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Impact of planning horizon on water distribution network design

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ABSTRACT

The continuous expansion of the Water Distribution Network (WDN) makes its design a dynamic process performed within many planning horizons. An appropriate planning horizon is important to save costs and avoid over-design. Typically, a master plan is practiced around every 20 years. The complexity of WDN and computational demands have prevented a full network study of the impact of planning horizons on system cost and efficiency. In this paper, a dynamic network model was employed to simulate the growth of WDN under different growth patterns (exponential and linear) and planning horizons to explore the optimum planning horizon under different interest rates. It is found that the choice of the optimum (i.e. least costly) planning horizon is sensitive to the interest rate. For both growth patterns, a shorter planning horizon is favored with higher annual interest rates while a longer planning horizon is favored with lower rates. With the same interest rate, exponential growth pattern generally favors a shorter planning horizon than a linear growth pattern due to more excess capacity provided at the beginning of the study period. The optimum planning horizon is longer than 20 years when the interest rate is lower than 3.0% for linear growth or 2.0% for exponential growth.

Key words: dynamic model, interest rate, planning horizon, water distribution network

HIGHLIGHTS

- Development of a dynamic WDN simulation model with multi-stage network optimization.
- Investigation of the optimum planning horizon of a whole WDN expansion regrading to different urban growth patterns and interest rates.

INTRODUCTION

As a critical part of urban systems, Water Distribution Networks (WDNs) continuously expand themselves over time to meet the growing demand of population growth. The master planning of WDNs is generally done over short-term planning horizons (typically about 20 years) with the objective of minimizing the system's cost to meet the water demand by the end of the planning horizon. Such practice prohibits excess capacity, thus the system might fail to meet the new water demand after the planning period and capacity expansion would be required (Hsu *et al.* 2008).

Long-term planning is favored considering economies of scale in pipes. Walski (2013) derived an equation describing the relationship between pipe cost and its capacity according to Equation (1):

$$\text{cost} = 2.67 \times \text{capacity}^{0.567} \tag{1}$$

This equation indicates that installing a large pipe costs less than several smaller pipes of the same capacity. On the other hand, it may avoid overdesign and save interest cost to build smaller parallel pipes over time instead of installing a larger pipe. There is a trade-off between economies of scale and excess capacity cost due to interest rate.

The problem of expansion size and timing is generally studied in the field of capacity expansion. On WDN design, research has been done on expansion scheduling over a planning period. Martin (1990) introduced a capacity expansion model to obtain an approximate least-cost design for phasing construction of pipes and pump stations of a linear water-supply pipeline over a planning period. Creaco *et al.* (2014) taken account of uncertainty in demand growth to phasing construction based on

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a probabilistic approach. Kang & Lansey (2014) have adopted scenario-based planning to incorporate multiple uncertainties of developments for a long-term planning horizon. Some multi-objective optimization models have been proposed for the phasing construction of pipelines, considering cost, resilience, pressure, and carbon emission (Creaco *et al.* 2013; Marques *et al.* 2018; Sirsant & Reddy 2021). Generally, the multiphase design of a WDN is more cost-effective than a single-phase design and more adaptive to changing conditions. But it also has higher computational cost which can be challenging for the design problem of a large network.

Only few papers were devoted to studying the optimum planning horizon for WDN expansion. Applying the model introduced by Manne (1961) to determine the optimal expansion size for a new facility, Scarato (1969) obtained the optimum expansion cycle for a water pipeline considering an infinite time period and assuming a linear water demand growth. The optimum planning cycle was found to depend on the interest rate. Higher interest rates lead to shorter optimum expansion cycles. Since water pipelines usually have a life span of over 100 years, Walski (2013) used a single pipe section to address the problem of optimum planning horizon for a total of 100-year period. He found that the optimum planning horizon drops from roughly 60 to 40 years as the annual interest rate increases from 1 to 5%. Considering the complexity feature of WDNs, this paper investigated the optimum planning horizon by simulating the dynamic growth of a whole network using spatial network models.

WDNs are complex networks that consist of many interconnected components, as suggested by Yazdani & Jeffrey (2011b). Currently, complex network researchers have introduced new concepts and tools to describe and model the complex behaviors of complex networks. Particularly, the research on spatial networks provides a foundation to simulate the complex topology of WDNs and their dynamics. Based on the assumption that every new edge is generated to efficiently connect the new node to the existing network, a few simple dynamic models are developed to study the growth of spatial complex networks (Barthélemy 2011). Even though those models are based on the mechanism of local optimization, some global structural properties can be reproduced. Specifically, Gastner & Newman (2006) proposed two similar models for the growth of spatial distribution networks, which can explain how optimal distribution networks become economical and efficient. Based on their models, we have developed and released a dynamic complex network model to simulate WDN growth patterns by incorporating engineering rules (Zeng *et al.* 2017). In this study, our model has been applied to a test case to generate a series of layouts of WDN expansion at different time periods within the study span with both linear and exponential population growth rates. The generated layouts are used for pipe sizing under different planning horizons. The impact of the planning horizon is investigated under different annual interest rates. Pipe sizing of the test case over a planning horizon is done based on an evolutionary algorithm, the parallel hybrid estimation of distribution algorithm and particle swarm optimization (PEDPSO) (Qi *et al.* 2016).

METHODS

Test case

The test case in base scenario is a synthetic WDN serving a squared city with a population of 106,029 uniformly distributed in the urban area. The average urban population density from 2005 and 2010 US Census data is around 1000 capita/km^2. In this study, the population density of the study city is set to 1,060.29 capita/km^2. The water network consists of a reservoir situated in the city's center, 145 junctions and 193 pipes (Figure S1). Shammas & Wang (2011) showed typical demand values for total water demand in the US ranging from 227.1 to 1,324.9 liters per capita per day (lpcd). In this study, average daily water demand is set to 518.4 lpcd, and the maximum hourly water demand is assumed to be 3 times of the average daily demand.

Population growth and water demand

The total study span for the test case is 100 years. Two population growth scenarios are investigated. One has exponential growth with a growth rate of 9.7% per 10 years which is the US population growth rate in the first decade of the 21st century reported by the 2010 US census. The other one is the linear growth pattern. System-wide water demand at different time points is shown in Table 1 for both growth patterns. At the end of the study span, both scenarios have the same size of population and water demand needs.

Modeling of WDN layout expansion

The development of water supply infrastructure is a dynamic process in accordance with the current and future water demands. In our previous work (Zeng *et al.* 2017), we have developed a dynamic complex network model to simulate the

Table 1 | Design parameters

	Linear growth		Exponential growth		
Planning horizon (years)	**Water demand (MGD)**	**Reservoir head (m)**	**Water demand (MGD)**	**Reservoir head (m)**	**D_{max} (inch)**
Base	14.517	50	14.517	50	–
10	16.700	55	15.941	53	36
20	18.882	60	17.459	56	36
30	21.065	65	19.167	60	36
40	23.247	70	21.065	64	36
50	25.429	75	23.057	69	42
60	27.612	80	25.334	74	42
70	29.794	85	27.801	80	42
80	32.071	90	30.458	86	48
90	34.349	95	33.400	93	48
100	36.626	100	36.626	100	48

layout expansion of WDN caused by the increasing water demands without hydraulic considerations. In this work, we apply the same model to simulate the layout expansion of the test case independent of hydraulics. Afterward, under different scenarios for the planning horizon and the interest rate, an optimization strategy is adopted to the same simulated layouts in order to minimize the capital cost while meeting the hydraulic requirement, which is described in the next section.

The method models a WDN as a simple planar graph $G = G(N, E)$ where N is the set of nodes (reservoir and junctions) and E is the set of edges (pipes) connecting the nodes. Additional water reservoirs were not considered although they can be modeled by a graph with multiple roots. Specifically, the dynamic model consists of two main modules: the node (water demands) generation module and the edge (pipes) generation module. The schematic flow chart of WDN layout generation is shown in Figure 1. At each time frame, the node generation module simulates the increase of new water demands according to population growth. Multiple new water demand nodes, the number of which is determined based on the population growth assuming that each node represents the water demand from a fixed size of growing population, are generated randomly with a uniform distribution within the urban area (A) that follows the scaling function according to Equation (2) (Marshall 2007; Bettencourt 2013):

$$A \propto P^{\alpha} \tag{2}$$

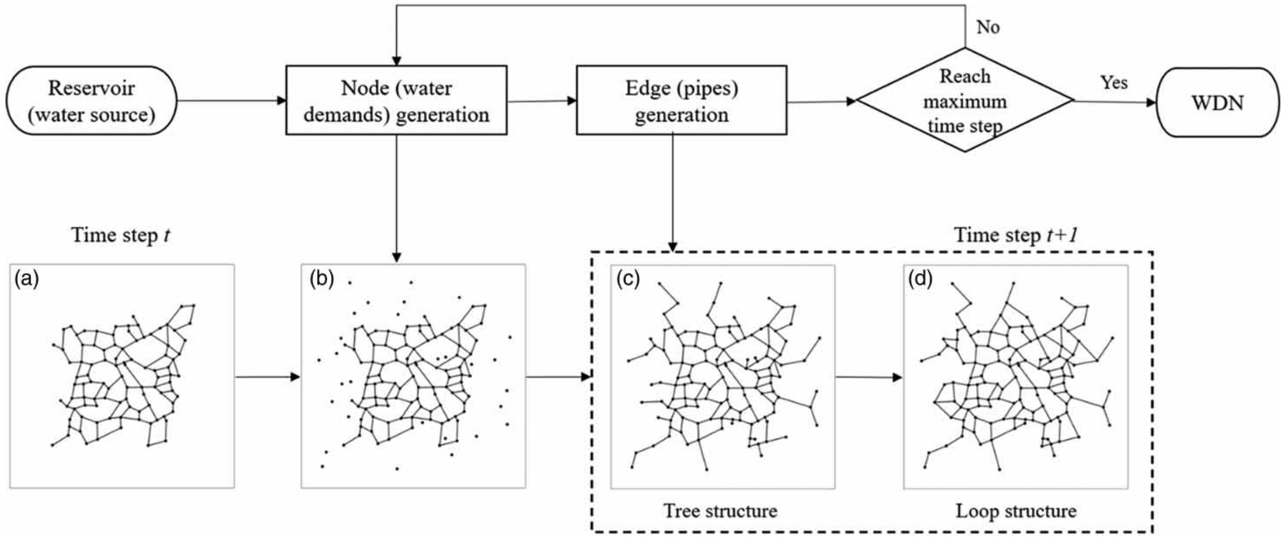

Figure 1 | Schematic flow chart of WDN layout generation.

where P is total population and α is a scaling factor characterizing how urban area grows with population, as shown in Figure 1(b). Following the node generation module, the edge generation module connects those new nodes to the existing WDN to meet the emerging new demands. The module consists of two steps in establishing the connections. In the first step, for each new demand node, the module adds only one edge to connect that node to the existing network, resulting in a tree-like structure (Figure 1(c)). The location of the edge is determined based on both the length of edge representing capital cost and the shortest path distance from the new demand node to the root node (reservoir) representing operational energy efficiency and water age. As in real-world WDN design and construction, looped structures would be preferred due to reliability considerations. In the second step, the module adds extra edges to the graph in order to form some loops. The extra edges are added based on edge length as well as a series of graphic and engineering constraints, where the details can be found in (Zeng *et al.* 2017). The final graph (Figure 1(d)) is then a more realistic simulation of the WDN layout expansion in response to the population growth. In this work, the length of each time frame is set to 10 years, thus the layout expansion is simulated in 10 time frames for a total study span of 100 years.

Modeling of WDN pipe sizing

In this study, four different planning horizons are investigated: 10, 20, 50 and 100 years. With a 10-year planning horizon, 10 sequenced designs of WDN expansion are required for the whole study span (100 years), while only one-time design is needed with a 100-year planning horizon. For each growth pattern, designs under different planning horizons adopt the same layouts of WDN expansion which are separately generated by the dynamic complex network model as presented in the last section. Pipe sizing is done based on the same strategy for all designs, which is described below.

Problem description

For each design, the problem is to minimize the total capital cost of all pipes while meeting water demand requirements. The decision variables are diameters of pipes laid in new sites to reach new demand nodes (initial pipes) and parallel pipes to the existing pipes to upgrade the existing network. The design of WDN expansion is performed in phases to meet gradual water demand growth. Each phase is assumed to be 10 years. For the 10-year planning horizon, the designed WDN expansion is constructed through one phase. The design is done based on the demand by the end of the planning period, while the cost is calculated at the beginning. For a longer planning horizon consisting of several phases, initial pipes connecting new water demand nodes are constructed by different phases that follow the projected time of the new nodes, while all parallel pipes are assumed to be constructed in the first phase of the planning period. The total cost (C) for the design is calculated as the present value at the beginning of the planning period. Mathematically, the objective function is shown in Equation (3):

$$C = \sum_{i=1}^{Z_1} c_i^0 L_i + \sum_{j=1}^{Z_2} \frac{c_j L_j}{(1+r)^{(k_j-1)y}} \tag{3}$$

where c_i^0 and c_i are the cost per unit length of the pipe used in parallel pipe i and initial pipe j respectively; L_i and L_j are the length of the parallel pipe i and initial pipe j, respectively; Z_1 and Z_2 are the total number of the parallel pipes and initial pipes built in the network, respectively; r is the annual interest rate; k_j is the phase index in which initial pipe j is constructed; y is the number of years in each phase (10 years). The hydraulic constraint in the optimization model is the minimum allowable pressure (25 m) requirement for each demand node. Hydraulic simulation is done by an external solver EPANET 2 (Rossman 1994) according to the maximum hourly water demand. Head loss (h_L) calculation is based on Hazen-Williams (H-W) shown in Equation (4):

$$h_L = 1.852L(Q/c)^{1.852}D^{-4.871} \tag{4}$$

where Q is the pipe flow rate (m^3/s); D is the pipe diameter (m); c is pipe roughness coefficient, set to 130 for all pipes. In the optimization process, costs involving pumping are not considered. The reservoir head is predefined before optimization. In this study, the reservoir head is set to increase as WDN expands (Table 1) which is independent of planning horizons.

Pipe options

The capital costs of new pipes include excavation, bedding, material cost, installation cost, and backfill, which are estimated according to the methodology of Clark *et al.* (2002). Parallel pipes are placed in parallel to existing pipes, which implies disruption and reconstruction of pavement roads, thus an additional 20% cost is accounted for parallel pipes. Pipe diameter options and costs are given in Table 2. In the USA, a distribution pipe is normally required with a minimum size of 6 (152.4 mm) or 8 inches (203.2 mm). In this study, the minimum pipe size used for all designs is set to 6 inches. The maximum pipe size for different designs is shown in the last column in Table 1.

Optimization algorithm

There are a lot of optimization algorithms developed to size pipes. In this study, pipe sizing is done based on PEDPSO (Qi *et al.* 2016), which is an evolutionary algorithm to find an optimum solution with less computational time and higher reliability. To further save computational time, a near-optimal solution is pursued by combining PEDPSO and graph theory, which reduces the number of pipe variables in optimization. Specifically, by assuming water is efficiently delivered to nodes from the source through the shortest distance path, the whole WDN represented by a simple planar graph is decomposed into a shortest-distance tree and remaining edges. For a WDN expansion design, the whole graph consists of existing edges presenting existing connections belonging to the previous network and new edges presenting initial pipes connecting new demands. Thus, the shortest-distance tree also consists of existing edges and new edges. For a network design, only existing edges in the shortest-distance tree are considered to place parallel pipes, and only initial pipes in the shortest-distance tree as well as possible parallel pipes are subjected to sizing by PEDPSO while other new pipes are all set to minimum allowable diameter (6 inch). Hydraulic simulation is still done to the whole looped network rather than the tree network to make sure the whole designed network meets the pressure requirement. A similar method was used by Zheng *et al.* (2011) to obtain a near-optimum solution for WDN design. Specifically, in our modified version of the algorithm, each individual of the population consists of $z_1 + z_2$ elements where z_1 and z_2 is the number of existing edges (possible parallel pipes) and new edges (initial pipes) in the shortest-distance tree respectively. The z_1 elements can take on a value of either 0 or from a set D containing all available pipe diameters, while z_2 elements can only take on a value from D. During the optimization process, a penalty function is introduced into the objective function to penalize network solutions with too low node pressure.

Total present cost

For each planning horizon scenario, the total present cost (PC) of WDN expansion over 100 years is calculated as below (Equation (5)):

$$PC = \sum_{p=1}^{P} \frac{C_p}{(1+r)^{(p-1)Y}} \tag{5}$$

Table 2 | Pipe diameter options and costs

Diameter (inch)	Diameter (mm)	Initial pipe cost ($/m)	Parallel pipe cost ($/m)
6	152.4	84.12	100.94
8	203.2	94.78	113.74
10	254.0	121.36	145.63
12	304.8	147.83	177.40
14	355.6	181.76	218.11
16	406.4	201.71	242.05
18	457.2	247.05	296.46
20	508.0	286.58	343.90
24	609.6	355.87	427.05
30	762.0	406.33	487.60
36	914.4	467.16	560.59
42	1066.8	550.95	661.14
48	1219.2	635.96	763.15

where C_p is the total cost for design p; P is the total number of designs; and Y is the total number of years in the planning horizon.

RESULTS AND DISCUSSION

Simulated WDN layout expansion

Using the dynamic WDN layout model that is independent of hydraulics, the WDN expansion at 10 different time steps is simulated based on two growth patterns (linear/exponential), as shown in Figures 2 and 3.

The simulated WDNs expand as time step progresses, incorporating an increasing number of nodes (n), edges (m) and independent loops (l) (Creaco & Franchini 2014) which are the minimum loops that are not cyclic permutations of each other, and longer average edge length (L_{avg} (m)), as listed in Table 3, which also listed some graphic metrics that were used by researchers to measure structural properties of WDNs (Yazdani & Jeffrey 2011a, 2011b; De Corte & Sörensen 2014), including average node degree ($<k>$), maximum node degree (k_{max}), meshedness coefficient (r_m) and route factor (q). Node

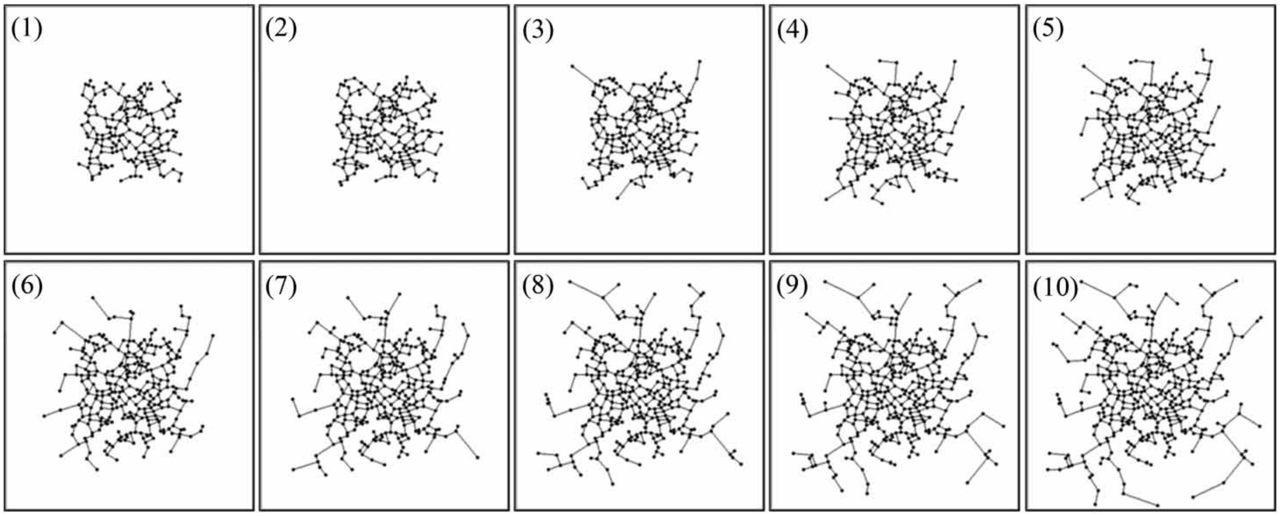

Figure 2 | Layouts of WDN expansions at 10 different time steps based on linear growth: (1) 10 years; (2) 20 years; (3) 30 years; (4) 40 years; (5) 50 years; (6) 60 years; (7) 70 years; (8) 80 years; (9) 90 years; (10) 100 years.

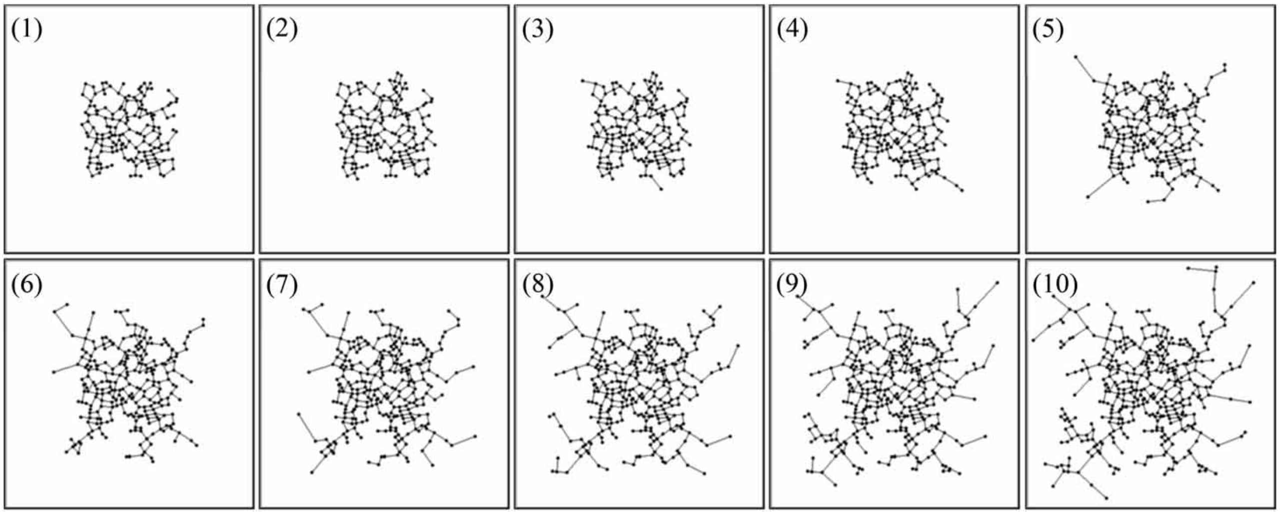

Figure 3 | Layouts of WDN expansions at 10 different time steps based on exponential growth: (1) 10 years; (2) 20 years; (3) 30 years; (4) 40 years; (5) 50 years; (6) 60 years; (7) 70 years; (8) 80 years; (9) 90 years; (10) 100 years.

Table 3 | Structural properties of the simulated WDN at different time steps

Planning horizon (years)	n	m	l	L_{avg}	$<k>$	k_{max}	r_m	q
Linear growth								
10	165	216	52	674	2.62	4	0.16	1.24
20	184	247	64	670	2.68	5	0.18	1.23
30	210	282	73	678	2.69	5	0.18	1.23
40	233	309	77	700	2.65	5	0.17	1.22
50	259	346	88	689	2.67	5	0.17	1.23
60	282	376	95	704	2.67	5	0.17	1.23
70	308	406	99	713	2.64	5	0.16	1.23
80	338	440	103	716	2.60	5	0.15	1.23
90	359	469	111	729	2.61	5	0.16	1.23
100	378	490	113	751	2.59	5	0.15	1.23
Exponential growth								
10	157	209	53	667	2.66	4	0.17	1.23
20	171	229	59	658	2.68	4	0.18	1.24
30	185	250	66	656	2.70	4	0.18	1.24
40	206	281	76	642	2.73	4	0.19	1.23
50	223	302	80	668	2.71	4	0.18	1.23
60	254	339	86	667	2.67	4	0.17	1.24
70	282	373	92	685	2.65	5	0.16	1.24
80	313	409	97	700	2.61	5	0.16	1.25
90	346	451	106	710	2.61	5	0.15	1.25
100	379	489	111	715	2.58	5	0.15	1.25

n, number of nodes; m, number of edges; l, number of independent loops; L_{avg} (m), average edge length; $<k>$, average node degree; k_{max}, maximum node degree; r_m, meshedness coefficient; q, route factor.

degree is the number of edges connected to a node. Average node degree is the average number of edges per node, which measures network connectivity. Tree-structure networks have an average node degree of about 2 while complete grid networks have an average node degree of about 4. As shown in Table 3, the generated networks have an average node degree larger than 2 and smaller than 3, which agree with real WDN patterns that are usually partially looped and less connected than complete grid networks (De Corte & Sörensen 2014). The maximum node degree for all generated networks is small (4 or 5), which indicates that WDNs are not scale-free networks (Barabási & Albert 1999) featured with the existence of highly connected nodes. Meshedness coefficient (Buhl *et al.* 2006) is the ratio of the number of total existing independent loops ($m - n + 1$) to the maximum possible loops ($2n$–5) for a planar graph, which is an indicator for the network redundancy. As listed in Table 3, even though the number of independent loops is increasing as WDN expands, the redundancy of the whole network does not necessarily increase. Route factor (Gastner & Newman 2006) measures the straightness of paths from other nodes to root, which is the average ratio of shortest distance from a node to the root through edges to its direct Euclidean distance to the root. It can be used as an indicator of network efficiency. The route factor for generated networks (1.22–1.25) is smaller than the four real WDNs (1.45–1.67) reported by Yazdani & Jeffrey (2011b). This is expected because the layout simulation model has ignored certain practical constraints in WDN development such as geography and hydraulics factors, however it is still within the range (1.1–1.6) observed by Gastner & Newman (2006) for other real spatial networks.

Pipe sizes

In this study, the simulated test case is sized under different planning horizons and annual interest rates. The scenarios for planning horizon include 10, 20, 50 and 100 years. The scenarios for interest rate include 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0 and

6.0%, where the rate is assumed to be constant over time steps. Thus, the total number of experiments is 32 for each growth pattern. The total number of new pipes built in a 100-year study span in all scenarios is listed in Table S1. As shown in Table S1, for both growth patterns, the total number of new pipes built is lower as the planning horizon is longer, while it is almost stable with different annual interest rates. Since the layout of WDN is the same for all planning horizons, the substantial difference in the pipe number indicates that WND design strategy under shorter-term planning horizon results in more parallel pipes to be built in order to meet minimum pressure requirement as the demand increases. The pattern of pipe diameters is consistent across different scenarios of annual interest rates for both growth patterns. Therefore we only present the pipe size distribution by different planning horizons in one typical scenario of interest rate and growth pattern (Figure 4: 3.0% annual interest rate for linear growth pattern). As shown in Figure 4, the expanded network designed with a 100-year planning horizon consists of more large pipes, followed by a 50-year planning horizon, than other planning horizons, while the network with 10-year planning horizon has more small pipes, followed by 20-year planning horizon. The results indicate that designs with longer-term planning horizons result in an increased number of large pipes which provide excess capacity at the beginning of a planning period.

Cost analysis

The total present costs for different scenarios are shown in Figure 5, which shows that the optimum planning horizon (i.e. achieving minimum present cost) for the study case depends on the annual interest rate, which is as expected. Generally, the results suggested that a shorter planning horizon is favored with a higher annual interest rate while a longer planning horizon is favored with a lower one.

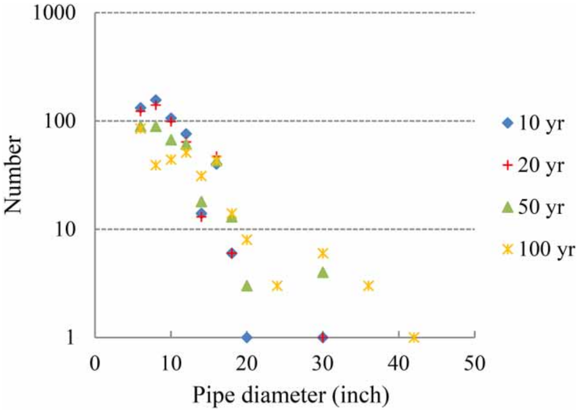

Figure 4 | Distribution of pipe diameters by four planning horizons (10, 20, 50 and 100 years) for the linear growth pattern with an annual interest rate of 3.0%.

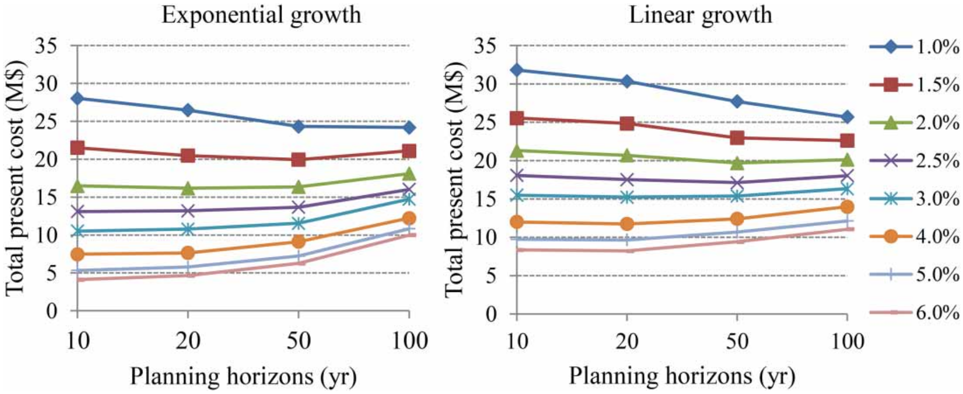

Figure 5 | Total present cost based on the planning horizon (x-axis) and the interest rate (different line plots) for the exponential growth (left) and the linear growth (right) scenarios.

For the linear growth pattern, as in Figure 5, the optimum planning horizons are 100 years with an annual interest rate lower than 1.5%, 50 years with an interest rate of 2.0–2.5%, and 20 years with an interest rate of 2.5–6.0%. Walski (2013) studied the impact of planning horizon on WDN design under different interest rates for a linear population growth pattern by using a single pipe section and concluded that the optimum planning horizon was from about 60 to 40 years as annual interest rate increases from 1 to 5%. The differences are due to the fact that this research modeled the whole network instead of a single section.

To further elaborate the mechanics of how the planning horizon affects WDN designs under different interest rates, two scenarios with a lower bound interest rate (1.0%) and upper bound interest rate (6.0%) were selected for further investigation. As analyzed in Section 3.2, design under a longer-term planning horizon results in more large pipes than a shorter-term planning horizon, which are built at the beginning of a planning period to provide excess capacity. In the scenario of low interest rate as shown in Figure 6, even though excess capacity requires extra cost initially, a long planning horizon can save money in the long run because economies of scale play the major role while the impact of interest rate can be ignored. However, when interest rates become high, the total present costs for WDN expansion is mainly determined by the costs at the beginning period. The long planning horizon design would lose its advantage from economies of scale due to too much extra cost at the beginning period (Figure 6).

For a test case with exponential growth pattern, as in Figure 5, the optimum planning horizons are 100, 50, and 20 years for annual interest rate of 1.0, 1.5 and 2.0%, respectively. When the annual interest rate goes up to 3.0% or more, the optimum planning horizon is 10 years. In general, the optimum planning horizons are shorter than those under a linear growth pattern. Compared to linear growth, exponential growth imposes less new water demands at the beginning of the study period. Thus,

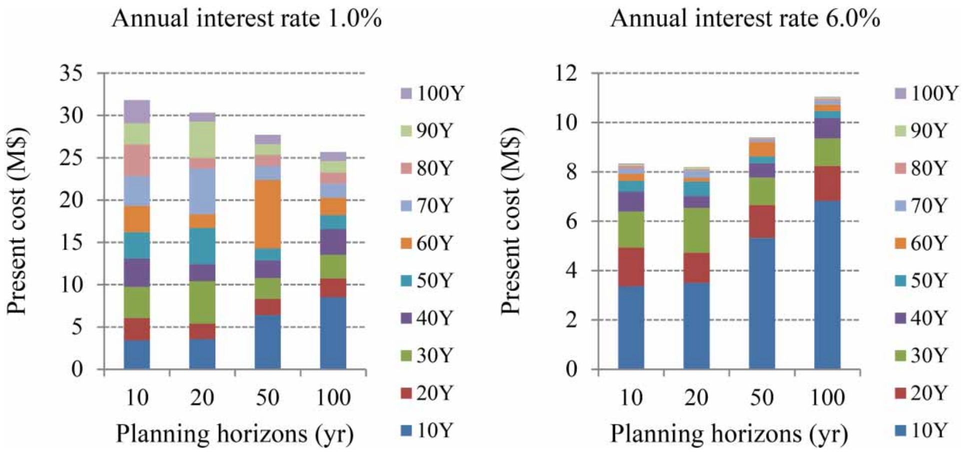

Figure 6 | The present cost of pipes built at each time step for linear growth pattern for annual interest rate of 1.0% (left) and 6.0% (right).

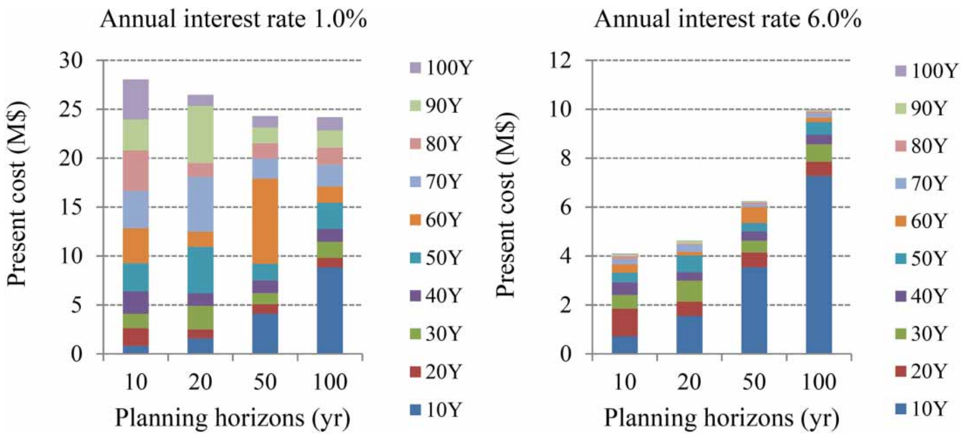

Figure 7 | The present cost of pipes built at each time step for exponential growth pattern for annual interest rate of 1.0% (left) and 6.0% (right).

for a longer-term plan horizon, even though the total demand at the end of the study span is the same for both linear and exponential growth patterns, exponential growth will result in more excessive capacity at the beginning of the study period, which also results in higher extra cost induced by interest. As shown in Figure 7, the difference in present cost at the beginning of the study span between different planning horizons becomes much higher in the exponential growth case. When the interest rate is as high as 6.0%, the extra cost for excessive capacity can completely exceed the savings from economies of scale, resulting in the preference towards a shortest planning horizon.

CONCLUSIONS

In this study, the impact of planning horizon on WDN design is analyzed through a synthetic city with a single water reservoir under various annual interest rate scenarios with two population growth patterns (exponential and linear). The results indicate that the choice of the optimum planning horizon is sensitive to the interest rate. For both growth patterns, a shorter planning horizon is favored with higher annual interest rates while a longer planning horizon is favored with lower rates as the balance between economies of scale and the excessive capacity cost induced by interest. An exponential growth pattern generally favors a shorter planning horizon than a linear one due to more excess capacity provided at the beginning of the study period. Based on the conclusions presented above, we propose that counties and municipalities experiencing high growth with access to low-interest funds should consider increasing their planning horizon beyond the customary 20 years, particularly if the growth pattern appears to be linear as opposed to exponential. Likewise, those areas experiencing low to flat growth rates should take a more immediate planning horizon.

It should be noticed that while this work is only focused on a single factor of interest rate on the planning of a water distribution network, in real cases the planning is a much more complex problem, affected by many factors including water availability, uncertainties of future water demand and node location, and geography of the planning area. Some factors could be further analyzed by the methodology given herein to provide more insights into the WND planning. For example, additional water availability can be considered by a multi-source simulation network model, which requires complex parameters to describe the geographical limitations. It is also possible to incorporate the Geographic Information System (GIS) into the proposed model, to connect multiple service areas based on the geographic properties of the city. With GIS, we can add the geographic factors, such as elevation difference between nodes and presence of river, into the WDN generation and optimization. For the optimization of the generated WDNs, the layout is subjected to pipe sizing to meet only one hydraulic requirement (minimum allowable pressure). Other hydraulic requirements such as minimum flow velocity can be added as extra hydraulic constraints into the objective function for the optimization algorithm. Also, the impacts of uncertainties of water demand and node location can be analyzed by using the simulation model to construct multiple water demand and node distribution scenarios. Furthermore, the proposed model has the potential to be used as a subsequent step to an urban planning study by investigating urban planning strategies under different social-economic and geographical considerations, which will change the modeling of water demand growth and the generation of new nodes correspondingly. Modeling and analysis of the WDN planning horizons in different patterns of the WDN layout can then be performed, for a more integrated urban planning and WDN planning study.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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