Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010;
posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

Surplus power factor as a resilience measure for assessing hydraulic reliability in water transmission system optimization

Wenyan Wu
PhD Candidate, School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, 5005, Australia
wwu@civeng.adelaide.edu.au
Holger R. Maier
Professor, School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, 5005, Australia
hmaier@civeng.adelaide.edu.au
Angus R. Simpson
Professor, M.ASCE, School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, 5005, Australia
asimpson@civeng.adelaide.edu.au

Abstract

The hydraulic reliability of a water distribution system (WDS) can be improved by increasing the resilience to failure conditions. In previous research, numerous measures have been developed to quantify network resilience which has been consequently linked to the hydraulic reliability of WDSs. Often, the difference between the output pressure head and the minimum required pressure head is required in the calculation of these network resilience measures. Difficulties arise when these measures are applied to water transmission systems (WTSs). The reason for this is that in a WTS, water is often pumped into a storage tank or reservoir, in which case the difference between the output pressure head and the minimum required pressure head is always zero. In order to overcome this shortcoming, it is suggested that the surplus power factor can be used as a network resilience measure, as calculation of this measure does not require the pressure value at the outlet of a WDS. In the research presented here, three case studies are used to assess the suitability of the surplus power factor as a network resilience measure for WDSs. A fourth case study

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

is used to demonstrate the application of surplus power factor as a network resilience measure for WTSs, to which the other measures cannot be applied. The results show that the surplus power factor can be used as a network resilience measure to incorporate hydraulic reliability considerations into the optimization of WDSs and particularly WTSs.

Key words

Water distribution systems; Water transmission systems; Network resilience; Hydraulic reliability; Surplus power factor.

Introduction

Hydraulic reliability is an important performance measure of water distribution systems (WDSs), as it refers directly to their basic function (Ostfeld et al., 2002). It is therefore often considered as the ultimate goal of WDS design (Li et al., 1993). However, there is no universally accepted approach for assessing the reliability of WDSs (Mays, 1996). A common way of characterizing the hydraulic reliability of WDSs is by measuring "how far" a system is from failure. The greater the excess capacity of a system in relation to a specified hydraulic failure condition, the more resilient the system is to hydraulic failures, thereby improving the hydraulic reliability of the system. It should be noted that this definition of hydraulic reliability is different from measures of reliability that refer to the probability of non-failure of WDSs (Tolson et al., 2004) and does not take account of mechanical failures, such as pipe breakage or the absence of alternative supply paths.

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

In previous research, a number of resilience-based hydraulic reliability measures have been developed for WDSs. As early as 1985, Gessler and Walski (1985) used the excess pressure at the worst node in the system as a benefit measure in a pipe network optimization problem to ensure sufficient water with acceptable pressure is delivered to demand nodes. Todini in 2000 developed a hydraulic reliability measure called the resilience index, which directly measures the ability of a network to overcome failure conditions. Other similar hydraulic reliability measures include the network resilience measure developed by Prasad and Park (2004); a robustness measure, as used in Kapelan et al. (2005) and Babayan et al. (2007); and the modified resilience index developed by Jayaram and Srinivasan (2008).

Difficulties arise when applying the above measures to water transmission systems (WTSs). This is because these measures have one thing in common – their calculation relies on the difference between the required and minimum allowed pressure heads at the outlet of the system, which are often zero in WTSs, as in such systems water is usually delivered into tanks or reservoirs. Thus, for WTSs, the values of the above measures are always zero. As a result, explicit consideration of hydraulic reliability as a design objective of WTSs remains a challenge.

In 2006, Vaabel et al. (2006) introduced the surplus power factor (s), which is based on the concepts of hydraulic power and energy transmission of flow in a pipe. The surplus power factor can be used to measure the network resilience of a hydraulic system subject to failure conditions simultaneously on the basis of both pressure and flow (Vaabel et al., 2006). More importantly, calculation of the surplus power factor does not require the value of the pressure head at the outlet of the system. Therefore,

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

the surplus power factor is an ideal candidate for the calculation of the network resilience of WTSs.

In this research, the surplus power factor developed by Vaabel et al. (2006) is validated against three existing network resilience measures using three benchmark case studies. Then, a three-tank system is used to demonstrate the application of the surplus power factor as a network resilience measure for WTSs, to which the other measures cannot be applied, as discussed above.

Surplus power factor (*s*)

The surplus power factor (s) was introduced by Vaabel et al. (2006) to evaluate the hydraulic power capacity of WDSs on the basis of both flow within pipes and pressure head at the inlets of pipes. In this research, the surplus power factor is also called the s factor for the sake of convenience.

For the system shown in Figure 1, Q_{in} and Q_{out} are the inflow and outflow of the pipe, respectively; H_{in} and H_{out} are the heads at the inlet and outlet of the pipe, respectively; *h* is the head loss within the pipe; and *q* is the flow within the pipe. The hydraulic power at the outlet of the pipe (P_{out}) can be calculated using the following equation (Vaabel et al., 2006):

$$P_{out} = \gamma\left(Q_{in}H_{in} - cQ_{in}^{\ a+1}\right) \quad (1)$$

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010;
posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

where, γ is the specific weight of water; c is the pipe resistance coefficient (that depends on the form of the head loss equation used); and a is the flow exponent. The maximum hydraulic power at the outlet of the pipe $P_{\max}$ can be expressed using the following equation (Vaabel et al., 2006):

$$P_{\max} = \frac{\gamma a}{c^{\frac{1}{a}}} \left(\frac{H_{in}}{a+1} \right)^{\frac{a+1}{a}} \tag{2}$$

Thus, the surplus power factor (s) is defined as:

$$s = 1 - \frac{P_{out}}{P_{\max}} \tag{3}$$

or:

$$s = 1 - \frac{a+1}{a} \left[1 - \frac{1}{a+1} \frac{Q_{in}{}^{a}}{Q_{\max}{}^{a}} \right] \frac{Q_{in}}{Q_{\max}} \tag{4}$$

where, $Q_{\max}$ is the flow that gives the maximum hydraulic power at the outlet of the pipe. The surplus power factor can be used as a measure of the network resilience of a hydraulic system. The range of the s factor is from zero to 1, as plotted in Figure 2. When s is equal to zero, P_{out} equals $P_{\max}$ and the hydraulic system works at its maximum capacity. Under this condition, any leakage can result in failure of the system in terms of meeting the needs of end water users, such as delivering enough water with sufficient pressure. As the value of the s factor increases, the resilience of the system to failure conditions increases. However, as long as the system delivers

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

water to end users, the value of s cannot reach 1, as when $Q_{in}/Q_{\max}$ reaches $\sqrt{3}$, the friction loss within the pipe will be equal to H_{in} and there will be no flow in the pipe. It should also be noted that in Figure 2, a given value of the s factor corresponds to two different values of $Q_{in}/Q_{\max}$. While this is theoretically correct, when Q_{in} is greater than $Q_{\max}$, very high input power values are required to achieve a certain s factor value, which results in extremely low efficiency within the system. Therefore, the condition of Q_{in} being greater than $Q_{\max}$ is not practical and can therefore be ignored for the purpose of estimating the network resilience of WDSs.

Case studies

A total of four case studies are investigated in this research. The first three case studies are used to assess the suitability of the surplus power factor as a network resilience measure. The last case study is used to demonstrate the application of the surplus power factor as a network resilience measure for a water transmission system (WTS), for which other network resilience measures cannot be used.

The first case study is a two-loop network, which was introduced in Abebe and Solomatine (1998), and then studied by Todini (2000) and Prasad and Park (2004). The details of this network can be found in Prasad and Park (2004). The second case study is the New York Tunnel (NYT) problem, which has been studied extensively by many researchers. Details of this problem can be found in Zecchin et al. (2006). The third case study is the Hanoi problem, which is also a WDS benchmark case study that has been considered by numerous authors. Details of this case study can also be

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

found in Zecchin et al. (2006). The fourth case study is a three-tank WTS consisting of a water source, a pump, eight pipes and three storage tanks. Water needs to be delivered into the three tanks via a looped network. Details of this case study can be found in Wu et al. (2010).

Validation results for the first three water distribution system case studies

In order to compare the utility of the surplus power factor as a measure of network resilience, The average s factor (s_{ave}) is compared with three commonly used network resilience measures, including the minimum surplus head I_m (Gessler and Walski, 1985), the resilience index I_r (Todini, 2000) and the modified resilience index MI_r (Jayaram and Srinivasan, 2008) for the first three case studies introduced previously. Definitions of the three resilience measures are provided below:

1) *Minimum surplus head (I_m)*: The minimum surplus head I_m is defined as the surplus pressure head at the worst node. This measure was used as a hydraulic benefit indicator in Gessler and Walski (1985), and then as a hydraulic reliability measure in Prasad and Park (2004).

2) *Resilience index (I_r)*: The resilience index *(I_r)* developed by Todini (2000) is defined as the quotient of the difference between the actual output power and the required output power and the difference between the total input power and the required output power.

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

3) *Modified resilience index (MI_r)*: The modified resilience index *(MI_r)* developed by Jayaram and Srinivasan (2008) is defined as the amount of surplus power available at the demand nodes as a percentage of the total minimum required power.

The actual configurations of the networks used for the comparison study are generated using a multiobjective optimization approach, in which the cost of the network is minimized and the network resilience represented by s_{ave} is maximized. The optimal fronts representing the tradeoffs between cost and s_{ave} for the three case studies are plotted in Figure 3. The values of the other three hydraulic reliability measures of these optimal solutions are also calculated. The number of optimal solutions investigated for each case study and the correlation between s_{ave} and the other three measures (I_m, I_r and MI_r) are summarised in Table 1. Values of the cost and network resilience measures of four typical solutions for each case study are summarized in Table 2. The numbers and square symbols in Figure 3 show the locations of these typical solutions on the corresponding Pareto-optimal front.

It can be seen from Figure 3 that there are significant tradeoffs between the cost of the network and the network resilience level represented by s_{ave} for all three case studies. Often, a small increase in cost can result in significant increase in network resilience. Both Tables 1 and 2 show that s_{ave} is highly correlated with the other three network resilience measures. The correlation coefficients between s_{ave} and I_r, and between s_{ave} and MI_r are 0.97 for the two-loop and Hanoi networks. The correlation between s_{ave} and I_m is slightly lower. This is because s_{ave}, I_r and MI_r are all calculated based on the performance of the whole network, whereas, values of I_m are mainly

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010;
posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

affected by a number of critical nodes (one node for the two-loop network, one node for the Hanoi network and three nodes for the NYT problem). In addition, the correlation between s_{ave} and the other three measures for the NYT problem are slightly lower. Again, the reason for this is that the I_m, I_r and MI_r values for the NYT problem are controlled by three critical nodes. In contrast, the available input power and internal resistance of the pipes have the biggest impact on the calculation of s_{ave}.

It is clear from the results presented above that although s_{ave} focuses on a different aspect of network resilience compared with the other three network resilience measures investigated, s_{ave} is highly correlated with these measures and can be used as an indicator of the network resilience of a WDS.

Application results for the three-tank water transmission system

The solutions for the three-tank WTS (Wu et al., 2010) are also generated using a multiobjective approach, in which the life cycle cost is minimised and s_{ave} is maximized. The life cycle cost is formulated as the sum of capital cost, pump refurbishment cost and operating cost. A design life of 100 years and a discount rate of 8% are used to calculate the pump refurbishment and operating costs. The life cycle cost evaluation process can be found in Wu et al. (2010).

The Pareto-optimal front formed by 507 optimal solutions is presented in Figure 4. It should be noted that for this case study, the values of I_m, I_r and MI_r are always zero,

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

regardless the configuration of the solution network, as water is delivered into tanks. Four typical solutions, which are marked using the unfilled square symbol and as solutions 1 to 4 in Figure 4, are selected for demonstration purposes. The network configurations of these four solutions are summarised in Table 3, and the flow distributions and s_{ave} values of these four solutions are summarised in Table 4.

It can be seen from Figure 4 that there are significant tradeoffs between life cycle cost and network resilience, as given by s_{ave}, for the three-tank WTS. Table 3 shows that as the pipe cost increases, the pump size decreases. This is because larger pipes result in smaller friction losses, which in turn reduces the power required to pump the required flow. The network resilience of this system is dependent on both pumping capacity and pipe sizes. As for this particular case study the pumps are sized according to the pipelines, pipe size dominates network resilience and thus the hydraulic reliability of the system. Solution 1 has the lowest pipe cost of $12.26 million. Table 4 shows that the s_{ave} values of solution 1 are also the lowest, indicating a low level of network resilience. As the pipe sizes increase (moving from solution 1 to solution 4), the s_{ave} values increase accordingly, indicating an overall increase in network resilience level. However, the minimum s factors ($s_{\min}$) of solutions 2 and 3 are still low, despite the increase in s_{ave} values. This is caused by the low s_{ave} values of pipe 1 of solution 2 and pipe 2 of solution 3. In contrast, solution 4 has a more evenly distributed surplus power, which is also represented by the significantly reduced difference between the average and minimum s factors. Compared to solutions 1 to 3, the average and minimum s factors of solution 4 are significantly

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

higher. However, the life cycle cost of solution 4 is two times higher than that of solution 3 and the pipe cost of solution 4 is quadrupled compared to that of solution 1.

Conclusions

In this research, the suitability of using the surplus power factor (s) as a measure of the network resilience of WDSs has been assessed. Similar to the majority of existing network resilience measures, such as the minimum surplus head (I_m), the resilience index (I_r), and the modified resilience index (MI_r), the surplus power factor does not consider mechanical failures of WDSs, such as pipe breakage or the absence of alternative supply paths. In contrast, it is predominately used to quantify the excess capacity of a system in relation to a specified hydraulic failure condition. However, the surplus power factor has one significant advantage over existing network resilience measures. As the calculation of the surplus power factor does not require the value of the output pressure head of a network, it can be used to evaluate the network resilience of water transmission systems (WTSs); whereas most existing surplus power based WDS hydraulic reliability measures cannot be applied to such systems.

In this research, the utility of the average surplus power factor (s_{ave}) as a network resilience measure was first tested by comparing it with three existing measures (the minimum surplus head (I_m), resilience index (I_r), and modified resilience index (MI_r)) for three WDS case studies. Then, a three-tank transmission system was used to illustrate the application of the surplus power factor as a network resilience measure for a WTS. It was found that there exist significant tradeoffs between the

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

cost and network resilience represented by the surplus power factor and the surplus power factor is highly correlated with the three existing network resilience measures for all three case studies considered. In addition, use of the surplus power factor as a network resilience measure was demonstrated for a WTS. Consequently, the surplus power factor can potentially be used as a network resilience measure to incorporate hydraulic reliability considerations into the optimization of WDSs and particularly WTSs.

References

Abebe, A. J. and Solomatine, D. P. (1998). "Application of global optimization to the design of pipe networks." *Proc. 3rd International Conference on Hydroinformatics*, Copenhagen, Balkema, Rotterdam.

Babayan, A. V., Savic, D. A., Walters, G. A., and Kapelan, Z. S. (2007). "Robust Least-Cost Design of Water Distribution Networks Using Redundancy and Integration-Based Methodologies." *Journal of Water Resources Planning and Management*, 133(1), 67-77.

Gessler, J. and Walski, T. M. (1985). "Water distribution system optimization." *Technical Rep. EL-85-11*, Department of the Army, U.S. Army Corps of Engineers, Washington, D.C.

Jayaram, N. and Srinivasan, K. (2008). "Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing." *Water Resources Research*, 44, W01417, 1417-1417.

Kapelan, Z. S., Savic, D. A., and Walters, G. A. (2005). "Multiobjective design of water distribution systems under uncertainty." *Water Resources Research*, 41(11), 11407.

Li, D., Dolezal, T., and Haimes, Y. Y. (1993). "Capacity reliability of water distribution networks." *Reliability Engineering and system safety*, 42, 29 - 38.

Mays, L. W. (1996). "Review of reliability analysis of water distribution systems." *Proc. Stochastic Hydraulics'96*, Balkema, Rotterdam, The Netherlands, 53-62.

Ostfeld, A., Kogan, D., and Shamir, U. (2002). "Reliability simulation of water distribution systems - singla and multiquality." *Urban Water*, 4, 53 - 61.

Prasad, T. D. and Park, N.-S. (2004). "Multiobjective Genetic Algorithms for Design of Water Distribution Networks." *Journal of Water Resources Planning and Management*, 130(1), 73-82.

Todini, E. (2000). "Looped water distribution networks design using a resilience index based heuristic approach." *Urban Water*, 2, 115 - 122.

Tolson, B. A., Maier, H. R., Simpson, A. R., and Lence, B. J. (2004). "Genetic algorithms for reliability-based optimization of water distribution systems." *Journal of Water Resources Planning and Management*, 130(1), 63-72.

Vaabel, J., Ainola, L., and Koppel, T. (2006). "Hydraulic Power Analysis for Determination of Characteristics of A Water Distribution System." *8th Annual Water Distribution Systems Analysis Symposium*, Cincinnati, Ohio, USA.

Wu, W., Maier, H. R., and Simpson, A. R. (2010). "Single-Objective versus MultiObjective Optimization of Water Distribution Systems Accounting for Greenhouse Gas Emissions by Carbon Pricing." *Journal of Water Resources Planning and Management*, 136(5), 1-11.

Zecchin, A. C., Simpson, A. R., Maier, H. R., Leonard, M., Roberts, A. J., and Berrisford, M. J. (2006). "Application of two ant colony optimisation algorithms to water distribution system optimisation." *Mathematical and Computer Modelling*, 44(5-6), 451-468.

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

Figure 1 Flows, heads and head loss for a single pipe (adapted from Vaabel et al. (2006))

Figure 2 Surplus power factor s as a function of Q_{in}/Q_{max}

Figure 3 Pareto-optimal solutions of the first three case studies

Figure 4 Pareto-optimal solutions of the three-tank water transmission network

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

Table 1 Correlation between the average s factor and the other three network resilience measures considered (I_m, I_r and MI_r) for the first three case studies

Network	Number of solutions	Correlation		
		s_{ave} and I_m	s_{ave} and I_r	s_{ave} and MI_r
Two-loop	186	0.94	0.97	0.97
NYT	737	0.75	0.82	0.82
Hanoi	962	0.93	0.97	0.97

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

Table 2 Typical solutions for the first three case studies

Case study	Solution number	Cost ($M)	s_{ave}	I_m	I_r	MI_r
Two-loop	1	0.419	0.55	0.44	0.21	0.03
	2	0.423	0.66	0.03	0.35	0.04
	3	0.678	0.84	5.51	0.66	0.08
	4	4.400	0.93	12.73	0.90	0.11
NYT	1	38.64	0.72	0.02	0.42	0.07
	2	56.61	0.81	0.02	0.49	0.08
	3	89.28	0.86	0.41	0.52	0.09
	4	292.82	0.91	6.39	0.88	0.15
Hanoi	1	6.081	0.37	0.01	0.19	0.45
	2	6.365	0.48	0.07	0.21	0.49
	3	7.235	0.60	4.38	0.26	0.61
	4	10.970	0.74	19.62	0.35	0.83

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

Table 3 Network configurations of four typical solutions of the three-tank water transmission system case study

Solution number	Pipe diameter (mm)								Pump size (kW)	Pipe cost ($M)
	Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 5	Pipe 6	Pipe 7	Pipe 8		
1	300	225	150	100	300	150	150	225	401	12.26
2	300	225	225	225	300	225	225	225	323	13.18
3	300	300	300	375	375	225	375	225	251	15.37
4	1,000	1,000	900	1,000	1,000	1,000	900	1,000	107	57.57

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

Table 4 Flow distribution and s factors of four typical solutions of the three-tank case study

Pipe No.	Solution 1		Solution 2		Solution 3		Solution 4	
	Flow (L/s)	s factor	Flow (L/s)	s factor	Flow (L/s)	s factor	Flow (L/s)	s factor
1	129.66	0.0013	126.36	0.0168	121.04	0.0495	121.28	0.8720
2	60.34	0.0148	63.18	0.0096	81.98	0.0710	60.64	0.9521
3	48.72	0.0130	40.00	0.4388	40.49	0.7110	40.01	0.9810
4	11.61	0.0101	23.18	0.5243	41.49	0.7614	20.64	0.9885
5	40.00	0.7143	46.36	0.6726	40.55	0.8334	41.27	0.9849
6	28.39	0.0019	23.18	0.5243	0.94	0.9730	20.64	0.9885
7	40.94	0.0008	40.00	0.4388	40.00	0.8356	40.01	0.9810
8	69.33	0.0014	63.18	0.0096	39.06	0.0632	60.64	0.9521
s_{ave}	0.0947		0.3294		0.5373		0.9625	
s_{min}	0.0008		0.0096		0.0495		0.8720	

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

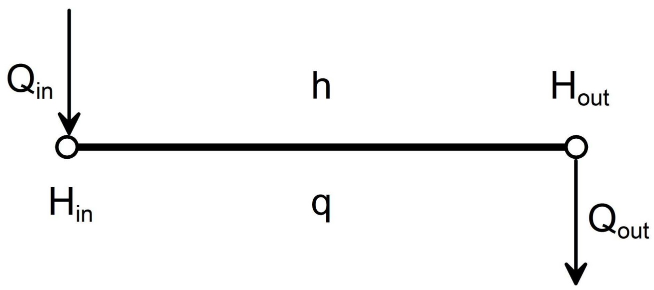

Figure 1 Flows, heads and head loss for a single pipe (adapted from Vaabel et al. (2006))

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

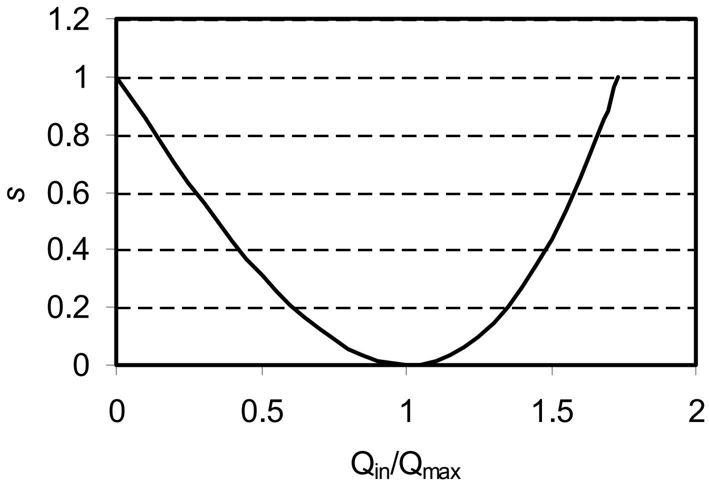

Figure 2 Surplus power factor s as a function of Q_{in}/Q_{max}

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

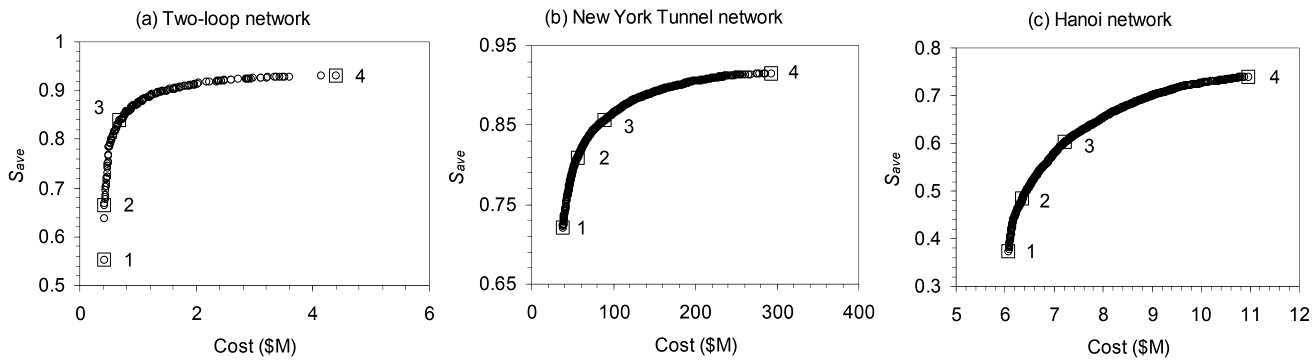

Figure 3 Pareto-optimal solutions of the first three case studies

Journal of Water Resources Planning and Management. Submitted May 13, 2010; accepted December 7, 2010; posted ahead of print December 9, 2010. doi:10.1061/(ASCE)WR.1943-5452.0000138

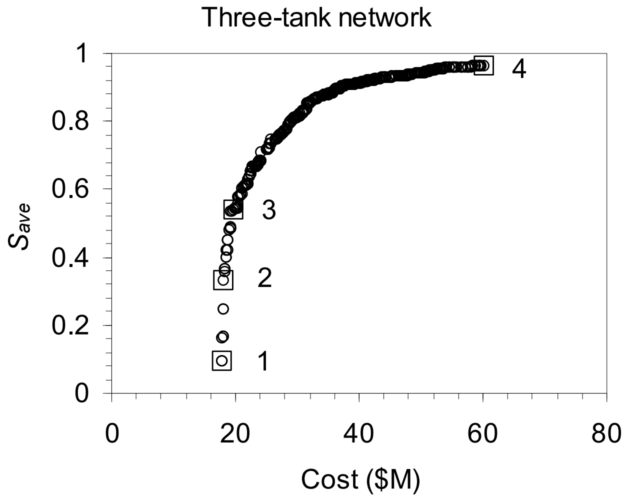

Figure 4 Pareto-optimal solutions of the three-tank water transmission network