8-1-2014

Sustainability Of Dual Water Distribution Systems For Fire Flow Condition

Nazli Yonca Aydin

Larry Mays

Theo G. Schmitt

11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

SUSTAINABILITY OF DUAL WATER DISTRIBUTION SYSTEMS UNDER FIRE FLOW CONDITION

NAZLI YONCA AYDIN (1), LARRY MAYS (2), THEO SCHMITT (3)
(1): Institute of Urban Water Management, University of Kaiserslautern, 67663, Kaiserslautern, Germany
(2): School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85287-5306, USA
(3): Institute of Urban Water Management, University of Kaiserslautern, 67663, Kaiserslautern, Germany

ABSTRACT

The objective of this study is to compare the sustainability of current water systems when a dual water distribution system (WDS) is used for the non-potable water purposes of fire protection, irrigation, and toilet flushing. Sustainability of urban WDS is evaluated in terms of hydraulic efficiency and water quality. The first step is to assess sustainability of an example urban WDS by using sustainability index (SI). The SI is measured by reliability, resiliency, and vulnerability performance indices. Pressure and water age are selected as main parameters to determine sustainability. Once the SIs for pressure and water age are calculated by using the extended period simulation in the U.S. Environmental Protection Agency EPANET, these parameters are aggregated into an overall score ($SI_{overall}$). The critical areas are identified and improved by either adding network elements (i.e. pumps, valves) or adding a second WDS (i.e. reclaimed WDS) to serve for non-potable water demand. Fire flow is added to the modified WDSs and the SI is calculated again. The proposed methodology and application for SI calculation of WDS proved to be a credible approach in identifying poor performance areas and improving water services. A dual WDS for fire flow, irrigation and toilet flushing can assist in providing sustainable water utilities in urban areas meeting future needs. A linear programming procedure is used to determine the minimum cost of the branched dual WDS.

INTRODUCTION

Centralized water distribution systems (WDSs) were considered to be adequate solutions in the early 1900s. Currently, sustainability of centralized infrastructures is questioned due to the changes that already have occurred and/or are expected in the future in terms of climate, population, and environmental stress [1]. Sustainable urban water management concepts together with the urban water infrastructure planning are crucial to overcome the problems associated with the water stress. Loucks [2] introduced a sustainability index (SI) calculation using reliability, resiliency, and vulnerability performance criteria to quantify and monitor sustainability of water supply over time. Sandoval-Solis et al. [3] improved the structure and dimension of the SI calculation proposed by Loucks [2]. The main purpose of the study was to compare alternative water management policies in the Rio Grande Basin.

Alternative water resource management approaches can be focused on decentralized or satellite water – wastewater systems using rainwater harvesting or reclaimed water as alternative resources for non-potable water demand (i.e. toilet flushing, outdoor irrigation, laundry, fire flow demand etc.). Traditionally, decentralization of a water network is considered for non–potable indoor uses such as toilet flushing, outdoor irrigation, and laundry. Although USEPA [4] suggested that using reclaimed water for fire protection is feasible, there are limited examples in the literature that analyze this achievability. Digiano et al. [5] modeled a dual distribution system for Briar Chapel in Chatham County, North Carolina. The result of this model showed that using reclaimed water for firefighting, irrigation and toilet flushing has decreased the water residence time significantly.

In this study, a SI assessment is applied to an example urban WDS (i.e. current WDS) and a proposed reclaimed (i.e. non-potable) WDS. The proposed non-potable WDS is designed using a linear programming (LP) optimization methodology. Fire protection, outdoor irrigation and toilet flushing are considered as non-potable water demands in this study. In order to assess sustainability of the example WDS, hydraulic efficiency and water quality performance indicators are used to calculate reliability, resiliency, and vulnerability. The nodal pressure and water age are determined for a hypothetical WDS as a function of operation time using the U.S. Environmental Protection Agency EPANET model [6]. Critical locations in terms of hydraulic performance in the current WDS are identified using the proposed SI methodology. Then, in order to increase the $SI_{overall}$ scores at these critical locations, two alternative approaches are proposed. One is to add new network components to increase the $SI_{overall}$ scores and the other is to design a reclaimed water distribution system to meet non-potable water demand, and fire flow. The SI methodology is applied to both alternatives with and without fire flow conditions in the WDSs.

SUSTAINABILITY INDEX METHODOLOGY

The extended period simulation (EPS) procedure of the EPANET is used to calculate pressure and water age parameters. In the first step, maximum and minimum pressure requirements are identified and an upper limit for water age is defined. Mathematically the satisfactory and unsatisfactory states of the pressure and water age are represented, respectively, as

$$P_{i,j,t} = \begin{cases} unsatisfactory\ (0)\ P_{i,j,t} < P_{\min} \vee P_{i,j,t} > P_{\max} \\ satisfactory\ (1)\ P_{i,j,t} \geq P_{\min} \vee P_{i,j,t} \leq P_{\max} \end{cases} \quad (1)$$

$$WA_{i,j,t} = \begin{cases} unsatisfactory\ (0)\ WA_{i,j,t} > WA_{\max} \\ satisfactory\ (1)\ WA_{i,j,t} \leq WA_{\max} \end{cases} \quad (2)$$

where $P_{i,j,t}$ is the pressure at node j in zone i at time t; P_{min} is the minimum pressure; P_{max} is the maximum pressure, $WA_{i,j,t}$ is the water age at node j in zone i at time t; and WA_{max} is the maximum water age allowed. In this study, P_{min} and P_{max} are identified as 40-psi (28.1 mH2O) and 80-psi (56.2 mH2O) without fire flow condition respectively. Pressure thresholds are site specific. Decision makers' preferences should be considered to identify the required pressure in the WDSs. ISO [7] minimum fire flow regulations were used as the minimum and maximum pressure thresholds under fire flow conditions. In this study, WA_{max} is identified as 24 hours. If water age parameters of nodes in the WDS are higher than 24 hours, then the performance of the node is assumed to be in the unsatisfactory state.

The SI is measured by reliability, resiliency, and vulnerability performance indices [2]. The following definitions of reliability, resiliency, and vulnerability follow the work of Hashimoto et al. [8].

Reliability (REL) is the probability that the WDS is in a satisfactory state defined as

$$REL_{k,i,j} = \frac{\#\text{ of times satisfactory occurs}}{\text{total}\#\text{ of time steps}} \quad (3)$$

where k refers to nodal pressure or water age at node j in zone i.

Resiliency (RES) represents how fast the system recovers from a failure defined as

$$RES_{k,i,j} = \frac{\#\text{ of times satisfactory follows unsatisfactory}}{\text{total}\#\text{ of times unsatisfactory occurs}} \quad (4)$$

Vulnerability (VUL) is the magnitude or duration of an unacceptable state of WDS in a certain time scale defined as

$$VUL_{k,i,j} = \frac{\#\text{ of times unsatisfactory occurs}}{\text{total}\#\text{ of time steps}} \quad (5)$$

The definition of the SI proposed by Sandoval-Solis et al. [3] is used to calculate the SI for pressure and water age for each node as follows,

$$SI_{k,i,j} = \left[REL_{k,i,j} * RES_{k,i,j} * (1 - VUL_{k,i,j})\right]^{1/3} \quad (6)$$

where k refers to nodal pressure or water age at node j in zone i. The SI score ranges from 0 to 1 for each node. In this study, a WDS is divided into different geographical zones, so that the $SI_{pressure}$ and $SI_{waterage}$ are evaluated for each zone by weighting each node with its demand. This weighting procedure is essential to identify the population effected by poor performance of the WDS. The following function is used to calculate the SI of each zone.

$$SI_{k,i} = \sum_{j=1}^{NJ_i} D_{i,j,dailu} SI_{k,i,j} / \sum_{j=1}^{NJ_i} D_{i,j} \quad (7)$$

where $D_{i,j,daily}$ is the daily demand of node j in zone i; NJ is the total number of junctions. Next, the SI for each zone in terms of pressure and water age are aggregated to produce one overall score of sustainability (i.e. $SI_{overall}$). The following equation is used to calculate the $SI_{overall}$ score.

$$SI_{overall,i} = \sum_{k=1}^{n} SI_{k,i} / n \quad (8)$$

where $SI_{overall,i}$ is the overall SI of ith zone, $SI_{k,i}$ is the SI of the ith zone with respect to the kth attribute, k is the individual index (i.e. pressure or water age) and n is the total number of attributes. In order to identify problematic regions in the WDS, $SI_{overall}$ is divided into four ranges: unacceptable (i.e. [0. 0.25]), moderate (i.e. [0.25, 0.5]), acceptable (i.e. [0.5. 0.75]), and ideal range (i.e. [0.75. 1]). In this study, if the $SI_{overall}$ of the zone is in "unacceptable" state, then the zone is assumed to be unsustainable.

Once critical locations are identified in terms of the proposed SI methodology, two separate approaches are considered for improvement measures in this study: (1) adding new pumps to increase the $SI_{overall}$ or (2) adding a reclaimed WDS to serve for non-potable water demand (i.e. toilet flushing, outdoor irrigation, fire flow). The SI methodology is applied to both alternatives with and without fire flow conditions. ISO [7] minimum fire flow requirements are used to simulate the fire flow in the modified water network (i.e. 1000 gallon per minute (GPM) for two hours with the minimum pressure head requirement of 20-psi (14.1 mH2O)). In this study, it is assumed that 75% of the current base demand will be met using the reclaimed water network at the identified problematic regions of the network.

An optimization model was applied for the design of a reclaimed WDS. Because the proposed reclaimed WDS is dendritic, a LP approach can be utilized and adapted from Mays and Tung [9]. The General Algebraic Modelling System [10] was used as the solver for the optimization model. The objective function of the optimization model is to minimize the sum of costs of the pipe network and the pumping during operation, expressed as

$$Minimize\ Z = \sum_{(i,j)\in I} \sum_{m\in M_{i,j}} C_{i,j,m} X_{i,j,m} + \sum_k CP_k\, XP_k \tag{9}$$

where I is the set of pipe links; $M_{i,j}$ is the set of candidate pipe diameters for the pipe connecting nodes i and j; $C_{i,j,m}$ is the cost per unit length of the m-th diameter for the link connecting nodes i and j; $X_{i,j,m}$ is the unknown length of pipe segment of the m-th diameter in the pipe reach between nodes i and j; CP_k is the unit cost of pumping head at location k; and XP_k is the unknown pumping head at location k. The decision variables are $X_{i,j,m}$ and XP_k.

Subject to the following constraints:

1. Length constraints for each link;

$$\sum_{m\in M_{i,j}} X_{i,j,m} = L_{i,j} \qquad (i,j)\in I \tag{10}$$

where $L_{i,j}$ is the length of the link connecting nodes i and j.

2. Conservation of energy constraints written from the source node location with known elevation (i.e. pressure head), H_s, to each of the delivery points.

$$H_{min,n} \le H_s + \sum_k XP_k - \sum_{(i,j)\in I_n} \sum_{m\in M_{i,j}} J_{i,j,m}\, X_{i,j,m} \le H_{max,n} \tag{11}$$

n=1,…,N

where $J_{i,j,m}$ is the hydraulic gradient of the pipe diameter m connecting nodes i and j. I_n is the set of pipes that defines the path to delivery point n. $H_{min,n}$ and $H_{max,n}$ are respectively the minimum and maximum allowable heads at delivery point n and N is the total number of delivery points.

3. Non-negativity constraints;

$$X_{i,j,m} \geq 0 \tag{12}$$

$$XP_k \geq 0 \tag{13}$$

CASE STUDY

The proposed methodology for the SI calculation of urban WDS is applied to an example network. The network is composed of 181 junctions, 2 reservoirs and 3 storage tanks. Elevations in the network range from minimum and maximum elevations of 320 ft (circa 96 m) and 622 ft (circa 190 m) respectively. Total base demands on nodes are approximately 385 gallon per minute (GPM) (≅87 cubic meter per hour (CMH)).

Analysis of existing system

The main purpose of the existing system analysis is to identify problematic locations in terms of sustainability in the current WDS. The example network is divided into five geographical zones based on the spatial distribution of nodes and elevations of the study area. These zones do not represent pressure zones but geographical regions. Total duration of the EPS is 144 hours; only the 24-hour time period from hours 96 to 120 is used to evaluate the $SI_{overall}$ of the WDS. Figures 1-A and 1-B illustrate the result of $SI_{pressure}$ and $SI_{waterage}$ for each node, respectively.

In this figure, sustainability indices of each node are represented in four categories. The SI values between 0 and 0.25 are representing “unacceptable” states and marked red in Figure 1-A and 1-B. The $SI_{overall}$ of zones 1, 2, 3, 4, and 5 are 0.63, 0.52, 1, 0.92, and 0.12, respectively. The $SI_{overall}$ results show that the Zone 5 has the lowest sustainability score. One reason for the

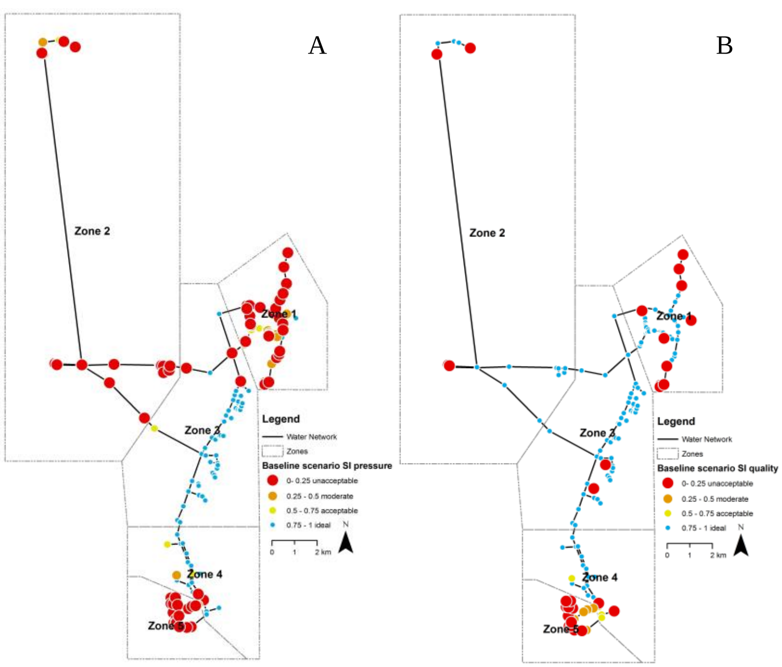

Figure 1. A. Sustainability indices for pressures in the existing system and B. Sustainability indices for water age in the existing system.

low $SI_{overall}$ is that the Zone 5 is at the most distant location from the resources and at the higher ground elevation. The elevation changes significantly from Zone 4 to Zone 5, making it difficult to sustain required nodal pressures in this portion of the network.

New pump approach

In order to increase the $SI_{overall}$ in Zone 5, a booster pump in close proximity to Zone 5 is added to the WDS. The SI methodology is applied to the modified WDS. Adding the booster pump to serve Zone 5 significantly improves the $SI_{pressure}$ and $SI_{waterage}$ scores (see Table 1). The $SI_{overall}$ score of the Zone 5 has increased from 0.12 to 0.76. The remaining $SI_{overall}$ results for all zones are given in Table 1. The next step is to examine the new pump approach under fire flow conditions. The fire event is simulated at Zone 5, since this zone had the lowest $SI_{overall}$ score previously. ISO [7] minimum fire flow requirement of 1000 GPM (63.1 liter/s) for two hours with the required pressure of at least 20-psi (14.1 mH2O) is applied to the selected node which is located at the elevation of 559 ft (170 m). The result of the SI for each zone under fire flow condition can be seen in Table 1.

Table 1. SI scores with a new pump added to the existing WDS.

Zones	SI scores without fire flow			SI scores with fire flow		
	$SI_{pressure}$	$SI_{waterage}$	$SI_{overall}$	$SI_{pressure}$	$SI_{waterage}$	$SI_{overall}$
1	0.43	0.74	0.59	0.26	0.76	0.51
2	0.11	1	0.56	0.07	1	0.53
3	0.97	1	0.99	0.89	1	0.95
4	0.44	0.99	0.72	0.2	0.99	0.6
5	0.53	0.98	0.76	0.15	0.82	0.48

A reclaimed water distribution system approach

In this approach, a reclaimed WDS is designed to meet the non-potable water demand as well as fire flow requirements. The non-potable water network is designed as a dendritic WDS and the LP optimization method is applied to determine pipe sizes and the cost of the network under fire flow condition (see Figure 2). The total non-potable water demand in this approach is approximately 225 m^3/d. Material, labor and equipment together with the backfill costs are investigated for the PVC type pipe cost requirements [11]. Four candidate pipe sizes are considered for each pipe in the reclaimed WDS (i.e. 6, 8, 10, and 12 inches; costs of these PVC pipes are found in [11]). Minimum and maximum allowed pressure heads in the LP method are set to 20-psi (14.1 mH2O) and 80-psi (56.2 mH2O), respectively. Fire flow is simulated with firefighting demand at the same location (see Figure 2.B) using the same minimum fire flow requirement in the ISO [7] standards. The optimal cost of the network is $81,700 and pipe sizes are given in Figure 2.B.

After pipe sizes are determined, the EPS is applied to reclaimed and potable WDSs using EPANET. Base demands at Zone 5 and part of Zone 4 in the potable network is decreased 75 % since the non-potable water demand is met using the reclaimed WDS. The SI methodology is applied to the reclaimed WDS and the potable WDS. The results are given in Table 2, which show that the $SI_{overall}$ in Zone 5 is 0.52 under fire flow condition while it was 0.48 in the new pump approach. One advantage of using a reclaimed WDS for fire flow is that the potable WDS is not affected by fire flow since fire flow demand is met using the reclaimed WDS.

Table 2. SI scores with a reclaimed WDS added.

Zones	SI scores without fire flow			SI scores with fire flow		
	$SI_{pressure}$	$SI_{waterage}$	$SI_{overall}$	$SI_{pressure}$	$SI_{waterage}$	$SI_{overall}$
Potable 1	0.45	0.57	0.51	0.45	0.57	0.51
Potable 2	0.08	1	0.54	0.08	1	0.54
Potable 3	1	0.99	0.99	1	0.99	0.99
Potable 4	0.6	0.99	0.8	0.6	0.99	0.8
Potable 5	0.71	0.33	0.52	0.71	0.33	0.52
Dual	0.87	0.99	0.93	0.83	0.99	0.91

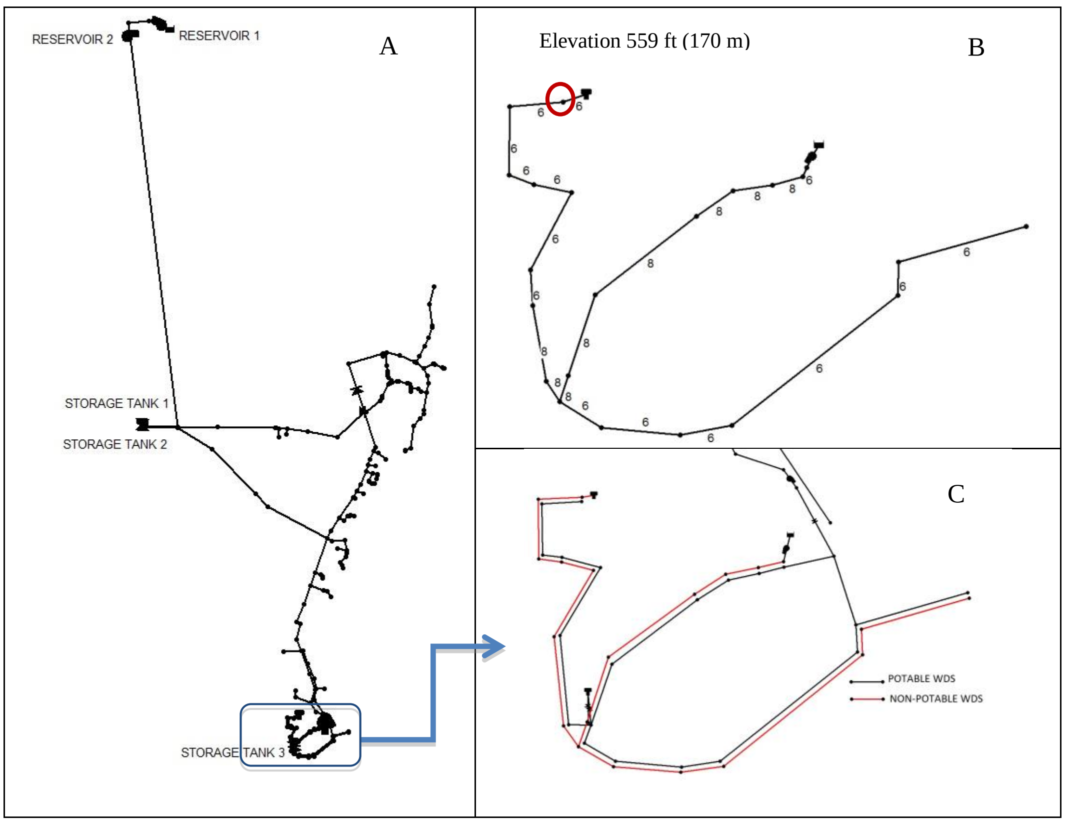

Figure 2. A. Potable and non-potable WDSs B. pipe sizes for non-potable WDS and simulated fire event location. C. The non-potable WDS.

CONCLUSION

The proposed methodology using reliability, resiliency, and vulnerability performance criteria is developed to assess the sustainability of potable and reclaimed WDSs in terms of hydraulic efficiency and water quality. The SI methodology illustrated using an example WDS in order to identify the problematic locations in the existing network. Once the problematic locations are identified, new network components are added to the network in order to improve the $SI_{overall}$. Results show that the $SI_{overall}$ of Zone 5 has increased from 0.12 to 0.76. Then, fire flow simulation using ISO [7] minimum fire flow requirements is applied to the modified WDS. The

$SI_{overall}$ score under fire event decreased to 0.48 in Zone 5. Even though the $SI_{overall}$ scores of Zone 4 and 5 are higher than 0.25 (i.e. identified sustainability threshold), the $SI_{pressure}$ of these zones are affected significantly from the fire flow simulation. Approximately 54 % and 71 % decrease is observed in Zone 4 and 5, respectively.

The reclaimed WDS is designed to meet fire flow and non-potable water demand using the LP optimization method. The SI methodology is applied to the potable and non-potable WDSs with and without fire flow demand. The result showed that the $SI_{overall}$ score of the reclaimed WDS is not affected significantly by fire flow. The $SI_{overall}$ scores of the potable WDS does not change since there is no fire flow demand in the potable WDS. On the other hand, $SI_{waterage}$ of Zone 5 has decreased by 66 % due to the significant base demand decrease at Zone 5 (i.e. 75 %). This problem can be solved by reducing the pipe diameters in the current WDS which will decrease the residence time. Overall, the proposed methodology and application for SI calculation of WDS is a credible approach in identifying poor performance areas. However, pressure and water age thresholds are site specific and should be determined considering decision makers' preferences or expert knowledge. The advantage of using a reclaimed WDS for fire flow is that the hydraulic efficiency and water quality parameters in the potable WDS are not affected by a possible firefighting event. In addition, a large amount of potable water can be saved by meeting non-potable and fire flow demand with the reclaimed water resource.

REFERENCES

[1] Marlow D.R., Moglia M., Cook S. and Beale D.J., "Towards sustainable urban water management: A critical reassessment", Water Research, Vol. 47, (2013), pp 7150-7161.

[2] Loucks D.P., "Quantifying trends in system sustainability", Hydrol. Sci. J., Vol. 42(4), (1997), pp 513–530.

[3] Sandoval-Solis S., McKinney D.C. and Loucks D.P., "Sustainability Index for Water Resources Planning and Management", Journal of Water Resources Planning and Management, Vol. 137(5), (2011), pp 381-390.

[4] USEPA (US environmental protection agency) "Guidelines for water reuse", EPA 625/R-04/108. Washington, (2004).

[5] Digiano F.A., Weaver C.C. and Okun D.A., "Benefits of shifting fire protection to reclaimed water", Journal American Water Works Association, Vol. 101(2), (2009), pp 65-74.

[6] Rossman L.A., "EPANET 2 Users Manual", U.S. Environmental Protection Agency, Cincinnati, USA, (2000).

[7] ISO, "Guide for determination of needed fire flow 2008" http://www.isomitigation.com/downloads/ppc3001.pdf Accessed 30 November 2013.

[8] Hashimoto T., Stedinger J. R. and Loucks, D.P., "Reliability, resiliency and vulnerability criteria for water resource system performance evaluation", Water Resour. Res., Vol. 18(1), (1982), pp 14–20.

[9] Mays L.W., Tung Y.K. "*Hydrosystems Engineering and Management*", Water Resources Publications, LLC, Colorado, USA, (1992).

[10] The General Algebraic Modeling System (GAMS), www.gams.com. Accessed 12 February 2013.

[11] JM Eagle Manufacturing Company Inc. Pipe Calculators & Engineering Resources; PVC vs Ductile Iron Pipe Installed Cost Comparison Calculator. http://www.jmeagle.com/contact2011/calc_links.html. Accessed 12 February 2013.