

Numerical Modelling of a Town Water Distribution Network

Optimum location of quality sensors

GHEORGHE I. LAZAR, ALBERT TITUS CONSTANTIN*, MARIE ALICE GHITESCU*, SERBAN VLAD NICOARA

Politehnica University Timisoara, Faculty of Civil Engineering, Department of Hydrotechnics, G.Enescu Str., 300021, Timisoara, Romania

The analysis following a numerical simulation aims to establish the water distribution system vulnerability to a contaminant release and so to estimate the optimum locations of several quality sensors to warn against the pollution effects. The TEVA-SPOT software toolkit (as specific EPANET extension) was engaged upon a study case regarding the water distribution network of Ortisoara Town in Timi County (4385 inhabitants). Five sets of sensors were consecutively considered for the numerical modelling, the engaged sensors being set for three values of the detection limit and of the response time. Assumed as a possible scenario, the designed sensors had to monitor the impact of injecting (at different given moments and network nodes) two types of contaminants (chemical and biological).

Keywords: Water quality, water network distribution, numerical modelling

The EPANET software platform, developed by the US Environmental Protection Agency, is largely employed in hydraulic developments modelling, covering also the fresh water distribution systems quality even for an extended simulation period of time. The simulation by a numerical model would estimate the expecting flow in the water supply network, but also the contaminants transport development, together with the related chemical interactions, respectively. The quality component in EPANET is rather limited to transport monitoring, meaning the fate of a single chemical substance (e.g. the fluoride, which can be used in a tracing survey, or the free chlorine, employed in the disinfectant decomposition study).

Simulating a complex system with interacting chemical substances can be achieved by a designated EPANET extension. This specific modelling capacity is acquired by a standard executable computer program endowed with a tools library of functions that allows the user to develop various personalized applications. This software tool is specified as EPANET-MSX, the MSX platforms covering multiple extension specifications (Multi-Species eXtension). Subsequently, the EPANET and this extension of it are incorporated in the TEVA-SPOT software toolkit, comprising also additional modules able to study the distribution system vulnerability to contaminants and to optimize the quality sensors positioning.

TEVA-SPOT (Ensemble Vulnerability Assessment and Sensor Placement Optimization Tool) integrates the analysis regarding sensors placing in water distribution systems, the software packages being also developed by USEPA (Sandia National Laboratories) [1, 2]. In this regard, SPOT includes the followings: (1) heuristic solutions of general use, which constantly mean live estimation of optimum location in minutes; (2) hole linear heuristic programing, leading to provable quality solutions; (3) exact solving, represented by global optimizing solutions; (4) boundary technics by which one can evaluate the optimization result. This optimization approach, concerning also sensors placement, includes the problem depiction too, either a default or a specific one. In any case, the problem's mathematical support can be described.

Considering the Mixed Integer Programming (MIP) approach, the software involves the standard expect-

impact Sensor Placement (eSP) solving, that looks to minimize the expected impact of a contamination incidents occurrence with respect to a specified sensors budget. Therefore, the most employed sensor in a Contaminant Warning System (CWS) design is the one for impact minimization in case of multiple contamination incidents, at a given budget. Since this approach can be employed to effective sensors positioning in large water distribution networks, it became the standard approach for SPOT too. An eSP based MIP placing approach for a set of sensors regarding an expected impact has the mathematical background represented by the following system [1]:

$$\begin{aligned}
 (\text{eSP}) \quad & \min \sum_{a \in A} \alpha_a \sum_{i \in L_a} d_{ai} x_{ai} \\
 \text{subject to} \quad & \sum_{i \in L_a} x_{ai} = 1 \quad \forall a \in A \\
 \text{where} \quad & x_{ai} \leq s_i \quad \forall a \in A, i \in L_a \\
 & x_{ai} \leq 1 - s_i \quad \forall a \in A, i \in L_a \setminus \{q\} \\
 \text{and to} \quad & \sum_{i \in L} c_i s_i \leq p \\
 \text{where} \quad & s_i \in \{0, 1\} \quad \forall i \in L \\
 & 0 \leq x_{ai} \leq 1 \quad \forall a \in A, i \in L_a
 \end{aligned}$$

As Berry et.al. (2010) describe, the expected impact of a contamination incidents occurrence defined on A is to be minimized [1]. For each incident $a \in A$, α_a is its share in phenomenon, usually a probability. The approach would integrate the contamination simulation results with respect to an ensemble of locations (marked as L , a location corresponding to a network node). For each incident a , $L_a \subseteq L$ is the locations assemble that can be contaminated by it. This way, a sensor in a location $i \in L_a$ can detect the contamination incident at the moment that the **first** one would reach to its place. Each incident is assisted by the **first** sensor that *feels* it. The impact d_{ai} of the contamination incident is to be defined for each incident $a \in A$ and location $i \in L_a$, as long as it is assisted by a location i . This impact measurement assumes that, once a contamination has its assisting sensors, any other contaminations effects are attenuated (as there is a proper delay that also considers the responding time of the water supply system). The s_i variable indicates the sensors placed in the network, c_i

* email: albert.constantin@upt.ro; alice.ghitescu@upt.ro

represents the cost of introducing a sensor in the water network at the location i , while p is the budget.

The x_{ai} variable indicates if the a incident is assisted by a sensor in location i . Basically, the users are able to monitor all the contamination incidents by the help of a given group of sensors. Considering that L includes an inactive location q , this *dummy* location would be included by all L sub-assemblies. The impact of such a location is to be handled in two different ways: (1) as the impact of the contamination incident at the end of the pollutants transport simulation, and so corresponding to an impact occurring without an on-line CWS or (2) as of zero impact. The first way considers the detection by this *dummy* location as a penalty, while the second one just ignores this location's detection (even if this doesn't have much sense without accompanying constraints regarding the number of detections that didn't work out).

The eSP approach is a slight generalization of the sensor placing model described by Berry et.al. [3], by which the *dummy* location impact is treated as a penalty (case for which the third constraint is redundant). The impact of detection by this location is more significant than all the other impacts for each incident and so the reference x_{ai} variable corresponding to it would be selected only in case that there are no other placed sensors being able to detect the given incident. By simply ignoring the constraint of this situation, Berry et.al. notice that the eSP is the same with the very well-known p -median problem of location enabling when $c_i = 1$ [4].

The p -median problem considers its p facilities (e.g. central deposits) as to be placed on m potential sites so that the summation of d_{ai} distances between each of the n clients (e.g. retail points) and the closest unit i to be reduced to a minimum. As comparing eSP problem with the p -median problem one can notice the following equivalences: (1) between sensors and facilities, (2) between contamination incidents and clients, and (3) between contamination impact and distance. While the eSP considers placing of several p sensors, the p -median problems generally considers its approach by placing all of the p facilities. In practice, the difference becomes irrelevant excepting the case when p gets close to the total number of possible locations.

Experimental part

The Town of Orisoara is situated in the Vinga's Plain, West of Romania, North of Timis County, at 24 km from Timisoara and 28 km from Arad. Crossed by the European Road E671 (fig. 1), the town covers an administrative territory of 14,232 hectares, being populated by 4385 inhabitants at the moment of this study.

The water distribution network meshing scheme was developed as overlaid on the Stereo70 topographic plan of the town and comprising the joints - mentioning their topographic coordinates x, y, z - and the pipe segments respectively. Knowing as given data the water requirements on all joints, the distribution network was modelled by EPANET 2.0, a 168 h simulation period (one week) being considered [5]. The hydraulic and water quality model was then set up and validated. Giving the next pictures (fig.2-5), the followings are defined:

- distribution network configuration (fig.2): water tank (R1); catchment pump (SP1) with its aspiration (P12) and pressing (P7) pipes; compensation tank (T1); network pump (SP2) with its aspiration (P9) and pressing (P17) pipes; joints and pipe segments denomination.



Fig. 1. Plan view of Orisoara Town (Google Earth)

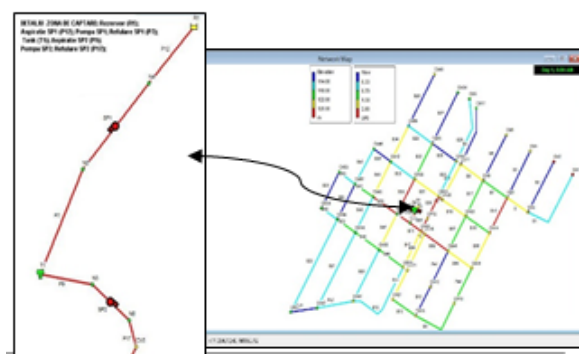


Fig. 2. Numerical model of the water distribution network in Orisoara Town (EPANET 2.0)

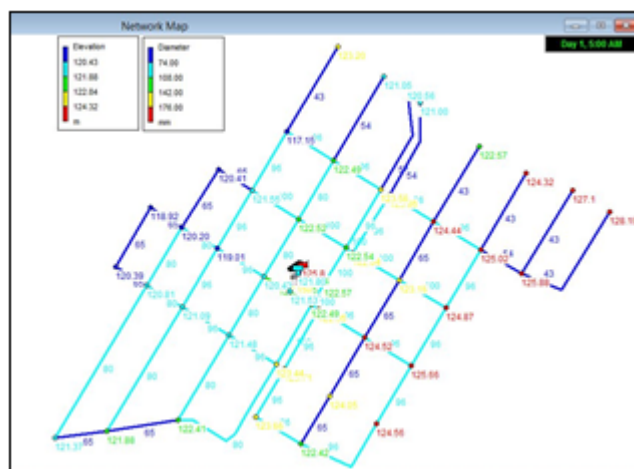


Fig. 3. Geometry data of the water distribution network in Orisoara Town, (joints elevation - mSL, pipe diam. - mm)

- characteristic data of the distribution network (fig. 3): joint levels in mSL; pipe segments diameters in mm, obtained by running the checking operation as for fulfilling the water requirements (according to 1343-1/2006 national regulation).

- hydraulic characteristics of the water system at the specific moment of 05:00 h of day 1 (fig. 4): water flow distribution in the network in l/s and hydraulic head at all the joints in mSL, respectively.

- hydraulic characteristics in the water distribution network along the entire simulation period of 168 hours (fig. 5), specifically corresponding to the T1 tank, the SP2 intermediate network pump (ensuring the required head and flow in the network) and to the most unfavourable joint CM1 in the system (with respect to the hydraulic head development).

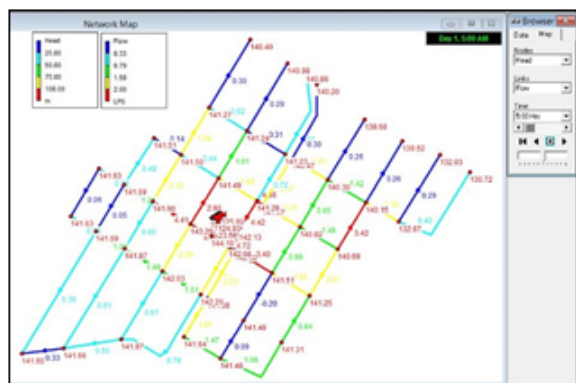


Fig. 4. Water flow (l/s) and joints hydraulic head (mSL) in Orisoara Town distribution network at 05:00 day 1

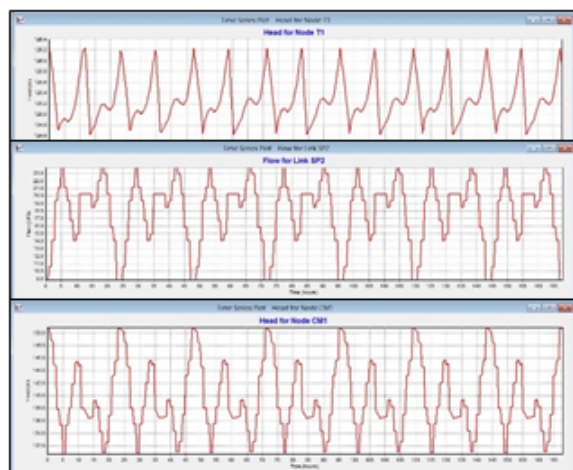


Fig. 5. Development of the water flow for the SP2 intermediate pump and of the hydraulic head at T1 tank

Water distribution network model by TEVA-SPOT 2.3.2 General procedure

TEVA-SPOT allows the user to define *scenarios* of numerical simulation for a water network contamination, of the contaminant/contaminants spread in the entire system, and to eventually analyze the possible consequences [6]. Subsequently, one would be able to present its results by a variety of graphs and spreadsheets. The final goals of a numerical simulation, together with its following analysis, are to estimate the vulnerability of the distribution system regarding contaminants releasing and to determine accordingly the optimum locations for placing water quality sensors that would properly monitor the phenomenon in order to limit its effects [6,7].

Additional knowledge for involving full EPANET-MSX capacities can be gained by studying the designated users' guide [8]. Engaging specific capacities leads to several modifications upon the EPANET model which are not immediately obvious to the user, e.g. the significant alteration of the data base structure in order to define the EPANET-MSX contaminants concentration. The following steps (in the given order) need to be proceeded in order to run MSX capabilities by TEVA-SPOT:

- define a new working environment;
- uploading the distribution system from the EPANET file of .inp extension;
- uploading the contaminants concentration data from the EPANET-MSX file;
- contaminants designation by Injection Definitions, indicating contaminant as unique or multiple;
- the contaminant species is to be designated from a given list, while the Start / Stop moments need to be mentioned;

-specific data need to be mentioned for multiple type of contaminants (Mass Injection Rate, Concentration Zero Threshold, Water Quality Tolerance, emissions, sub-species);

-the available species are determined by those established as so in the .msx file in EPANET.

Subsequently the user should continue to proceed by the following steps:

-junctions set definition, specifying the group of contamination scenarios by the help of a random generating process;

-output files (C:\TEVA-SPOT Database Name\ Collection\Ensemble Name\Health Impact Analysis), which give details regarding the joints receiving a contaminant dose (below or above mentioned values);

-output files of Infrastructure Impact Analysis (IIA) module (C:\TEVA-SPOT Database\Collection Name\ Ensemble Name\Infrastructure Impact Analysis). The text file mentions the total length (meters) of contaminated pipe (based on contamination references), below or above a given dose, for each specified concentration (mg/L);

- define the ability to run the contamination effects on the Health Impact Analysis without reacting to the produced dose;

- define the pattern for the tap water consumption schedule, from 00:00 to 24:00 h;

- specify the number of worst case fatality/dosage scenarios to save in Health Impact Analysis, which would allow the user to perform a detailed study a reduced number of scenarios based on dose levels.

Data input and edit, model running and validation

Further information for launching TEVA-SPOT and Collection and Ensemble defining or loading can be found in the User's Manual TEVA-SPOT Toolkit [1, 2].

Figure 6 presents the standard menu bar for TEVA-SPOT as importing the retea Orisoara.inp file containing specific data previously defined in EPANET and then saved under proper format [9]. The graphical representation of the described water distribution network appears after confirming the load of the selected file. More options are revealed by right-clicking on the tap icon, (fig. 6) meaning to visualize characteristics defined by EPANET and eventually altering them by the help of pull-down submenus.

Table 1 presents the main input parameters considered to run TEVA-SPOT in its Ensemble Mode, corresponding to the fresh water distribution network of the Town of Orisoara. One should keep in mind that TEVA-SPOT is based on an extended period of simulation considering the involvement of at least one contaminant. Thus, the Quality option for the EPANET components (the file of .inp extension) has to be set as for chemical type.

Figure 6 (down-left) presents the options in ensemble module, where the several specifications (regarding time, water quality, hydraulic or simulation parameters) are made by edit or by check marks.

As shown by figure 7 (upper-left), the Cv2 junction (node) is considered for introducing a contaminant of a specific quality (BIO class, settled initially as 1). Similarly are assigned the nodes R1 and T1 with a contaminant of another quality (CLS class, settled as 1).

The Chemical type is considered for the Quality data type for the EPANET components (fig. 7, upper right). The EPANET .msx file containing the standard info regarding the contaminants [8] is imported and the first contaminant is specified as of CLS class in the ensemble options menu. The graphic area presented by figure 7 (down) is opened

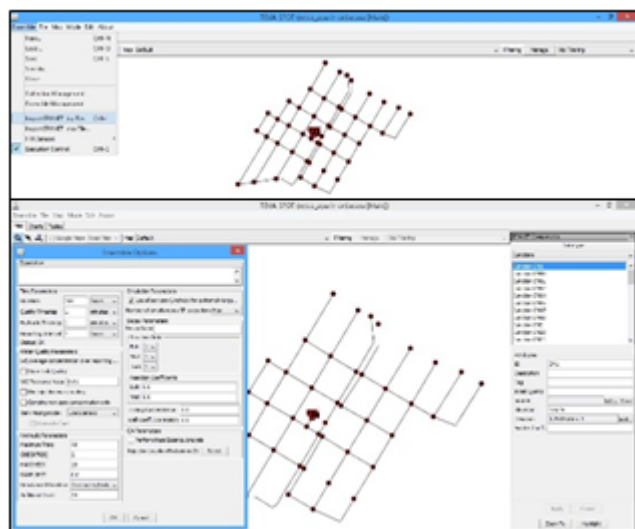


Fig. 6. Water distribution network import from EPANET to TEVA-SPOT (upper); Network characteristics view, ensemble options, facilities edit and validation (down)

	INPUT parameter	Parameter level
EPANET simulation	Simulation period of time (duration)	168 ore
	Scenarios (junctions injection set)	All junctions of non-zero demand
	Time of injection (moment and duration)	1 hour and 10 hours contaminant
	Estimated population	4385 (basic requirement)
	Mass injection rate	50 mg/min and 1740 mg/min contaminant
Health Impact Analysis (HIA)	Contaminant (agent)	Registers contaminant data
TSO for the Impact Analysis	Response time (min)	By user designation according to accepted impact values as mg/l for chemicals and toxins or as units/l for organisms and cells
	Delay (min)	
	Detection limit (mg/l)	
	Database filename	
Infrastructure Impact Analysis (IIA)	Contaminant (agent) name	By user designation as mg/l for chemicals and toxins or as units/l for organisms and cells
	Concentration thresholds	
Sensor Placing (SP)	Exposing model I (water ingestion)	As basic requirement
	Sensor set sizes (six sets)	0, 3, 6, 9, 12, 15
	Response time (three moments)	0, 360, 720 minute
	Detection limits (three values)	0, 0.01, 1.0 mg/l
	Solver algorithm	Heuristic
	Objective / Statistics	Exposed population, average or other value

Table 1
INPUT PARAMETERS FOR
ENSEMBLE MODE IN
TEVA-SPOT

by choosing Execution Control in the general menu. Specific running menus are revealed for the four distinctive modules: Input Generation, Scenarios, Health Impacts Analysis and Sensor Placement, each of these concluding by three options: Edit, Execute and Terminate (as validation in case the model running was adequate). The figure 7 (down-left) shows that the Edit option in Input Generation was considered as for initializing the population parameter

(resulting the additional window where population number of 4385 inhabitants was introduced). The water usage per capita is consequentially calculated (in gallons/day) by clicking on Calc. The parameter becomes valid by confirmation (check mark) in the left menu and the Execute option becomes available in the Status submenu. The Termination options is to get invalid once the execution is performed and the red graphic mark on the left becomes green as a confirmation that the process developed properly and the user can proceed to the next step.

Figure 8 presents the mentioned validation (upper-left) and accessed Edit menu in Input Generation (upper-right) to reach Upstream & Downstream Nodes execution where the total analysis duration of 168 h was confirmed. Consequently the Upstream & Downstream Nodes turns valid and it may be marked as checked, and further on the Execute option is to be chosen in the now available Status area. The Termination option becomes invalid once the operation was performed and the red graphic mark on the left becomes green indicating the proper development (see the middle part of the figure) and the availability for the next step. The additional window of several specific injection data (fig.8, middle right) was revealed by accessing the Scenarios edit menu. The first agent injected to the water distribution network at a 50mg/min rate was defined of CLF type with a concentration threshold of 0.001mg/L and a water quality tolerance of 1.0E-6mg/L. The 0 start time and 1 hour stop time were confirmed. Agent #1 and All Nodes (52) are selected for injection and node set definition respectively in the Edit BaseEnsemble Parameters menu, and so the injection model is defined

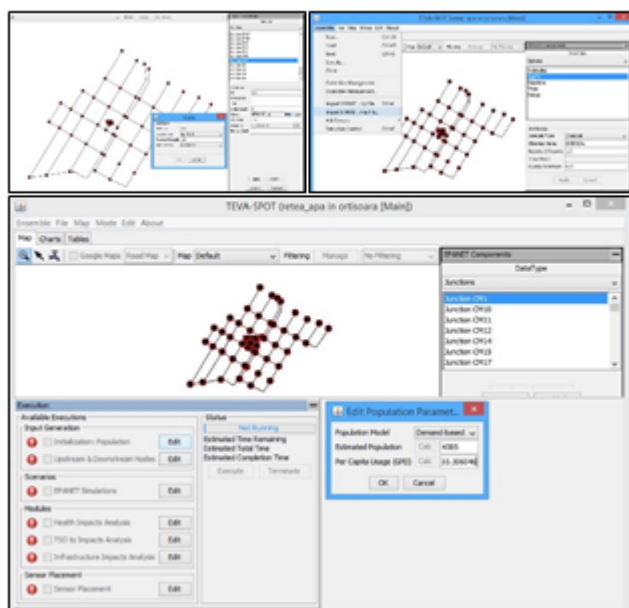


Fig. 7. The Cv2 junction is set as the source node to introduce the contaminant as Chemical type

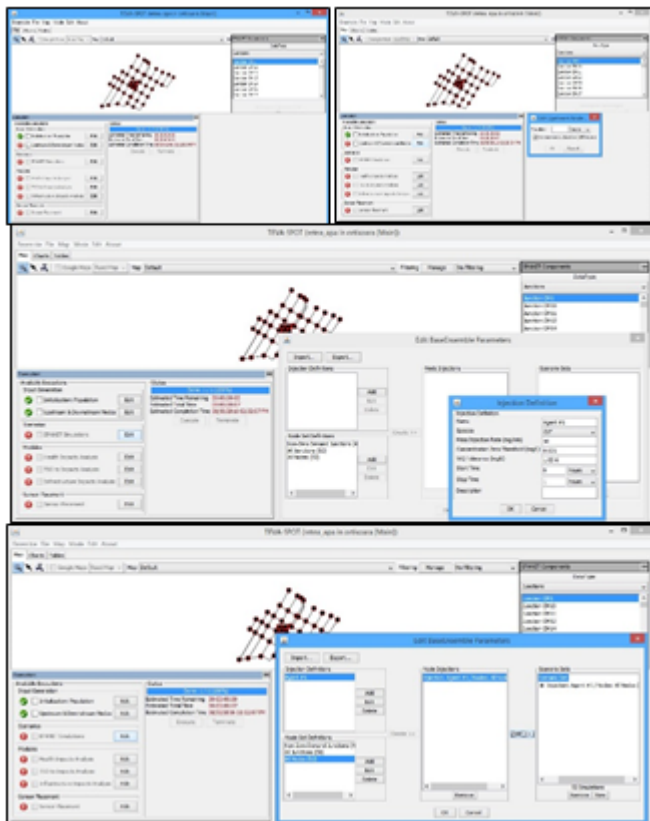


Fig. 8. Upstream & Downstream Nodes edit and analysis duration endorsement (upper); scenarios edit by defining the first injected agent, of CLF type (middle); scenario Set definition, as associated to the first agent (down)

by hitting the Create button. Finally, a scenario set is defined by adding the first contaminant agent.

The figure 9 shows the node definition for Agent #2 contaminant releasing, the Cv2 junction also to which the name *Noduri (1)* was assigned (the program automatically adds the number of junctions). By proceeding as previously, the polluting substance Agent #2 is defined, of BIO class with a mass injection rate of 1740mg/min, a concentration zero threshold at 0.001mg/L, a 1.0E-6mg/L tolerance in water quality and injected from the start time of hour 73 to the stop time of hour 84. Also similarly, the injection model was defined in the Edit BaseEnsemble Parameters menu

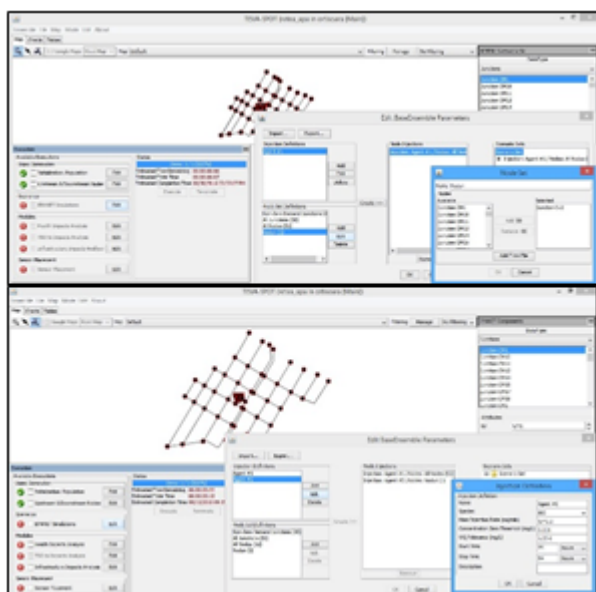


Fig. 9. Injection node selection and definition for the second contaminant agent (upper); Definition of the second injected agent and scenario set upgrading (down)

by selecting Agent #2 and *Noduri (1)*, followed by its adding to the scenario set. Once the operation is confirmed by the OK button, the EPANET Simulations execution options becomes valid and can be marked as checked. As a consequence, the Execute option in the right Status area becomes accessible. After developing this operation, the Terminate option gets unavailable and the red graphic mark on the left becomes green (fig. 10 upper-left), which means that the operation went on properly and the user can move to the next step involving the Health Impact Analysis module.

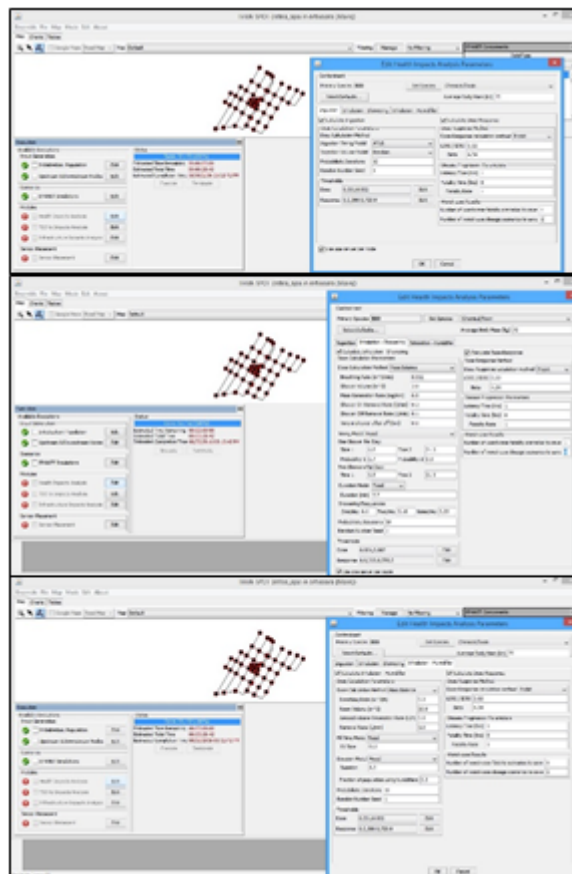


Fig. 10. Health Impact Analysis module edit - ingestion (upper); inhalation by showering (middle) and inhalation by humidifier (down) parameters

The accessed HIA edit module is shown in the upper-right part of figure 10 by the add-on window where different facilities regarding the parameter ingestion are available. After selecting and confirming these several options one can step on to the next menu regarding inhalation by showering (middle part of fig. 10) and so on to the inhalation by humidifier one (lower). Once the submenus crossed-through, the considered data is confirmed by OK option and so the Health Impacts Analysis execution option on the left sub-window becomes valid and can be marked as checked. Hence, the Execute option in the Status area is to be considered and after its completion the Terminate option turns disabled while the red graphic mark on the left turns green (fig. 11 upper-left), meaning that the operation went on correctly and the user can move to the next step engaging the Infrastructure Impacts Analysis module.

The upper-right part in figure 11 shows the edit sub-window of Infrastructure Impacts Analysis module where one needs to specify the type of contaminant substance (here considered as BIO species) and the admitted concentration thresholds. By confirming the considered data (OK) the Infrastructure Impact Analysis execution option on the left becomes valid and can be marked as checked.

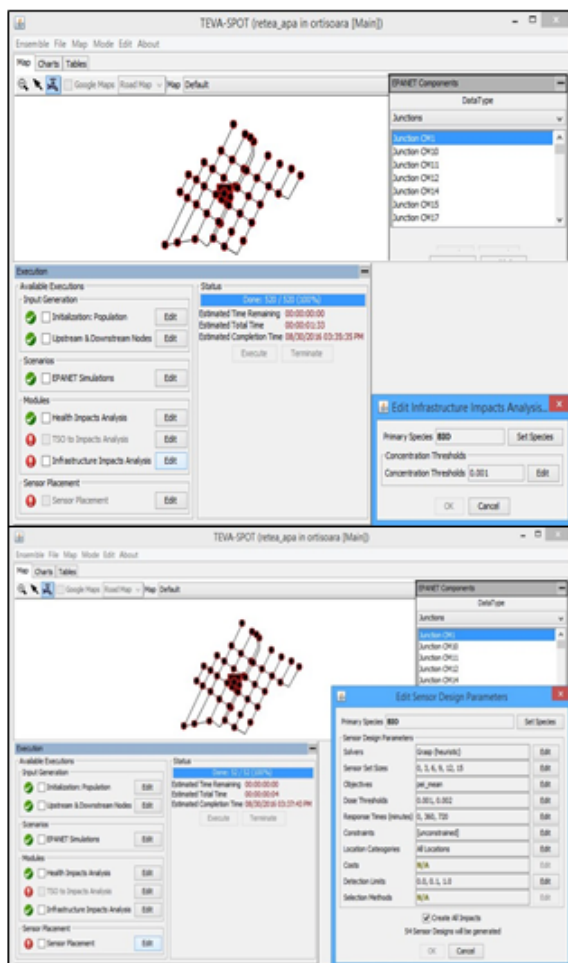


Fig. 11. Infrastructure Impacts Analysis module edit (upper), Sensor Placement module edit (down)

The execution can be now performed (Execute option on the Status area) after which the red graphic mark on the left turns green (fig. 11 down-left), meaning that proper result developed and so the user can step on to the last module, the Sensor Placement, as shown by the sub-window on down-right part of the same figure. Specific data starting with the contaminant type (BIO species) and continuing with sensors parameters is supplied and once confirmed the Sensor Placement execution option on the left turns valid and can be marked as checked. The red graphic mark on the left turns green, meaning that proper result had been reached, by executing the option offered in the Status area.

Results and discussions

By running the formerly described execution options of TEVA-SPOT analysis module we reached the following results assembled according to their specific type (maps, charts and tables).

The charts are graphs developed in the ensemble analysis module by running an impact simulation upon health (meaning not by engaging the sensor placing algorithm). No diagram was appointed as an embedded graph. A list of all the graphs produced by analyzing the health effect development is revealed by accessing the Charts submenu. They would present the established influence upon health either as a time series, as a cumulative distribution function or as a scenario. Figure 12 brings the graphic representation of the estimated number of infections, disease and fatalities upon 100th percentile of town population against time due to the injections at CM1 (50mg/min of a CLF class contaminant from the start time 0 h to the stop time 1 hour) and Cv2 (1740mg/min of

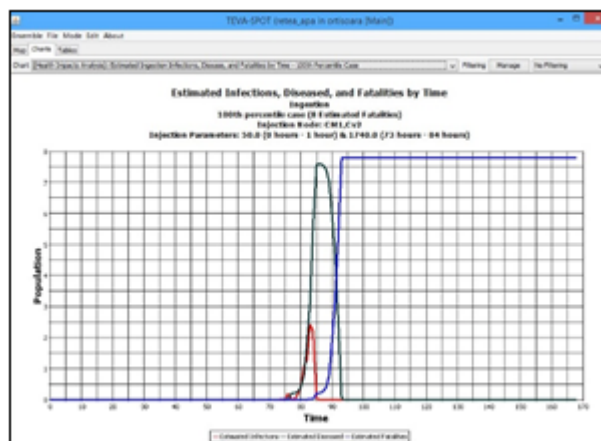


Fig. 12. Estimated time development of infections, diseased and fatalities as percent of town population

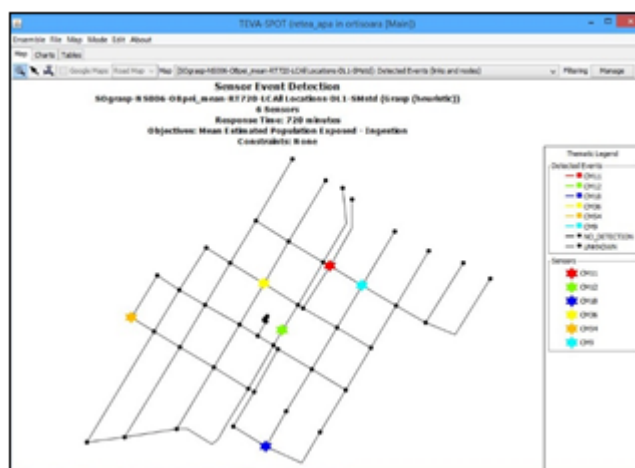


Fig. 13. The optimum position for the 6 water quality monitoring sensors in the water distribution network of Ori'oara Town

a BIO class contaminant from the start time 73 h to the stop time 84 h) nodes, and according to effect surveillance assumed at Ingestion.

The map output is acquired through the ensemble analysis module by running a health impact analysis and engaging the sensor set placing algorithm. The list of all produced maps is revealed by accessing the Map submenu. In a convenient way, the map naming follows a specific pattern: the first part is related to the chosen optimization solver and the rest of it refers the number of sensors, optimization objective, response time, location categories, detection limit and finally the selection method.

Conclusions

Five sets of sensors were separately considered for the numerical modelling, successively comprised of 3, 6, 9, 12 and 15 sensors, respectively, following the reference settlement of the network with no sensors. The general option considered in the program was Mean Estimated Population Exposed - Ingestion (pei_mean), the engaged sensors being set for three values of detection limits (0.0, 0.01 and 1.0 mg/L) and with response times (0, 360 and 720 min).

The main goal of the present analysis by numerical simulation was to estimate the vulnerability of the water distribution system to contaminant releases and to establish the optimum location of a water quality set of sensors in the network, in order to warn the owner and so to reduce the contamination effects.

As about the ending detail, it has no specific meaning for the present study but is an available topic for a subsequent research. Therefore, for example the produced figure 13 - SOheuristic-NS006-OBpei_mean-RT720-LCAllLocations-DL1-SMstd - indicates the sensors detection events estimated for optimum location according to the next design parameters: the heuristic Solver, the Number of Sensors is 6, the OBjective is to estimate the mean value of population exposed to ingestion, the Response Time is 720 min, the Location Category refers to all locations, the Detection Limit is 1 and the Selection Method is standard. In case the user goes for Sensor Location option, their positions will be signaled by a star symbol of different colors according to their category (i.e. existing, selected and ignored).

Two types of maps-Sensor Location and Detected Events (for nodes and links, or either for nodes or for links) – will be associated to each of the produced sensor placement alternative.

There was no data regarding the available budget in the town finances and therefore the present study did not follow the specific condition concerning the restricted budget p as part of the equation system (1.1). We have to mention also that the budget foreseen for the sensors acquisition should cover the purchase of a SCADA Station type of database too.

In conclusion, taking into account the mentioned considerations and also the relatively reduced spread of the water supply network (52 nodes), the 6 water quality sensors set situation was adopted as a foremost proposition for the water infrastructure manager, the devices optimum location being indicated by the extracted map in figure 13.

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Manuscript received: 27.11.2017