# WDNetXL-WDNetGIS

## Content

## 1. *IDEA-RT and WDNetXL-WDNetGIS*

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***IDEA-RT*** provides innovative technical-scientific tools to support the analysis and management of complex systems in civil and environmental engineering, in order to promote awareness of decisions in terms of effectiveness, rationality (replicability), integration, flexibility and efficiency. IDEA-RT's technology transfer paradigm is based on the development of advanced tools in a high-level programming environment and their implementation as simple functions in software packages familiar to technicians, such as Microsoft Office® Excel, QGIS and ArcGIS®, ArcGIS -PRO®. This allows to quickly develop, update and test tools for specific applications in collaboration with users. This achieves a dynamic and real-time transfer of technical-scientific research outside the academia, but also within university courses, where future technicians and decision makers are trained as economic operators in civil and environmental engineering. The transfer of technical-scientific research takes place through the following main activities:

- technical-scientific innovations for analysis and decision support in civil and environmental engineering through innovative tools, integrated on users' systems,
- continuous training on innovative tools through courses aimed at researchers and technicians in the fields of water cycle management as well as engineering companies,
- development and customization of innovative tools.

For this reason, IDEA-RT is a unique provider of innovation and technology transfer service worldwide with high technical-scientific skills in the field of hydraulic system management.

**WDNetXL** is a software package, developed as addin for Microsoft Office® Excel, which allows great flexibility for implementing new features and making available to users (technicians, students, researchers) documentation and presentations, online help, etc. according to various levels of details and purposes.

**WDNetGIS** implements all functions of WDNetXL analysis module as a plug-in in the GIS environment (QGIS, ArcGIS®, ArcGIS-PRO®), using database in ESRI® Shapefile and Geodatabase data storage formats. Next releases will manage the all data storage formats commonly implemented in GIS water company infrastructures, such as SQLite and PostGIS.

The user-friendly environment of the WDNetXL-WDNetGIS interface system, within well-known and commonly data management environments, allows working without prior specific training on the software. This allows users to focus immediately on innovations of technical and hydraulic issues. Figure 1 summarizes the capacity of WDNetXL-WDNetGIS system to connect to different data sources and the interoperability with the GIS environment and Microsoft Office® software, in order to develop customized solutions in C++ or Python.

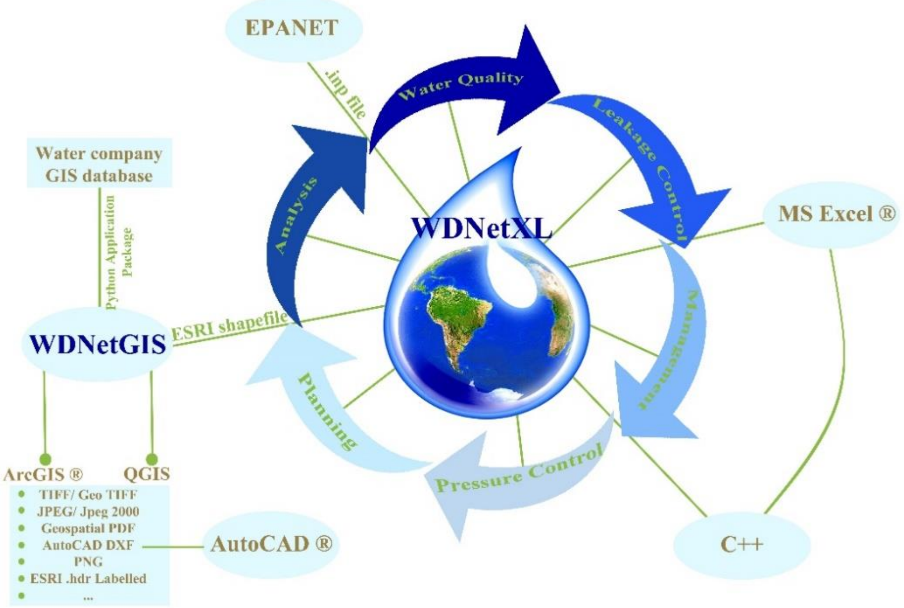


Figure 1. WDNetXL-WDNetGIS interface system interoperability.

WDNetXL-WDNetGIS is also equipped with its own 3D map tool viewer, designed for supporting hydraulic analysis through the visualization of the connectivity of the network elements and for accounting for real plano-altimetric layout of the network, supporting operating actions. Figure 2 shows the WDNetXL-WDNetGIS viewer window (above) and a 3D view chosen by dynamically rotating the image (below) for the water distribution network of Taranto, Italy. The tool can be used in parallel to internal GIS returns and processing in WDNetXL.

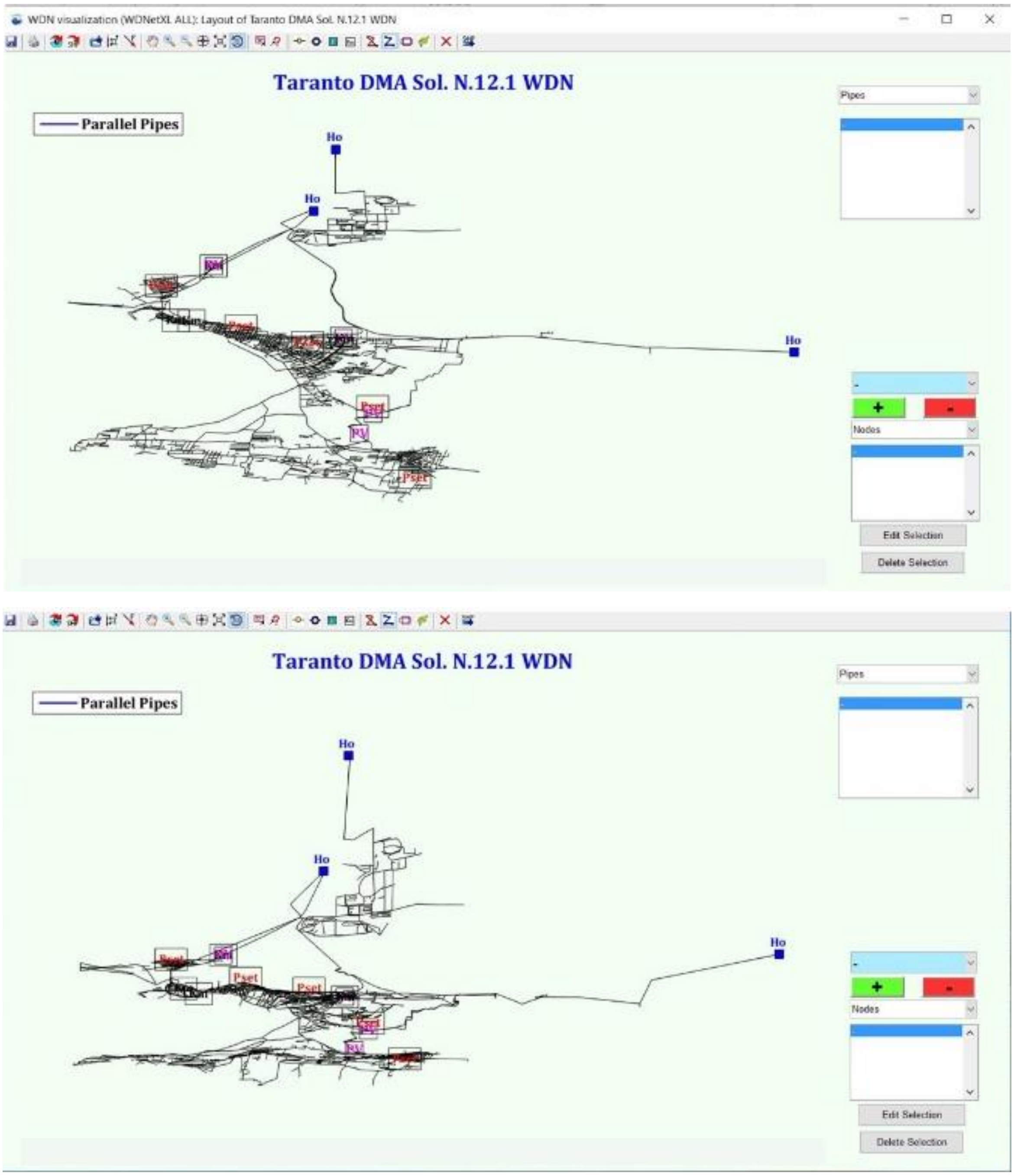


Figure 2. WDNetXL-WDNetGIS map viewer layouts (WDN Taranto).

## 1.1 *WDNetXL-WDNetGIS vs. EPANET*

The innovations implemented in WDNetXL-WDNetGIS framework for hydraulic and topological analysis supporting WDN management decisions are made evident form the comparison with functionalities of EPANET, which are basically the same of the majority of commercial software packages.

# WDNetXL vs. EPANET

| **Hydraulic and topological functionality** | **WDNetXL** | **EPANET** |
|---|---|---|
| 3D viewer | YES | NO |
| Representation of hydraulic devices and valves as attributes of each *link* object | YES | NO |
| *Demand-Driven* Analysis | YES | YES |
| *Pressure-Driven* Analysis | YES | NO |
| Analysis of variable level tanks within the GGA (G-GGA) | YES | NO (1) |
| Analysis of variable level tanks supplied from nodes internal to the network (higher than the maximum level of the tank) or external pipelines | YES | NO |
| Hydraulic analysis with real topological variations | YES | NO (2) |
| *Pressure-driven* analysis to evaluate the water supply to individual users | YES | NO |
| *Pressure-driven* analysis of hydrants | YES | YES (3) |
| *Pressure-driven* analysis of volumetric losses (background leakages and unreported bursts) at individual pipe level | YES | NO (4) |
| Pressure driven analysis of local private tanks | YES | NO |
| *Pressure-driven* analysis for evaluation of the supply to multi-story buildings | YES | NO |
| *Pressure-driven* analysis of free orifices connections | YES | NO |
| Simple rules | YES | YES |
| Complex rules | YES | YES |
| Unlimited demand time pattern | YES | YES |
| Patterns of pressure setting for valves and variable speed drive pumps | YES (5) | YES |
| Pattern of speed factors for variable speed drive pumps | YES | YES |
| Flow setting pattern for flow control valves | YES | YES |
| Topological analysis of districts (DMA) | YES | NO |
| Topological analysis of the isolation valve system (IVS) | YES | NO |
| *Pressure-driven* analysis of failures accounting for IVS | YES | NO |
| *Pressure-driven* analysis of *burst* in the pipelines | YES | NO |
| "Non-heuristic" modelling of pressure reduction (or sustain) valves locally and remotely (electrical) controlled (control with nodes inside the network) | YES | NO (6) |
| "Non-heuristic" modelling of variable speed pumps with local control or with nodes inside the network | YES | NO (6) |
| Assessments of energy consumption and carbon footprint of all types of pumps | YES | YES (7) |
| 3D viewer | YES | NO |

(1) EPANET, like all commercial software packages, does not calculate the level of the tanks within the GGA solver as a separate variable. The level of the tanks is corrected between one simulation and the following with a mass balance which, due to the lack of accuracy, causes errors that turn into instability when more variable level tanks are hydraulically close each other. The Generalized-GGA (G-GGA) solves the problem and allows hydraulic simulation even in the presence of variable level tanks only (i.e. absence of reservoirs).

(2) EPANET, like all commercial software packages, does not perform topological analysis when a pipe is closed or closes during the simulation (hydraulic directional and/or pressure control devices), but assigns a minimum flow rate ($10^{-6}$ l/s) to model the

| |
|---|
| closure. This causes problems of accuracy and robustness of the solution, particularly for complex and/or large systems, not allowing different types of optimization (for example the hydraulic optimization of DMA). WDNetXL detects the topology before (e.g. in the case of an isolation valve system that disconnect a portion of the network) and during hydraulic simulations (e.g., for closing unidirectional or controlled devices when flow reversal occurs). |
| (3) EPANET, like almost all commercial software packages, applies a modelling expedient to calculate *emitters* that are born as free orifices to simulate hydrants. The modelling expedient is not suitable for the calculation of a large number of hydrants, while WDNetXL calculates the hydrants as free orifices (with exponent also different from ½ for the case of bursts) within the pressure driven G-GGA, i.e. the Newton-Raphson method uses the derivative schemes with advantages in accuracy (especially with reference to the global mass balances of the system), robustness and speed of the analysis. |
| (4) EPANET, like all commercial software packages, does not calculate the volumetric losses as a function of pressure of single pipes, but uses the emitters in the nodes to lump the outflow from joining pipes. Besides the problems of accuracy and robustness of the simulation (see point 3), the method alters the realistic representation of volumetric losses and relative results. Furthermore, it does not allow the preservation of information at the pipe level, which is useful, for example, to plan replacement works. |
| (5) WDNetXL allows, in addition, the possibility of setting the control pressure setting of the variable speed pumps. |
| (6) EPANET, like almost all commercial software packages, implements heuristic rules for calculating hydraulic resistance (valves regulated by pressure or flow). WDNetXL calculates the hydraulic resistances of controlled devices as known variables within the G-GGA, thus allowing the control nodes of devices to be positioned also within the network. |
| (7) EPANET, like almost all commercial software packages, does not allow variable efficiency with the duty point of the variable speed pumps. WDNetXL calculates both the energy consumption and the power of the individual pumps, for each simulation of the operating cycle, considering the variable efficiency and also returning the value of the CO2 produced. |

## 2. *Advanced hydraulic modelling for supporting water distribution network management*

At the beginning of the 20th century, Water Distribution Networks (WDNs) were designed to provide a vital service for human health and supporting economic development, industrial activities and fire protection. Network hydraulic modeling arose the necessity of developing hydraulic verification criteria of the network design in order to satisfy supply statistical water requests of the several types of users (civil, commercial, industrial) and fire protection needs; it was especially suited for Anglo-Saxon contexts. As such, the WDN modelling has been developed to calculate pressure at the nodes of the network, for fixed pipes roughness and users' *statistical demands*. The validation of design solutions was the assessment of pressures at network nodes compared to *minimum pressure for a correct service*; in relation to fire protection, the validation was the calculation of the *minimum residual flow rates and pressure for a correct hydraulic performance of hydrants*.

In 1988 Todini developed the Global Gradient Algorithm (GGA), which a few years later became EPANET's “hydraulic engine,” developed by Rossman of the U.S. agency. E.P.A (Environmental Protection Agency). The modern software packages generally adopt the same algorithm and, in any case, *all classic hydraulic simulators are created for hydraulic validation and not for management purposes, i.e. they allow the calculation of the pressure at the nodes "constraining to the fixed water demands at nodes" and therefore the technique is called* ***demand-driven***.

The progressive urban development has produced increasingly large, complex and aged aqueduct networks for which management needs have arisen with respect to water quality, water losses, reliability, energy optimization, rehabilitation, etc. In 2003 Todini faced the issue of hydraulic simulation that allows to calculate the “actual” *demand* supplied to users when pressure is *lower than minimum pressure for a correct service*. As stated by Giustolisi and Walski (2012), Wagner's model (1988), reported in Eq. (1) and shown in Figure 3, defines an *actual demand* $d(i,t)$ in the $i$-th node at $t$ time step (e.g. hour) which, only for pressure larger than $P^{ser}(i)$, *minimum pressure for a correct service*, is equals to *statistical customer demand* component; while it equals zero for pressure lower than orifices' height $P^{min}(i)$ and it is determined by Torricelli's law for *pressure-deficient condition*. Therefore, Wagner's model is closer to the real hydraulic behavior of the network, i.e. customers modulate, in *statistical sense*, the flow rate as long as pressure is high enough, while they get the maximum flow rate (the maximum volume in a unit of time) allowed with the available pressure consequent to the actual hydraulic state of the network according to Torricelli's law for fully open devices.

$$d(i,t)=\begin{cases} d^{req}(i,t) & P(i,t)\geq P^{ser}(i) \\ \dfrac{d^{req}(i,t)}{\sqrt{P^{ser}(i)-P^{min}(i)}}\sqrt{P(i,t)-P^{min}(i)} & P^{min}(i)<P(i,t)<P^{ser}(i) \\ 0 & P(i,t)\leq P^{min}(i) \end{cases} \tag{1}$$

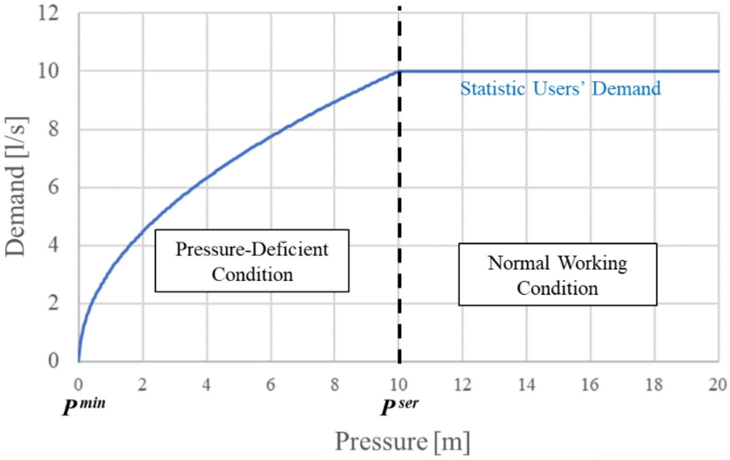


Figure 3. Pressure-demand plot for customers.

## 2.1 *Real water losses*

Pipe deterioration defines, for unit pressure, the real water losses value which, in scientific literature, is divided into *background* leakages, *reported* bursts and *unreported* bursts. Assuming that *reported* ones are repaired or under observation, *background* leakages and *unreported* bursts have the greatest effects on network water balance depending on pressure.

Therefore, ***volumetric water losses*** represent an asset management indicator as they reveal, on one hand, the *pipes deterioration and aging* and, on the other hand, the *effectiveness of pressure and leakage control strategies* adopted so far in the network.

*Background leakages* refer to small-scale water leaks spread in the hydraulic system while, according to the technical-scientific classification, *burst* leakages have higher flow rates and therefore can be localized. *Bursts* are generally the *natural evolution of background leakages* driven by external factors, such as pipe material, thermal stress, etc., and entail major water outflows. *Background* leakages have a global influence on the WDN behavior but generally do not affect the quality of the service in terms of minimum pressure, while *burst* leakages can have either local or global influence on the service, depending on their position along the network and their outflow compared to the global water capacity of the network. Therefore, the asset management operations must be planned considering the reduction of *volumetric water losses* as a significant control management indicator, which can prevent generation and propagation of burst leakages.

In 2008 Giustolisi developed the model of leakage demand component (the volumetric losses as a function of pressure) and the solving algorithm to evaluate the leakage rate at each pipe within the hydraulic model. This model, based on Germanopoulos' one (1985), computes the water losses at ending nodes of each pipe based on deterioration factor and the average pressure along the pipe. In the hydraulic model of the network, the losses calculated along the pipes are then concentrated in the nodes in which they converge, in order to provide the demand component of the ***volumetric losses*** in each node of the water supply network, see Eq. (2). The demand components are added to the *actual demand* of users, as shown in Figure 4.

$$d^{leak}\left(i,P(k,t)\right)=\begin{cases}\dfrac{\beta(k)L(k)P(k,t)^{\alpha}}{2} & P(k,t)\geq 0\\ 0 & P(k,t)<0\end{cases}\qquad(2)$$

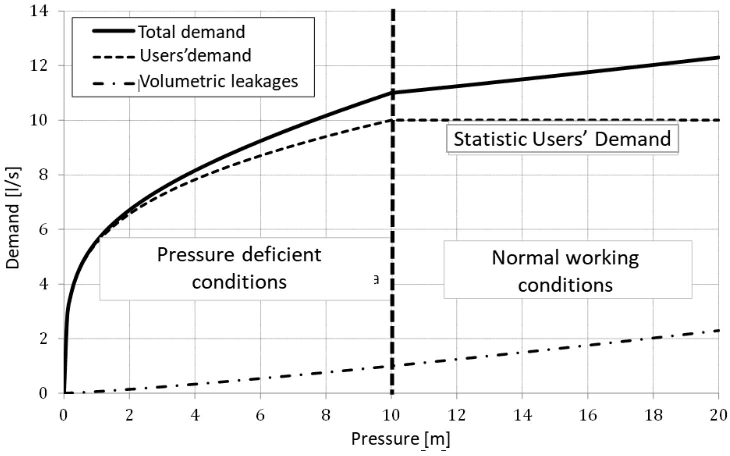


Figure 4. Pressure users demand and water losses at nodes.

The Germanopoulos model parameter ($\alpha$) is a function of the material and can be assumed unitary, as a first approximation. Figure 5 represents, in a simplified way what has been adopted in advanced modeling. The ***volumetric losses*** from pipes are assumed as uniformly distributed and include those that are generated along private connections, up to the water meters. The leaks in the individual pipes are then related to the average pressure as in Eq. (2). During the hydraulic simulations, the flow rates of the ***volumetric losses*** are concentrated in the nodes, without mass balance errors but introducing an energy balance error, which is generally completely negligible compared to the system uncertainties.

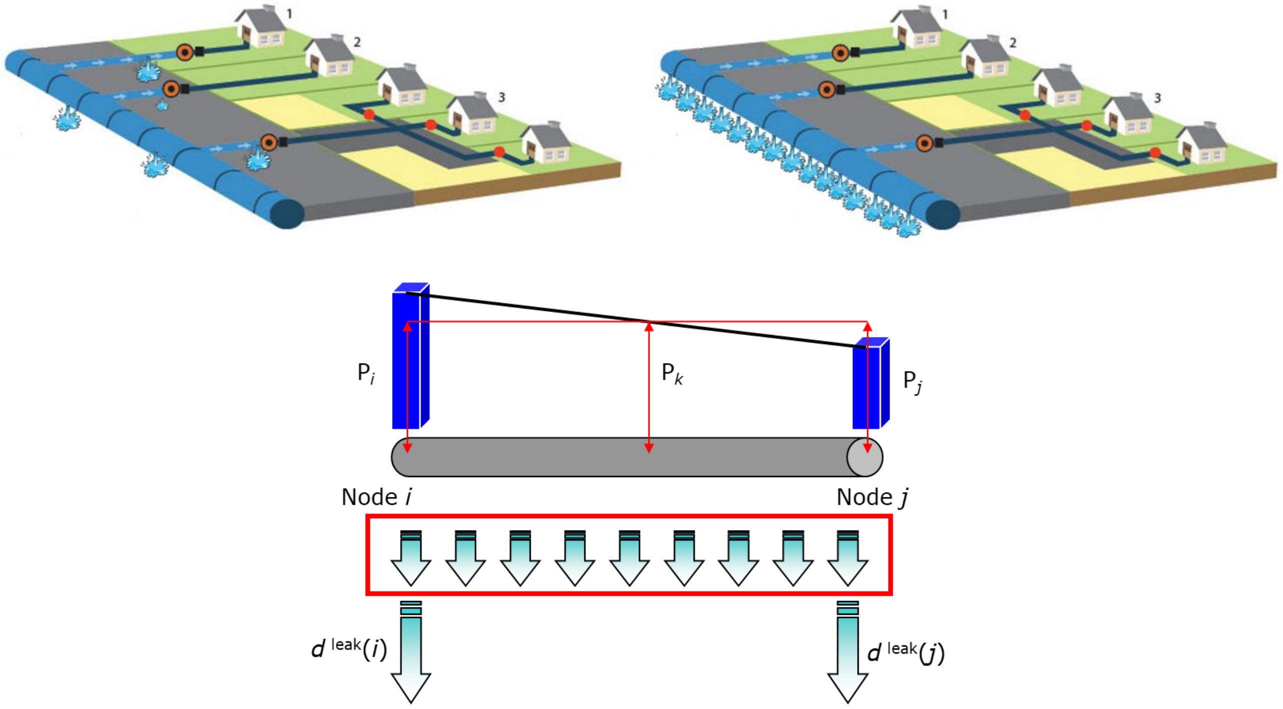


Figure 5. Volumetric losses and their representation in the hydraulic model

It is worth noting that representing the ***volumetric losses*** with concentrated hydrants at ending nodes of the network, besides making the hydraulic analysis inaccurate, causes loss of information at individual pipe level (since it is concentrated a priori in the nodes), i.e. information on pipe deterioration and connections, which is essential to support the choice of pipes to replace. Furthermore, it has to remark that classic hydraulic solvers, such as EPANET, adopted the *demand-driven* approach although **water losses cannot be fixed a priori because they are functions of average pipe pressure.** Therefore, **the simulation of WDN for management purposes always requires *pressure-driven analysis***, both to model water losses and for the hydraulic validation of the water supply conditions at users.

The *volumetric leakage model* assigns to each pipe a deterioration parameter ($\beta$), which is a global indicator of network deterioration, therefore very useful for WDN management. **The factor $\beta$ determines, for each pipe, the outflow leakages in m$^3$/day. The sum of leakages along each pipe determines the global water losses of the network that, divided by the total pipeline length of the network pipes, provides the average linear indicator of water losses m$^3$/km/day, which is reported in the macro-indicator M1a by the Italian Regulatory Authority for Energy, Networks and Environment (ARERA).**

It is possible to estimate the volume of global daily water losses $V_{WDN}^{leak}$ as a function of the average pressure in the network $P_{WDN}$ and the total pipeline length $L_{WDN}$ as: $V_{WDN}^{leak} = L_{WDN} \cdot \beta \cdot P_{WDN}^{\ \alpha}$. Therefore:

$$\beta = \frac{V_{WDN}^{leak}}{L_{WDN} \cdot P_{WDN}^{\alpha}} = \frac{\mathrm{M1a}}{P_{WDN}^{\alpha}} \quad \text{or} \quad \beta P_{WDN}^{\alpha} = 1.16 \cdot 10^{-8}\,\mathrm{M1a} \qquad (3)$$

Considering $\alpha$=1, the average pressures in the network between 5 and 100 m and M1a between 15 and 140 $m^3$/km/day, as detected by AREA for Italian networks, the average deterioration parameter $\beta$ ranges from $10^{-9}$ and $10^{-7}$.

Figure 5 summarizes some results of the WDNetXL-WDNetGIS hydraulic simulation, with reference of the volumes of each demand components (left) and the distribution of leakage volumes along pipes, with the M1a rate for the case study (right).

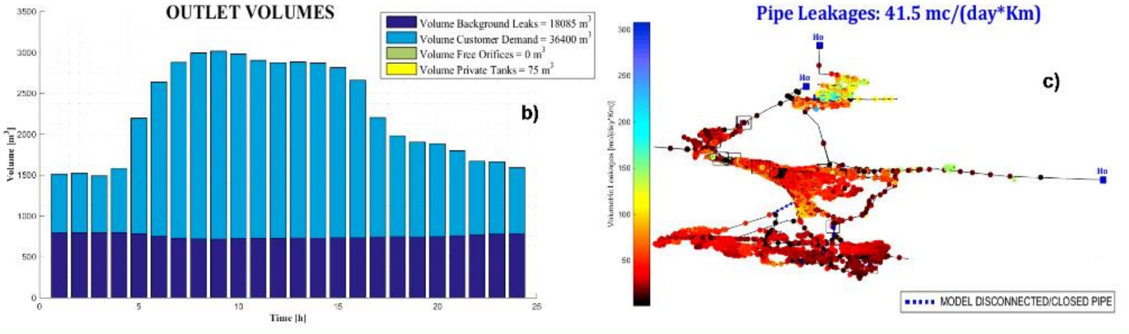


Figure 6. Pipes volumetric leakages (right) and outlet volumes (customer demands and background lekages) (left) for WDN Taranto.

## 2.2 *Model calibration based on mass balance*

As mentioned above, the advanced hydraulic modeling of the networks to support WDN management must be pressure-driven, and should account at both energy losses in the pipes (i.e. roughness), but also at how they relate network water losses as a function of system pressure. *Therefore, the calibration must be extended and primarily based on mass balance concepts*.

To this end, various types of users should be first characterized, at least in terms of their average water demand over a daily or weekly operating cycle. Moreover, the flows introduced into the network by water sources, i.e. tanks and/or pumping systems, must be measured. The calibration of the hydraulic model allows to separate, from the total flow rate entering the WDN, the *statistical component of demand*, i.e. that linked to users' consumption, from the *deterministic* one of the volumetric water losses, i.e. as function of the average pipe pressure.

Figure 7 shows in a simple way how the problem is the separation of the two main components that determine the WDN mass balance starting from the measurement of the flow rate patterns entering the system. The separation cannot do without the evaluation of the average pressures in the network and, therefore, the calibration of the roughness or the hydraulic resistances of the pipes, since they determine the water losses in order to get calibrated $\beta$ values as realistic and accurate as possible with respect to the available information (pressure and flow measurements).

Operationally, the calibration for management purposes is a dynamic process that starts by assuming $\beta$ related, for example, to diameters, pipes age and the number of connections.

Analysis conducted on several networks has shown that the variation of the $\beta$ parameter does not affect the pressures in the network but, rather, the distribution of the losses along pipes. Therefore, pressure measurements, although useful for checking the pressure status returned by the hydraulic model, are necessary to a lesser extent than in classic calibration models. Moreover, this approach makes the calibration related to mass balance concepts rather robust than that based on pressure monitoring only, which depends on current demand scenario and it can be affected by local disturbing effects.

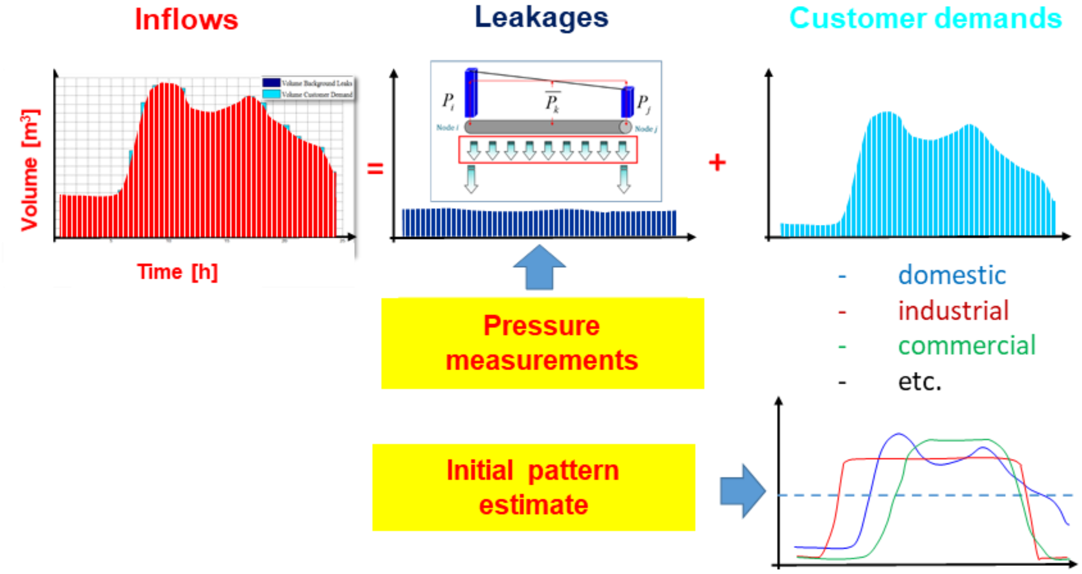


Figure 7. Pattern components of network inflows (leakages and customer demands)

### 3. *Hydraulic analyses in WDNetXL-WDNetGIS*

The advanced hydraulic modeling in the WDNetXL-WDNetGIS system is the main innovative element supporting the analysis to support effective and efficient management of water networks. Some innovative and distinctive aspects of WDNetXL-WDNetGIS dealing with the definition of the hydraulic model and the hydraulic and topological analysis capabilities are illustrated below.

#### 3.1 *Network connectivity validation*

The WDNetXL-WDNetGIS system, as a unique system on the international panorama, integrates topological analysis functions adapted from *complex network theory*, before and during hydraulic simulation. This allows performing the following connectivity checks, starting from the data import and model creation phases, for example from EPANET inp format data and/or from GIS databases used by water companies.

### *3.1.1 Identification of isolated nodes and abandoned (closed) pipes*

The connectivity analysis of the system identifies nodes and trunks isolated from the network, i.e. not fed by water sources. When defining the model, this allows to highlight specific parts of the system where detailed topological information need to be cross checked. Note that, during the hydraulic simulation, the model in WDNetXL-WDNetGIS is able to perform hydraulic analyses even with disconnected elements, and referring to the parts still connected to the water sources (i.e. tanks, pumps).

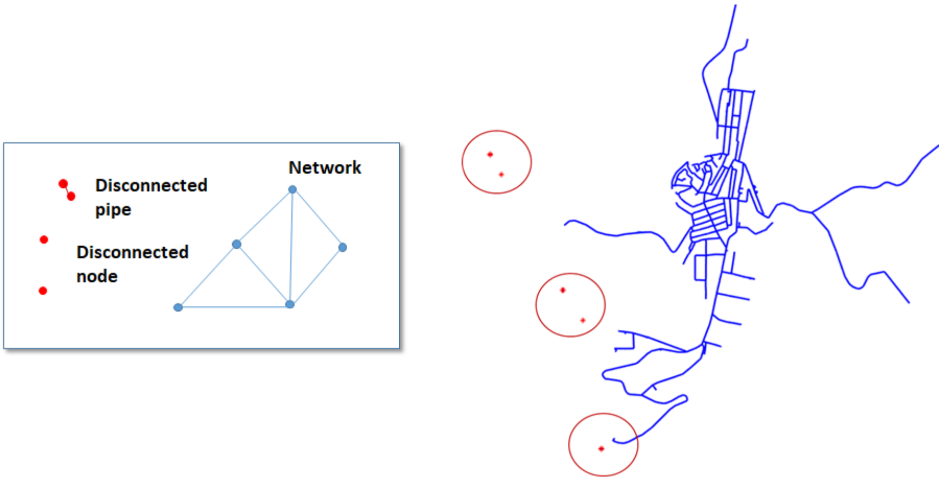


Figure 8. Disconnected pipe and disconnected nodes detection

### *3.1.2 Identification of disconnected (unsupplied) network portions*

When portions of networks are disconnected due errors in source data (lack of connectivity), the system detects them without preventing from the hydraulic simulation of the connected portions to water sources (e.g. tanks, pumps). When the disconnection is due to the intended closure of devices, for example in the case of maintenance works, WDNetXL-WDNetGIS system identifies both WDN portions that are intentionally isolated ad those that may be disconnected due to the same closures. This task is carried on automatically and without requiring preliminary model manipulations (e.g. pipes removal).

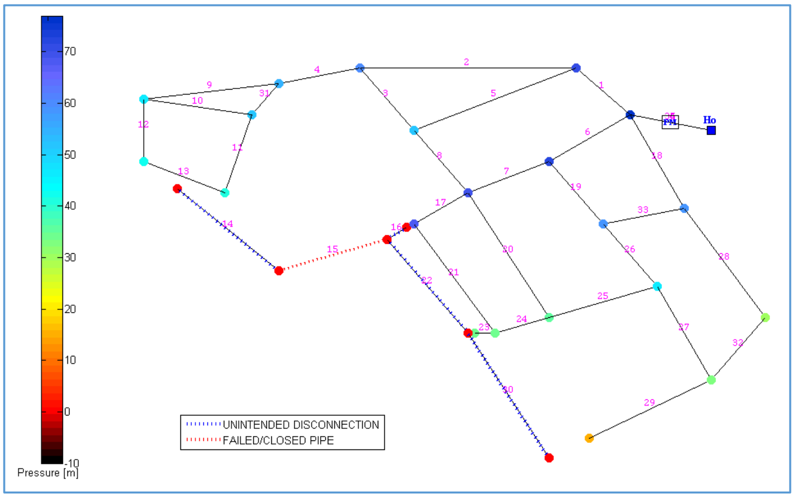


Figure 9. Identification of disconnected portions of the network due maintenance works.

### 3.2 *Definition of pipes hydraulic resistance*

Evenly distributed head losses along a pipe (ΔH) can be calculated though the Darcy-Weisbach formula:

$$\Delta H = \frac{\lambda}{2gD^5} Q^2 L = KQ^2 L \tag{4}$$

where *D* is the internal diameter of the pipe, *L* its length, *Q* the flow rate passing through it and λ is the friction factor, that can be considered independent of *Q* in the distribution networks since fully rough turbulent flow conditions prevail. In the case of long-standing service systems, i.e. hydraulic models developed for management purposes, the data available on internal pipe diameter are only indicative since it they do not account for possible fouling, partially closed valves, etc. which are not detailed in available data. Considering these operative conditions, the friction factor λ is intended as a corrective parameter of the pressure drop which encompasses all the effects not directly represented by the internal diameter.

Therefore, Eq. (4) reports that, for management model calibration, it is more rational to evaluate the unitary hydraulic resistance K, since it is not possible to separate the contribution of roughness from the uncertainty on the real internal diameter of the pipes, which appears with exponent 5.

In WDNetXL-WDNetGIS, the unit hydraulic resistances are shown in a table of asset features to which the individual pipes are addressed. It is also possible to implement exponents other than 2 in the formulation (4). For example, where the U.S.A. system, which refers to the Hazen-Williams formula, the exponent 1,852 is allowed. Anyway, please consider that the use of the latter non-European formulation is questionable given the fully rough turbulent flow regime occurring in the main pipes in the hydraulic models.

### 3.3 Pressure-driven hydraulic solver

WDNetXL-WDNetGIS is equipped with a *pressure-driven* hydraulic simulator which allows to represent all the outflow (demand) components with appropriate pressure functions. The simulator can also work in classic *demand-driven* mode, with higher level of accuracy than standard commercial products, since its hydraulic solver has been already conceived as *pressure-driven*.

The possibility of reproducing the pressure-driven operation allows defining peculiar types of demand suited for specific contexts like, for example, those associated with the presence of private water storages or multi-story buildings.

#### 3.3.1 Direct connection of single users to WDN

When users are directly connected to the network (no private tanks) the hydraulic solver refers to the Wagner model, as described above, which allows to calculate, besides the demand supplied in *normal* service conditions, the demand supplied in *pressure-deficit* condition. Therefore, when operating with WDNetXL-WDNetGIS platform, in addition to the *statistical* average water demand, which may vary over time according to a given demand pattern, the *pressure values for a correct service* $P_{ser}$ or the *minimum pressure to supply any demand* $P_{min}$, must be defined or as shown in Figure 10.

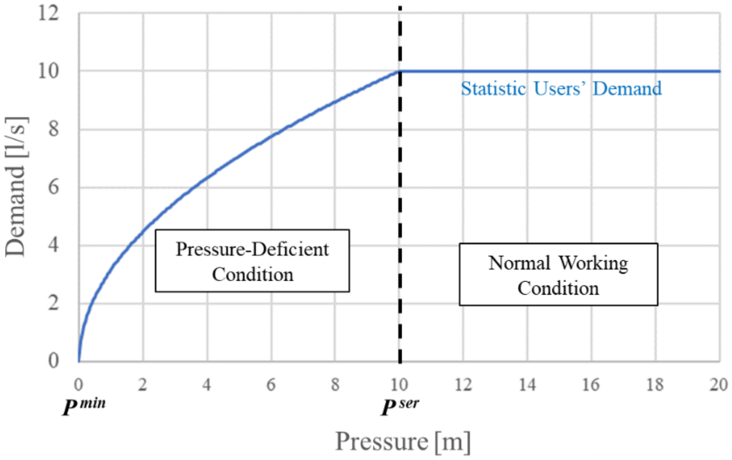


Figure 3. Pressure-demand plot for users.

#### 3.3.2 Direct connection to multi-story buildings

Figure 11 represents the model node in red, although the demand is actually supplied through devices at various floors of a building. In WDNetXL-WDNetGIS it is possible to define, for each model node, the number of floors and the inter-story height Δz, while the demand function independently calculates the water demand rates that would be deliverable at each floors, even accounting for pressure deficient conditions at that floor.

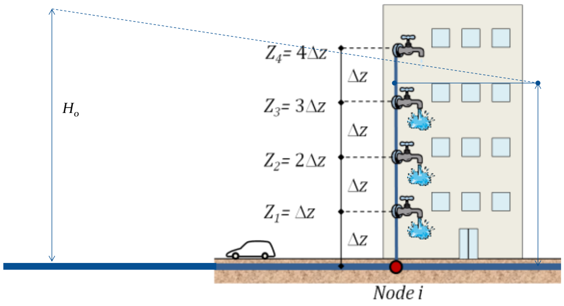


Figure 11. Water demand at model nodes accounting for multi-story buildings.

### 3.3.3 Private tanks

Private water storage (tanks) are not allowed in commercial software packages, thus technicians have to conceptualized them through modeling “tricks”. In fact, these software packages are mostly developed in technical contexts which did not account for the presence of such systems. Conversely, in Mediterranean countries private tanks, both in the basement floors or on the top of buildings, are widespread and should be accounted for while managing water scarcity scenarios. Figure 12 represents the supply scheme through private tanks. The hydraulic model in WDNetXL-WDNetGIS is able to simulate the filling/emptying processes in each tank by defining the maximum private storage, $V_{max}$, a volume available at the beginning of the simulation, $V_{ini,}$ and parameters relating to the valve feeding the tank ($C_{max}$ , $I_{ctr}$).

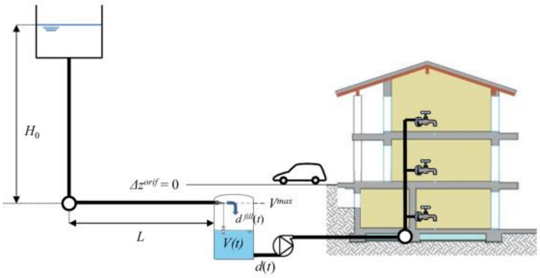


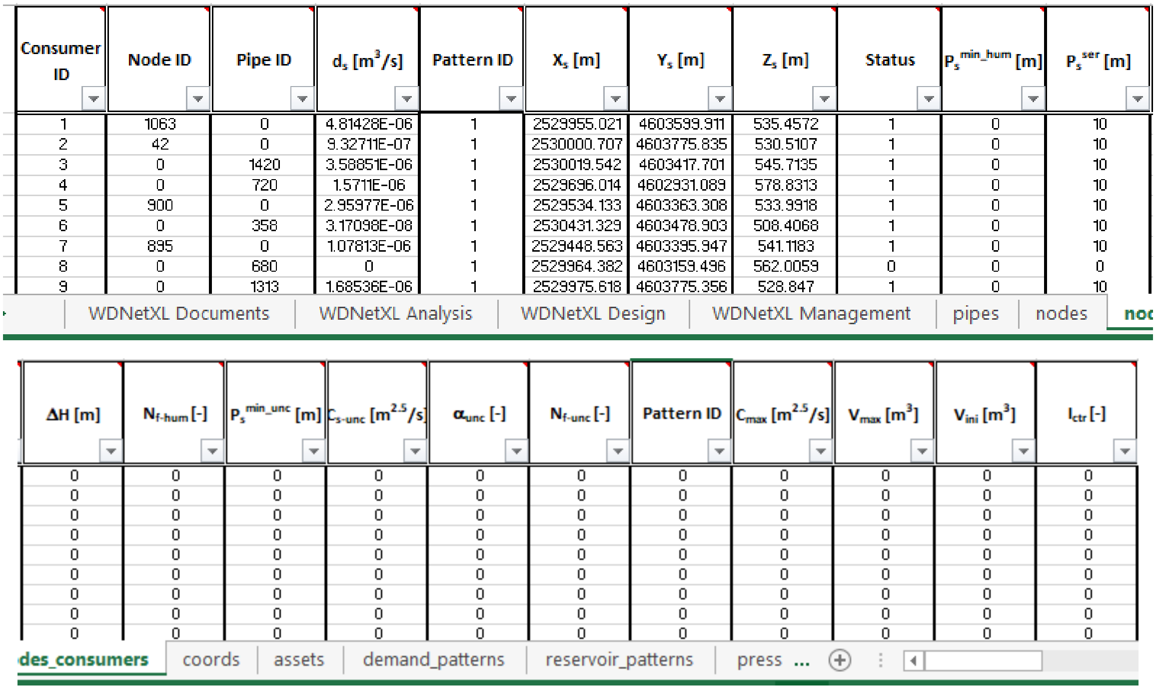
Figure 12. Modelling demand accounting for private tanks.

### 3.3.4 Single-consumer demand definition and simulation

The WDNetXL-WDNetGIS system imports WDN data stored in the GIS database of the water company, which is commonly used for management and accounting purposes. The import functionality, besides importing geometric, topological and hydraulic features of the network, creates a new hydraulic model, and, whenever required, synchronize the detailed GIS data with an existing hydraulic model, e.g. imported in WDNetXL from EPANET inp file. In addition, the WDNetXL-WDNetGIS system allows to import geographic and water consumption data about single consumers, without lumping water requests to the network nodes. This allows to perform two distinct type of analysis:

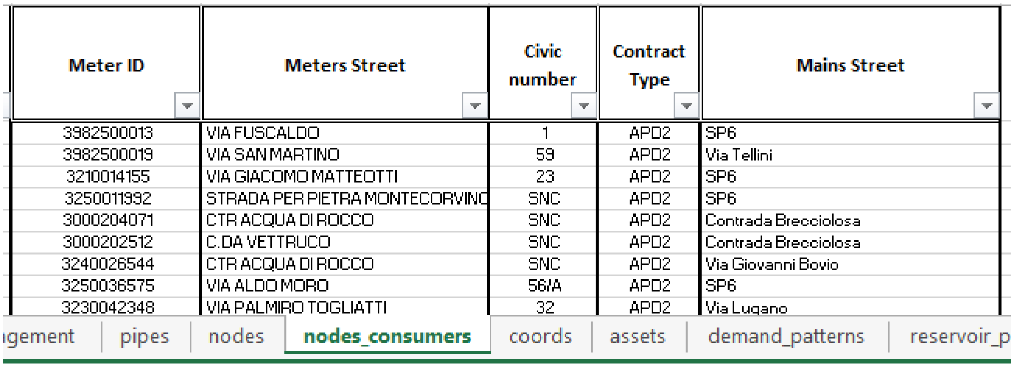
- *demand-driven* or *pressure-driven* analysis of all demand components, depending on pressures at the nodes as defined in the hydraulic network model (standard modeling);
- *demand-driven* or *pressure-driven* analysis of all demand components, depending on each pressure at each consumer, using the geo-referencing of water meters and related consumption data records. This innovative modeling paradigm does not require significant increases in calculation times while allowing to update current model data using GIS database, accounting for the termination of water supply for some users, or new connections and related water consumptions data. In addition, it prepares for the acquisition of detailed data that may be available in the near future such as, for example, the height of the buildings and the number of floors or the presence of private tanks at single consumers level. This innovative hydraulic simulation feature in WDNetXL-WDNetGIS allows detailed analysis of the service conditions, pointing out possible deficit for some users.

Figure 13 shows the "*nodes_consumers*" table, where the following information are reported: *statistical* demand ($d_S$), the demand patterns associated to the user type (Pattern ID), the geographic coordinates of water meters ($X_S$, $Y_S$, $Z_S$), the "Status" of active or non-active users, minimum pressure ($P_s^{min\text{-}hum}$) and pressure to provide a correct service ($P_s^{ser}$) according to the Wagner's model; number of floors ($N_{f\text{-}hum}$) and floor height ($\Delta H$); minimum pressure ($P^{min\_unc}$), outflow coefficient ($C_{s\_unc}$) and exponent ($\alpha_{unc}$) for free orifices; modeling parameters of private storage volumes serving private tank ($C_{max}$ ,$V_{max}$, $V_{ini}$, $I_{ctr}$).



| Consumer ID | Node ID | Pipe ID | $d_s$ [m$^3$/s] | Pattern ID | $X_s$ [m] | $Y_s$ [m] | $Z_s$ [m] | Status | $P_s^{min\_hum}$ [m] | $P_s^{ser}$ [m] |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1063 | 0 | 4.81428E-06 | 1 | 2529955.021 | 4603599.911 | 535.4572 | 1 | 0 | 10 |
| 2 | 42 | 0 | 9.32711E-07 | 1 | 2530000.707 | 4603775.835 | 530.5107 | 1 | 0 | 10 |
| 3 | 0 | 1420 | 3.58851E-06 | 1 | 2530019.542 | 4603417.701 | 545.7135 | 1 | 0 | 10 |
| 4 | 0 | 720 | 1.5711E-06 | 1 | 2529696.014 | 4602931.089 | 578.8313 | 1 | 0 | 10 |
| 5 | 900 | 0 | 2.95977E-06 | 1 | 2529534.133 | 4603363.308 | 533.9918 | 1 | 0 | 10 |
| 6 | 0 | 358 | 3.17098E-08 | 1 | 2530431.329 | 4603478.903 | 508.4068 | 1 | 0 | 10 |
| 7 | 895 | 0 | 1.07813E-06 | 1 | 2529448.563 | 4603395.947 | 541.1183 | 1 | 0 | 10 |
| 8 | 0 | 680 | 0 | 1 | 2529964.382 | 4603159.496 | 562.0059 | 0 | 0 | 0 |
| 9 | 0 | 1313 | 1.68536E-06 | 1 | 2529975.618 | 4603775.356 | 528.847 | 1 | 0 | 10 |

| ΔH [m] | $N_{f\text{-}hum}$ [-] | $P_s^{min\_unc}$ [m] | $C_{s\text{-}unc}$ [m$^{2.5}$/s] | $\alpha_{unc}$ [-] | $N_{f\text{-}unc}$ [-] | Pattern ID | $C_{max}$ [m$^{2.5}$/s] | $V_{max}$ [m$^3$] | $V_{ini}$ [m$^3$] | $I_{ctr}$ [-] |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |



| Meter ID | Meters Street | Civic number | Contract Type | Mains Street |
|---|---|---|---|---|
| 3982500013 | VIA FUSCALDO | 1 | APD2 | SP6 |
| 3982500019 | VIA SAN MARTINO | 59 | APD2 | Via Tellini |
| 3210014155 | VIA GIACOMO MATTEOTTI | 23 | APD2 | SP6 |
| 3250011992 | STRADA PER PIETRA MONTECORVINO | SNC | APD2 | SP6 |
| 3000204071 | CTR ACQUA DI ROCCO | SNC | APD2 | Contrada Brecciolosa |
| 3000202512 | C.DA VETTRUCO | SNC | APD2 | Contrada Brecciolosa |
| 3240026544 | CTR ACQUA DI ROCCO | SNC | APD2 | Via Giovanni Bovio |
| 3250036575 | VIA ALDO MORO | 56/A | APD2 | SP6 |
| 3230042348 | VIA PALMIRO TOGLIATTI | 32 | APD2 | Via Lugano |

Figure 13. Table of “nodes_consumers” in WDNetXL-WDNetGIS.

Figure 14 summarizes the hydraulic simulation report for each consumer: on the left is shown the information about the type of consumers (i.e. the demand patterns), on the right the average pressure calculated for each consumer meter over an operating cycle, as got from the WDNetXL-WDNetGIS hydraulic analysis.

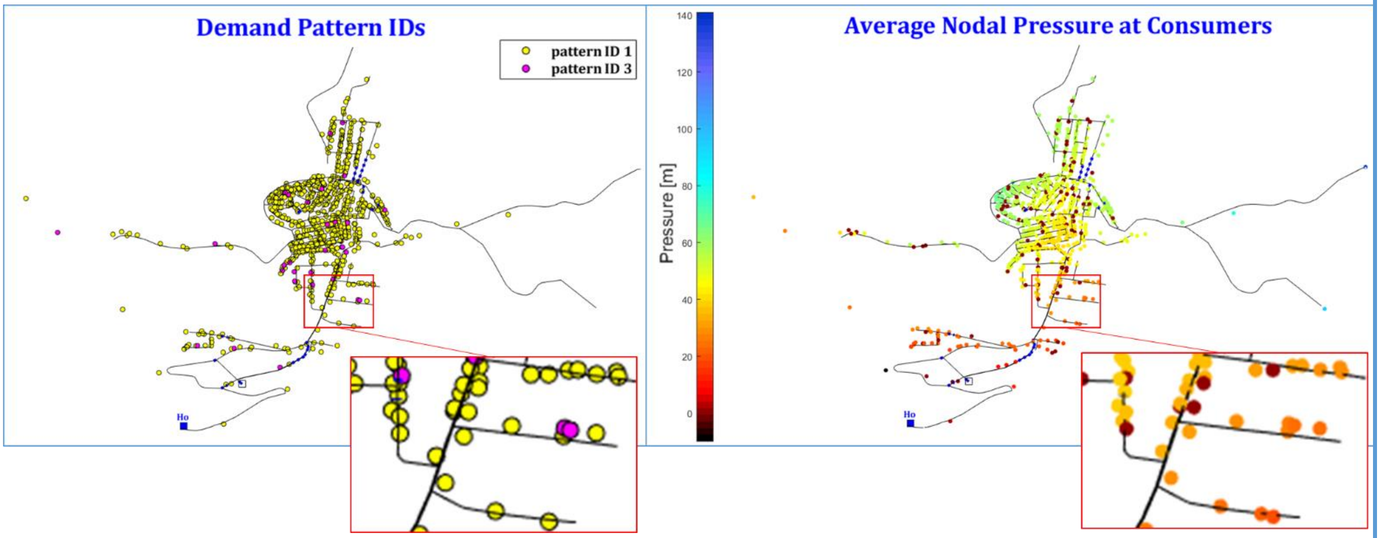


Figure 14. Single-users definition (left), average nodal pressure at consumers (right) in WDNetXL-WDNetGIS.

### 3.3.5 *Volumetric water losses*

This component of water losses, as mentioned above, is the most significant for management purposes and represents both *background* losses, with lower discharge and difficult to detect by field survey, and *unreported* bursts, entailing larger outflows. Figure 15 recalls the modeling assumptions for volumetric losses along pipes.

Figure 16 shows, for each pipe, the total volume of water losses in $m^3$/km/day from 24-hour extended period simulation. The latter information, therefore, allows identifying those pipes with maximum volumetric losses due to the joint effect of the deterioration (parameter $\beta$) and the average pressure calculated along each pipe, providing hydraulically consistent indications for management actions and strategies.

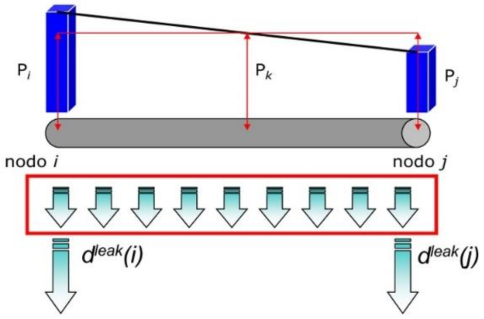


Figure 15. Leakage model versus pressure along pipes.

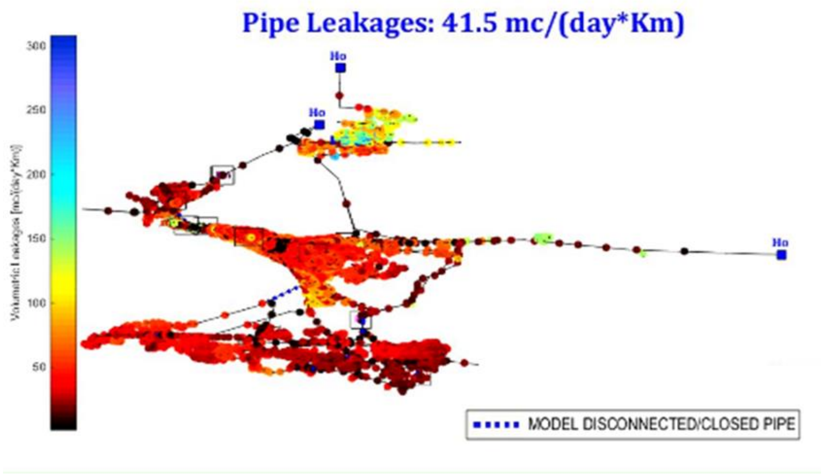


Figure 16. Volumetric losses at pipe level for a DMA design solution of Taranto WDN, Italy.

### 3.4 *Representation of hydraulic devices as attributes of the link objects*

WDNetXL-WDNetGIS introduces an optional topological representation of hydraulic devices and all types of valves as pipe objects or topology links.

For example, Figure 17 shows the two conceptual schemes of the representation considering the sectioning gate valves, normally closed to form monitoring districts (DMA), or the isolation valves, normally open and closed, if necessary, to separate WDN portions for maintenance work. On the left the valve is represented by an additional link, on the right it is defined as the feature of the main link, that is of the trunk on which it is installed.

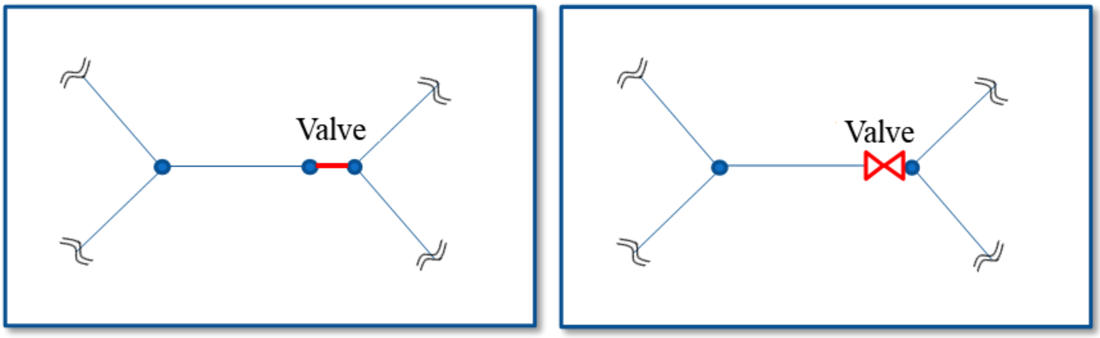


Figure 17. Valve as separate link (left) and as link object feature (right).

Every hydraulic device is defined in "*pipes*" table on *Device Position* column, which indicates the presence of vault where the device is installed.

$$\text{Device position} = \begin{cases} 0 & \text{device position information not available} \\ 1 & \text{device nearby node 1} \\ 2 & \text{device nearby node 2} \end{cases}$$

Whereas the position of the device is defined, the column $D_{k\text{-}device}$ in "*pipes*" table allows to assign to the hydraulic device a diameter different from its main pipe diameter, so that it can be used in hydraulic calculations. This representation, while preserving the integrity of the geometric data of the network, avoids the creation of 1-meter *fictitious links* on the network topology shapefile to accommodate the representation of hydraulic devices and valves of all types. This representation allows consistence between shapefile format in WDNetGIS (which assumes valves and devices as point objects) and WDNetXL data format. WDNetXL data format is defined by tables which hold all the necessary information about geographic coordinates of the network features and the related attribute tables. WDNetXL and WDNetGIS are completely interoperable, by allowing to upload WDNetXL xlsm files directly from WDNeGIS, without transforming data in shapefile.

### 3.5 *Valve operation modeling*

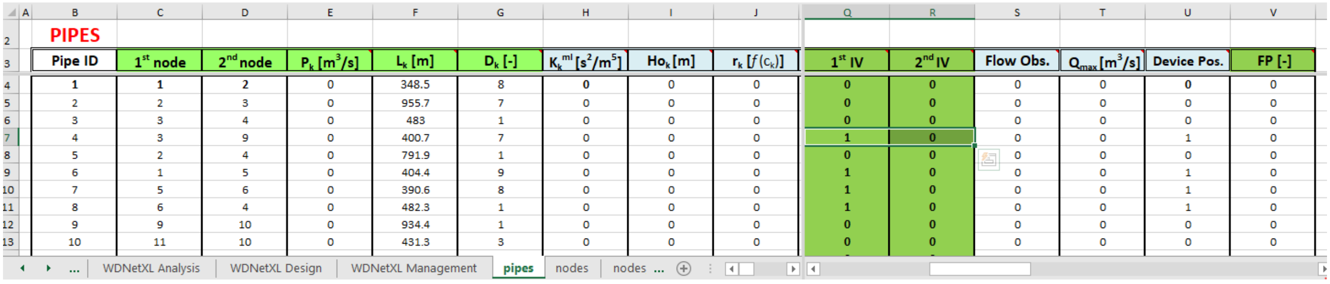
WDNetXL-WDNetGIS allows to model all types of regulation and control valves. It is possible to plan controls using simple and complex rules, as shown in the table "WDNetXL-WDNetGIS vs. EPANET". In particular, WDNetXL is able to model the functioning of some peculiar valves, such as:

- isolation valves (IVS analysis),
- sectioning valves (DMA analysis) and abandoned pipes,
- flow control valves (FCVs) e check valves,
- pressure-sustaining and pressure-reducing valves (PCV) also with internal control nodes in the network and controllability analysis,

- any type of gate valve.

### 3.5.1 *Isolation Valve System (IVS)*

The **isolation valves** are usually **open during normal system operation,** they are closed during the planned or unplanned maintenance work (pipes failure or rehabilitation)



PIPES

| Pipe ID | 1st node | 2nd node | $P_k$ [$m^3/s$] | $L_k$ [m] | $D_k$ [-] | $K_k^{ml}$ [$s^2/m^5$] | $Ho_k$ [m] | $r_k$ [$f(c_k)$] | 1st IV | 2nd IV | Flow Obs. | $Q_{max}$ [$m^3/s$] | Device Pos. | FP [-] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 0 | 348.5 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 2 | 3 | 0 | 955.7 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 3 | 4 | 0 | 483 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 3 | 9 | 0 | 400.7 | 7 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 5 | 2 | 4 | 0 | 791.9 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 1 | 5 | 0 | 404.4 | 9 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 7 | 5 | 6 | 0 | 390.6 | 8 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 8 | 6 | 4 | 0 | 482.3 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 9 | 9 | 10 | 0 | 934.4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 11 | 10 | 0 | 431.3 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Figure 18. Green-colored columns point to IVS addition.

Figure 18 shows table of pipes, where "*1^st IV*" and "*2^nd IV*", highlighted in green, indicate the presence of isolation valves nearby the first or second node of the pipe. In the case of valve installation in both nodes, it is not necessary to define the *Device position* column. The WDNetXL-WDNetGIS system allow to automatically define TCVs, as defined in the EPANET model, as isolation valves, during the import data operation.

The topological analysis of the network allows, once the IVS is created, to identify the network segments that can be isolated, as explained in Figure 19.

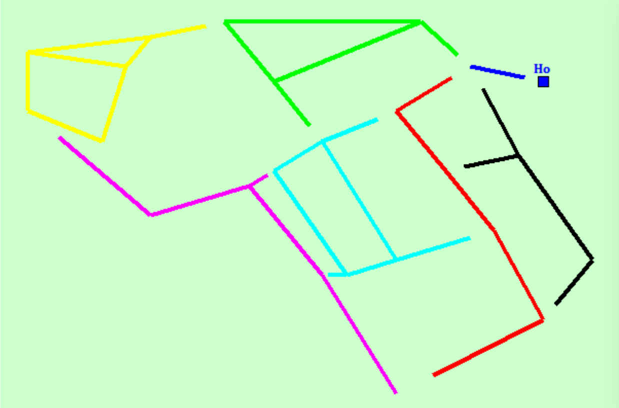
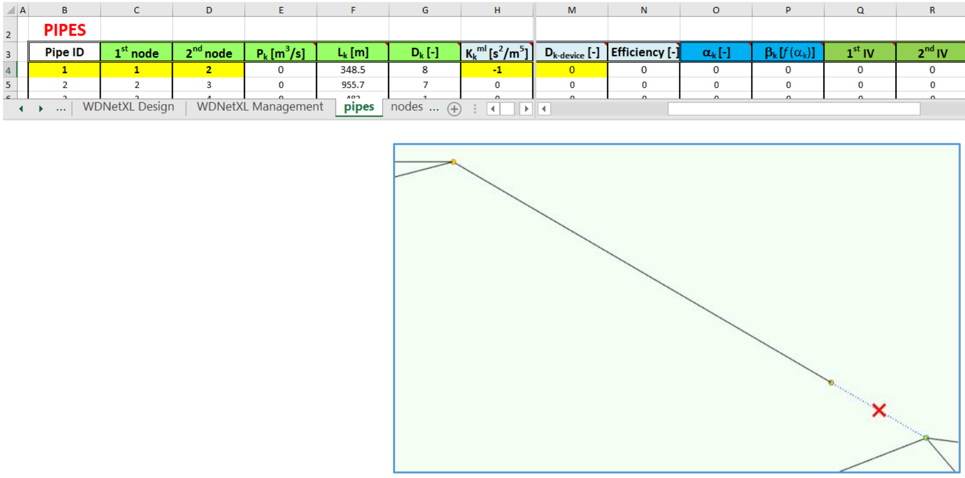


Figure 19. Network segment divisions after isolation valve system closing.

### 3.5.2 *Sectioning gate valves and abandoned pipes*

WDNetXL-WDNetGIS allows defining **sectioning gate valves** which, unlike the isolation valves, are **closed during normal system operation**; for example, they are used bound monitoring districts areas (DMA). In this case, the *Device Position* column indicates the position of the valve and the value -1 in the $K_k^{ml}$ column indicates that it is closed (see Figure 20).



**PIPES**

| Pipe ID | 1st node | 2nd node | $P_k$ [m$^3$/s] | $L_k$ [m] | $D_k$ [-] | $K_k^{ml}$ [s$^2$/m$^5$] | $D_{k\text{-device}}$ [-] | Efficiency [-] | $\alpha_k$ [-] | $\beta_k$ [$f(\alpha_k)$] | 1st IV | 2nd IV | Flow Obs. | $Q_{max}$ [m$^3$/s] | Device Pos. | FP [-] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 0 | 348.5 | 8 | -1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 2 | 2 | 3 | 0 | 955.7 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Figure 20. Table of pipes (above) and sectioning gate valve visualization in WDNetXL (below).

If the *Device Position* value is zero, the system detects an *abandoned* pipe, reported pipeline as "closed" in other software (e.g. in EPANET), displayed as in Figure 21, but ignoring it during the hydraulic calculation.

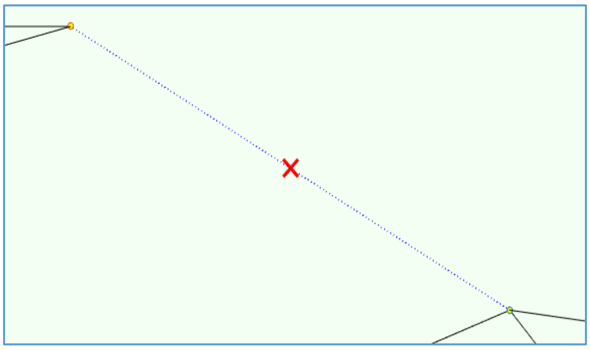


Figure 21. Abandoned or "closed" pipes visualization.

### 3.5.3 Flow Controls Valves (FCVs) and Check Valves

The flow controls valves (FCVs) are modeled in WDNetXL-WDNetGIS adopting a well-known scheme in the literature which determines, within the hydraulic solver, the localized pressure drop associated to the device in order to reduce the flow rate to the desired value (Giustolisi et al. 2012). This scheme, avoiding heuristic numerical devices, allows to treat in a similar way also unidirectional non-inversion valves of the flow. It should be noted that, unlike most commercial software, the topological analysis integrated within the hydraulic analysis in WDNetXL-WDNetGIS allows performing simulations with variable topology. This means that it allows determining the hydraulic status of the system by identifying the network still connected against the possible valve closure during extended period simulations, e.g. 24 hours.

### *3.5.4 Pressure Control Valves (PCVs): local and remote control*

Pressure control (reduction or sustain) valves can represent a valuable element in the asset management strategy, both in relation to the objective of reducing losses and with respect to keep adequate pressure conditions for the water supply. The classic design of PCV location and settings assumes hydraulic control valves, which maintain assigned pressure settings values immediately downstream of the device. In recent years, RRTC (*Remote Real-Time Controlled*) electric control valves have been increasingly used which are controlled through a hydraulically critical (*sentinel*) node inside the network. With reference to leakage reduction objective, the RRTC control scheme allows optimizing the reduction of ***water losses***, against a small number of installations and reducing the possible interferences between devices, which may be due to the variability in the hydraulic functioning during the operating cycle. In fact, the *sentinel* node is an indicator of the functioning of the system with respect to the variation of the water requests over time. Moreover, the pressure control at this node requires the indication of a single control pressure value (at least equal to the pressure for correct service). Classic control of PCV would require a variable pressure setting values (e.g. varying hourly) due to variability of water demand, to have the same efficacy as RRTC schemes. Unlike other commercial calculation software, WDNetXL-WDNetGIS allows to define the PCV indicating the *target pressure* ($P^{set}$) at any control node in the WDN, with either a unique value or variable over time. Figure 22 shows the pressure control by means of a PCV installed in a small water network, Apulian, along the trunk feeding the network from the reservoir and controlled to maintain a pressure $P^{set}$ = 13 m in the remote control node, or simulating an RRTC scheme with hourly time step. Note that the simulation returns the pressure trend in node N1; these pressure values would be those to be set, for each hour, immediately downstream of the valve in the case of classic hydraulic (local) control. Therefore, the hydraulic model in WDNetXL-WDNetGIS allows analyzing the optimal operating scenario (RRTC) also providing indication on the $P^{set}$ pattern as a reference for the classic control. This aletter information can support planning in those contexts where, for example, a PCV is already installed even with a limited number of set-points.

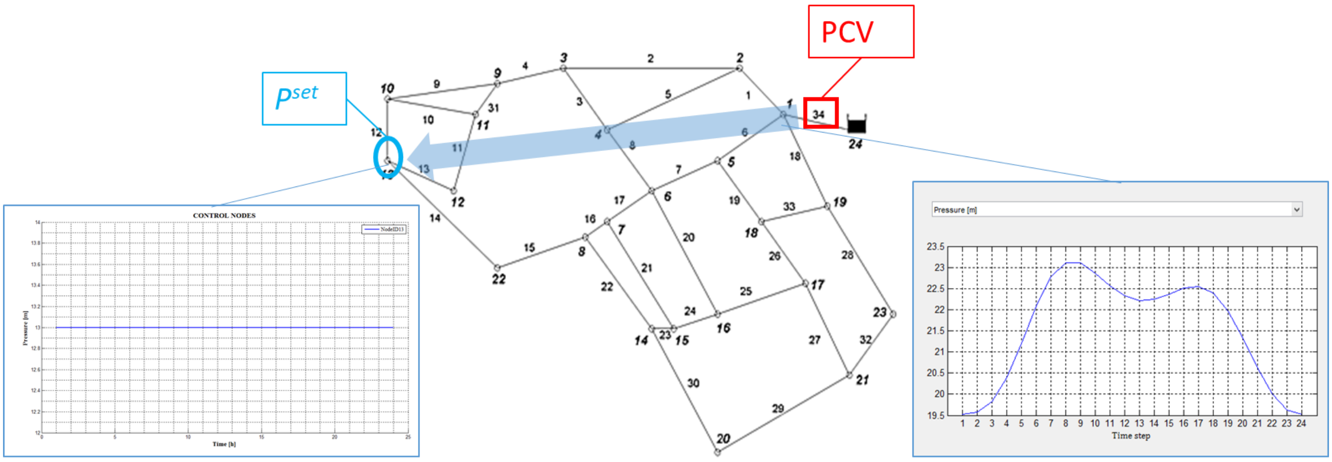


Figure 22. Simulation of a pressure control valve by a remote node.

## 3.6 *Time-control of valves*

When control valves are defined with time patterns of the opening degree, WDNetXL-WDNetGIS allows defining the same pattern with reference to the coefficient of concentrated head loss created by the valves itself in the system.

Besides supporting the setting of valves according to trial-and-error approach, WDNetXL-WDNetGIS allows, for example, to simulate optimal valve regulation scenarios by means of hydraulic analysis in an RRTC scheme and evaluating the time pattern of head losses from the same simulation in order to set the time control of valves.

## 3.7 *Modeling variable level tanks*

Considering variable level tanks, such as urban compensation tanks, WDNetXL-WDNetGIS platform, as explained in “WDNetXL-WDNetGIS vs. EPANET” section, implements an algorithm which overcomes the knows instabilities of EPANET and EPANET-like software tools (Giustolisi et al., 2012). The stability of the algorithm in WDNetXL-WDNetGIS also allows to simulate the operation of networks where on variable level tanks are defined only, i.e. without the need to define any "reservoir" at a known head level. Furthermore, WDNetXL-WDNetGIS allows representing the feeding schemes of each tank as shown below which, although they are very common in water networks, cannot be represented in other commercial software without introducing heuristic "rules" or "controls". Anyway, it has to remark that such expedients may compromise the stability of the calculation.

### 3.7.1 *Tanks supplied by external pipelines modeling*

WDNetXL-WDNetGIS can define an external water supply, independent from WDN, for “tanks”, as shown in Figure 23.

Furthermore, it is possible to define user-demand in the same node, either for *demand-driven* or *pressure-driven* analysis.

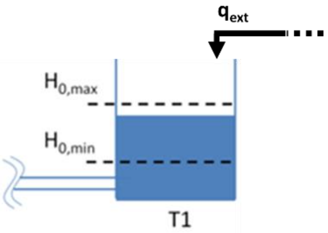


Figure 23. Scheme of tank supplied by external source

Figure 24 shows the case of the *Apulian* test network in which all nodes are replaced with variable level tanks fed by an external pipeline. Despite the reduced hydraulic resistance of the pipes between the tanks, which in other software would induce instability conditions of the simulation, the result shows that the variation of the head in the tanks is modeled with stable behavior, even in the absence of fixed-level tanks (reservoirs).

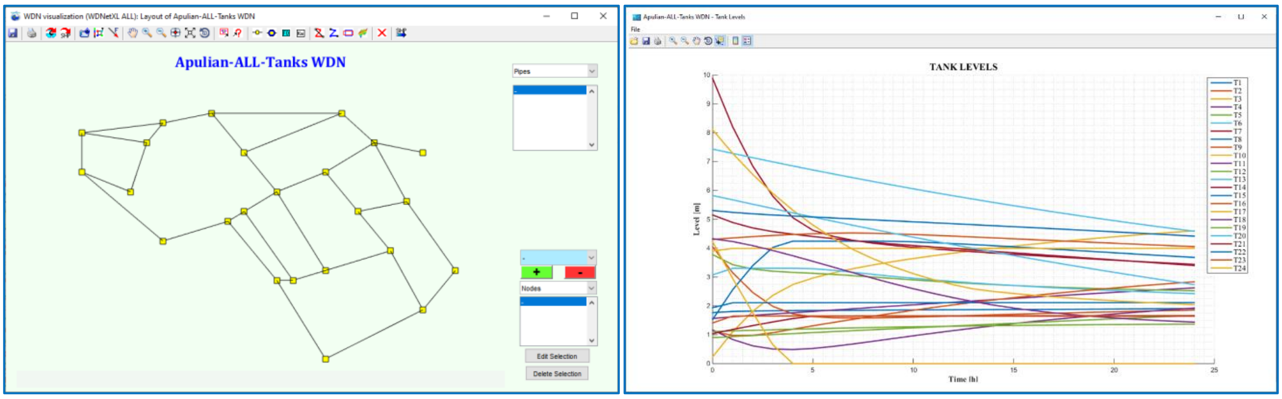


Figure 24. *Apulian* WDN simulation considering variable-tanks at every nodes: network layout (left), tanks water levels (right).

### *3.7.2 Tanks supplied from above (hydraulic disconnection)*

In many WDN schemes the "tanks" represent compensation water storages fed by the same network by means of a nozzle with free flow from above. This scheme, in turn, introduces a hydraulic disconnection as shown in the diagram in Figure 25. In this case the model in WDNetXL-WDNetGIS allows to represent the tank fed from a node inside the network (N101 in the Figure) for which the outflow coefficient of a free nozzle must be defined.

This possibility, which is unique in WDNetXL-WDNetGIS, allows to define these elements without resorting to "rules" or "controls", nor to numerical devices of any kind, with evident advantages of stability in the calculation.

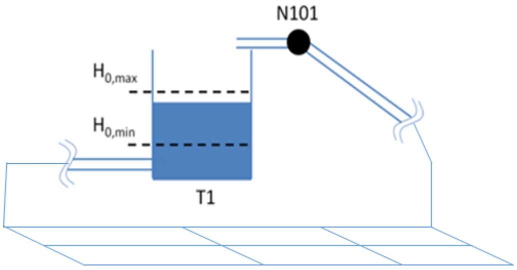


Figure 25. Tank scheme supplied by a network node with hydraulic disconnection.

### 3.7.3 *Tank with conical shape*

WDNetXL-WDNetGIS allows defining and modeling non-cylindrical "tanks" (see Figure 26) and, in particular, conical ones.

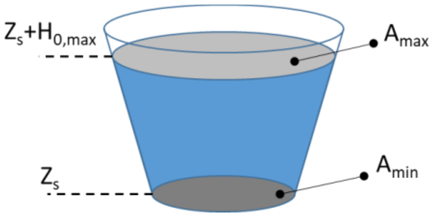
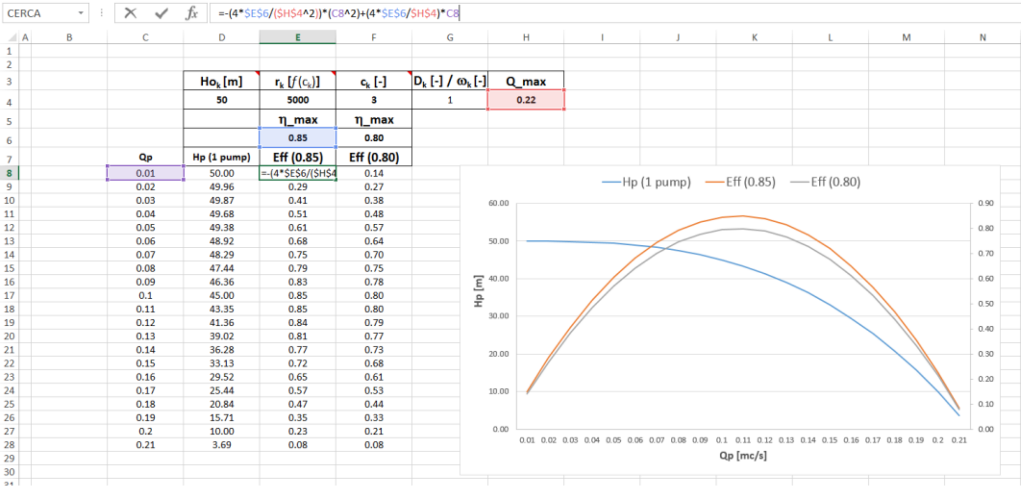


Figure 26. Non-cylindrical tank modeling in WDNetXL-WDNetGIS.

WDNetXL-WDNetGIS platform allows IDEA-RT to implement any further changes related to specific needs in the definition of these elements.

## 3.8 *Pumping systems*

WDNetXL allows defining the parameters of the flow-head and flow-efficiency characteristic curves both automatically, while importing data from EPANET inp files or, manually, using the MS-Excel® functions starting from measured pump duty points. It hat to remark that, unlike EPANET or other software based on the same solver, the aforementioned curves are defined as continuous functions and never as piecewise linear curves. This feature overcome numerical problems in favor of stability and robustness of solutions. In addition, the possibility of viewing the pump characteristic curves in MS-Excel® and modifying their parameters manually, enable user to perform immediate verification and adjustments, whenever needed. Figure 27 shows the visualization in MS-Excel® of the characteristic curves of the pumps.



```
=-(4*$E$6/($H$4^2))*(C8^2)+(4*$E$6/$H$4)*C8
```

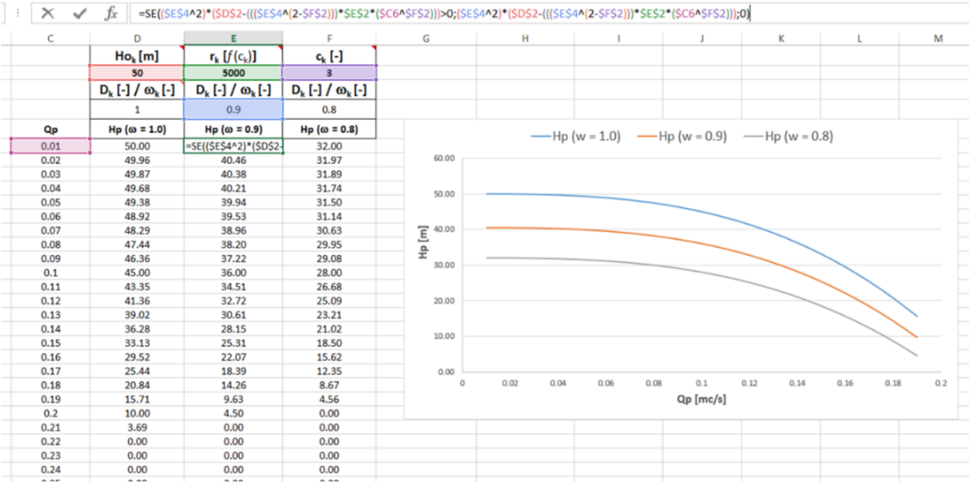
| Ho$_k$ [m] | r$_k$ [f(c$_k$)] | c$_k$ [-] | D$_k$ [-] / ω$_k$ [-] | Q_max |
|---|---|---|---|---|
| 50 | 5000 | 3 | 1 | 0.22 |
|  | η_max | η_max |  |  |
|  | 0.85 | 0.80 |  |  |

| Qp | Hp (1 pump) | Eff (0.85) | Eff (0.80) |
|---|---|---|---|
| 0.01 | 50.00 | =-(4*$E$6/($H$4 | 0.14 |
| 0.02 | 49.96 | 0.29 | 0.27 |
| 0.03 | 49.87 | 0.41 | 0.38 |
| 0.04 | 49.68 | 0.51 | 0.48 |
| 0.05 | 49.38 | 0.61 | 0.57 |
| 0.06 | 48.92 | 0.68 | 0.64 |
| 0.07 | 48.29 | 0.75 | 0.70 |
| 0.08 | 47.44 | 0.79 | 0.75 |
| 0.09 | 46.36 | 0.83 | 0.78 |
| 0.1 | 45.00 | 0.85 | 0.80 |
| 0.11 | 43.35 | 0.85 | 0.80 |
| 0.12 | 41.36 | 0.84 | 0.79 |
| 0.13 | 39.02 | 0.81 | 0.77 |
| 0.14 | 36.28 | 0.77 | 0.73 |
| 0.15 | 33.13 | 0.72 | 0.68 |
| 0.16 | 29.52 | 0.65 | 0.61 |
| 0.17 | 25.44 | 0.57 | 0.53 |
| 0.18 | 20.84 | 0.47 | 0.44 |
| 0.19 | 15.71 | 0.35 | 0.33 |
| 0.2 | 10.00 | 0.23 | 0.21 |
| 0.21 | 3.69 | 0.08 | 0.08 |

Figure 27. Pump curves visualization in WDNetXL-WDNetGIS.

### 3.8.1 *Variable Speed Pumps (VSPs): local and remote control*

WDNetXL-WDNetGIS allows to analyze the operating curves of variable speed drive pumps in MS-Excel® as shown in Figure 28.



```
=SE(($E$4^2)*($D$2-((($E$4^(2-$F$2)))*$E$2*($C6^$F$2)))>0;($E$4^2)*($D$2-((($E$4^(2-$F$2)))*$E$2*($C6^$F$2)));0)
```

| Ho$_k$ [m] | r$_k$ [f(c$_k$)] | c$_k$ [-] |
|---|---|---|
| 50 | 5000 | 3 |
| D$_k$ [-] / ω$_k$ [-] | D$_k$ [-] / ω$_k$ [-] | D$_k$ [-] / ω$_k$ [-] |
| 1 | 0.9 | 0.8 |

| Qp | Hp (ω = 1.0) | Hp (ω = 0.9) | Hp (ω = 0.8) |
|---|---|---|---|
| 0.01 | 50.00 | =SE(($E$4^2)*($D$2- | 32.00 |
| 0.02 | 49.96 | 40.46 | 31.97 |
| 0.03 | 49.87 | 40.38 | 31.89 |
| 0.04 | 49.68 | 40.21 | 31.74 |
| 0.05 | 49.38 | 39.94 | 31.50 |
| 0.06 | 48.92 | 39.53 | 31.14 |
| 0.07 | 48.29 | 38.96 | 30.63 |
| 0.08 | 47.44 | 38.20 | 29.95 |
| 0.09 | 46.36 | 37.22 | 29.08 |
| 0.1 | 45.00 | 36.00 | 28.00 |
| 0.11 | 43.35 | 34.51 | 26.68 |
| 0.12 | 41.36 | 32.72 | 25.09 |
| 0.13 | 39.02 | 30.61 | 23.21 |
| 0.14 | 36.28 | 28.15 | 21.02 |
| 0.15 | 33.13 | 25.31 | 18.50 |
| 0.16 | 29.52 | 22.07 | 15.62 |
| 0.17 | 25.44 | 18.39 | 12.35 |
| 0.18 | 20.84 | 14.26 | 8.67 |
| 0.19 | 15.71 | 9.63 | 4.56 |
| 0.2 | 10.00 | 4.50 | 0.00 |
| 0.21 | 3.69 | 0.00 | 0.00 |
| 0.22 | 0.00 | 0.00 | 0.00 |
| 0.23 | 0.00 | 0.00 | 0.00 |
| 0.24 | 0.00 | 0.00 | 0.00 |

Figure 28. VSP pump curves validation in WDNetXL-WDNetGIS.

WDNetXL-WDNetGIS you can run the following simulations:

- VSP with time pattern of assigned *speed factor*: similar to EPANET;
- VSP controlled by pressure in any node of the network (Remote Real Time Control, RRTC): the simulation returns the pattern of the speed factors of the VSP to guarantee the target pressure in the control (*sentinel*) node. It is possible to define a fixed or variable target pressure over time at the control node.

The simulation of an RRTC scheme allows evaluating, at a model level, the effectiveness and efficiency of a remote-control scheme before bearing the burden of the installation. Figure 29 shows the example of a VSP installed on the pipe of the *Apulian* network feeding the network from the reservoir, controlled by a node inside the network (node 10).

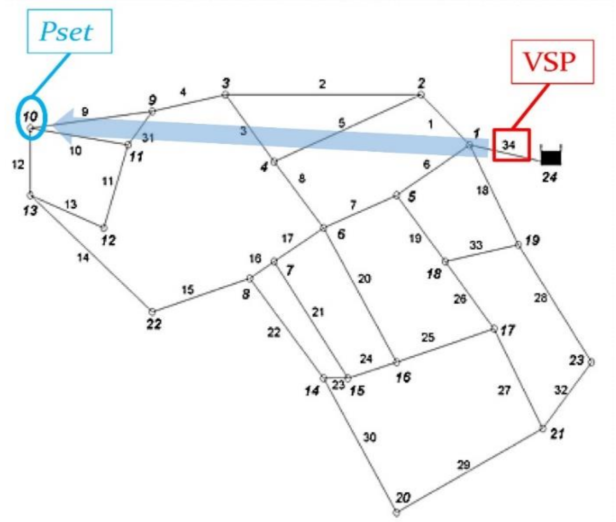


Figure 29. *Apulian* network: VSP on pipe 34; pressure setting on control node.

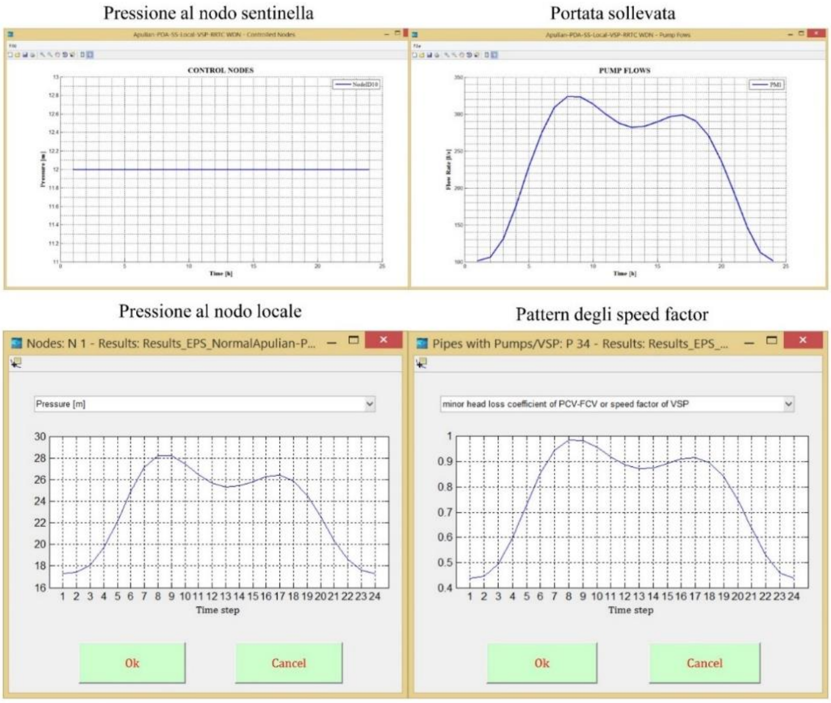


Figure 30. Patterns of pressure simulated at control node, pump flows, pressure at local node and *speed factor* for network scheme in Figure 29.

Figure 30 shows the pressure at the control node and the pump flow rate, the pressure at the local node (N1) as well as the speed factor pattern of the VSP, calculated by WDNetXL-WDNetGIS to keep the control node pressure constant. The pattern of the speed factor could be used to set the VSPs themselves, in the absence of a "real-time" remote control device.

### 3.8.2 *Modelling pumping from wells*

The wells, can be represented as pump systems connected to an unlimited water sources with constant hydraulic grade (commonly known as “reservoirs”). Moreover, they can be defined as pumps connected to variable level tanks, allowing to evaluate the variations of the water level inside the wells, affecting effects groundwater table. It is possible to set *ad hoc* curves describing the pressure drops inside the aquifer starting from undisturbed level of the aquifer, based on field tests. Figure 31 shows the results of the pumping simulation from a well field, each represented as a variable level “tank”: the total flow rate is shown on the left plot and the variation of water level inside the well on the right plot. The same figures show below the results got from by using EPANET on the same simulation; the instability in simulating the water level in the tanks also affect the stability of the total pumped flow.

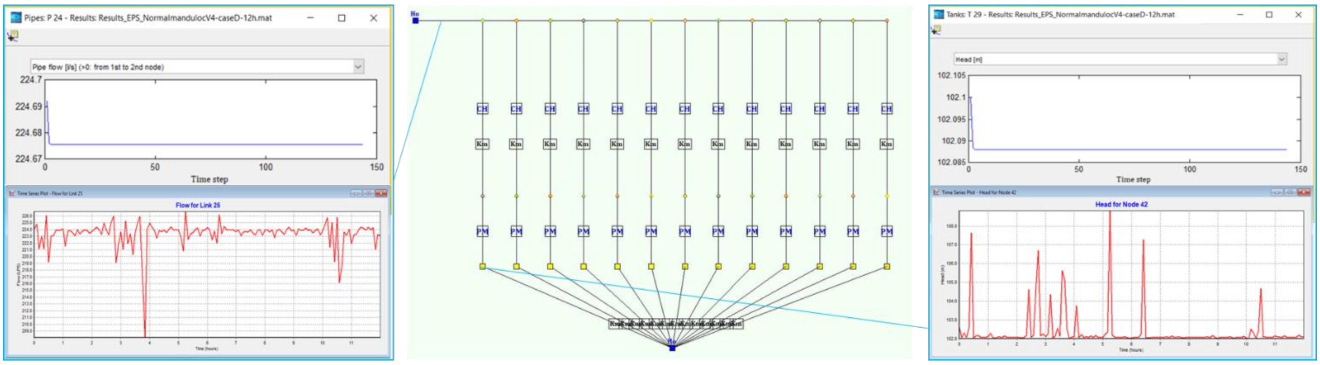
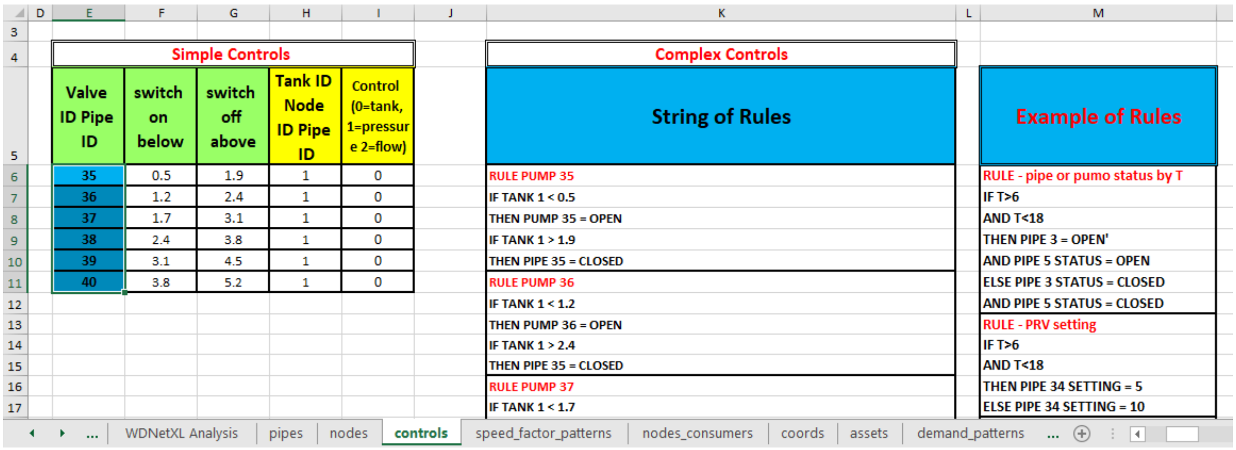


Figure 31. Simulation of pumping from wells in WDNetXL-WDNetGIS vs. EPANET.

### 3.9 *Simple and complex controls*

WDNetXL-WDNetGIS allows importing every kind of controls and rules as defined in EPANET. It is possible to define opening/closing gate rules according to the water level in a tank, the pressure in a node and the water flow along a pipe. The Figure 32 shows table of controls in WDNetXL, which refers to pumps/valves controls (left), complex controls (center), with some examples of setting rules, like controls of pump state over time, controls of the set-points of pressure reducing valves (right).



**Simple Controls**

| Valve ID Pipe ID | switch on below | switch off above | Tank ID Node ID Pipe ID | Control (0=tank, 1=pressure 2=flow) |
|---|---|---|---|---|
| 35 | 0.5 | 1.9 | 1 | 0 |
| 36 | 1.2 | 2.4 | 1 | 0 |
| 37 | 1.7 | 3.1 | 1 | 0 |
| 38 | 2.4 | 3.8 | 1 | 0 |
| 39 | 3.1 | 4.5 | 1 | 0 |
| 40 | 3.8 | 5.2 | 1 | 0 |

**Complex Controls**

**String of Rules**

RULE PUMP 35
IF TANK 1 < 0.5
THEN PUMP 35 = OPEN
IF TANK 1 > 1.9
THEN PIPE 35 = CLOSED
RULE PUMP 36
IF TANK 1 < 1.2
THEN PUMP 36 = OPEN
IF TANK 1 > 2.4
THEN PIPE 35 = CLOSED
RULE PUMP 37
IF TANK 1 < 1.7

**Example of Rules**

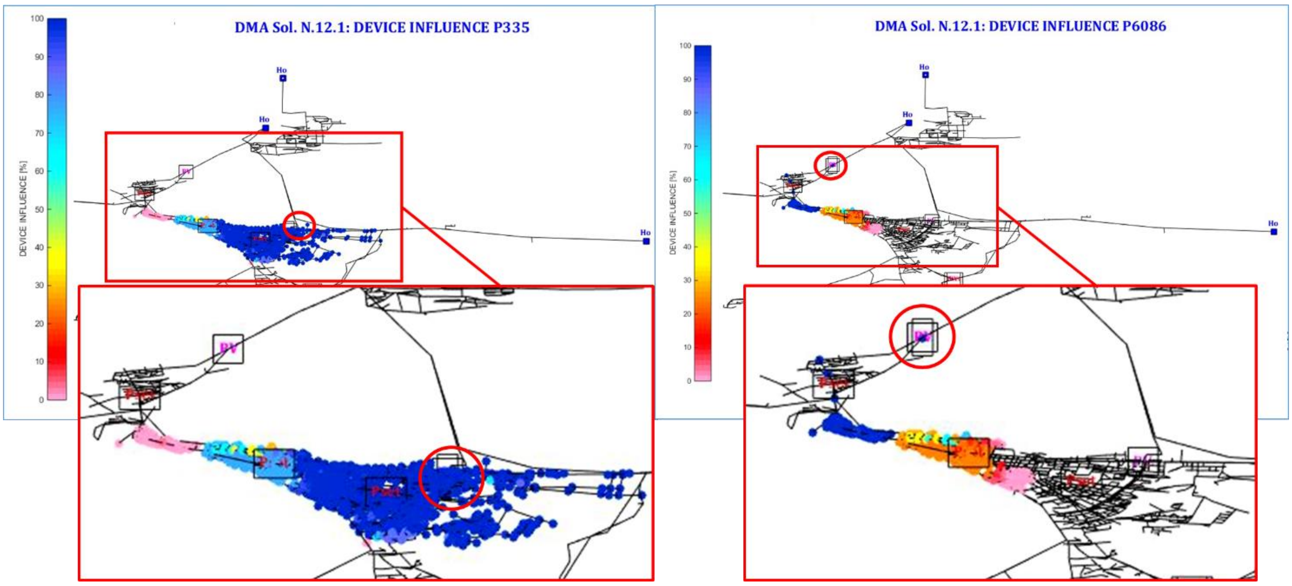
RULE - pipe or pumo status by T
IF T>6
AND T<18
THEN PIPE 3 = OPEN'
AND PIPE 5 STATUS = OPEN
ELSE PIPE 3 STATUS = CLOSED
AND PIPE 5 STATUS = CLOSED
RULE - PRV setting
IF T>6
AND T<18
THEN PIPE 34 SETTING = 5
ELSE PIPE 34 SETTING = 10

Figure 32. WDNetXL tables of controls.

## 3.10 *Evaluation of influence areas for each hydraulic device in the WDNetXL-WDNetGIS simulation*

WDNetXL-WDNetGIS allows, as a unique feature compared to any other commercial software, to analyze the influence of each control device on each node of the network during an operating cycle. For example, the figure below shows, for a large Apulian network, the influence of two pressure control valves. The blue nodes (100% influence) are always supplied and controlled by the valves indicated with a red circle. The nodes with the lowest influence value are supplied, or controlled, only partially by the same valves.

This analysis allows to support the planning of these devices, avoiding ineffective control configuration and also highlighting the need for multiple devices to control the same area.



DMA Sol. N.12.1: DEVICE INFLUENCE P335

DMA Sol. N.12.1: DEVICE INFLUENCE P6086

Figure 33. Analisi delle aree di influenza di due valvole di controllo della pressione in una grande rete pugliese.

### 3.11 *Pipes hydraulic importance identification*

The preliminary assessment of the importance of pipes is performed using the classic *Edge Betweenness* (Girvan and Newman, 2002), a more appropriate centrality metrices for the infrastructure systems analysis, tailored by Giustolisi et al. (2019) for the specific peculiarities of the water distribution networks. The proposed metric is useful for analyzing the hydraulic behavior of the network (Simone et al., 2019). The methodology allows to analyze the topological domain of the water distribution network aimed at understanding their role related to the hydraulic behavior, which acts as a support for planning and management activities. The main features of the tailored centrality metric are: (i) it considers the different roles of nodes within the network (tanks, demand nodes, etc.); (ii) it assigns a weight to the various pipes, generally corresponding to asset characteristics (e.g. length, diameter, hydraulic resistance, etc.) so as to include the characteristics of the physical domain and (iii) it considers the presence of hydraulic devices in terms of information on flow directions. This analysis allows to classify the relevance of the pipes and to assess in advance the importance of closing or adding a pipe in the connective structure of the network based on its topological position (and hydraulic characteristics). WDNetXL preliminary identifies pipes with highest value of centrality metrics, known as *Edge Betweenness*. These pipes normally indicate the most relevant ones for the system hydraulics in terms of flow simulated by the model, with a correlation of over 70%. Figure 34 shows the pipelines with 20% highest values of the Edge Betweenness for the *Apulian-two* network.

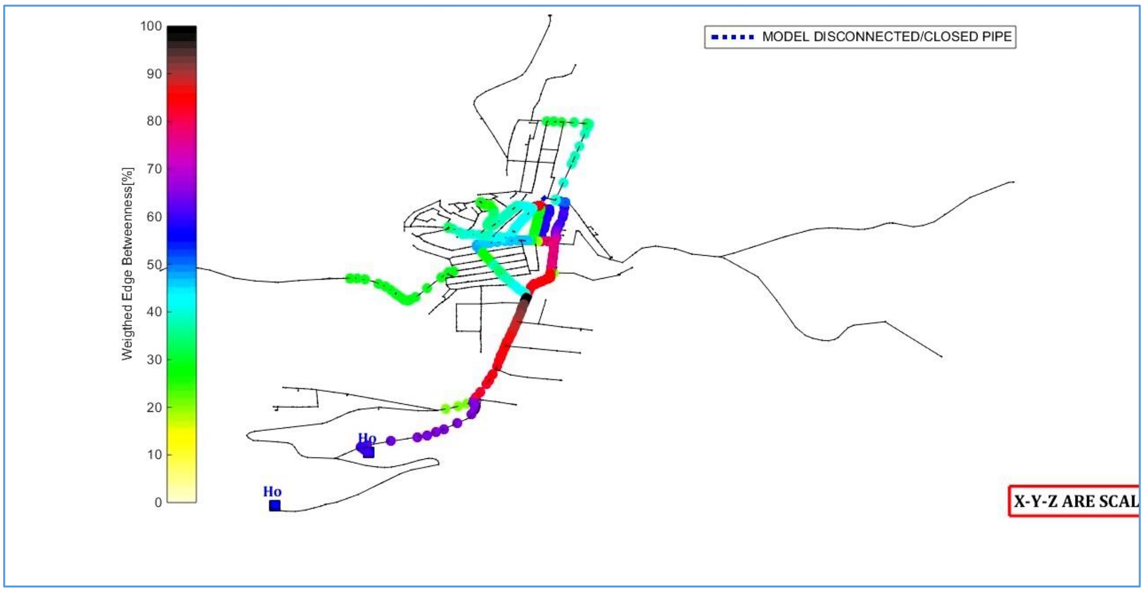


Figure 34. Hydraulic relevance analysis for *Apulian-two* network.

## 4. District Metered Areas (DMA) design and monitoring

The district design aims at partitioning the network into districts to improve WDN management, in particular with respect to *water balance monitoring* aimed at identify water losses. For this reason, in literature they are also called District Metered Areas (DMAs). Indeed, the district design is also intended with reference to pressure monitoring, aimed at knowing the pressure status in different parts of the system for management purposed and to support the calibration of hydraulic model parameters, identifying *pressure monitoring districts*.

Therefore, district design is an operation based on the topological analysis of the network, i.e. on the identification of districts separated by measuring devices (pressure or flow) or sectioning gate valves, installed in vaults/manholes. Assuming the device positions in the network, (as defined in section 3.4), the analysis of monitoring district areas (DMA) in WDNetXL-WDNetGIS allows to:

- identify the modules/segments of the network by taking the "conceptual" cuts at the pipes hosting devices as property of the *link* object,
- identify the DMA obtained assuming the installation of flow meters or sectioning gate valves for the specific DMA configuration,
- identify *pressure districts*, defined by pressure gauges and the bounds of the DMA.

The following figures show the analysis of the DMA designed for a large Apulian network:

- *segmentation of the topological network structure of the aqueduct*: aimed at identifying the modules/segments separated by "conceptual" cuts, in which flow meters or sectioning gate valves can be installed; since not all the "conceptual cuts" will host devices or valves, the segments/modules identified represent the *maximum* number of DMAs (58 in the figure);
- *hydraulic districts*: identification of the DMAs for the mass balances monitoring, by positioning sectioning gate valves and flow meters (57 in the figure);
- *pressure districts*: identification of pressure districts, assuming pressure gauges both on the edge and inside each DMA for mass balances.

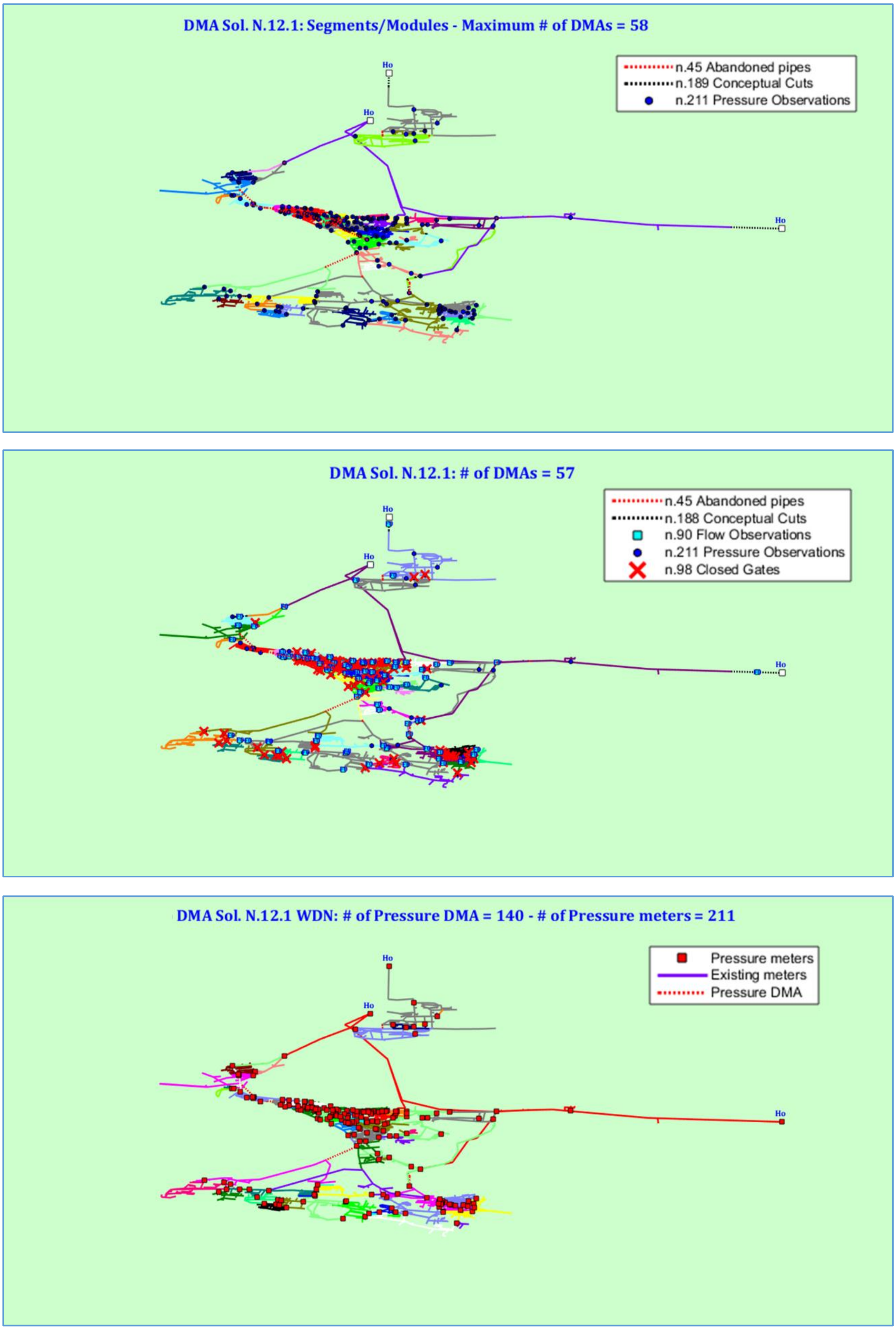


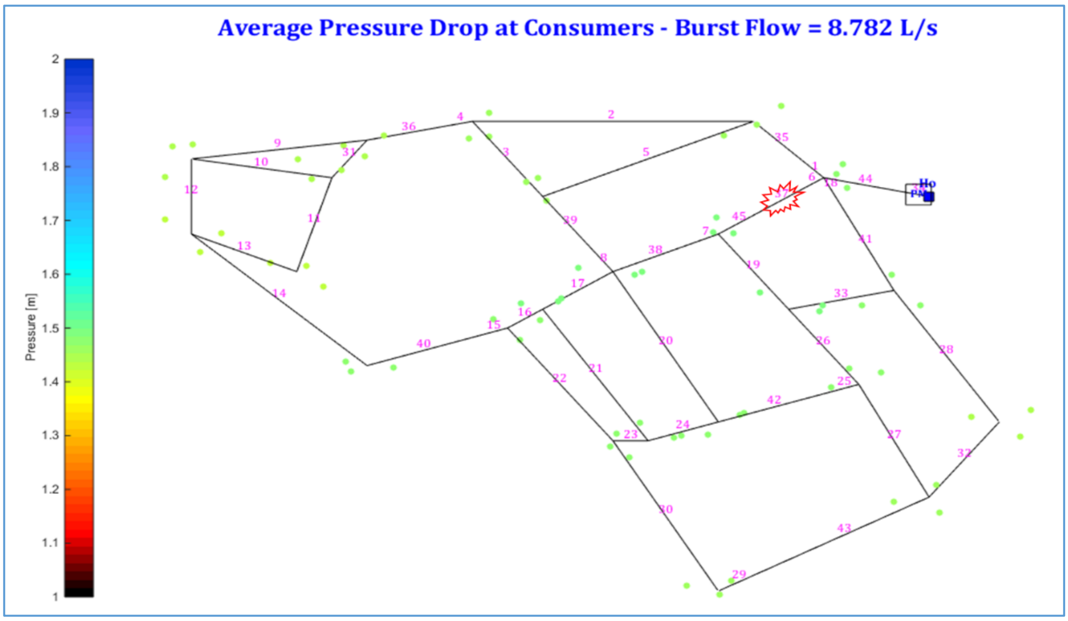
Figure 35. DMA Analysis for a large Apulian network.

## *5. Analysis of abnormal operating scenarios*

Pipeline breakage events are studied as random phenomena, associated to internal or external factors but statistically related to leakages and network deterioration. The *pressure-driven* hydraulic simulation in WDNetXL-WDNetGIS allows to analyze the functioning of the network in abnormal operating conditions, which can result into risk of possible pressure and supply shortages to users. In particular, it is possible to evaluate the effects of *bursts* events either before or during repair works (i.e. requiring closing isolation valves). It has to remark that the analysis of these scenarios, is crucial for assessing the reliability of the system, as indicated by ARERA with the M2 macro-indicator since it enables assessing the impact on users in terms of complete unsupplied demand (due to the isolation of the portions affected by the works) and partial unsupplied demand (due to possible deficit in some hours of the operating cycle),

### 4.1 *Modelling bursts events*

Bursts can have significant effects on the ability to supply water to the network. The possibility of performing accurate analysis (*burst analysis* function in WDNetXL-WDNetGIS), which takes into account the demand supplied to consumers and the volumetric losses at the same time, represents a key feature to assess system reliability. Figure 36 shows the results of the burst analysis for the *Apulian* network where broken pipe is marked in red.



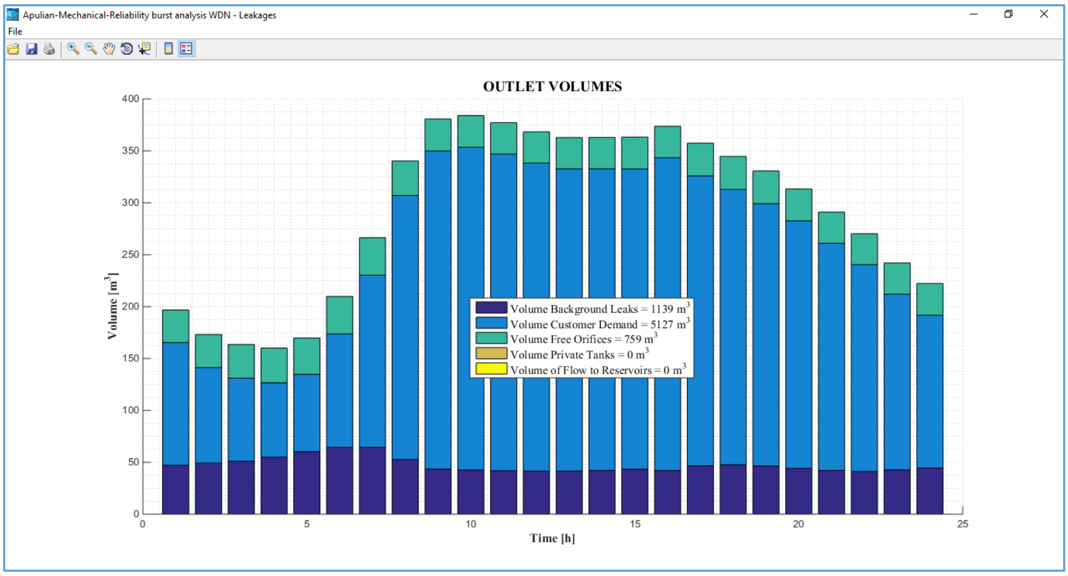


Figure 36. Failure analysis for *Apulian* network.

## 4.2 *Modeling WDN with closed isolation valves*

As mentioned in table “WDNetXL vs. EPANET”, WDNetXL-WDNetGIS allows the simulation of WDN with closed sectioning gate valves, e.g. at the edge of DMA, accounting for the real topological variations of the network. As mentioned in the section "Representation of hydraulic devices and valves as property of the link object" WDNetXL automatically associates a small pipe close to the node where the sectioning gate valve is defined as pipe feature. Therefore, the simulation considers the closure of this small pipe rather than the whole pipe. The same section reports the definition of isolation valves, useful for separating network segments to allow programmed or unexpected works.

This section reports the topological effect of closing isolation valves to exemplify also the topological-hydraulic operation of closing sectioning gate valves of DMA. The difference between isolation and sectioning gate valves is not in the topological treatment in WDNetXL, but lies in the fact that the former are normally open and, during analyses of segment isolation, they disconnect the portion of the network involved in maintenance work; while the latter are always closed to hydraulically configure DMA. Figure 37 shows the division into segments for the analysis of the isolation valve system (IVS), which returns also the association between segments and the isolation valves to be closed in a MS-Excel® file.

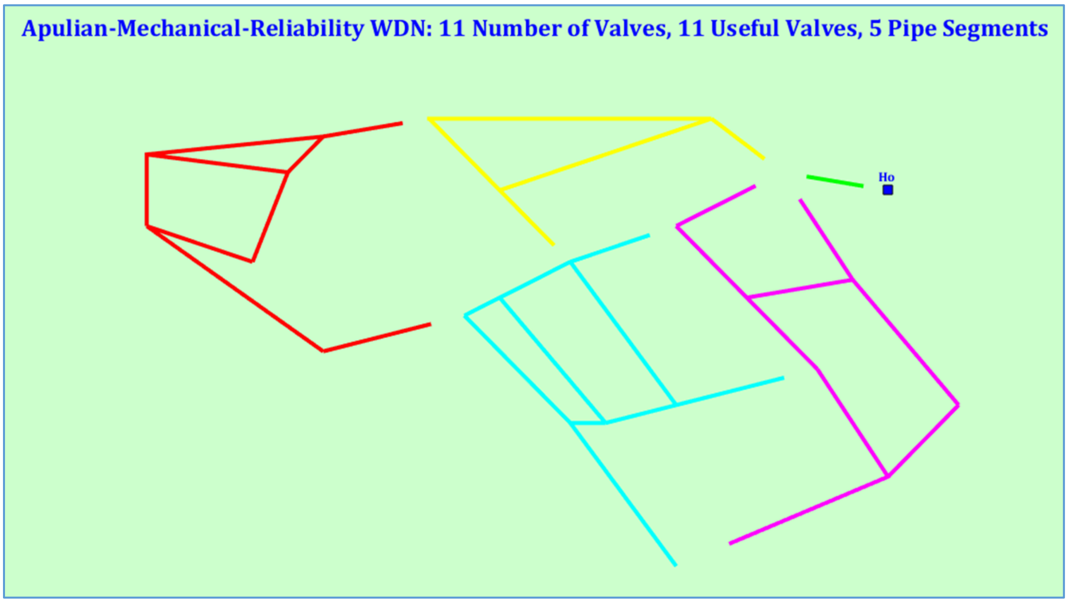
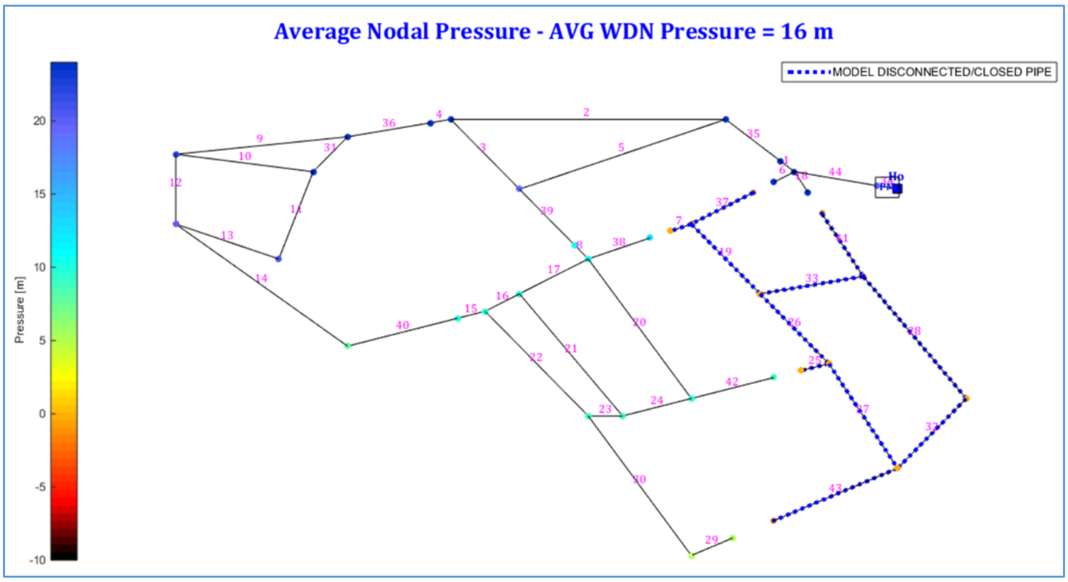


Figure 37. Network segments design after closing isolation valves.

In the failure events which requires closing the magenta-colored district, the hydraulic simulation recognizes the portion of the network which has to be isolated and the unintentionally disconnected portions, i.e. disconnected from pumps or tanks. The simulation results are shown in Figure 38.



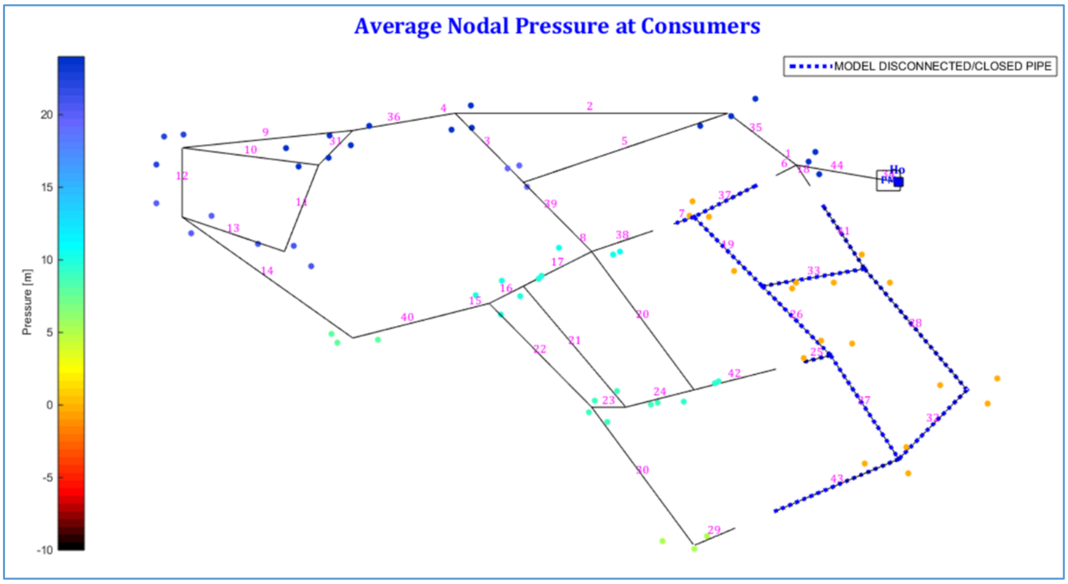


Figure 38. Scenario analysis after closing a segment in the *Apulian* network: nodal pressure and pressure at consumers' nodes.

## 6. Computing capabilities

### 6.1 Large Networks

The hydraulic model of WDNetXL-WDNetGIS implements the solving algorithm called Generalized Global Gradient Algorithm (G-GGA) that allows the analysis for planning and management of networks of any size. The effectiveness and robustness of the hydraulic model have been acknowledged at international level with publications in the most relevant journals in this field and tested on real large size networks. The hydraulic model, in fact, allowed the solution of thousands of topological and hydraulic configurations for networks like Milan, Bari, Taranto, Acilia (Rome) and various networks in Puglia (Italy) and Norway, for the analysis and support of DMA design.

Due to the continuous development and improvement of the system, any of these cases showed instabilities. The robustness, accuracy and computational efficiency of the G-GGA for real large networks has been tested using optimization procedures that modify the hydraulics, the state of the devices and the topology of the network hundreds of thousands of times during the search for best solutions. The capability of running models of large networks is also guaranteed by 64bit architecture which is used to deploy WDNetXL-WDNetGIS applications. A statistical analysis of the simulations for the 24 hours of the operating cycle was performed on six large real networks using an Intel® Core i7 laptop, in order to provide detailed information on the main characteristics of each simulation.

| L [km] | # Reservoirs | # Tanks | # Pumps | # PCV | CPU GGA/ EGGA [sec] | Average value of the squared errors of the energy and mass balance | Maximum error of the energy balance | Maximum error of the mass balance | Average value of the error of the energy balance | Average value of the error of the mass balance | Number of Iterations of GGA/ EGGA | CPU WDN model [sec] | Error Global Mass Balance [$m^3/s$] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2000 |  |  | 96 |  | 0.0119 | 5E-11 | 7E-04 | 3E-09 | 4E-07 | 1E-11 | 11 | 0.3356 | 1.1E-07 |
| 1300 | 1 | 15 | 33 | 134 | 0.0066 | 3E-10 | 2E-04 | 6E-02 | 6E-08 | 1E-05 | 151 | 2.2326 | 0.0377 |
| 900 | 2 | 12 | 60 (25 VSP) | 117 | 0.0069 | 3E-11 | 2E-05 | 7E-04 | 3E-09 | 9E-08 | 82 | 1.5409 | 0.00063 |
| 700 | 1 |  | 5 |  | 0.0075 | 1E-09 | 9E-06 | 7E-03 | 1E-08 | 4E-07 | 15 | 0.3569 | 0.00712 |
| 400 | 3 |  |  | 5 | 0.0070 | 4E-08 | 2E-02 | 1E-06 | 1E-05 | 1E-09 | 19 | 0.4176 | 9.4E-07 |

## 6.2 *Extended period simulation scenearios*

The hydraulic model of WDNetXL-WDNetGIS allows defining extended period simulations of any duration, with user-defined time step, in compliance with steady state hydraulic modeling assumptions which are common to all software used to support WDN planning and management. For example, the software was used in the context of functional optimization (e.g. pipes sizing and variable level tanks) and operational (e.g. pump scheduling) optimization procedures that required thousands of extended period simulations equivalent to 168 steps per hour. The ability to manage 64bit computing represents a further guarantee of storing patterns and extended period simulations even for large networks compared to other calculation software based on the 32bit EPANET hydraulic solver.

## 7. *WDNetXL*

The system includes six modules, whose characteristics are briefly reported below.

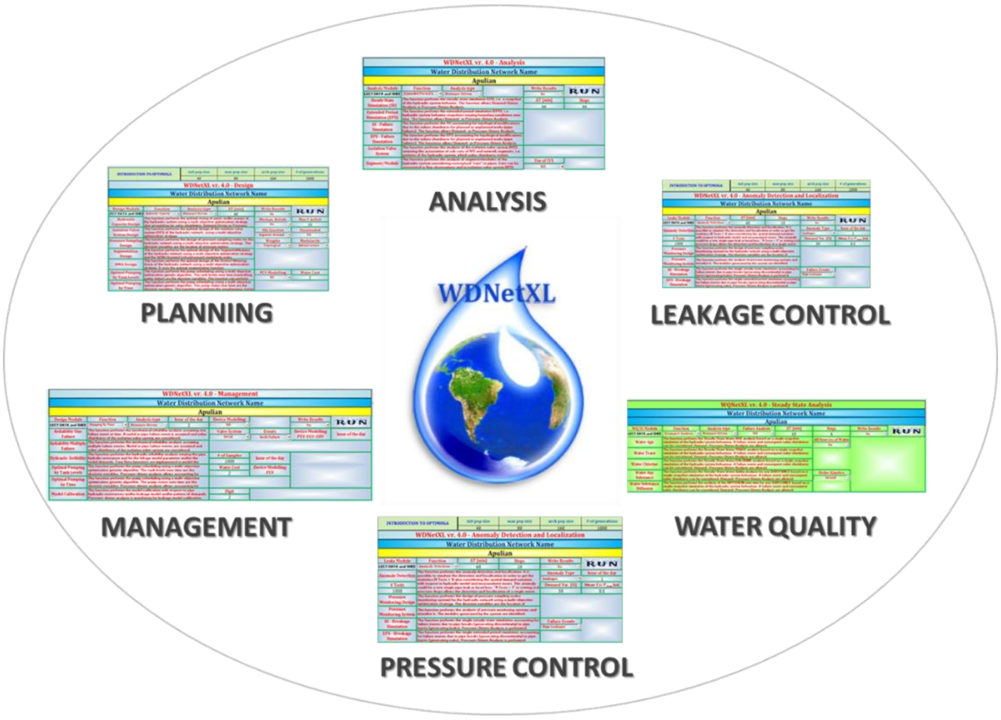


Figure 38. WDNetXL system modules.

***WDNetXL Analysis Module*** is the main WDNetXL module. The six functions of the module allow:

- the Extended Period Simulation (EPS), i.e. snapshots of the hydraulic system behavior with the boundary conditions changing over time; it can be run as *demand-driven* or *pressure-driven* analysis,
- the Extended Period Simulation (EPS) considering pipes burst events: *pressure-driven* analysis is mandatory,
- the simulation of the extended period considering the topological changes due to the closure of isolation valves to allow planned or unplanned maintenance work (pipe failure or rehabilitation); the function allows *demand*- and *pressure-driven* analysis, but the second analysis is preferred,
- the identification of the areas of influence for each hydraulic device during the simulation of the extended period,
- the analysis of the isolation valve system (IVS) by returning the association of subsets of IVS and network segments, i.e. portions of the hydraulic system isolated by closing the isolation valves,
- segmentation analysis and hydraulic district identification (DMA).

***WDNetXL planning/design module***: the module allows to face different planning/design problems. It mainly uses the multi-objective optimization and returns Pareto fronts of scenarios as decision support for management and design problems. The eight functions of the module allow:

- pipe sizing and/or pump selection using a multi-objective optimization strategy which also takes into account the isolation valve system (IVS): the function supports either *demand*- or *pressure-driven* analysis,
- isolation valve system management and design using a multi-objective optimization strategy and the modularity index tailored from complex network theory,
- planning/design of pressure monitoring using a multi-objective strategy and modularity index tailored from complex network theory to identify pressure-metering districts (i.e., pressure meters are installed in the districts edges).
- planning/design of topological segmentation using a multi-objective optimization and modularity index, in order to evaluate *nested virtual districts* useful for the following function,
- District Metering Areas (DMAs) planning/design using a multi-objective optimization strategy and the modularity index tailored from complex network theory, in order to evaluate different DMA configurations for supporting final decisions; *pressure-driven* analysis is mandatory,
- pump scheduling, as *time patterns*, using a multi-objective optimization strategy; the function can concurrently perform pipe sizing, design of variable level tanks or selection of pumps for the whole network; in *pressure-driven* analysis is recommended,
- pump scheduling, as *controls by water levels in tanks*, using a multi-objective optimization strategy; the function can concurrently perform pipe sizing, design of variable level tanks or selection of pumps for the whole network; in *pressure-driven* analysis is recommended,
- Asset rehabilitation management and design assuming fixed percentages of pipe replacement and considering the reduction of *volumetric losses*; *pressure-driven* analysis is mandatory.

***WDNetXL management module***: the module deals with various aspects related to water distribution network management. The six functions of the module allow:

- mechanical reliability analysis, assuming scenarios with pipes bursts or complete pipes breakage, or maintenance work planning requiring the closure of IVS; *pressure-driven* analysis is mandatory,
- mechanical reliability analysis, considering concurrent multiple failure events, *pressure-driven* analysis is mandatory,

- hydraulic reliability analysis assuming varying hydraulic resistance and/or volumetric losses and/or node demands, *pressure-driven* analysis is suggested,
- pump scheduling, as *time patterns*, using a multi-objective optimization strategy; *pressure-driven* analysis is suggested,
- pump scheduling, as *controls by water levels in tanks*, using a multi-objective optimization strategy; *pressure-driven* analysis is recommended,
- model calibration related to pipes hydraulic resistance and/or volumetric leakage model and/or demand patterns; pressure-driven analysis is recommended.

***WDNetXL leakage detection module***: the module supports pre-location of leaks to support leakages detection surveys. The three function of the modules allow:

- pre-location of pipes bursts assuming anomalies between model forecasting and pressure/flow measurements,
- design of pressure monitoring using a two-objective optimization strategy; it returns several pressure monitoring district configurations (number of measures versus infrastructure modularity index),
- Analysis of pressure monitoring districts.

***WDNetXL pressure control module***: it implements some strategies for reducing *volumetric losses*, in order to maximize the actual technical life of pipes. The three functions allow:

- extend period simulation, i.e. snapshots of hydraulic system behavior by assuming boundary conditions changing over time and considering pressure reduction/sustain valves and/or variable speed pumps; *pressure-driven* analysis is mandatory,
- extended period simulation considering pipes bursts events and pressure reduction/sustain valves and/or variable speed pumps; *pressure-driven* analysis is mandatory,
- extended period simulation considering topological changes due to the isolation valves closure to allow planned or unexpected maintenance work (pipe rehabilitation or repair works) and considering pressure reduction/sustain valves and/or variable speed pumps; *pressure-driven* analysis is recommended.

***WQNetXL***: it is module related to the water quality in Water Distribution Network, assuming either pipes bursts conditions or isolation valves closing.

## *8. WDNetGIS*

The WDNetGIS data structure (developed for the common GIS software, such as QGIS and ArcGIS®) in ESRI Shapefile (.shp) is fully compatible with the Excel addin WDNetXL. It allows to integrate geographical and topological information with hydraulic information, that is, to rationally associate the fiscal and cadastral data base (GIS - Geographic Information Systems) with the hydraulic model, thus supporting various activities related to analysis, management and planning of water networks. In particular, the main WDNetGIS functions are:

- hydraulic model import from different formats, i.e EPANET .inp files;
- connection to the commonly GIS database formats;
- synchronization between the hydraulic model and data related to the geographic and asset information of the network, stored in the GIS database used by water companies;
- association of consumption data to the synchronized model.

The WDN layout (pipes, nodes and pressure/flow meters, controls and regulations) are exported as ESRI® Shapefile. WDNetGIS also allows to choose the coordinate reference system for georeferencing layers in GIS software map canvas, thus integrating missing information of the network with Web Map Services visualization.

Each feature of the network is represented as point or line. According to the devices' representation in WDNetXL (see 3.4), each node (i.e. vertices of each pipe, flow and pressure controls devices and meters) are defined as bidimensional points, whereas pipes are defined as linear features (i.e. bidimensional polylines). Each device is represented in GIS map canvas with a unique symbology (see Figure 39). All hydraulic devices are geo-referenced and correctly displayed as points associated to pipes where they are installed. It allows accuracy in the device representation and consistency with the rational definition of the hydraulic model. An example of the devices representation in the map canvas is in Figure 40:

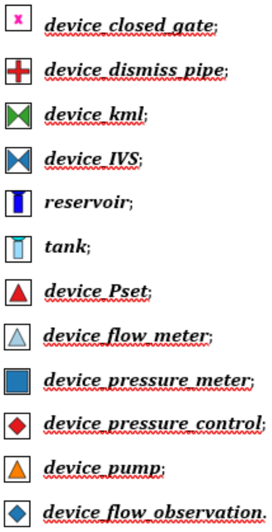


Figure 39. Devices symbology legend.

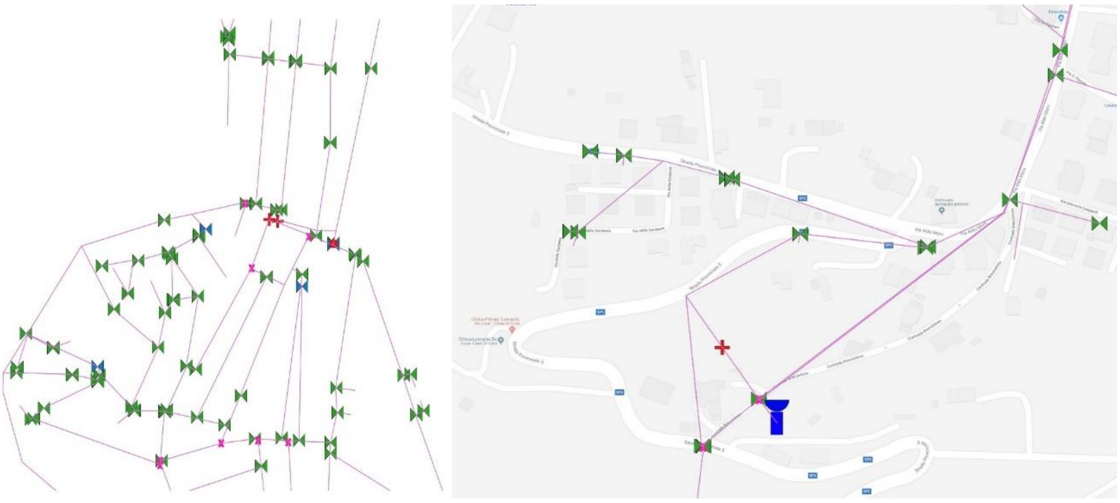


Figure 40. WDN devices representation on GIS map canvas.

WDNetGIS data structure allows the definition of each network feature based on two conceptual visualization levels, shown in Figure 41:

- real network layout (hydraulic model), reporting pipes in the original data format, for operational management purposes,
- connectivity between pipes and nodes (connectivity model), which accurately represents the network topology in order to support assessments related to the hydraulic system domain.

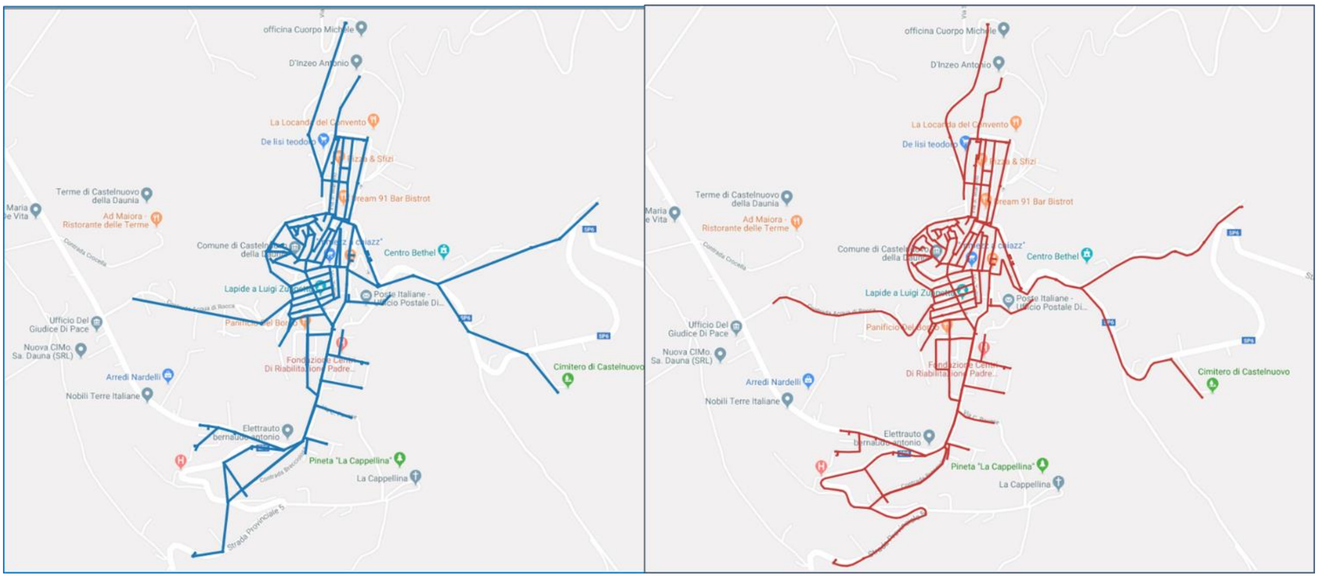


Figure 41. Connettività tra tubazioni e nodi della rete (sinistra), tracciato reale delle condotte della rete (destra) in WDNetGIS.

The WDNetGIS hydraulic simulation returns a group of geo-referenced layers according to the reference system of pipes and nodes layers, and saves as ESRI Shapefile (.shp). The output layers represent the evolution of hydraulic variables during the simulation.

Data of the hydraulic models in WDNetGIS can be updated adding the consumption data (e.g. meter readings) using the synchronization with fiscal and cadastral database stored in the GIS water company, thus allowing the analysis of operating scenarios consistent with all the information of management interest. The synchronization between the hydraulic model data and the GIS management data preserves the completeness of the original information allowing prompt verification of the original data.

Figure 42 (left) shows the result of the synchronization process: the red dotted sections represent the pipes that are no longer in the GIS database (e.g. abandoned) but still included in the hydraulic model, the blue features represent the pipes that are in the GIS database but missed in the hydraulic model and the cyan features represent the pipes common to both databases (i.e. asset data such as diameter and length are verified). Figure 42 (right) shows the association of fiscal and geographical data, or meter readings, with the synchronized network.

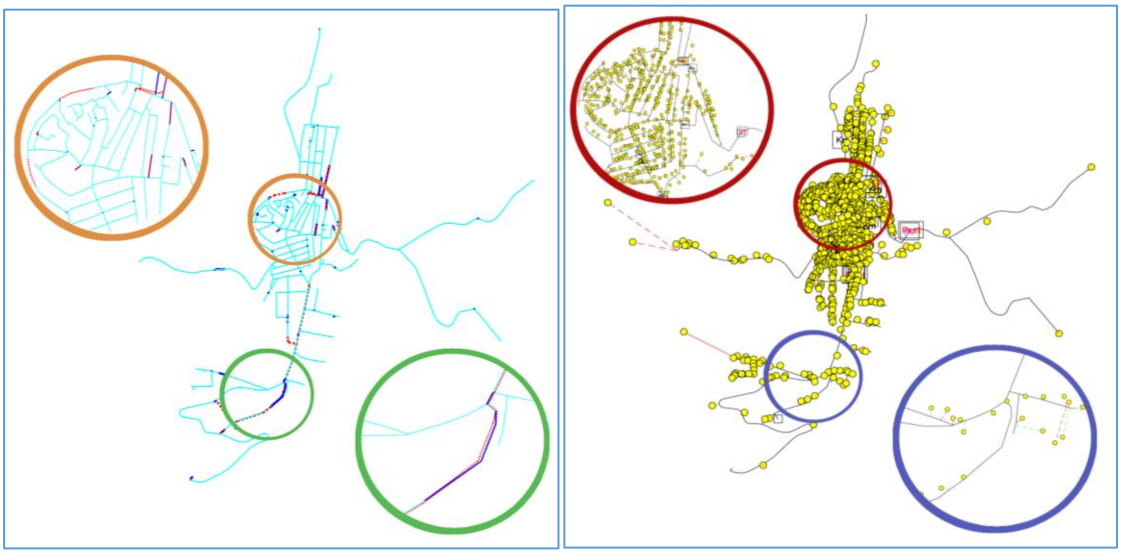


Figure 42. Real WDN layout integrated to GIS data (left), WDN synchronized model merged to water meters positions and water consumptions (right).

It is worth noting that, unlike commercial software packages, WDNetXL-WDNetGIS is based on functions that can be easily and quickly customized and/or expanded according to specific user’s requests, in particular adapting the WDNetXL-WDNetGIS to interface with the specific data management systems.

Any changes in WDNetGIS can be synchronized in WDNetXL through the ESRI® *shapefile* (* .shp) in order to allow using the additional planning and management modules in WDNetXL.

The innovative product/process transfer strategy underlying WDNetGIS allows to test and use new functions in every GIS environment. Furthermore, the possibility of interface customization with every GIS data management platform offers allows new functions in the WDNetGIS-WDNetXL system.

### 9. *Returning results in EPANET*

The integrated hydraulic and topological analysis features implemented in WDNetXL-WDNetGIS highlight the ability to carry out a more realistic evaluation of the WDN by integrating the phenomenological formulation of the initial and boundary conditions in the basic hydraulic equations In addition, it provides simulation results that area more accurate and faster than other commercial software pacakges. In particular, WDNetXL-WDNetGIS is able to evaluate all demand patterns referred to nodes, (consumers, private tanks, water losses) and devices behavior (hydraulic resistances, speed factors of variable speed pumps, valve closure states, etc.) as calculated according to the peculiar boundary conditions during the operating cycle (e.g., daily or weekly). Therefore, it is possible to exports all results data in EPANET, defined as snapshot of the WDN behavior during the operative cycle. In this way, the EPANET hydraulic model would be more realistic and accurate than other hydraulic models. Nonetheless, the hydraulic model returned in EPANET loses its forecasting capabilities when applied outside the operative boundary conditions used for its creation. For example, if the *volumetric losses* changes, after a network asset rehabilitation operation, when the operating conditions of the pressure control devices change or after a DMA design implementation in the network, pressure variations in the network, as evaluated in EPANET, cannot modify the fixed pattern of volumetric water losses.

***In order to allow the complete use of the hydraulic models, IDEA-RT usually offer some licenses of the WDNetXL and WDNetGIS analysis module together with on-the-job training for the personnel of water companies.***

## *10. References*

Germanopoulos, G. 1985 A technical note on the inclusion of pressure dependent demand and leakage terms in water supply network models. *Civil Eng. Syst.*, 2(3), 171–179.

Girvan M. & Newman M. 2002. Community structure in social and biological networks. *Proceedings of the National Academy of Sciences*, 99(12), 7821–7826.

Giustolisi, O., Berardi, L., Laucelli, D. 2014 Modeling local water storages delivering customer-demands in WDN models, *J. Hydr. Eng.*, 140(1), 89-104.

Giustolisi, O., Berardi, L., & Laucelli, D. 2012a Accounting for directional devices in WDN modeling. *J. Hydr. Eng.*, 138(10), 858-869.

Giustolisi, O., Berardi, L., Laucelli, D. & Savic, D.A. 2012b A Computationally efficient modeling method for large size water network analysis. *J. Hydr. Eng*., 138(4), 313-326.

Giustolisi, O. & Walski, T.M. 2012 A Demand Components in Water Distribution Network Analysis. *J. Water Resour. Plan. Manage.*, 138(4), 356 -367.

Giustolisi, O., Berardi, L. & Laucelli, D. 2012c Generalizing WDN simulation models to variable tank levels. *J. Hydroinf.*, 12(3) 562–573.

Giustolisi, O. & Laucelli, D. 2011 Water distribution networks pressure-driven analysis using EGGA. *J. Water Resour. Plan. Manage.*, 137(6), 117-127.

Giustolisi, O. 2010 Considering actual pipe connections in WDN analysis. *J. Hydr. Eng.*, 136(11), 889–900.

Giustolisi, O. & Todini, E. 2009 Pipe hydraulic resistance correction in WDN analysis. *Urban Water J.*, 6(1), 39–52.

Giustolisi, O., Savic, D.A. & Kapelan, Z. 2008a Pressure-driven demand and leakage simulation for water distribution networks. *J. Hydr. Eng.*, 134(5), 626–635.

Giustolisi, O., Berardi, L., Laucelli, D., Savic, D., Kapelan, Z. (2016). Operational and Tactical Management of Water and Energy Resources in Pressurized Systems: Competition at WDSA 2014. *J. Water Res. Plan. and Manage,* 142(5).

Girvan M, Newman ME (2002) *Community structure in social and biological networks*. Proc Natl Acad Sci 99(12):7821–7826

Giustolisi, O., Kapelan, Z. & Savic, D.A. 2008b An algorithm for automatic detection of topological changes in water distribution networks. *J. Hydr. Eng.*, 134(4), 435–446.

Giustolisi, O., Ridolfi, L., Simone, A. (2019). "Tailoring Centrality Metrics for Water Distribution Networks." *Water Resource Research*, USA., 55, 2348–2369,

Gupta, R. & Bhave, P. R. 1996 Comparison of methods for predicting deficient network performance. *J. Water Resour. Plan. Manage.*, 122(3), 214–217.

Hamam, Y.M. & Brammeler, A. 1971 Hybrid method for the solution of piping networks. *Proc. IEEE*, 118, 1607–1612.

Kesavan, H. K. & Chandrashekar, M. 1972 Graph-theoretic models for pipe network analysis. *J. Hydr. Div.*, 98(2), 345–364.

Isaacs, L. T. & Mills, K. G. 1980 Linear theory method for pipe network analysis. *J. Hydr. Div.*, 106, 1191–1120.

Martin, D. W. & Peters, G. 1963 The application of Newton's method to network analysis by digital computers." *J. Inst. of Water Engrs.* X, 115–129.

Piller, O. & Bremond, B. (2001) Modeling of Pressure Regulating Devices: A Problem Now Solved. *Proc. 3rd Annual Symp. on Water Distribution Systems Analysis*, ASCE, Reston, Va., Section: 1, Chapter: 290.

Piller, O. & Van Zyl, J.E. 2007 A unified framework for pressure-driven network analysis. *Proc. Water Management Challenges in Global Change: Proceedings of Computer and Control in Water Industry (CCWI2007)*. Ulaniki, B., Vairavamoorthy, K. & Butler, D. (eds), Taylor & Francis, London, UK, 25–30.

Piller, O. & Van Zyl, J. E. 2009 Pressure-driven analysis of network sections via high-lying nodes. In: Boxal, J. & Maksimovic, C. (eds). *Proceedings of Computer and Control in Water Industry*. Taylor & Francis, London, UK, 257–262.

Reddy, L.S. & Elango, K. 1989 Analysis of water distribution networks with head dependant outlets. *Civ. Eng. Syst.* 6, 102–110.

Rossman, L.A. 2000 *Epanet2 Users Manual*. US Environmental Protection Agency, Cincinnati, OH.

Shamir, U. & Howard, C.D.D. 1968 Water distribution network analysis. *J. Hydr. Div.* 94, 219–234.

Simone A., Ciliberti F.G., Laucelli D.B., Berardi L., Giustolisi O. (2019) *Edge Betweenness for Water Distribution Networks domain analysis*. Journal of Hydroinformatics, accepted 16 August 2019.

Tanyimboh, T.T. & Templeman, A.B. 2004 A new nodal outflow function for water distribution networks." *Proc. 4th International Conference on Eng. Computation Technology* (CD-ROM), Civil-Comp Press, Stirling, UK, paper 64.

Tanyimboh, T.T., Tabesh, M. & Burrows, R. 2001 Appraisal of source head methods for calculating reliability of water distribution networks. *J. Water Res. Plan. Manage.* 127(4), 206–213.

Todini, E. & Rossman, L.A. 2013 A unified framework for deriving simultaneous equations algorithms for water distribution networks. *J. Hydr. Eng.*. 139(5), 511-526.

Todini, E. 2011 Extending the global gradient algorithm to unsteady flow extended period simulations of water distribution systems. *J. Hydroinf.*, 13(2), 167–180.

Todini, E. 2003 A more realistic approach to the “extended period simulation” of water distribution networks. In: Maksmovic C., Butler D. & Memon, F. A. (eds). *Advances in Water Supply Management*. A.A.Balkema Publishers, Lisse, The Netherlands, 173–184.

Todini, E. & Pilati, S. 1988 A gradient method for the solution of looped pipe networks. *Computer Applications in Water Supply*, vol. 1. John Wiley & Sons, New York, 1–20.

Tucciarelli, T., Criminisi, A. & Termini, D. 1999 Leak analysis in pipeline systems by means of optimal valve regulation. *J. Hydr. Eng.*, 125(3), 277–285.

Wagner, J.M., Shamir, U. & Marks, D.H. 1988 Water distribution reliability: simulation methods. *J. Water Res. Plan. Manage.*, 114(3), 276–294.

Wood, D.J., & Charles, C.O.A. 1972 Hydraulic network analysis using linear theory. *J. Hydr. Div.*, 98, 1157–1170.

Wood, D.J., & Rayes, A.G. 1981 Reliability of algorithms for pipe network analysis. *J. Hydr. Div.*, 107, 1145–1161.