply becomes in a densely populated (717 Habitants per $km^2$) area in Mediterranean coast. The catchment, treatment and transport of water in this area (Barcelona metropolitan) is managed by the company ATLL Concessionària de la Generalitat de Catalonia. Once water has been treated, it is distributed to 36 municipalities in the metropolitan area, through a distribution network comprising 5500 km of pipelines and 150 header tanks, which can store up to 540000 $m^3$ of drinking water. This distribution is carried out by nine different companies (public and private). The public–private consortium Aigües de Barcelona (AB) manages a part of the distribution networks in this region.

In next sections, different management levels in the supply (transport) and distribution networks will be considered. The characteristics that define these levels are the functionalities, the physical elements involved (e.g., tanks, pumps, valves), the size of these elements, the meshing grade of the network and the area they cover.

First of all, there is the regional supply network that covers a wide area and it links the water sources in the catchment with water treatment, usually containing river reaches, free-surface channels, reservoirs, pumping stations, etc. It has a large storage capacity and geographical extension, but it usually has a tree-like structure (low meshing) (see Chaps. 10 and 19 for more details). The transport network (second level) draws water from the regional network. It is managed by the water supply utility and has a structure similar to the regional one but with a smaller dimension. More importantly, this type of network is usually pressurized. It has storage capacity and pumping stations. It is normally organized into pressure levels, according to service needs and topographic elevation of the demand sectors. The output of this network is monitored (both pressure and flow) and corresponds to the input of the distribution network. The lowest level, the distribution network, is a meshed pressurized pipe network, which delivers water to individual consumers within the pressure levels. The instantaneous individual demands are the most uncertain parameter of the network, because in general they are not measured online.

## 2.3 Water Transport Network

The Barcelona water transport network (WTN) supplies water to approximately 3 million consumers, distributed in 23 municipalities in a 424-km$^2$ area. Water can be taken from both surface and underground sources. The most important ones in terms of capacity and use are Ter, which is a surface source, and Llobregat, where water can be taken from one surface source and one underground source. Water is supplied from these sources to 218 demand sectors through around 4645 km of pipes. The complete transport network has 63 storage tanks, 3 surface sources and 7 underground sources, 79 pumps, 50 valves, 18 nodes and 88 demands. The network is controlled through a SCADA system (Fig. 2.1). As it will be discussed in Chap. 12, for the predictive control scheme, a prediction horizon of 24 h is used. This record is updated at each time interval with a sampling time of 1 hour.

In Fig. 2.2, the whole network representation using the conceptual model used by the model predictive controller that corresponds to a simplification of the real system:

- Each demand sector corresponds to a subnetwork serving a given pressure level.
- Each actuator can integrate several pumps or valves working in parallel.

A water network system will generally contain a number of flow or pressure control elements, located at the supplies, at the water treatment plant inlets or within the network, and controlled through the telecontrol system.

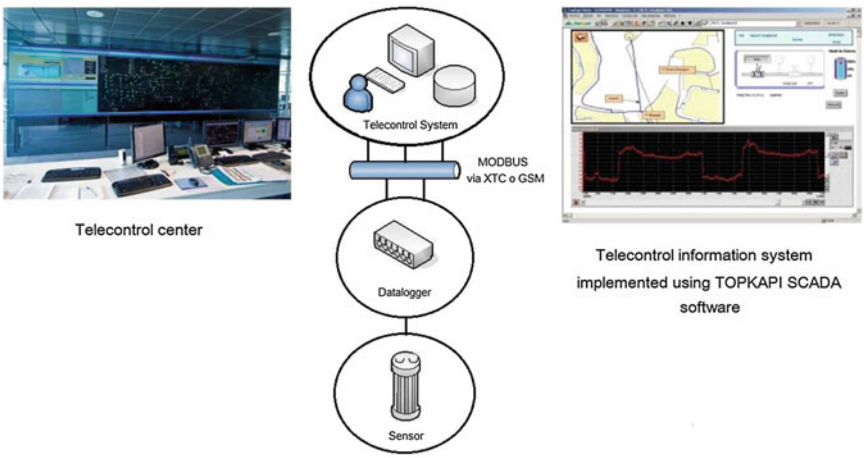


**Fig. 2.1** Telecontrol of Barcelona water distribution system

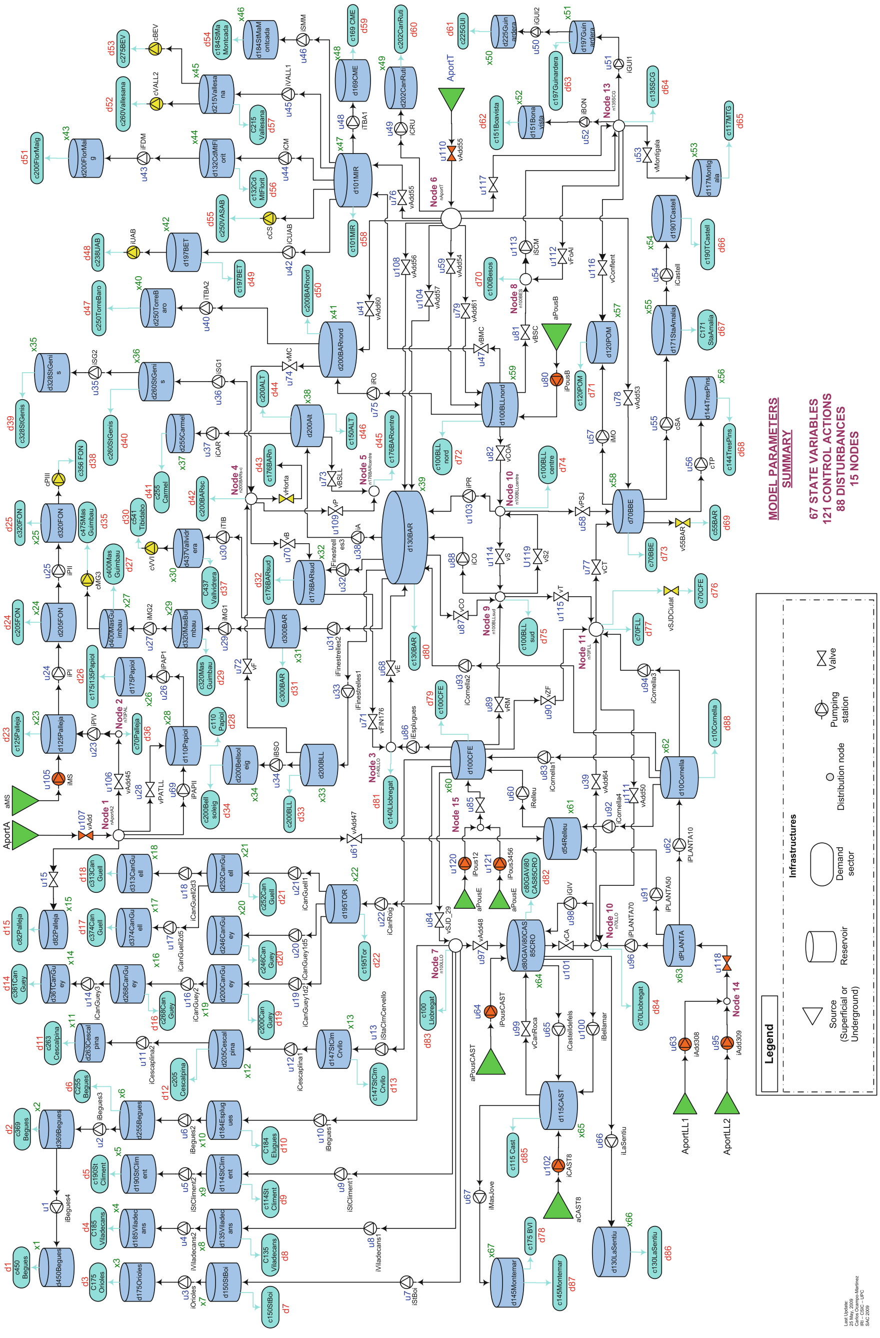


**Fig. 2.2** Barcelona water transport network description

A section of the Barcelona water transport network has been selected in Chap. 13 to apply optimal control including pressure constraints (see Fig. 2.3). Specifically, 12 pressure zones that belong to the municipality of Barcelona (see Fig. 2.4), representing 18 % of the total network length and 23 % of the total annual water consumption. Within these pressure zones, there are 5 water tanks, 6 pumping stations and 7 regulation valves, with an annual energy consumption of 4.4 GWh. Energy consumption is highly dependent on the specific exploitation strategy decided by the utility (see Fig. 2.5).

This section of the network is representative of the complete network because it contains all the different kinds of state and control elements. The following figure shows a diagram of the study network, including the control elements, tanks, demands and connecting pipes. This network has five tanks (blue colour) and other five tanks that have the function of water sources (green colour) to substitute the rest of the network. It also has seven pumping stations, one flow valve, ten pressure valves and forty-seven demands.

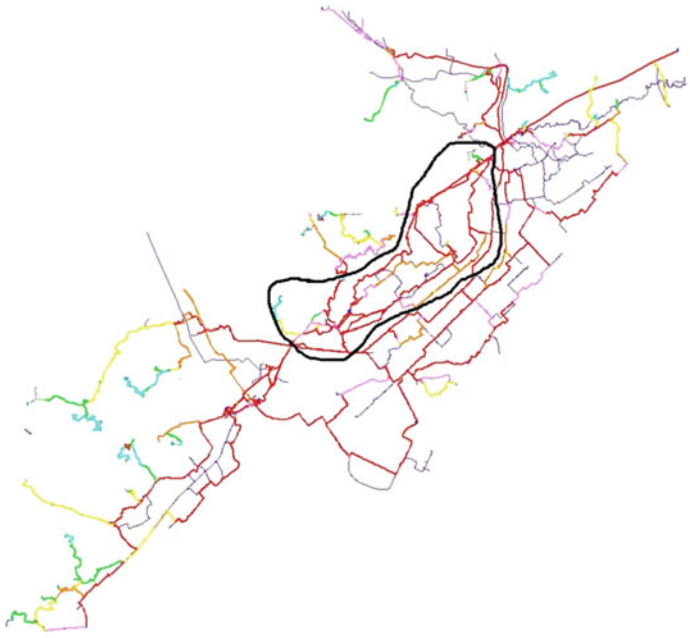

**Fig. 2.3** Simulation model of a portion of Barcelona WTN

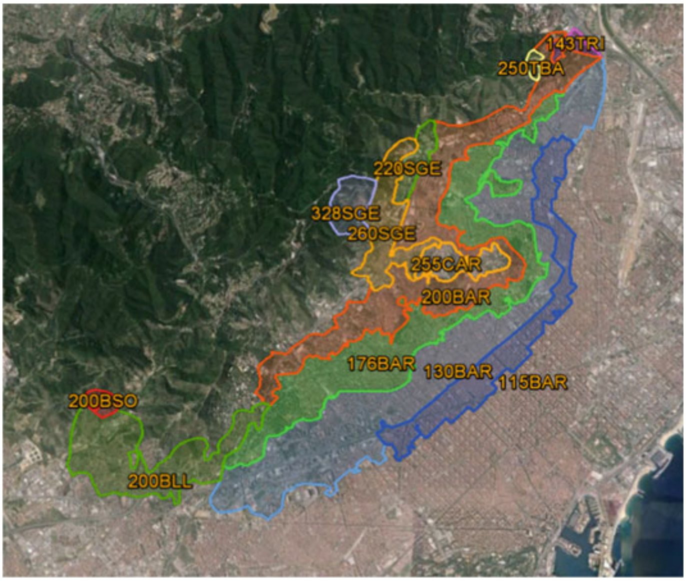


**Fig. 2.4** Map of the portion of the Barcelona WTN

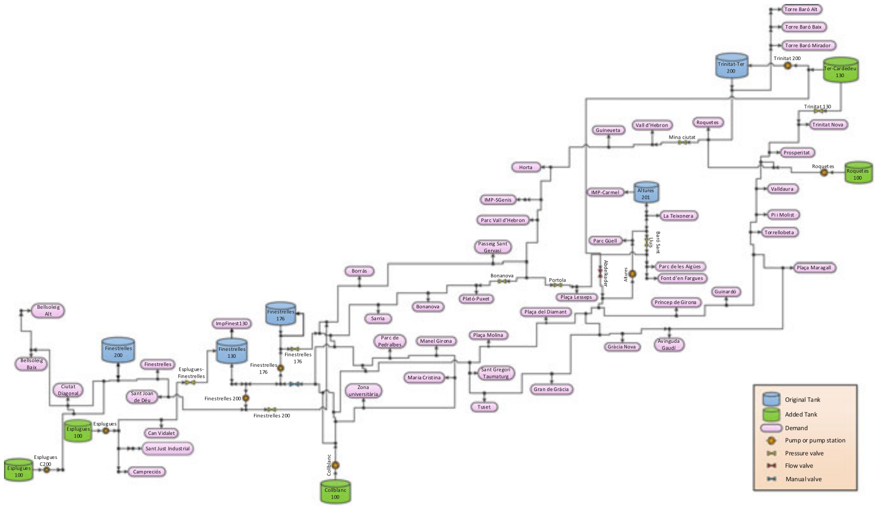


**Fig. 2.5** Conceptual model of portion of Barcelona WTN

## 2.4 Water Distribution Network

The water distribution network of Barcelona (WDN) is organized in different pressure levels that supply water to the district metered areas (DMA). The elements of pressure levels and DMA are slightly different, and thus, it is worth to analyse them separately and highlight the chapters related to each of these systems. The organization of water distribution networks in DMA started in UK in 1980s and demonstrated to be a keystone for the performance improvement of networks. Both control and supervision benefit from the information provided by these units. Current research focus especially on the performance within these subsystems. In Barcelona, each sector (DMA) has the following configuration (see Fig. 2.6):

- One or two control points. In each of them, there is a continuous flow and pressure measurement (1 value/10 min) and, optionally, a pressure reducing valve.
- Optionally, one water quality control point, with the measurement of free residual chlorine, conductivity, pH and temperature (1 value/hour).
- Optionally, some internal pressure points (1 value/10 min).
- Some boundary closed valves.
- A data logger with a modem to get the signals from the field equipment and daily transmit data to the control centre.

Regarding customers consumption, there is a water meter for each customer. Some of them have automatic meter reading (AMR) and there is one sector with

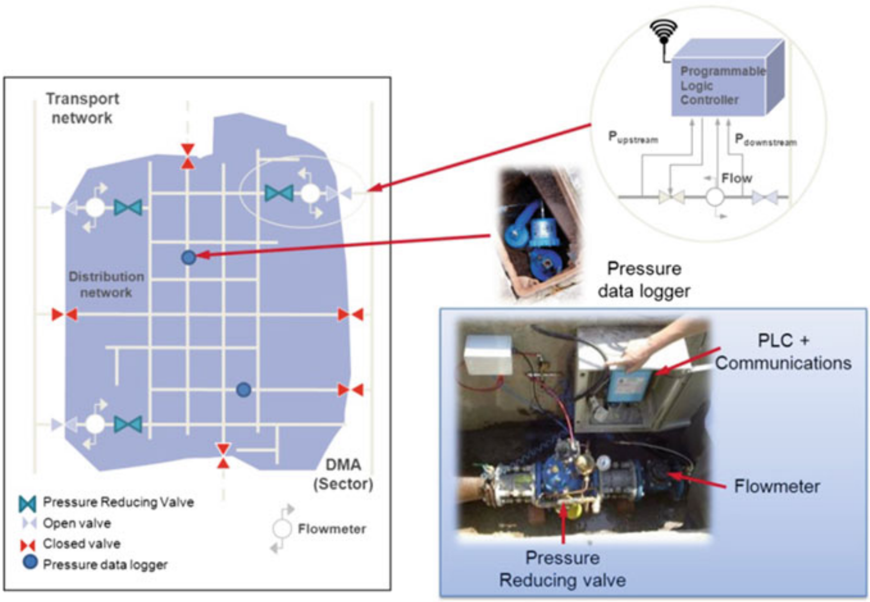


**Fig. 2.6** Standard configuration for a DMA in Barcelona

a 100 % of AMR that can provide detailed information about all the customer's consumption (hourly value). The control applied to the DMA is rather simple and its aim is to assure the supply with a guaranteed pressure. Nevertheless, the modelling of both hydraulic and chemical, presented in Chaps. 3–6, provides a wide research field in supervision. The efficiency of the DMA is assured in the simplest approach by searching leaks on field using acoustic devices. This leak monitoring is slow and costly and can be supported by more sophisticated methods. Chapter 8 presents how leakage management can be improved in the distribution network. Also the chlorine supervision based in models DMA includes some of the elements modelled and calibrated in Chaps. 3–6. These models lead to better performance through the supervision of the system. Two main issues in the water service that motivate this supervision:

- The efficiency in terms of balance between water delivered and produced. Leakage monitoring may be done on a routine basis or when major losses are suspected between night and day water demands [5]. Methods for locating leaks range from ground-penetrating radar to acoustic listening devices [4]. Some of these techniques require isolating and shutting down part of the system. Techniques based on locating leaks from pressure monitoring devices allow a more effective and less costly search in situ [8].

**Fig. 2.7** Level 55 of the transport network

- The water quality in terms of assuring a good concentration of chlorine, the used chemical for disinfection. A good modelling approach of the chlorine decay allows to assure a correct concentration in all the service points in the DMA while reducing the high concentrations at the input and the use of chemicals. These models are used to detect abnormal situations related to this concentration [6].

Zone 55 is a part of the transport network presented in Sect. 2.4 and shown in Fig. 2.7. Its two inflows (Cantabria and Drassanes) and four outflows (Llull, Alaba, Joan de Borbó and Passeig Colon) have chlorine monitors. These chlorine measurements and the little meshing of the network make it quite suitable for the calibration of the chlorine decay model. This model is used within one of the DMAs that obtain


**Fig. 2.8** Nova Icària DMA. In *red*, the two inflows, (flow and pressure sensors) and in *green*, the inner pressure sensors

the water from this zone, Nova Icària. This DMA has two inlets (Alaba and Llull), 1996 nodes and 3442 pipes. In Fig. 2.8, the water network of Nova Icària DMA can be seen from the EPANET file which contains the hydraulic model of this network. In this figure, the two DMA inlets have been highlighted using red star symbols. Nova Icària DMA is instrumented by flow and pressure sensors at every inlet. The sample time associated with all these sensors is set to 10 min. The results of the chlorine model calibration and its application for supervision are presented in Chap. 8. Six pressure sensors were installed for the leak detection and localization, they are highlighted in Fig. 2.8 using green star symbols. The methodology applied and the results in a pilot test with a real leak are described in Chap. 7.

A smaller DMA is used for illustrating the modelling, sample design and calibration procedures in Chaps. 4 and 5. Canyars DMA is situated in Castelldefels (Catalonia). The network model is composed of 721 pipes and 698 junctions. Water is supplied from the transport network through a pressure reduction valve, depicted in Fig. 2.9 with a blue triangle. Pressure and flow are monitored at the water inlet with a sample time of 10 min. The resolution is 0.3 l/s for the flow sensor, and 0.1 mwc for the pressure sensor. The minimum night flow is of about 3 l/s, and the peak hour flow is 27 l/s. Pressure control is applied to this network, fixing the pressure level at 38 metres during night-time and at 47 metres during daytime. The average daily maximum head loss in the network is 13.4 m. Three pressure sensors were installed, signalled in Fig. 2.9 with green stars.

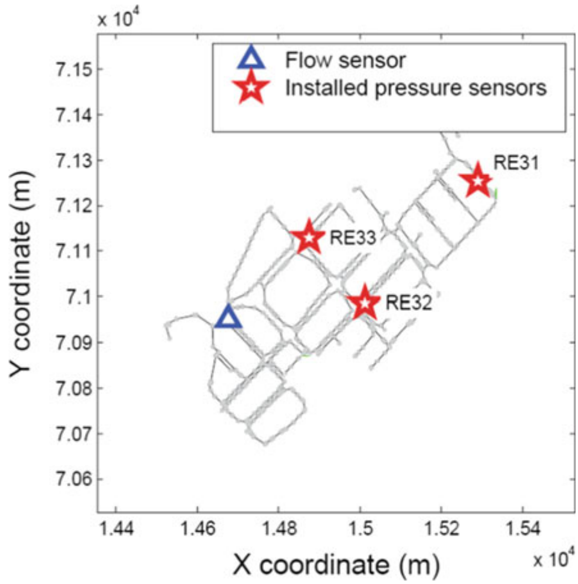


**Fig. 2.9** Canyars DMA. In *blue triangle*, the inflow (flow sensor and pressure control), and in *green stars*, the inner pressure sensors

## 2.5 Software

The simulator used for the state estimation in the network throughout this book is EPANET.[1] EPANET is a widely used software in the academia to model water distribution piping systems. It is a public domain software that may be freely copied and distributed. It was developed by the US Environmental Protection Agency (EPA). EPANET performs extended period simulation of the water movement and quality behaviour within the pressurized pipe network as the transport and distribution networks. It tracks the flow of water in each pipe, the pressure at each node and the height of the water in each tank. The EPANET-MSX is the multi-species extension that allows prediction of chemical concentration throughout the network during a simulation period, water age, source and tracing. The use of the EPANET Programmer's Toolkit is a dynamic link library (DLL) of functions that allow developers to customize EPANET to their own needs. The functions can be incorporated into Windows applications written in C/C++, Delphi, Pascal, Visual Basic or any other language that can call functions within a Windows DLL. In the $CS^2$AC webpage ([3]), the adaptation for MATLAB (both 32 and 64-bit) is available. The combination of the power of simulation of EPANET together with the analytics of MATLAB allowed the application of the sophisticated algorithms described in following chapters.

Additionally, a simulator of the Barcelona water transport network has been built using MATLAB/Simulink and validated using real data coming from real scenarios (see Fig. 2.10). This model has been accepted by the company as a good representation of the actual water network behaviour and is used for its operational control [7] in Chap. 12, e.g., optimize water production and transport costs, guarantee a minimum volume in the tanks for eventual emergencies and smooth operations of the actuators to extend the life of the equipment. The *network* block is composed by different elements (blocks), such as tanks, nodes, pumps, valves and demands. Each demand

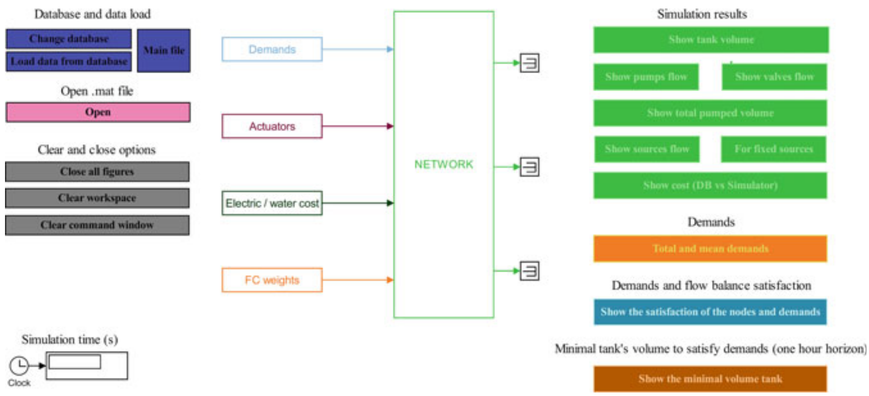


**Fig. 2.10** Main Simulink screen of the Barcelona network simulator

[1]https://www.epa.gov/water-research/epanet.

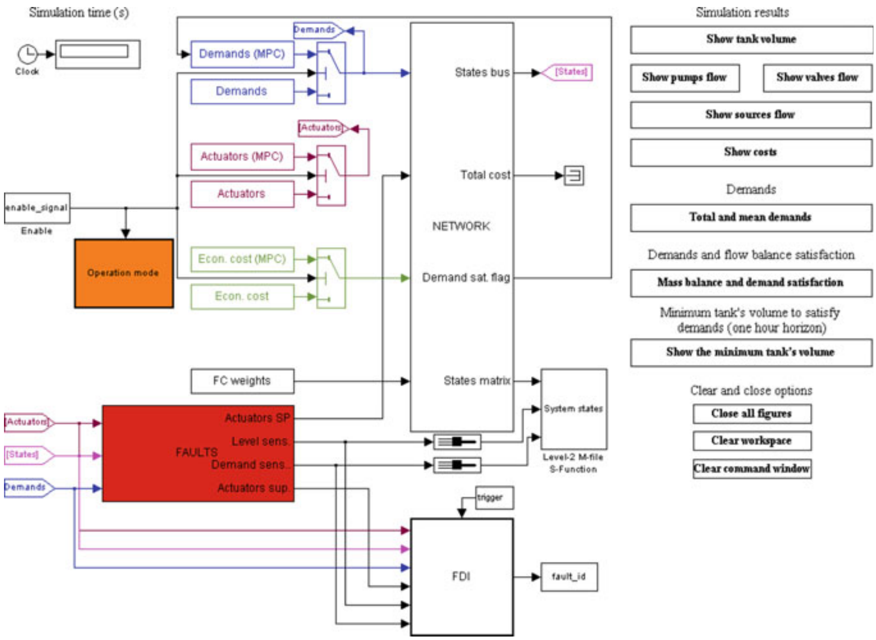


**Fig. 2.11** MATLAB/Simulink Barcelona supply network simulator graphical user interface with a fault module

of this supply network is actually a district metered area of hundreds to thousands of users. Also, each actuator may integrate several pumps or valves working in parallel.

This simulator is equipped with a fault module (see Fig. 2.11) that allows to provide synthetic scenarios of the network under study and to design and test new control schemes and fault detection and identification (FDI) approaches as the one presented in Chap. 11 as well as the fault-tolerant control strategies presented in Chap. 14.

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