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# An integrated model driven by agent-based water end-use forecasting to evaluate the performance of water and wastewater pipeline systems

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**Summary of key findings**

In spite of their hydraulic, temporal, and spatial connections, water and wastewater pipeline systems are traditionally planned and designed in a stationary and separated manner, and this practice may have already rooted future system operation risk at these early stages. An integrated model was developed to evaluate the performance of these two water systems planned and designed according to tradition water demand quota approaches. The integrated model included an agent-based water end-use model to generate water demand and wastewater discharge, which was used to drive a water distribution system model, i.e. EPANET 2.0, and a sewage system model, i.e. SWMM 5.0. In the case study, the proposed model forecasted a lower water demand and wastewater discharge as compared with the traditional approach. However, the greater diurnal fluctuation would cause operation problems during the peak hour as well as off-peak periods, such as low water head and long water age on the fringes of the water distribution systems, and overload of sewers in densely populated areas and high risk of siltation in the sewage system.

**Background and relevance**

Water demand is the determining factor for the planning of urban water and wastewater pipeline systems, and water demand quota per capita or per land area is widely applied to forecast the total as well as spatially disaggregated water demand over the planning area. Although taking daily and diurnal variations into account, this traditional approach is generally stationary. On the one hand, water demand quota may not be kept up-to-date in practice. For example, the Code for Design of Outdoor Water Supply Engineering (GB50013-2006) in China significantly reduced the water demand quota as compared with the Code for Urban Water Supply Engineering Planning (GB 50282-98). However, the former has not been updated since then, and the water demand statistics in 2013 showed that the provincial average of the urban domestic water demand was even less than the lower limit of the quota for a medium-size or small city in four provinces. So the stationary water demand quota may lead to oversized water systems, especially in the context that urban water demand per capita has continuously decreased or stabilized in recent years in China, which could cause unnecessary financial burdens and operation problems, e.g. water quality deterioration in supply systems and siltation in sewage systems. On the other hand, the traditional stationary approach evaluates the performance of water and wastewater pipeline systems considering only several worst cases, e.g. peak hour water demand for water distribution systems and peak and off-peak hour discharges for sewage systems, rather than the possible diurnal and seasonal variations of water quantity. Only through modeling these continuous, full-spectrum variations, could the cumulative or even extreme effects on system operation be identified, such as long residence time at certain nodes in water distribution systems in winter and cumulative impact of several hours of peak and near-peak discharges on downstream pipes in sewage systems in summer.

In addition to the stationary problems discussed above, water and wastewater pipeline systems are traditionally separately planned, designed, evaluated and operated, although water demand in water distribution systems planning is usually used to derive the produced wastewater considering a discharge coefficient for sewage systems planning. Since clean water obtained from taps is normally discharged into sewers after use instantly or with a certain delay (e.g. water for clothes washing in washing machines) in households, water and wastewater pipeline systems are obviously temporally and hydraulically coupled in a city. Thus it is highly likely that some households, e.g. on the fringes of a city, may suffer from water and wastewater service problems concurrently, e.g. poor drinking water quality and sewer blockage, which may cause aesthetical nuisances or even health concerns. For water companies and authorities, these "hotspots" should be identified and given careful consideration, which offers them the opportunity to fix these problems simultaneously, given that the spatial layout of these two systems is usually overlapped, e.g. underground along a same street or within a same utility tunnel.

To this end, this paper aims to develop an integrated model to evaluate, at the planning stage, the performance of water and wastewater pipeline systems planned according to traditional approaches. In order to include the hydraulic coupling between these two systems, the models for water distribution systems and sewage systems, i.e. EPANET 2.0 and SWMM 5.0 respectively, are driven by the same agent-based water end-use forecasting model.

End-use models are bottom-up ones that forecast water demand starting from the points where water is supplied and used, and they have been experiencing fast development since the 1990s when modern smart metering technologies mature (DeOreo et al., 1996; Mayer et al., 1999; Jacobs and Haarhoff, 2004; Blokker et al., 2010; Carragher et al., 2012; Scheepers and Jacobs, 2014). End-use models, both residential and non-residential, capture the underlying causal relationships between water demand and water use behaviors (e.g. frequency and duration) as well as water-using appliance stocks and efficiency (e.g. flow and volume), which would still hold true when structural conditions change in the future, such as socio-economic, technical and climatic features (Jacobs and Haarhoff, 2004; White et al., 2004; Galan et al., 2009; Beal et al., 2011; Blokker et al., 2011). A water end-use model was developed in this study to forecast urban domestic water demand considering its increasing proportion in the total urban water demand in China, while all the other uses, e.g. industrial uses, were estimated according the traditional water demand quota approach. Compared with previous residential water end-use models, which only involved water use behaviors taking place in residences either indoor or outdoor (Jacobs and Haarhoff, 2004; Blokker et al., 2010; Scheepers and Jacobs, 2014), the major difference of the proposed model is that it also included personal water uses occurring in other surroundings, e.g. drinking water in the office and urinating at a shopping center. So all the direct personal water needs were considered in the model.

Considering the variability of water demand among different residents and households, an agent-based method was adopted, and currently the model only simulated two types of agents, i.e. residents and households. For each resident, key features that may impact water use behaviors, e.g. gender, age and occupation, were randomly generated according to official statistics, while those for households, e.g. size, members and water-using appliance stocks and specifications, were also derived from statistics and surveys. Water use behaviors were categorized into individual-based ones, including drinking, toilet flushing, teeth brushing, hand/face washing, and shower/bath, and household-based ones, including cooking, dishwashing, and laundering. The frequency, timing and volume of each water use behavior were investigated through household surveys, and their empirical probabilities were followed to randomly generate a series of water use events for each resident or household agent in a day (Blokker et al., 2010; Scheepers and Jacobs, 2014). This is where previous residential end-use model studies stop when the aggregated time series of water demand could be obtained. For the purpose of this study, however, water demand should also be spatially disaggregated, i.e. allocated to each land parcel, in order to calculate the water demand and wastewater discharge for each node of water distribution systems and sewage systems respectively.

On account of this, the planned land use map and time budget statistics for urban residents were also acquired. Based on the Chinese time budge statistics, five major categories of activities were identified, including personal basic physiological needs (e.g. sleep, excreting, and hygiene) and housework, work/study, shopping, leisure and entertainment, and medical care and hospitalization, and the relationships between these activity categories and land use types were established. For example, a resident employed by a bank would be located in a land parcel for commercial and financial uses during working hours and return home in a land parcel for residential uses after work. Therefore, at each time step, individual water demand was added to the demand of the land parcel where she/he was currently located, while household water demand was always added to that of the same land parcel where it was located. The same rule applied to wastewater discharge estimation.

EPANET 2.0 and SWMM 5.0 were used to simulate the water distribution system and sewage system respectively in the case study. The layout of the two systems from the master plan was compiled as input files to the software and remained unchanged in succeeding performance evaluation. The specification of the two systems, e.g. pipe diameter and slope, was determined with the software according to the current planning and design codes. Finally, the performance of these two systems was evaluated by driving the software with water demand and wastewater discharge forecasted by the proposed agent-based water end-use model.

## Results

According to the master plan of the case study city, a peak-day domestic water demand quota of 230 L/d/capita was chosen, which was slightly higher than the median of the allowed arrange of the quota by the design code. Based on this, 238 thousand $m^3$ of water would be needed in the case study area and correspondingly 190 thousand $m^3$ of wastewater be discharged on the peak day, among which 138 and 110 thousand $m^3$ would be associated with domestic uses. The agent-based water end-use model produced lower estimates, indicating potential oversize problem of the two water systems. The peak-day water demand and wastewater discharge would be 211 and 169 thousand $m^3$ respectively with 111 and 89 thousand $m^3$ arising from domestic uses. However, the model simulated greater diurnal fluctuations in water demand and wastewater discharge with the peak-hour factors 2.14 and 2.41 respectively, which were much higher than those defined by the design codes, i.e. 1.5 and 1.3 respectively.

As revealed by the simulation results of EPANET and SWMM, the two water systems suffered operation problems during the peak hour. Figure 2(a) showed that 50 nodes, 6.2% of the total, on the eastern, southern, and northern fringes of the water distribution system could not satisfy the required water pressure, i.e. 28 m, and Node 654 only had a water head of 24.79 m. In the sewage system, the peak-hour wastewater discharge caused the overload of sewers in densely populated areas, as shown in Figure 2(b) and the depth to diameter ratio of 189 pipes, 20.8% of the total, was above 0.75.

Great diurnal fluctuations in water quantity also resulted in operation concerns of the two water systems during off-peak periods. Assuming residual chlorine of 1.0 mg/L in treated water at the waterworks and a medium decay rate of 0.005 min-1 (Kiene et al., 1998), a residence time of 10 hours would cause the residual chlorine below 0.05 mg/L, which is the minimum requirement at the extremity of the water distribution system by the national standard, if a first-order decay is followed. Unfortunately, as shown in Figure 2(c), 118 nodes, 14.6% of the total, had a water age longer than 10 hours, and they would be at a risk of failure to comply with this minimum requirement on residual chlorine. Regarding the sewage system, siltation becomes a concern if the velocity in the sewer is lower than the self-cleansing one, i.e. 0.6 m/s. It was found, as illustrated in Figure 2(d), that over 55.9% of the total number of sewers had velocity lower than 0.6 m/s in more than 20 hours on the peak day.

## Discussion

The agent-based water end-use model forecasted a lower water demand and wastewater discharge as compared with the traditional water demand quota approach in the case study. However, the greater diurnal fluctuation would cause operation problems during the peak hour as well as off-peak periods, such as low water head and long water age on the fringes of the water distribution systems, and overload of sewers in densely populated areas and high risk of siltation in the sewage system. The integrated model could be further applied to evaluate the impact of other socio-economic and climatic changes on water and wastewater pipeline systems, which could also be extended to include other components of urban water systems, e.g. separate or combined storm water systems, waterworks, and wastewater treatment plants.

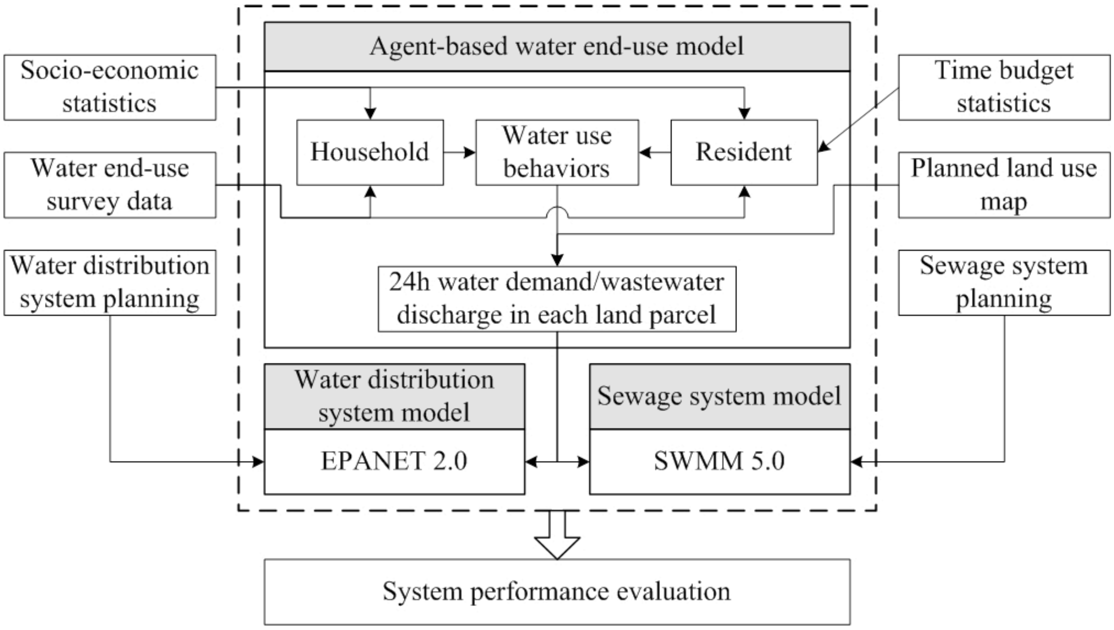


**Figure 1 Overall design of the study.**

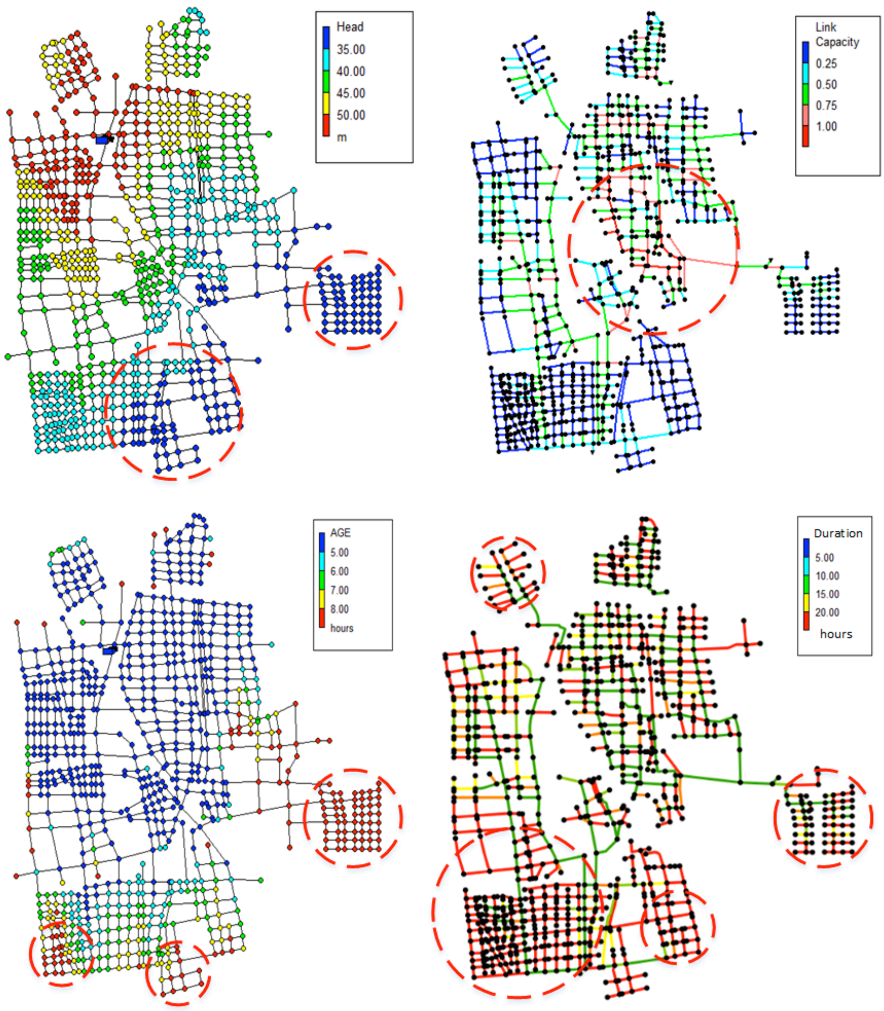


**Figure 2 The hydraulic performance of water network system. (a) Water head and (c) Water age in the water distribution system; (b) Depth to diameter ratio and (d) Duration with a lower velocity than the self-cleansing one, i.e. 0.6 m/s, in the sewage system.**

## References

DeOreo W B, Heaney J P, Mayer P W. Flow trace analysis to assess water use. Journal American Water Work Association, 1996, 88(1): 79-90.

Mayer P W, DeOreo W B, Optiz E M, Kiefer J C, Davis W Y, Dziegielewski B, Nelson J O. Residential end uses of water. Denver: AWWA Research Foundation and American Water Works Association, 1999.

Jacobs H E, Haarhoff J. Structure and data requirements of an end-use model for residential water demand and return flow. Water SA 2004, 30(3): 293-304.

Scheepers H M, Jacobs H E. Simulating residential indoor water demand by means of a probability based end-use model. Journal of Water Supply: Research and Technology-AQUA, 2014, 63(6): 476-488.

Blokker E J M, Vreeburg J H G, van Dijk J C. Simulating residential water demand with a stochastic end-use model. J. Water Resour. Plan. Manage.-ASCE 2010, 136(1): 19-26.

Carragher B J, Stewart R A, Beal C D. Quantifying the influence of residential water appliance efficiency on average day diurnal demand patterns at an end use level: A precursor to optimised water service infrastructure planning. Resources, Conservation and Recycling, 2012, 62: 81-90.

Beal C, Stewart R A, Spinks A, Fielding K. Using smart meters to identify social and technological impacts on residential water consumption. Water Science & Technology: Water Supply, 2011, 11(5): 527-533.

Blokker E J M, Peiterse-Quirijns E J, Vreeburg J H G, van Dijk J C. Simulating nonresidential water demand with a stochastic end-use model. Journal of Water Resources Planning and Management, 2011, 137(6): 511-520.

White S, Milne G, Riedy C. End use analysis: issues and lessons. Water Science & Technology: Water Supply, 2004, 4(3): 57-65.

Galan J M, Lopez-Paredes A, del Olmo R. An agent-based model for domestic water management in Valladolid metropolitan area. Water Resources Research, 2009, 45, W05401.

Kiene L, Lu W, Levi Y. Relative importance of phenomena responsible for chlorine decay in drinking water systems. Water Science & Technology, 1998, 38(6): 219-227.