water

Supplementary Materials for

Improving the Performance of Water Distribution Networks Based on the Value Index in the System Dynamics Framework

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1. Materials and Methods

1.1. Goal and Scope

Table S1 shows the summary of included and excluded items in the defined system boundaries. Because the environmental impacts of the disposal phase are negligible compared to the other phases [1], it is not considered to be within the system boundaries.

Table S1. Summary of items included and excluded in the system boundaries.

LCA Phase	Included in the Study	Excluded from the Study
Production	Raw materials (polyethylene, cast iron, steel), pipe manufacturing equipment (extruder for plastic pipe, castings, etc.), protective coatings for the pipes (bitumen glue, cement mortar, zinc)	Production and maintenance of the equipment used in the production line
Transportation	Transportation distances, vehicle type	Production and maintenance of the vehicles.
Installation	Installation tools (drilling, roller for compaction), materials required in the trenches (sand, gravel)	Production and maintenance of the installation machinery
Operation	Transportation distances, vehicle type, drilling, roller, materials required in the trenches	Production and maintenance of the installation machinery, replacement of the pipes

1.2. Life Cycle Inventory

Table S2 indicates the registered inventory data for the 200 mm ductile iron pipe in Simapro. As per the table, the production phase consists of the raw materials and processes to manufacture the pipes. In the installation phase, a 30 km distance was considered for transportation of the pipes and the materials required in the trenches. Moreover, a 15 km distance was considered for the transport of the extra excavation soil to the deposit land. According to the specifications of the proposed trenches by international standards [2,3] and typical trenches in the study area, two types of trenches were considered. The trenches’ dimensions are indicated in Figure S1.

Table S2. Inventory data for 200 mm Ductile Iron (DI) pipe based on the functional units of different phases [4,5].

LCA Phase	Input (Process/Materials)	Inventory Data (Process/Materials)	Unit	Value
Production	Cast iron	Cast iron {GLO}∣ market for ∣ Alloc Def, S	kg	32.3
	Production process	Metal working, average for metal product manufacturing {GLO}∣ market for ∣ Alloc Def, S	kg	32.3
	Cement mortar (interior coating)	Cement mortar {GLO}∣ market for ∣ Alloc Def, S	kg	3.53
	Bitumen (external coating)	Bitumen adhesive compound, hot {GLO}∣ market for ∣ Alloc Def, S	kg	0.19
	Zinc oxide (external coating)	Zinc {GLO}∣ market for ∣ Alloc Def, S	kg	0.08
	Zinc coating process	Zinc coat, pieces, adjustment per micro-m {GLO}∣ market for ∣ Alloc Def, S	m^2	0.63
Transportation	Transportation of pipes	Transport, freight, lorry >32 metric ton, EURO4 {GLO}∣ market for ∣ Alloc Def, S	tkm	1.08
	Transportation of sand	Transport, freight, lorry 16–32 metric ton, EURO4 {GLO}∣ market for ∣ Alloc Def, S	tkm	7.23
	Transportation of gravel	Transport, freight, lorry 16–32 metric ton, EURO4 {GLO}∣ market for ∣ Alloc Def, S	tkm	5.32
	Transportation of extra soil of the trench excavation	Transport, freight, lorry 16–32 metric ton, EURO4 {GLO}∣ market for ∣ Alloc Def, S	tkm	6.44
Installation	Crushed gravel	Gravel, crushed {GLO}∣ market for ∣ Alloc Def, S	kg	177.31
	Sand	Sand {GLO}∣ market for ∣ Alloc Def, S	kg	241.74
	Excavator	Excavation, hydraulic digger {GLO}∣ market for ∣ Alloc Def, S	m^3	0.87
	Vibrating compactor	Machine operation, diesel, <18.64 kW, steady-state {GLO}∣ market for ∣ Alloc Def, S	h	0.5
Operation	Transportation of emergency vehicle	Transport, passenger car, large size, diesel, EURO 4 {GLO}∣ market for ∣ Alloc Def, S	km	5
	Excavator	Excavation, hydraulic digger {GLO}∣ market for ∣ Alloc Def, S	m^3	9
	Crushed gravel	Gravel, crushed {GLO}∣ market for ∣ Alloc Def, S	kg	532
	Sand	Sand {GLO}∣ market for ∣ Alloc Def, S	kg	725
	Transportation of sand and gravel	Transport, freight, lorry 16–32 metric ton, EURO4 {GLO}∣ market for ∣ Alloc Def, S	tkm	37.7
	Transportation of extra soil of the trench excavation	Transport, freight, lorry 16–32 metric ton, EURO4 {GLO}∣ market for ∣ Alloc Def, S	tkm	18.9
	Vibrating compactor	Machine operation, diesel, <18.64 kW, steady-state {GLO}∣ market for ∣ Alloc Def, S	h	1

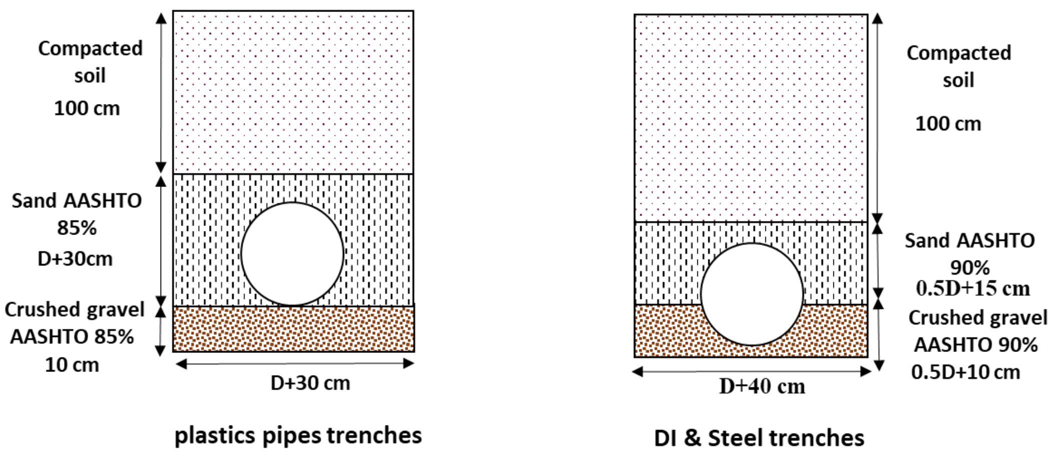


Figure S1. Dimensions of the typical trenches in the installation phase of the case study [2–4].

1.3. Life Cycle Impact Assessment

In Eco-Indicator 99 (EI 99), there are two impact categories: a) midpoint effects including climate change, respiratory effects, and ozone layer depletion, and b) endpoint effects including damage to human health, damage to ecosystem quality and damage to resources. Regarding inventory data, the environmental impacts were classified as midpoint effects and then converted to three endpoint categories. The final result was a dimensionless quantity called an "eco-indicator" [6]. TRACI (tool for the reduction and assessment of chemical and other environmental impacts) was also employed in order to evaluate the cumulative CO_2 emissions during the operation time of WDNs. TRACI is a midpoint impact assessment methodology developed by the U.S. Environmental Protection Agency (EPA) [7]

1.4. Correlation between Simulated and Observed Data

The accuracy of the SD model was evaluated in order to investigate the correlation between the simulated and observed data in the developed model. For this purpose, the following indicators were used: the coefficient of determination (*R*), the root mean squared error (*RMSE*) and the ratio of observed and simulated standard deviation (*Rs*).

$$R = \frac{\sum_{i=1}^{n}(simulated_i - simulated_{ave})(observed_i - observed_{ave})}{\sqrt{\sum_{i=1}^{n}(simulated_i - simulated_{ave})^2 \sum_{i=1}^{n}(observed_i - observed_{ave})^2}}, \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(simulated_i - observed_i)^2}{N}}, \quad (2)$$

$$Rs = \frac{S_{simulated}}{S_{observed}} = \frac{\sum_{i=1}^{n}(simulated_i - simulated_{ave})^2}{\sum_{i=1}^{n}(observed_i - observed_{ave})^2}, \quad (3)$$

where $simulated_i$ is the *i*th simulated data, $observed_i$ is the *i*th observed data, $simulated_{ave}$ is the mean of simulated data, $observed_{ave}$ is the mean of observed data, N is the number of data, $S_{simulated}$ is the standard deviation of simulated data and $S_{observed}$ is the standard deviation of observed data.

2. Case Study

A part of Tehran's water distribution network (WDN) was selected as the study area. Tehran, the capital of Iran, is located in the north part of the country. Unofficial statistics declared that about 700 pipe breaks/day had occurred in the 9323 km of Tehran's WDN because of aging [8]. This problem makes it necessary to apply some strategies for improving the performance of the WDNs. As the WDN of Tehran could not be modeled in its entirety, a part of the southern region of the WDN was selected for the case study. This study area consists of six pressure zones. The characteristics of each pressure zone are given in Table S3. Network data was collected from the Tehran Province Water and Wastewater Company (TPWWC) [4]. Schematics of the WDN are shown in Figure S2.

Table S3. The characteristics of each pressure zone in the considered WDN [4].

Pressure zone	Maximum Height (m)	Minimum Height (m)	Area (Hectares)	2012	2016
				Residents (Persons)	Residents (Persons)
1	1170	1124.5	222.4	48,626	50,784
2	1142.1	1108	85	31,632	31,093
3	1138.8	1117	37.1	6135	7265
4	1111.4	1093.6	30.8	9807	10,114
5	1131	1104.4	18.5	10,100	9289
6	1110.3	1096.3	19.3	6032	6304
Total			413.1	112,332	11,4849

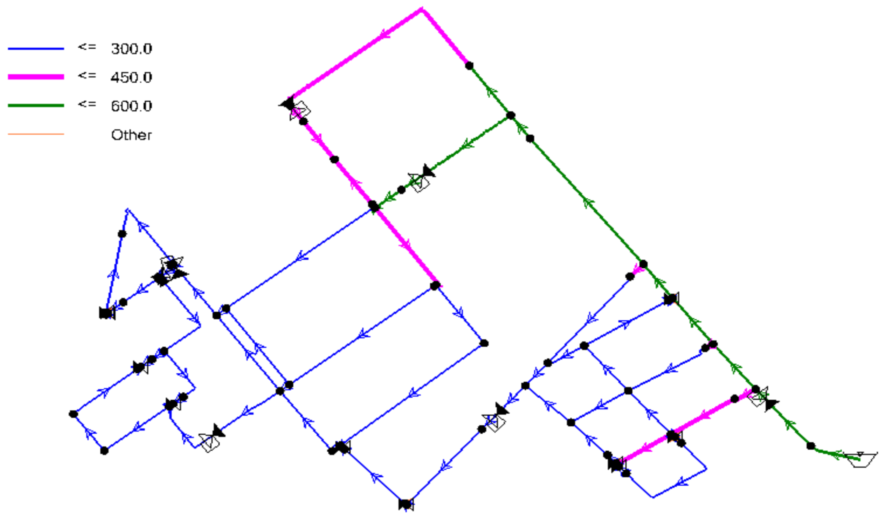
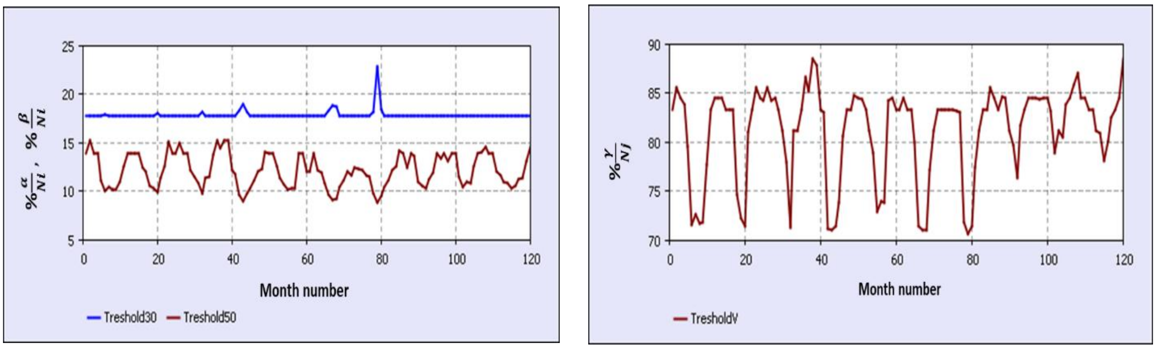


Figure S2. Schematic of the WDN.

3. Results and Discussion

3.1. Hydraulic Assessment of the WDN

Figure S3a indicates the percentage of the nodes with pressures less than 30 m ($\%\alpha/Ni$) and greater than 50 m ($\%\beta/Ni$) in each time step. The percentage of pipes with a flow velocity less than 0.8 m/s ($\%\gamma/Nj$) during the simulation time is demonstrated in Figure S3b. As shown in Figure S3a, due to the excess pressure of the network the percentage of nodes with pressure more than 50 m changed. Meanwhile, there were not dramatic oscillations in the values of $\%\alpha/Ni$. Because of an increase in the average pressure from the 84th month, the minimum values of $\%\beta/Ni$ from months 84 to 120 rose compared to the minimum values of months 40 to 83. However, the values of $\%\alpha/Ni$ remained constant after the 84th month. The reason was that the increase in the average pressure from the 84th month was less than one meter and there were no nodes with a pressure greater than 29 m in the variable of α (the nodes with the pressure less than 30 m). According to Figure S3b, the flow velocity in most of the pipes was less than the optimal velocity. Moreover, decreasing the total inflow to the WDN since the 84th month affected $\%\gamma/Ni$ significantly.



(**a**) (**b**)

Figure S3. Changes of the variables used in Hydraulic Performance Index (HPI) calculation during the simulation time (2007–2016): (**a**) $\%\frac{\alpha}{Ni}$ & $\%\frac{\beta}{Ni}$; (**b**) $\%\frac{\gamma}{Nj}$.

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