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WQNetXL: A MS-Excel Water Quality System Tool for WDNs

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Abstract

WQNetXL is a system tool for water quality analyses of water distribution networks (WDNs). WQNetXL is a collection of MS-Excel add-ins. The user-friendly environment allows just in time research transfer to students and technicians, sometimes anticipating research publications. Being water quality analyses based on network hydraulics, WQNetXL embeds the recent advances in hydraulic analyses already implemented in WDNetXL (the system tool for analysis, planning and management of WDNs). Thus, WQNetXL performs water quality also using the advances related to modelling of e.g.: background leakages; pressure-deficient conditions; pressure/flow controlled devices; private tanks; multi-floor orifices; etc.

Keywords: Water Network Segmentation; Districtualization; Sectorization; Modularity Index; Infrastructure Segmentation

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1. Introduction

Environmental, financial, social, and normative constraints are increasing the complexity in managing water distribution networks (WDNs) and water companies ask for reliable indications for the effective allocation of capital investments. In recent years the rapid improvements and pervasiveness of information technology, as well the increasing computational capabilities, have motivated researchers in developing advanced analysis tools and strategies to support WDN analysis, planning and management activities. However, direct transfer of innovations from scientific/technical research to the intended recipients is often hampered by many practical constraints. On the one

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hand, incorporating new methodologies in existing commercial packages might imply modifications of the software architecture and significant investments by software companies. On the other hand, technicians are often reluctant to change their consolidate practices in favor of new tools, although they would permit more advanced and targeted responses to technical problems. All this makes difficult the transfer of research achievements to daily real scale applications. WDNetXL system (www.hydroinformatics.it) has been developed to fill this gap entailing a research transfer paradigm which makes readily available the most advanced analysis and decision support methodologies into a worldwide known data-management environment (Excel in Microsoft Office® - MS-Excel) [1]. In this manner, introducing the most recent contributions in WDNetXL to efficiently solve technical problem can be performed quickly without the need of changing the software architecture, which is MS-Excel, and allowing a rapid research transfer even for educational purposes.

We here present WQNetXL which is a system tool focused on water quality analyses for WDNs; similarly to WDNetXL, WQNetXL is intended to perform a rapid research transfer in order to make available enhanced functions for water quality analyses (age/trace of the water and transport of reacting substance) which are the base of enhanced function for managing hydraulic system water security/quality.

It is worth noting that water quality analyses are based on network hydraulics and kinetics of travelling substances; therefore WQNetXL can take benefit of the advances in hydraulic modelling and system analysis of WDNetXL being developed in the same paradigm and using the same base of data.

To this purpose it is to recall that water quality is generally performed, e.g. in EPANET2 (Rossman, 2000) [2], using the classic demand-driven analysis, i.e. the nodal demands are considered fixed *a priori* in the hydraulic model.

Nevertheless, a more realistic prediction of the behavior of WDNs needs to consider the different components of demands actually present in all the networks, see Giustolisi and Walski [3] for further details. For example, customer-based demands and background leakages are always existent in the hydraulic systems; therefore, it is mandatory to model water quality (e.g., computing the water age or the amount of substance reaching faucets) more realistically using enhanced hydraulic analyses.

In particular, through the function both for enhanced hydraulics and system topology analyses already built in WDNetXL, WQNetXL models water quality considering:

- background leakages, using Germanopoulos' model [4,5];
- pressure-deficient conditions for satisfaction of customers' water requests, using Wagners' model [6,7];
- multi-floor orifices in order to consider multi-floor buildings [3];
- private tanks filling/emptying process [8];
- flow control device [9];
- pressure control devices and variable speed pumps, also remotely controlled;
- network hydraulics as a consequence of pipe failures considering topologic changes due to valve shutdowns [10].

We here present the first version of WQNetXL which is devoted to enhance water quality analyses through enhancing hydraulics. This is the base for the development of design and management functions coupling effective and advanced water quality analyses and optimization procedures driven by specific cost-benefit objectives.

In order to show the analyses feature, the Apulian network water age and trace is computed in a failure scenario.

2. Hydraulics of water distribution networks

A steady-state simulation model run is a snapshot representing the average behavior of the real hydraulic system in a time interval ΔT. The hydraulic system is then supposed to be in a steady-state condition during ΔT.

An extended period simulation (EPS) model run is a sequence of steady-state snapshots of the hydraulic system. It is a strategy to model the changes of the hydraulic system state over time. These changes are related to boundary conditions such as required demands (volumes in ΔT), levels of tanks, status of pumps, status of valves, etc.. Therefore, in EPS each snapshot represents the average hydraulic system behavior in the time interval ΔT which is the step size of the simulation. The time variable t_s is here assumed as the starting time of each snapshot while its ending time is $t_{s+1} = t_s + \Delta T$, which is the time variable of the successive snapshot.

The mathematical formulation of a snapshot at time t_s, for a given hydraulic system composed of n_p pipes, n_n internal nodes and n_0 reservoirs, is based on $(n_p + n_n)$ energy and mass balance equations,

$$\begin{cases} \mathbf{A}_{pp}(t_s)\mathbf{Q}_p(t_s)+\mathbf{A}_{pn}\mathbf{H}_n(t_s) = -\mathbf{A}_{p0}\mathbf{H}_0(t_s) \\ \left[\begin{array}{lll} \mathbf{A}_{np}\mathbf{Q}_p(t_s) & = \dfrac{\mathbf{V}_n(t_s)}{\Delta T} & \text{demand-driven analysis} \\ \mathbf{A}_{np}\mathbf{Q}_p(t_s)-\dfrac{\mathbf{V}_n(\mathbf{H}_n(t_s),t_s)}{\Delta T} & = \mathbf{0}_n & \text{pressure-driven analysis} \end{array}\right. \end{cases} \tag{1}$$

where t_s = discrete time variable related to the s-th snapshot of the hydraulic condition in $t_s + \Delta T$; $\mathbf{Q}_p = [n_p,1]$ column vector of unknown pipe flow rates varying over time t_s; $\mathbf{H}_n = [n_n,1]$ column vector of unknown nodal heads varying over time t_s; $\mathbf{H}_0 = [n_0,1]$ column vector of known nodal heads of reservoirs varying over time t_s; $\mathbf{V}_n = \mathbf{d}_n\Delta T = [n_n,1]$ column vector of volumes (average demand per ΔT) of water withdrawals in the nodes varying over time t_s; ΔT = time interval of the real hydraulic system snapshot; $\mathbf{A}_{pn} = \mathbf{A}^T_{np}$ and $\mathbf{A}_{p0}$ = topological incidence sub-matrices of size $[n_p,n_n]$ and $[n_p,n_0]$, respectively, derived from the general topological matrix $\bar{\mathbf{A}}_{pn}=[\mathbf{A}_{pn} \mid \mathbf{A}_{p0}]$ of size $[n_p,n_n+n_0]$. Afterward, each EPS snapshot provides $\mathbf{Q}_p(t_s)$ and $\mathbf{H}_n(t_s)$.

In pressure-driven analysis the water volumes $\mathbf{V}_n(\mathbf{H}_n(t_s),t_s)$, i.e. the average demands $\mathbf{d}_n(\mathbf{H}_n(t_s),t_s)$, of each demand component are computed for each time window ΔT of the snapshot.

2.1. Demand-driven analysis (DDA) and pressure-driven analysis (PDA)

In the past, the hydraulic modeling was generally performed using the approach of prior fixed demands, i.e. fixed volumes, in the single snapshot although varying over time t. As a consequence, the first form of the two mass balance equations in (1) was used. As a result, the volumes (fixed demands in ΔT) drive the solution ($\mathbf{Q}_p(t_s)$; $\mathbf{H}_n(t_s)$) of the system in (1) and the analysis was named demand-driven. DDA generally applies when the nodal volumes can be fixed because known *a priori* or when they are assumed. Recently, hydraulic modeling is performed using the most realistic assumption of a demand or volume dependency on pressure and time t, i.e. $\mathbf{d}_n(\mathbf{H}_n(t_s),t_s)$ or $\mathbf{V}_n(\mathbf{H}_n(t_s),t_s)$. As a consequence, the second form of the mass balances in (1) is used. Therefore, the pressures drive the solution ($\mathbf{Q}_p(t_s)$; $\mathbf{H}_n(t_s)$) of the system in (1) and the analysis is named pressure-driven.

2.2. Steady-state assumption

Hydraulic modeling is performed assuming that a real hydraulic system is in a steady-state condition in each time interval ΔT, whilst these steady-state conditions vary over time each ΔT. Thus, hydraulic modeling assumes in each snapshot slow time-varying boundary conditions such as demands, water tank levels, working condition and state of control valves, etc. Under these assumptions, the inertial and dynamic effects are considered negligible and are not considered in the hydraulic model. Nevertheless, at a smaller time and spatial scales some demands are actually pulses having a volume and a stochastic behavior (e.g., due to a customer use of a faucet) while other demands are unit volumes on time from continuous flows (e.g., background leakage outflows) [3].

The model volumes are actually a summation of demand components related to the water withdrawals from different types of orifices [3], for example two typical components are the customer demands and the background leakages and the related volumes are $\mathbf{V}_n^{cust} = \mathbf{d}_n^{cust}\Delta T$ and $\mathbf{V}_n^{leaks\ t} = \mathbf{d}_n^{leaks}\Delta T$, respectively.

3. Water quality analysis

Once steady-state modelling is performed in order to predict the hydraulic system behavior over time, the flow rate at each t_s, $Q_k(t_s)$, is known and, in PDA, the actual customer demands (in pressure deficient conditions) and background leakages are computed [3]. Clearly, they depend on to the system boundary conditions in $t_s + \Delta T$.

In order to perform water quality modelling with the base hydraulics of the system behavior at t_s, the partial differential equation of the advective transport within pipes [11,12,13] is used,

$$\frac{\partial C_k}{\partial t} = -v_k\left(t_s\right)\frac{\partial C_k}{\partial x} + r_k\left(C\right) = -v_k\left(t_s\right)\frac{\partial C_k}{\partial x} + r_k C_k^{\alpha} \tag{3}$$

where C_k [g/m^3] = concentration of the substance travelling into the k-th pipe of the network (in general a mass/volume unit); $v_k(t_s)$ [m/s] = flow velocity (= $Q_k(t_s)/\mathrm{A}_k$ = flow/pipe cross-sectional area) into the k-th pipe related to the snapshot t_s; r_k = reaction rate of the kinetic of the travelling substance, and α = exponent of the kinetic of the substance. The dimension of r_k is [s^{-1}] in the case of first order kinetic (α = 1), otherwise it depends on the order.

The analytical solution of the Eq. (1) exists for the α = 0,1,2,

$$\begin{array}{lll} \dfrac{\partial C(x,t)}{\partial t} + v(t_s)\dfrac{\partial C(x,t)}{\partial x} - r = 0 & C(x,t+\tau) = C\left(x - v(t_s)\tau, t\right) + rt & \alpha = 0 \\ \dfrac{\partial C(x,t)}{\partial t} + v(t_s)\dfrac{\partial C(x,t)}{\partial x} - rC = 0 & C(x,t+\tau) = C\left(x - v(t_s)\tau, t\right)e^{r\tau} & \alpha = 1 \\ \dfrac{\partial C(x,t)}{\partial t} + v(t_s)\dfrac{\partial C(x,t)}{\partial x} - rC^2 = 0 & \dfrac{1}{C(x,t+\tau)} = \dfrac{1}{C\left(x - v(t_s)\tau, t\right)} - 2rt & \alpha = 2 \end{array} \tag{4}$$

where $\tau \leq x/v(t_s)$ = time interval of the integration.

Assumed a source, mass entering into the hydraulic system over time and the kinetic of the substance, water quality analysis is generally performed in order to compute:

- the total amount of the mass outputs from nodes assuming a boundary condition. I.e., the mass outputs from nodes without accounting for travelling time;
- the total amount of the mass outputs from nodes, e.g. after each time interval T. I.e., the time pattern of the substance arrivals in nodes integrated in T. The system boundary condition could vary or not and T usually equals ΔT.

Instead, age and the trace of the water are specific analyses. They are not related to a real substance travelling into the network and are used in order to understand the hydraulic systems behavior.

In fact, the aim of the water age analysis is the calculation, for each node, of the weighted age of the water passing from the assumed source and reaching nodes through the different paths whose length is variable and dependent on pipe flow velocities. The paths connecting each node with the source(s) contribute according the total travelling time and volume of the water to the nodal water age.

The aim of the water trace analysis is the calculation, for each node, of the fraction of water volume/flow of the customer-demands which passed from the assumed source.

In both the analyses (water age and trace), it is of interest the analysis of the stationary condition when applying the Eq. (3). I.e., we simulate the water quality of a travelling ~~substance~~ chemical in order to achieve the total mass outputs (which is the water age or trace in special cases of Eq. (3) as above reported) assuming a boundary condition of the hydraulic system.

3.1. Water age, trace and total amount of substance mass

In the case we are only interested to the total amount of the mass outputs from nodes of the entered substance and/or to water age/trace modelling, it is possible to assume $T_k(t)$= $L_k/v_k(t)$ (= travelling time of the water into the k-th pipe related to the snapshot conditions t) and write

$$\begin{array}{lll}
\dfrac{\partial age(x,t)}{\partial t}+v(t_s)\dfrac{\partial age(x,t)}{\partial x}-1=0 & age(L_k,t+T_k)=age(0,t)+T_k(t) & \text{water age}\\
\dfrac{\partial tr(x,t)}{\partial t}+v(t_s)\dfrac{\partial tr(x,t)}{\partial x}=0 & tr(L_k,t+T_k)=tr(0,t) & \text{water trace}\\
\dfrac{\partial C(x,t)}{\partial t}+v(t_s)\dfrac{\partial C(x,t)}{\partial x}-rC^{\alpha}=0 & \begin{cases} C(L_k,t+T_k)=C(0,t)+rT_k(t) & \alpha=0\\ C(L_k,t+T_k)=C(0,t)e^{rT_k(t)} & \alpha=1\\ 1/C(L_k,t+T_k)=1/C(0,t)-2rT_k(t) & \alpha=2 \end{cases} & \text{substance travelling}
\end{array} \tag{5}$$

where the variable *age* [time] and *tr* [dimensionless] are introduced for water age and trace analyses, respectively.

Assumed the hydraulic status of the system in a steady-state snapshot t, Eqs. (5) and the analysis of the network directed graph allow computing the nodal water age/trace and the total amount of mass outputs for real substances. To the purpose of the analysis, the complete mixing in internal nodes is assumed,

$$C_j=C_{k\notin I_j,x=0}=\frac{d_{j,ext}(t_s)C_{j,ext}+\sum_{k\in I_j}Q_k(t_s)C_{k,x=L_k}}{d_{j,ext}(t_s)+\sum_{k\in I_j}Q_k(t_s)} \tag{6}$$

where C_j = substance concentration or water age/trace in the mixing j-th node; Q_k = k-th pipe flow rate of pipes incident the node j; I_j = set of pipes incident the node j with flows entering the node j; $d_{j,ext}$ = inflow at the node j, if any, having value $C_{j,ext}$.

Note that for water age the source(s) of the analysis are simply initialized with the computational environment precision (e.g. $2\text{x}10^{-16}$ in Matlab) while the initialization of the water trace is performed entering a concentration equal to 100 or 1 to source(s). Finally, also for tanks the complete mixing is assumed, although modelling them in WQNetXL takes advantage of a more complete mass balance [14] with respect to classic modelling of tanks e.g. in EPANET [2].

It is worth noting that the calculation of the stationary condition of water quality varying the hydraulic system boundary conditions over time t_s, i.e. in EPS, can be computed for each time step separately, using the principle of superimposition of effects being Eq. (3) linear. In fact, in stationary conditions e.g. the water age at each t_s will vary according to the stationary condition computed for each t_s.

3.2. Modelling transport of the mass

When the transport of the mass from source(s) to nodes for a given snapshot conditions t_s is modeled, we assume that the hydraulic condition in $t_s + \Delta T$ is maintained over time and the total amount of the mass outputs from nodes after each T, i.e. the time pattern of the substance arrivals in nodes integrated into each T is computed.

To this purpose Lagrangian time-based approach to track the fate of discrete parcels of water as they move along pipes and mix together at junctions and tanks between fixed-length time steps [12] using travelling parcels and a τ a fraction of T is used as in [2]. τ is the water quality time step (in WQNetXL fixed T/60 min); for the pipes whose travel time T_k is shorter than T/60 min, T_k is fixed equal to T/60 min. This is an approximation error making slower the propagation, whilst the substance mass balance of the water quality analysis has the same order of approximation of the base hydraulics.

Generally it is assumed $T = \Delta T$, i.e. the base hydraulics is computed considering the filling/emptying of tanks in a snap-shot ΔT which equals the integration time T for substance pattern in nodes.

When the substance pattern in nodes is computed considering EPS, it is assumed that the boundary conditions varying over time is a standard cycle, and at each ΔT the variable depending on t need to be updated in water quality equations [12].

4. Water quality of the Apulian network using WQNetXL

We here use the Apulian network (see Giustolisi et al. [5] for further details) in order to show the strategy described in the previous section. The minimum required pressure for any service and for a correct service were assumed equal to 0 and 10 m, respectively, and kept constant through the network. The parameters of Germanopoulos' model [4] for background leakages were set equal to α=1.2 and β=5.03×10^{-8} for the entire network (i.e., a leakage level equal to about 12.5% of customer-based demand).

It was assumed a tank in the node 10 having a sectional area of 1,000 m^2 initial level at 48.5 m (comprised the elevations), 45.5 m and 50.5 m minimum and maximum level, respectively. The tank is filled by an external pipe with a discharge equal to 100 l/s [14]. In fact, the level of the tank is higher than the level of the reservoir (= 35 m). Fig. 1 reports the network layout and the daily pattern of the customer demand factors.

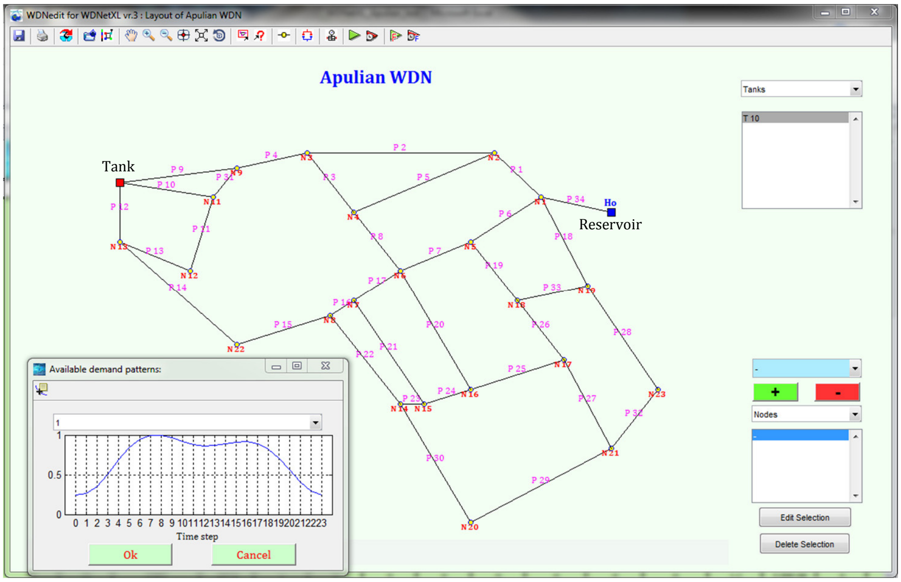
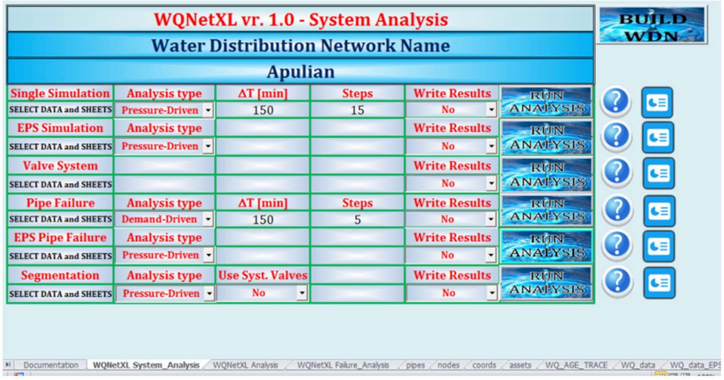


Fig. 1. Network layout and demand time pattern

4.1. WQNetXL system

As reported in the Introduction, WQNetXL works in MS-Excel environment. The network can be downloaded from a standard “inp” file generated by EPANET and the data about pipes, nodes, asset, etc. are written into sheets of a template. The procedure also sets the data of the network for hydraulic and water quality analyses template which are functions, defined into the add-ins, grouped into three 3 sheets as in Fig. 2-4.

In fact, the sheet named *WQNetXL System_Analysis* (see Fig. 2) contains the functions related to the hydraulic analysis (single simulation and extended period simulation, EPS) using DDA or PDA and the failure analysis with valve shutdowns. To this purpose, the function of the label *valve system* in Fig. 2 allows the analysis of segments generated by the isolation valve system that can be set in the sheet *pipes*.



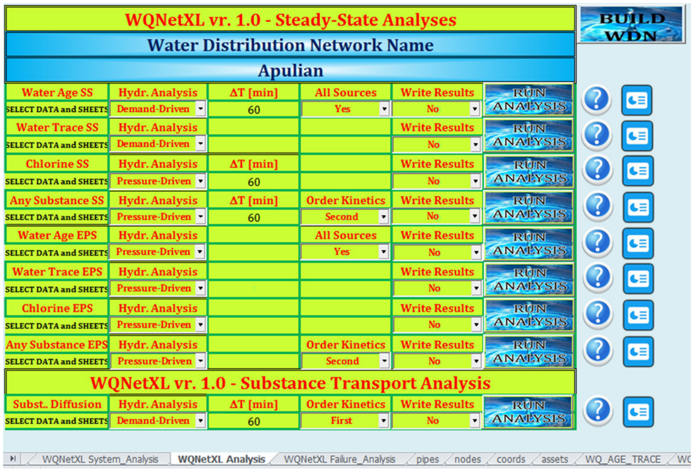
WQNetXL vr. 1.0 - System Analysis

Water Distribution Network Name

Apulian

Single Simulation	Analysis type	ΔT [min]	Steps	Write Results
SELECT DATA and SHEETS	Pressure-Driven	150	15	No
EPS Simulation	Analysis type			Write Results
SELECT DATA and SHEETS	Pressure-Driven			No
Valve System				Write Results
SELECT DATA and SHEETS				No
Pipe Failure	Analysis type	ΔT [min]	Steps	Write Results
SELECT DATA and SHEETS	Demand-Driven	150	5	No
EPS Pipe Failure	Analysis type			Write Results
SELECT DATA and SHEETS	Pressure-Driven			No
Segmentation	Analysis type	Use Syst. Valves		Write Results
SELECT DATA and SHEETS	Pressure-Driven	No		No

Fig. 2. Hydraulic and topological analyses in WQNetXL



WQNetXL vr. 1.0 - Steady-State Analyses

Water Distribution Network Name

Apulian

Water Age SS	Hydr. Analysis	ΔT [min]	All Sources	Write Results
SELECT DATA and SHEETS	Demand-Driven	60	Yes	No
Water Trace SS	Hydr. Analysis			Write Results
SELECT DATA and SHEETS	Demand-Driven			No
Chlorine SS	Hydr. Analysis	ΔT [min]		Write Results
SELECT DATA and SHEETS	Pressure-Driven	60		No
Any Substance SS	Hydr. Analysis	ΔT [min]	Order Kinetics	Write Results
SELECT DATA and SHEETS	Pressure-Driven	60	Second	No
Water Age EPS	Hydr. Analysis		All Sources	Write Results
SELECT DATA and SHEETS	Pressure-Driven		Yes	No
Water Trace EPS	Hydr. Analysis			Write Results
SELECT DATA and SHEETS	Pressure-Driven			No
Chlorine EPS	Hydr. Analysis			Write Results
SELECT DATA and SHEETS	Pressure-Driven			No
Any Substance EPS	Hydr. Analysis		Order Kinetics	Write Results
SELECT DATA and SHEETS	Pressure-Driven		Second	No

WQNetXL vr. 1.0 - Substance Transport Analysis

Subst. Diffusion	Hydr. Analysis	ΔT [min]	Order Kinetics	Write Results
SELECT DATA and SHEETS	Demand-Driven	60	First	No

Fig. 3. Water quality analysis in WQNetXL

WQNetXL vr. 1.0 - Steady-State Analyses (Failure)

Water Distribution Network Name

Apulian

Water Age SS	Hydr. Analysis	ΔT [min]	All Sources	Write Results
SELECT DATA and SHEETS	Demand-Driven	60	Yes	No
Water Trace SS	Hydr. Analysis			Write Results
SELECT DATA and SHEETS	Demand-Driven			No
Chlorine SS	Hydr. Analysis	ΔT [min]		Write Results
SELECT DATA and SHEETS	Pressure-Driven	60		No
Any Substance SS	Hydr. Analysis	ΔT [min]	Order Kinetics	Write Results
SELECT DATA and SHEETS	Pressure-Driven	60	Second	No
Water Age EPS	Hydr. Analysis		All Sources	Write Results
SELECT DATA and SHEETS	Pressure-Driven		Yes	No
Water Trace EPS	Hydr. Analysis			Write Results
SELECT DATA and SHEETS	Pressure-Driven			No
Chlorine EPS	Hydr. Analysis			Write Results
SELECT DATA and SHEETS	Pressure-Driven			No
Any Substance EPS	Hydr. Analysis		Order Kinetics	Write Results
SELECT DATA and SHEETS	Pressure-Driven		Second	No

WQNetXL vr. 1.0 - Substance Transport Analysis (Failure)

Subst. Diffusion	Hydr. Analysis	ΔT [min]	Order Kinetics	Write Results
SELECT DATA and SHEETS	Demand-Driven	60	First	No

Fig. 4. Water quality analysis in WQNetXL

The sheets named *WQNetXL Analysis* and *WQNetXL Failure_Analysis*, see Fig. 3 and 4, contains the functions related to water quality which are based on the hydraulic analysis (see functions in *WQNetXL System_Analysis*). They differ for the possibility to perform water quality analyses assuming or not a failure scenario, i.e. the hydraulic base analysis is performed considering the topological modifications due to valve shutdowns in order to isolate failed pipes [10]. The functions in *WQNetXL Analysis* and *WQNetXL Failure_Analysis* are the analyses of the stationary condition, both considering steady-state (SS) and EPS hydraulics as in Fig. 3 and 4, for water trace and age and also for chlorine or any substance, see section 3. The reaction rate *r* of the substance to be used in the kinetic of the third of Eq. (5) can be given as sum of the wall and bulk rate as in EPANET [2]. All this functions allow writing results in MS-Excel by means of templates and in Matlab. Furthermore, a movie of the water quality analysis is generated in the case of EPS.

Finally, *WQNetXL Analysis* and *WQNetXL Failure_Analysis* contain one function to analyse the transport process into the network of any substance for a given kinetics.

4.2. Water age and trace in Apulian network

In order to show WQNetXL features, we here report the water age and trace analyses in EPS considering a failure scenario, i.e. valve shutdowns. It is assumed that the pipe 6 fails, therefore the segment analysis reported in Fig. 5 allows isolating the segment of the failed pipe (the red segment in the figure).

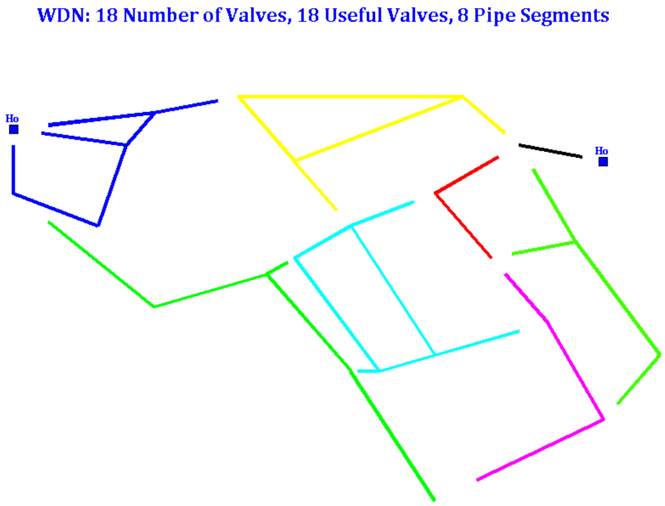


Fig. 5. Isolation valve system segments

The age analysis in Fig. 6 reports the weighted average age of water under the failure scenario requiring the valve shutdowns to isolate the segment of pipes 6 and 19 (see Fig. 5). The water age is performed considering the sources of water (tank and reservoir as in Fig. 6). Fig. 6 shows as the water in the tank (node 10) has age of about 12 h which is consistent with the fact that the tank is filled with fresh water. There are three nodes (5, 15 and 20 of Fig. 1) having a high age of the water (about 18 h) being the network under pressure deficient condition in that section, i.e. the water travels with low velocities. In fact those three nodes are supplied by the tank, instead of the reservoir as in a normal condition, due to the topological modification which significantly changes the system hydraulics.

In order to confirm the above statement and the importance of the correct hydraulic prediction of the system behavior, Fig. 7 shows the same analysis in a normal working condition (i.e. without failure of pipe 6). The nodes from 5-6-7-14-15-16-27-18-20-21-22 (see Fig. 1) have a lower water age (1-2 h vs. 10-18 h) because the flow rate and velocities are higher being not the hydraulic system in a pressure-deficient condition for those nodes. In fact, the reservoir supplies the water to that section of the network differently from the previous case.

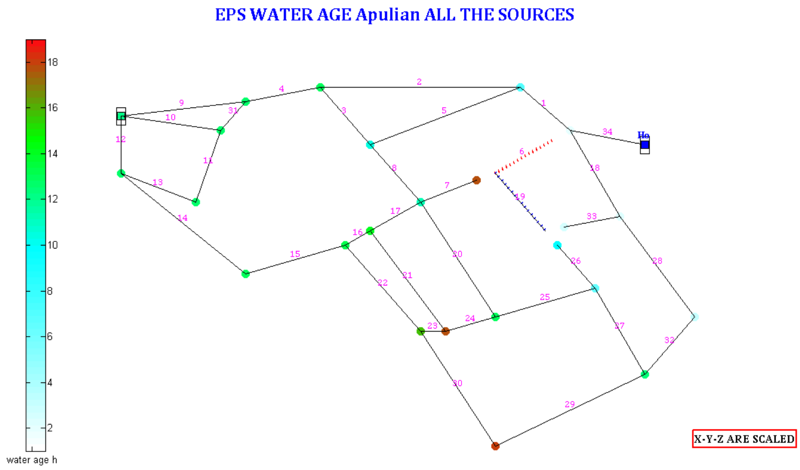


Fig. 6. Water age analysis under the considered failure scenario

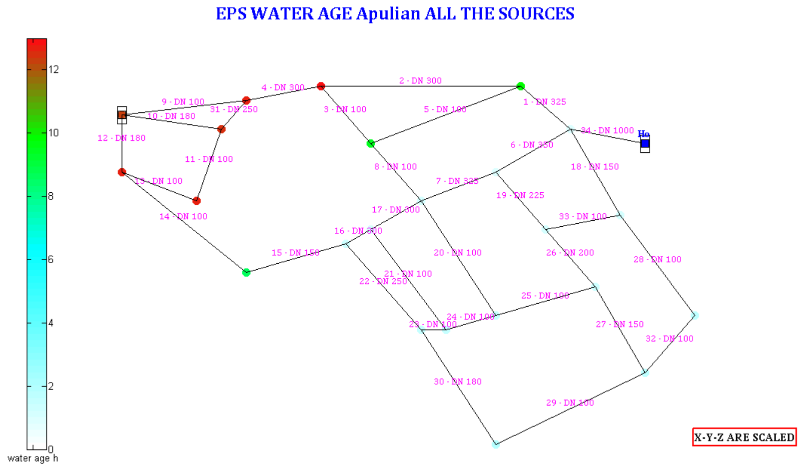


Fig. 7. Water age analysis in the normal working condition

Fig. 8 and 9 report the water trace analyses related to the tank and reservoir in the same hydraulic conditions. The analysis is consistent with the water age because it indicates that the tank delivers the water to a large portion of the network (see Fig. 8), while the reservoirs supplies a small portion of the network due to the failure event on pipe 6 which excludes a relevant path to deliver water from the reservoir.

5. Concluding remarks

The work has presented WQNetXL, which is a collection of MS-Excel add-ins for water quality analyses of water distribution networks (WDNs). The user-friendly environment allows just in time research transfer to students and technicians, sometimes anticipating research publications and embeds the recent advances in hydraulic analyses already implemented in WDNetXL.

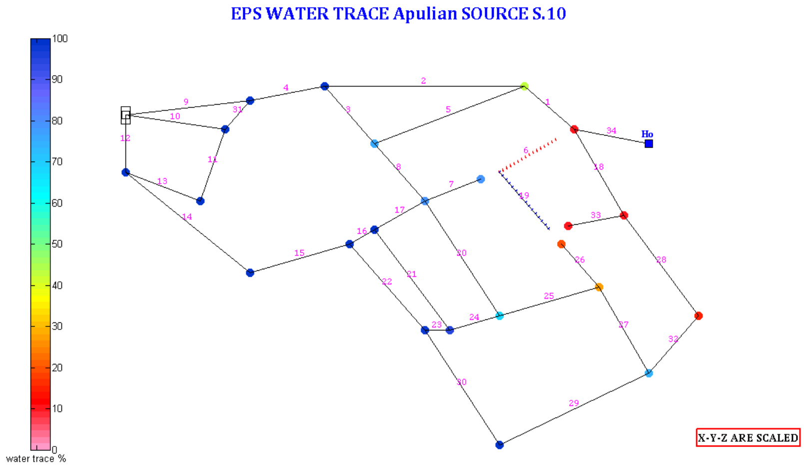


Fig. 8. Water trace analysis with respect to tank

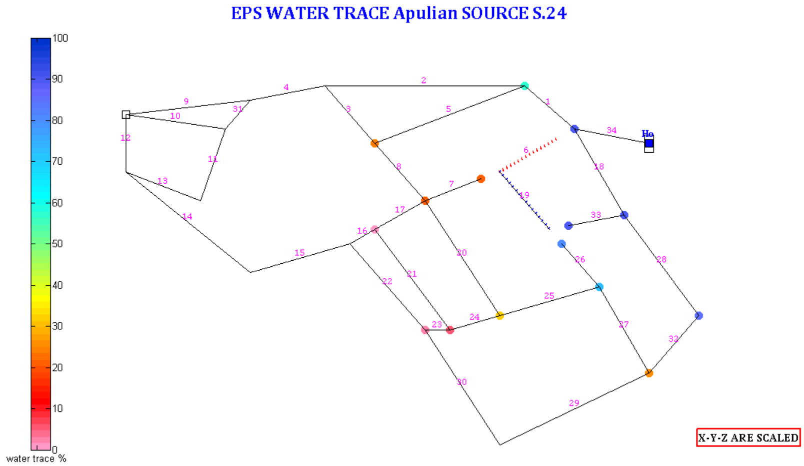


Fig. 9. Water trace analysis with respect to reservoir

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