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Implications of Urban Form on Water Distribution Systems Performance

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Abstract This paper presents the results of an investigation into the relationship between urban form and the performance of a water distribution system. The effect of new development or redevelopment on the performance of an expanded rehabilitation of the well-known Anytown water distribution system is examined to provide an insight into their interaction, which can be considered along with other aspects of renewal to achieve more sustainable urban areas. A range of urban growth rates, urban form and water efficiency strategies are studied in relation to the system's key performance indicators of total cost, resilience and water quality. The urban forms considered in this work are compact/uniform, monocentric, polycentric and edge developments. These development patterns are representative of common development approaches widely applied in urban planning. They also correspond to future settlement patterns, based on adopting four future (socio-economic) scenarios so called Policy Reform (PR), Fortress World (FW), New Sustainability Paradigm (NSP), and Market Forces (MF) respectively. Three growth rates and two water demand efficiency levels are considered. It is concluded the rate and type of urban development has major implications for the redesign and operation of existing water infrastructure in terms of total cost, water quality and system resilience, with uniform expansion (PR) resulting in the most cost-effective system upgrade by a considerable margin. Polycentric expansion as a representative urban form for New Sustainability Paradigm is the least cost-effective if it relies on centralised water distribution system to provide service to customers. Edge expansion (MF) has both the cheapest and the most expensive expansion costs depending on location of the expansion. Monocentric urban development (FW) does not result in the most cost-effective system contrary to what has been reported in the literature. Water efficiency measures had relatively little impact on overall performance as it was balanced out with demand increase due to new growth.

Keywords Water distribution systems · Urban form · Growth · Water quality · Reliability · Scenarios

1 Introduction

The relationship between shape, size and density of urban land use and its sustainability is widely debated in the urban planning community. The relative sustainability of, for example,

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high and low urban densities, or centralized and decentralized settlements is still disputed (Williams et al. 2000). Some argue, the search for the “ideal” land use pattern just risks trying to simplify a very complex system (Guy and Marvin 2000). So, there is still little consensus on which urban form will result in more sustainable development, or indeed if this is either achievable or desirable. To help settle this debate, more objective assessments of the performance of cities in relation to the organization of land use are urgently needed (Newton 2000).

Water systems and land use patterns have always shaped each other (Moss 2003). A study by Slater et al. (1994) of development and catchment management plans concluded that lack of experience in proactive involvement with urban planning in the UK has led to “a clear lack of impact in the early Catchment Management Plans (CMPs) and there is no clear favourite for particular patterns of land use” (quoted in Slater et al. 1994). Carter et al. (2005) also argue that “a fundamental contributing factor to many urban water management problems is a failure to adopt an integrated approach to water management and land use planning” (quoted in Carter et al. 2005). A number of recent studies focus on urban growth (EPA 2006; EA 2007; Filion 2008) and highlight the importance of taking into account the utility sector at an early stage of development/redevelopment planning.

Urban growth in regions that are already heavily developed can put pressure on supporting infrastructure (such as transport, water and sewer systems, energy, etc.). Urban growth typically affects demand for water, generation of runoff, costs of water infrastructure, water quality, and the efficiency of service delivery. These challenges can be exacerbated by the density of population and the social, economic and environmental characteristics of urban settlements. It is very important that the water utilities are aware of planners’ growth forecast and associated demand so that they can better manage the supply and demand situation.

In the study reported in this paper, the focus is on one aspect of urban performance, namely that of the water distribution infrastructure. This consists of exploring the relationship between urban growth of different types and the performance (arguably sustainability) of an existing water distribution system and its ability to accommodate that growth satisfactorily. Key performance indicators are evaluated under different growth and water efficiency scenarios.

2 Urban Growth and Water Infrastructure

2.1 Water Management

In the context of England and Wales, the relationship between projected urban growth and water management emerges particularly in the statutory production of Catchment Abstraction Management Strategies (CAMS), Strategic Asset Management and Water Resources Management Plans. Catchment abstraction management strategies indicate the availability of water resources within the strategy area where there may be excess water available to meet the needs of new development or the demands need to be met from elsewhere. CAMS are also important to wastewater service provision since the availability of water within rivers is important for maintaining sufficient dilution of wastewater discharges. Strategic asset management and water resources management plans “set out in detail how the private water companies in England and Wales plan to balance supply and demand for water in their supply area over a 25 year period and take into account the economic, environmental and social implications of these plans” (quoted in Defra 2008). Water companies identify schemes to address any shortfall in supply capability which will determine the investment required. “These schemes are generally a combination of demand management and resource development, in line with the twin-track approach to water management” (quoted in Defra 2008). Within the 5-year asset management cycles, spending is planned to meet regulatory requirements. The decisions on the operation and maintenance of the assets of a water distribution system require the operator to balance costs with future performance including the quality of service experienced by the customer. Proper justification for pipe renewal is driven by hydraulic performance, water quality performance, structural failure and leakage (Skipworth et al. 2002). Asset management processes are necessary because changes in demand and deterioration of systems can cause hydraulic deficiencies which can lead to increase in operational costs. Rehabilitation and expansion of water systems can be a significant financial burden for operators which usually fund them by passing the costs to customers. Proactive rehabilitation and planned expansion can optimise investment.

The impact that growth will have on demand for water supply depends on several factors including: the size of the existing population and the per capita consumption of people living in existing homes, the uptake of domestic water meters, water efficiency education and incentives to save water, the number of new houses built and their forecast occupancy rate (population), and the expected per capita consumption of water of the population in the new properties, which is influenced by the sustainable design of the buildings (e.g. based on Code for Sustainable Homes). The Code for Sustainable Homes (CSH 2006) is a national voluntary standard in England and Wales for the sustainable design and construction of new homes. This is an important consideration when assessing the water demand of new developments as new homes will (in theory at least) comply with minimum performance standards for water use. Following publication of the CSH, a minimum regulatory standard for water consumption in new homes came into force in April 2010 (CLG 2009) which sets water use at home and outside the home at 125 l per head per day (L/h/d).

2.2 Urban Growth Pattern

Different urban development patterns have implications for social, environmental and economic aspects of the region. There is an extensive literature that discusses and evaluates factors that influence the costs of urban infrastructure and services (Marchand and Charland 1992; Altshuler and Gomez-Ibanez 1993; and Blais 1996). There is consensus that spatial factors affect the costs of development, urban infrastructure and services. In particular, the density of the development and its location influence the costs of providing services (quoted in Blais 1996). There is less agreement on the interrelationship of urban form and costs of urban infrastructure. Frank (1989) reanalyzed several studies conducted between the 1950s and 1980s that examined relationships between land use and infrastructure costs. He concluded that "infrastructure costs were highest in situations of low density and for development located a considerable distance from centralized public services" (quoted in Frank 1989). IBI group (1990) compared capital and operational costs for water supply and sewer systems for three different development patterns (spread, central and nodal) for Toronto city. In the spread and nodal patterns, growth is mainly distributed outside existing built-up areas and in the central pattern it stays within build-up areas. Their study showed overall capital costs of utilities differ on average by more than 50 % with the central model having the lowest per capita costs and the spread model the highest. Their results suggest that high density developments result in lower costs because there are more dwellings per unit length of the infrastructure.

The majority of studies make comparison between densities for the same development type and some between different patterns of development considering capital and operational costs. However none of the studies to date consider the reliability and quality of services delivered. This paper demonstrates the impact of alternative urban development forms including density, size, and configuration on the water infrastructure considering capital and operational costs as well as the quality and quantity of water delivered.

3 Method

3.1 Anytown

The Anytown water distribution system (Walski et al. 1987) has been used in this study (Fig. 1). The link and node data, as well as details of different loading conditions and the variation in water use throughout the day are available from CWS (2004) and Farmani et al. (2005b, 2006).

3.2 Growth and Water Efficiency Scenarios

In this study, the performance of the network is assessed for three alternative development strategies under three growth rates and two water efficiency scenarios. The development strategies are as follows:

(i) Compact - uniform development within the existing urban area (Fig. 2a),
(ii) Planned - monocentric (Fig. 2b) and polycentric (Fig. 2c) development within the existing urban area and
(iii) Edge expansion - development of new settlements as urban extensions (Fig. 3).

These have been chosen as representative of common development approaches widely applied in urban planning (Echenique et al. 2010). They also correspond to settlement patterns for four future (socio-economic) scenarios (Policy Reform, Fortress World, New Sustainability Paradigm, and Market Forces) that are based on a substantial body of work produced over 20 years by the global scenarios group (Raskin et al. 2002).

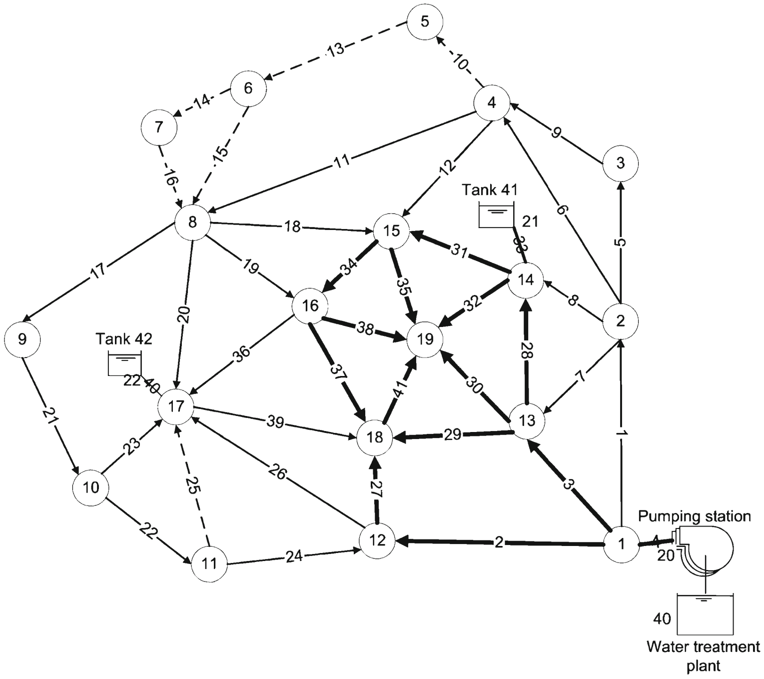

Fig. 1 The Anytown network (original layout)

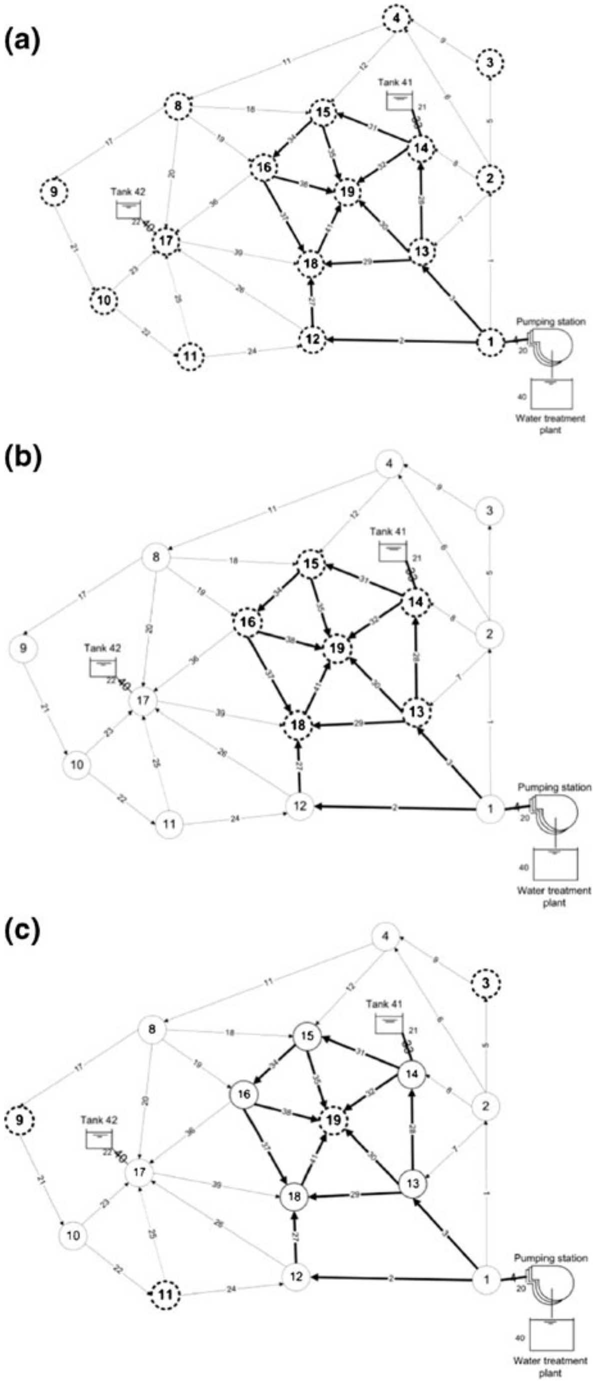

Fig. 2 **a** Compaction–uniform development (growth has been distributed uniformly throughout the existing urban area). **b** Planned development- monocentric (growth has been concentrated in a single region of the existing urban area). **c** Planned development- polycentric (growth has been concentrated in a number of regions of the existing urban area)

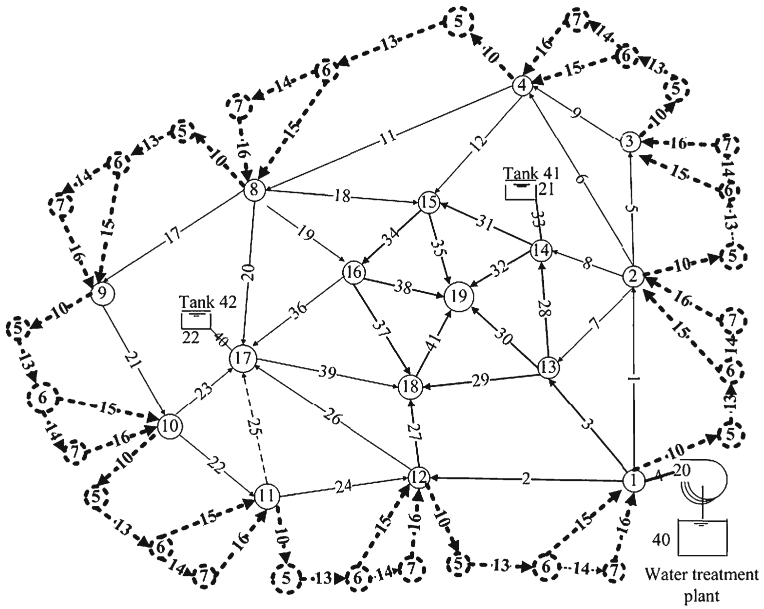

Fig. 3 Alternative edge developments each assessed separately in this paper (growth is considered as urban extensions)

The three growth rates considered are:

a. No new growth
b. Medium growth and
c. High growth.

The 'no new growth case' (a) considers only the projected demand from the original problem setting of 43,608 m^3/d (8,000 gpm) as applied to the existing housing stock. In the two other growth cases (b and c), the new residential area will require 16,353/21,804 m^3/d (3,000/4,000 gpm) additional demand under medium and high growth respectively over 20 years (EA 2009). It is assumed, however, that changes in population and the resulting demand will differ spatially for the different land use patterns. Under the 'compaction' urban form, this additional demand is distributed uniformly throughout the demand nodes. Under 'planned development', this demand is allocated equally to randomly chosen nodes (13, 14, 15, 16, 18, 19 for 'mono-centric development' and nodes 3, 9, 11 and 19 for 'poly-centric development'). Nine alternative 'edge developments' are assessed as shown in Fig. 3 with the additional demand being equally divided between the three new demand nodes. Temporal changes have not been explicitly considered in restructuring of the water infrastructure.

Table 1 summarizes two plausible water efficiency scenarios as related to the three proposed growth rates (a, b and c). The chosen water efficiency targets are based on the 'Code for Sustainable Homes' (CSH 2006). Indoor water use is one of the environmental issues considered with increasing standards at three levels. The targets for maximum indoor water consumption at levels, 1/2, 3/4 and 5/6 are 120, 105 and 80 L/h/d respectively. The levels 3/4 water consumption can be met using standard products on the market that are acceptable to the end user (e.g. dual flush toilets, low consumption dishwashers and washing machines), however to achieve levels 5/6, rainwater harvesting or greywater reuse is required.

Table 1 Growth and water efficiency scenarios

Scenario	Existing homes Per capita (L/head/day) Total (m^3/d, gpm)	New homes Per capita (L/head/day) Total (m^3/d, gpm)
1. No retrofit		
a. No new growth	150 43,608 / 8000	
b. Medium growth	150 43,608 / 8000	120 16,353 / 3000
c. High growth	150 43,608 / 8000	120 21,804 / 4000
2. Retrofit		
a. No new growth	120 34,886 / 6400	
b. Medium growth	120 34,886 / 6400	120 16,353 / 3000
c. High growth	120 34,886 / 6400	120 21,804 / 4000

150 L/head/day=39.63 gal/head/day; 120 L/head/d=31.7 gal/head/d

Scenario 1 (no retrofit) considers ‘business as usual’ water consumption for existing homes (i.e. 150 L/h/d, typical in the UK) and new homes with water efficient appliances (i.e. levels 1/2, 120 L/h/d). Scenario 2 is the retrofit scenario, based on the assumption that water efficient appliances are fitted in both new and existing homes.

The no new growth scenarios (1.a and 2.a) only require that the existing infrastructure is upgraded to meet the past growth in demand (with and without retrofit) while for the other scenarios, the system must contend with the additional demand as specified in Table 1.

3.3 Modelling

The problem has been set up as a multiobjective optimization study following the approach developed by Farmani et al. (2005b), except for the addition of water quality as a third objective (to study the impact of alternative urban growth patterns on water age). In addition, there are changes to the magnitude (16,353/21,804 m^3/d (3,000/4,000 gpm) instead of 9,812 m^3/d (1,800 gpm)) and allocation of demand due to the new residential areas. EPANET2 (Rossman 2000) has been used as both the hydraulic and water quality solver. The trade off calculations between total cost, resilience index and water quality have been carried out using the well-known NSGAII multiobjective genetic algorithm (Deb et al. 2002). Considering reliability or resilience measures as one of the objectives for optimum design of water distribution networks has become a common practice in recent years (Todini 2000; Farmani et al. 2005b, 2006; Bano et al. 2011; Chandapillai et al. 2012) and finding a single solution with minimum cost is no longer acceptable (Farmani et al. 2005a).

Multiple runs were carried out with a GA population size range of 20–50 sample solutions, 90 % probability of crossover, a probability of mutation between 0.3 %–0.5 % and allowed to run for 10,000–25,000 generations, resulting in 500,000 solution evaluations for each run. The aim of multiple optimization runs in this case is not to find global optimum solutions for the different problem settings but to make sure that near optimal / optimal solutions have been identified to enable a valid comparison. It is understood that to locate the optimum Pareto front many more solution evaluations would be required due to the complex nature of the problem under study.

4 Solutions and Analysis

4.1 General Performance

Details of the pipe, tank, operational and the total costs, water age and resilience index for no expansion under scenario 1 (1.a) and scenario 2 (2.a) are as follows:

> No expansion, scenario 1 (1.a): 2.48, 0.51, 5.1 and 8.09 ($million), 50 (hours) and 0.21.
> No expansion, scenario 2 (2.a): 3.42, 0, 4.47 and 7.89 ($million), 11 (hours) and 0.26.

Details of the total cost, water age and resilience index for all the feasible solutions *with minimum cost* (extracted from the Pareto surface of different runs) are given in Tables 2 and 3 for alternative expansion patterns under scenarios 1 and 2 respectively.

Clearly, the most important difference between the solutions is the total cost, which ranges from $7.89 M for the retrofit, no new growth case (2.a) to $15.48 M for the no retrofit, high growth, edge expansion case (1.c), a nearly doubling of cost. The main differences in total cost are associated with the capital costs of the pipes and the tanks (Tables 2 and 3). This is because, in order to facilitate the different *patterns* of growth, reinforcement of different sections of system was necessary. Generally, one new tank is included at different locations with different volume sizes for solutions under both scenarios and growth rates. The exceptions to that are:

- the case of uniform expansion (no new tank)
- solutions with edge development next to nodes 2-3 and 12-1 and
- the solution for scenario 2.a.

For this latter case, not only were no new tanks added, but a pump operational schedule was proposed without use of existing tanks. This resulted in the lowest water age (11 h) solution proposed. In the majority of options, the location of a new tank was either at the development nodes or at nodes adjacent to the new developments.

4.2 Optimum Design and Operation under Different Urban Forms

As expected, the lowest total cost solutions are those for the ‘no new growth’ options (1.a, 2.a). Among the urban expansion solutions under growth (1.b, 1.c, 2.b, and 2.c), the uniform expansion solutions generally have the lowest total cost and highest resilience index values (Figs. 4 and 5). The relatively low cost is due to the fact that no new tanks are required, the number of existing pipes that are reinforced is limited and duplicated pipes take the minimum pipe sizes possible in order to meet the demand criteria. Flexibility and redundancy in the network are provided by all the demand nodes having alternative supply paths for water in the event that some pipes go out of service. The majority of new duplicated pipes connected to a node have similar pipe sizes. This indicates a high degree of robustness in the network which is supported by the relatively high resilience index values. This demonstrates advantage of compaction/uniform expansion (representative of urban characteristic for policy reform future) that is the ability to take advantage of excess productive capacity in already developed areas.

Table 2 Summary of total costs, water age, and resilience for scenario 1 (no retrofit)

Urban form	Expansion nodes	Medium growth (1b)						High growth (1c)					
		Costs ($million)				Water age (hours)	Network resilience	Costs ($million)				Water age (hours)	Network resilience
		Pipe	Tank	Operational	Total			Pipe	Tank	Operational	Total		
Uniform	All	4.13	0	6.85	10.98	34	0.21	5.38	0	7.46	12.84	37	0.22
Monocentric	13, 14,15, 16, 18, 19	4.08	0.66	6.94	11.68	38	0.17	5.01	0.68	7.47	13.16	42	0.17
Polycentric	3, 9, 11, 19	6.61	0.63	6.81	14.04	36	0.18	6.07	0.61	7.45	14.13	37	0.19
	1-2	4.82	0.37	6.84	12.03	43	0.17	5.40	0.55	7.44	13.39	34	0.2
	2-3	5.55	0	6.86	12.41	40	0.19	5.34	0.53	7.40	13.27	39	0.19
	3-4	5.30	0.53	6.81	12.63	35	0.17	5.79	0.62	7.38	13.79	34	0.18
	4-8	5.21	0.56	6.83	12.6	40	0.18	5.39	0.55	7.40	13.34	43	0.16
	8-9	6.94	0.36	6.85	14.15	46	0.19	7.64	0.43	7.41	15.48	39	0.14
	9-10	7.30	0.53	6.81	14.64	32	0.17	6.99	0.57	7.49	15.05	34	0.18
	10-11	5.97	0.44	6.81	13.22	45	0.18	5.99	0.53	7.44	13.96	42	0.17
	11-12	5.61	0.43	6.80	12.84	42	0.21	4.95	0.51	7.41	12.87	39	0.19
	12-1	4.34	0	6.85	11.19	39	0.22	5.05	0.53	7.42	13.01	40	0.23
	Average (edge expansion)				12.86	40	0.19				13.8	38	0.18

Table 3 Summary of total costs, water age, and resilience for scenario 2 (retrofit[a])

Urban form	Expansion nodes	Medium growth (2b)						High growth (2c)					
		Costs ($million)				Water age (hours)	Network resilience	Costs ($million)				Water age (hours)	Network resilience
		Pipe	Tank	Operational	Total			Pipe	Tank	Operational	Total		
Uniform	All	3.63	0	5.97	9.61	41	0.2	3.70	0	6.50	10.2	42	0.23
Monocentric	13, 14,15, 16, 18, 19	4.03	0.73	6.01	10.77	43	0.18	4.97	0.77	6.45	12.19	42	0.19
Polycentric	3, 9, 11, 19	5.41	0.55	5.94	11.91	48	0.2	7.25	0.66	6.43	14.34	39	0.16
	1-2	3.90	0.49	5.88	10.27	48	0.15	4.24	0.52	6.46	11.22	44	0.2
	2-3	4.39	0.56	5.89	10.85	44	0.17	4.96	0.60	6.45	12.01	36	0.15
	3-4	4.43	0.62	5.90	10.95	41	0.18	5.54	0.70	6.44	12.68	40	0.19
	4-8	4.07	0.57	5.92	10.57	38	0.19	4.88	0.73	6.76	12.37	42	0.2
	8-9	5.44	0.61	5.87	11.92	46	0.15	6.45	0.63	6.50	13.58	44	0.16
	9-10	5.15	0.60	5.88	11.63	37	0.14	6.23	0.68	6.44	13.35	40	0.13
	10-11	4.86	0.63	5.87	11.36	38	0.13	5.91	0.64	6.43	12.98	35	0.16
	11-12	4.93	0.66	5.84	11.43	35	0.17	5.58	0.57	6.44	12.59	42	0.21
	12-1	2.92	0.58	5.88	9.38	40	0.23	4.10	0.61	6.43	11.14	36	0.2
	Average (edge expansion)				10.93	41	0.17				12.44	40	0.18

[a] The cost of retrofitting has not been included

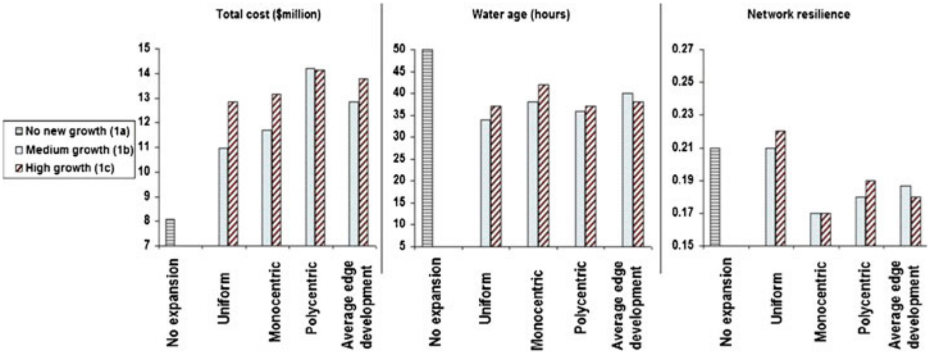

Fig. 4 Total cost ($million), water age (hours), and resilience for scenario 1- no retrofit

Polycentric expansion (New Sustainability paradigm future) introduces heterogeneous variations in the spatial distribution of water demand with a large number of hotspots, posing a challenge for infrastructure planning and operation. This is demonstrated by the highest total costs and lower resilience index values. Even though a large number of the pipes have been reinforced by duplicated pipes to satisfy demand at different locations, there is no uniformity (i.e. similar pipe sizes) in the network, resulting in lower reliability (Figs. 4 and 5). This indicates that polycentric development, as a representative urban form for New Sustainability Paradigm, will not be able to deliver the expected service without major capital investment and long term operational and maintenance costs if it relies on centralised water system.

In the case of edge expansion (Market Forces future), costs are also increased since more pipes and installations have to be added. However, the reliability of the system is lower as compared with infill expansion; in order to keep the costs down not much redundancy has been introduced in the system (Figs. 4 and 5). To match a similar level of resilience in the system, more alternative water supply paths for new nodes are required. This can lead to increasingly inefficient systems as infrastructure investment for upgrading and maintenance of existing networks is diverted to support water system expansion. Also edge developments usually require longer pipeline systems, making them less efficient to operate. Depending on

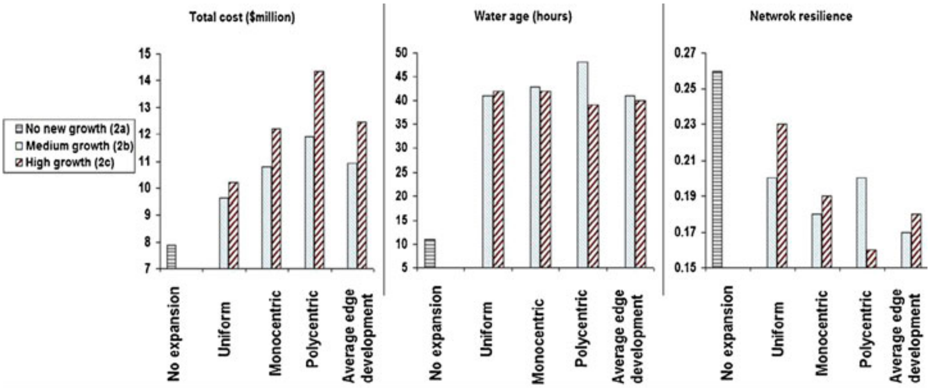

Fig. 5 Total costs ($million), water age (hours), and resilience for scenario 2 - retrofit (The cost of retrofitting water efficient appliances has not been included.)

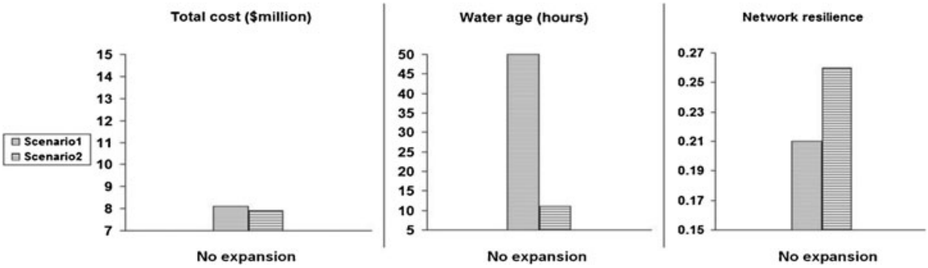

Fig. 6 Results of scenarios 1 and 2 for no new growth

closeness to the main source of supply, some of the edge expansion options have the lowest cost.

Water age is a function of water demand, system design and operation. As the distribution pattern of demand varies among different types of urban form, while total demand is the same, the result is different system operation and system design as demonstrated by the solutions presented in the Tables 2 and 3 and Figs. 4 and 5. Also the new storage tanks and number of the existing storage tanks that contribute to operation of the system have major influence on the water quality. Overall uniform, monocentric and polycentric expansion solutions have higher resilience index values, therefore are more robust due to having more connectivity. Of course, this can have a negative effect on water quality depending on system operation as more connectivity means more retention time and therefore higher water age values as demonstrated by the water age values in Tables 2 and 3 and Figs. 4 and 5.

4.3 Optimum Performance under Different Growth Rates

Comparison of the results under the three growth rates under scenario 1 indicates that the poorest performing solution from a water quality point of view is the no new growth case (i.e. existing demand) as it has the highest water age (50 h). Increasing expansion rate from zero to medium and high rates resulted in improvement of water quality for both the other growth rates under scenario 1, which in turn resulted in a decrease in most resilience index values. This suggests that an underutilized system has been used to accommodate some of the increase in demand while new component addition addresses the rest.

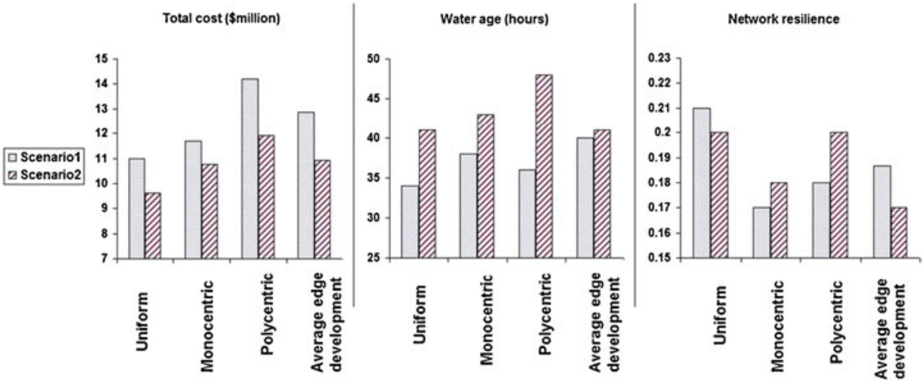

Fig. 7 Results of scenarios 1 and 2 for medium growth rate

The no new growth solution for scenario 2 resulted in not only no addition of new tanks but also an operational schedule without use of the existing tanks. This resulted in the lowest water age (11 h) in the system yet the highest resilience index value of 0.26 (Fig. 6). Solutions with fewer storage tanks or none at all tend to have higher resilience index values, implying greater hydraulic reliability. All this implies that the resilience index is somewhat limited in its representativeness of mechanical reliability because if a pump fails and there is no water in storage, demand cannot be supplied.

Figures 7 and 8 indicate that different growth rates and scenarios have similar solution patterns for different urban forms. In general, scenario 2 (i.e. retrofit) has lower cost, higher water age and higher resilience solutions in comparison with scenario 1 (i.e. no retrofit). However it should be noted that the cost of retrofitting water efficient appliances has not been included in scenario 2.

The growth rate increase from medium to high resulted in increases in the cost of delivering water. Overall, high growth has higher water quality and slightly lower resilience values.

5 Summary and Conclusions

This paper investigates the implications of urban form on water infrastructure performance. The effect of new developments or redevelopments on a benchmark water distribution system has been examined to provide an insight into their interaction which can be considered along with other aspects of urban renewal to achieve more sustainable urban developments.

Underutilization of the distribution system capacity due to water efficiency and the need for network extensions due to growth has been analysed to assess suitability of three urban forms (compact/uniform development, planned (monocentric and polycentric) development and edge expansion) in urban development using total cost, resilience and water quality as three key performance indicators. An expanded rehabilitation of the well-known Anytown system has been considered where the design variables are the pipe rehabilitation decisions, tank sizing, tank siting and pump operation schedules. Three growth rates were considered with two scenarios covering alternative water efficiency options.

The results were presented for 24 h design and operational conditions for different elements of urban forms including density, size, and configuration. The results show that the main difference between the solutions is indeed due to the alternative urban forms chosen. In general, for different growth rates and alternative water efficiency options, the changes in

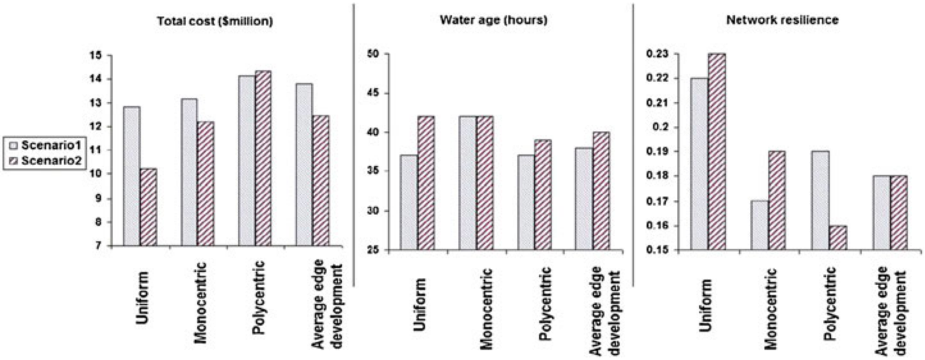

Fig. 8 Results of scenarios 1 and 2 for high growth rate

the three performance indicators for the solutions follow a similar pattern. In the majority of cases, a new tank was introduced either at the new development nodes or nodes adjacent to the new development. In just a few cases, no new tank was introduced and in one case none of the existing tanks contributed to the 24 h daily operation (scenario 2.a). This was not captured by the resilience index resulting in over-estimated reliability for these systems.

From a total cost point of view, for the new growth cases (medium and high), the most cost-effective networks corresponded to solutions based on uniform expansion both with and without retrofitted water efficiency. The most costly were the polycentric developments. In all growth cases water age decreased (i.e. water quality improved) compared with the no new growth (no expansion) case, implying an improvement after development.

Contrary to general belief that edge expansion is the most expensive type of urban expansion, results indicated that this is mainly dependent on the location of the edge development and it can be the most economic development if the location is right. In all but the uniform expansion case without retrofit, network resilience declined after development.

The impact of introducing retrofitted water efficiency measures was found to be relatively small for this case study as it was balanced out with demand increase due to new growth and certainly, adequately performing solutions were readily found. Caution is however needed with solutions including oversized distribution mains and storage tanks (e.g. scenario 1.a) as these will have negative effects on water quality due to low flow velocity and long retention time.

It can be concluded that, based on the results from the Anytown system, the rate and type of urban development has major implications for redesign and operation of existing water infrastructure in terms of total cost, water quality and network resilience, with uniform expansion being the most cost-effective by a considerable margin. This highlights importance of proactive involvement of water providers and urban planners to ensure that growth forecast and associated demand have been fully taken into account by the water service provider and there is sufficient capacity to manage the supply and demand.

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