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# Improving water and energy metabolism efficiency in urban water supply system through pressure stabilization by optimal operation on water tanks

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ABSTRACT

Water supply consumes 2–3% of the worldwide energy. Water distribution system, which accounts for 70% electricity consumption of water supply, is a key link of urban water and energy metabolism. The operation of the secondary water supply system (SWSS) has great influence on the pressure stability and associated energy consumption as well as water loss of urban water distribution. This research developed an approach based on the hydraulic solver EPANET and genetic algorithm (GA) to investigate the impacts of two different operation strategies, user demand regulation (UDR) and tank level regulation (TLR) of SWSS, on pressure stability and energy efficiency. The results showed that the strategy of TLR could reduce the pressure fluctuations and increase the minimal pressure of the distribution network under the same supply–demand condition. Reduction of the pressure fluctuations is beneficial to the reliability and leakage control of pipe networks. Increase of the minimal pressure indicates that less energy is lost during the distribution. Therefore, the TLR strategy of SWSS can support to initiatively lower the water pressure of the pumps at the water plant outlet, thus improves the water and energy metabolism efficiency in urban water supply system.



## 1. Introduction

Water supply is an energy-intensive industry, consuming 2–3% of the worldwide energy, more than 70% of which is used in the distribution system (James et al., 2002). Therefore, improvement of energy metabolism in water distribution systems (WDS) has become an issue of concern with the ever-increasing water demand (Boulos et al., 2001) and a need to reduce greenhouse gas production. Energy consumption in WDS can be reduced by pressure control, which can be implemented by operating pumps in the water supply plant (Cembrano et al., 2000) and installing pressure reduction valves (PRVs) in the water pipe network. Besides the energy savings, pressure control for WDS can significantly improve the pipe network's safety, because high pressure and pressure fluctuations usually lead to more pipe breaks and water loss (Lambert, 2001). Therefore, many researchers have studied ways to control water pressure in pipe networks and achieved promising results (Araujo et al., 2006; Martínez et al., 2007; Nicolini and Zovatto, 2009; Salomons et al., 2007; Xu et al., 2014a; Xu et al., 2014b). The effect of type selection, installation position and installation number of PRVs on reducing pipe leakage and loss has also been analyzed and discussed (Fantozzi et al., 2009; Meyer et al., 2009).

Most published research has focused on PRV installation and optimal management and control. However, water use plays also an important role in pressure variation of the WDS. The water use can be divided into two categories. One is to directly get adequate water from the primary pipe network, as the water pressure in the network is high enough. The other is to get water from additional pumping system, as many customers are in high stories of tall buildings. In China, the additional pumping system, which is called secondary water supply system (SWSS) in this study, usually contains a storage tank, a valve connecting the storage tank to the primary network and a pump connecting the storage tank to the service pipes. Of course, in the normal state water use by users that are directly connected to the primary WDS is not easy to control. However, the existence of storage tanks in the SWSS makes it possible to regulate the water use, i.e. controlling the inlet flow of the storage tanks. Making effective use of storage tanks is helpful for energy saving and improving the pipe network's safety (e.g., filling them during off-peak periods and draining them during peak periods). The impact of SWSS operation on the primary WDS should be emphasized, especially when the number of storage tanks and the total storage volume are too large. In many cities of China, buildings with more than six stories are usually equipped with storage tanks. Therefore, how to regulate these tanks has been a problem facing the water utilities in China.

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The storage tanks have three basic functions: (i) Additional water pumping. This is the fundamental function of the SWSS. The water stored in the tanks is pumped to high-elevated receivers by the pumps after the tanks. (ii) Supply security. When the primary pipe network fails, the storage tanks can supply water to its receivers. (iii) Regulation of water use. Tanks store water when water demand is low while releasing water when demand is high. To a certain extent, this characteristic relieves the conflict between supply and demand. However, due to insufficient investment, most of the tanks are controlled using ball float valves, meaning that the water levels of the tanks vary within a narrow range. This kind of tanks is general in China nowadays, although may not be the case in other countries. The incomplete functioning of storage tanks can increase energy consumption. For one thing, the pump head needs to be adjusted frequently due to water demand variation during the day. The pumps cannot operate at their best efficiency point persistently. For another thing, the pump head must be raised to satisfy the lowest pressure demand at the critical point in the WDS, which means extra electricity expense. Furthermore, the leakage and loss in the WDS increase under higher pressure.

Overall, the operation of the water tanks has some impacts on the primary water supply network. The goal of this paper is to assess the impacts and to investigate the optimal regulation of the water tanks. The study investigates several typical pipe networks and discusses the relationship between tank volume and regulation effect. The results show that tank level regulation is beneficial to pressure stability and the associated energy efficiency.

## 2. Methods

In this paper, a hydraulic model for SWSS was developed and used to optimize operation of storage tanks. Two assessment criteria, the junction pressure's fluctuation intensity $H_v$ and lowest working pressure $H_{min}$, were defined to evaluate the effects.

### 2.1. Model of water distribution network

The hydraulic model for secondary water supply systems is based on EPANET (Rossman, 2000), which is provided by the USEPA (United States Environmental Protection Agency) and broadly used (Avesani et al., 2012; Senyondo, 2009; Tabesh, 2009; Torres, 2009). It performs extended period simulation of the water hydraulics and quality behavior within pressurized pipe networks.

### 2.2. Assessment criteria

Two indices, the fluctuation intensity of nodal pressure and the lowest working pressure of the network, were defined to assess the effects of storage tank regulation on the water distribution system.

Pressure fluctuations are harmful to a WDS because in many cases pipe bursts are not caused by high water pressure but by pressure fluctuations. In this study, the pressure fluctuation $H_v$ was defined as the average of the standard deviation of all junction pressures. The lower the $H_v$ is, the better the network performs.

$$H_v = \frac{\sum_{j=1}^{m} \sqrt{\sum_{i=1}^{n} \frac{\left(H_i^j - \overline{H^j}\right)^2}{n-1}}}{m} \tag{1}$$

where $H_i^j$ is junction $j$'s pressure at hour $i$, $\overline{H^j}$ is the mean of junction $j$'s pressure during the whole simulation period, $m$ is the number of junctions and $n$ is the number of time steps.

In the WDS, there exists a threshold value that satisfies all receivers' lowest pressure demand. If the lowest working pressure $H_{min}$ is lower than the threshold, the source pressure must be increased, which will increase energy consumption. However, extra pressure can be reduced and energy will be saved if the lowest working pressure is too high. Therefore, the consideration of $H_{min}$ is to investigate whether the lowest working pressure could be raised through operating the storage tanks under the given pressure at the pump station. If so, there will be a potential to reduce the water pressure of the pumps at the water plant outlet to save energy.

### 2.3. Tank operation strategies

Regulation is realized through controlling the inflow into storage tanks. Fig. 1 describes the structure of a storage tank. Two operation strategies were distinguished.

(1) User-Demand Regulation (UDR): this means the inflow of tanks is equal to the outflow. The level of tanks remains constant. Actually, there is a time lag between the water use and the water level dropping and rising in the tank. So over very short periods this strategy can balance the inflow and outflow. In this study, this effect is ignored.

(2) Tank-Level Regulation (TLR). During peak use time, the inflow is small, but increases as the tank water level drops; during off-peak periods, the inflow is large, but decreases as the tank water level climbs. The inflow stops when the tank level rises to the highest value.

### 2.4. Method for optimizing combination

In this study, a genetic algorithm (GA) was applied to optimize the combination of operation strategies among different tanks for pressure stability and energy reduction. GA is a method to search for global optimal solutions using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover (Goldberg, 1989). Compared to a traditional heuristic search algorithm, GA is effective and efficient when confronted with combinatorial problems (Mitchell, 1999). During the optimization, a binary string 1001…01 was encoded, where each digit represented a tank, and the length of the string was the total number of tanks, 1 represented TLR and 0 meant UDR. The optimization was to find the best combination (string) under which the ratio $H_{min}/H_v$ had a maximum value.

## 3. Benchmark tests of the method

The developed method was verified by two benchmark networks supplied with the EPANET installation. The networks were slightly modified to meet the requirements of the research. The networks were assumed to be in normal conditions, i.e. there was no such abnormal condition as water supply interruption.

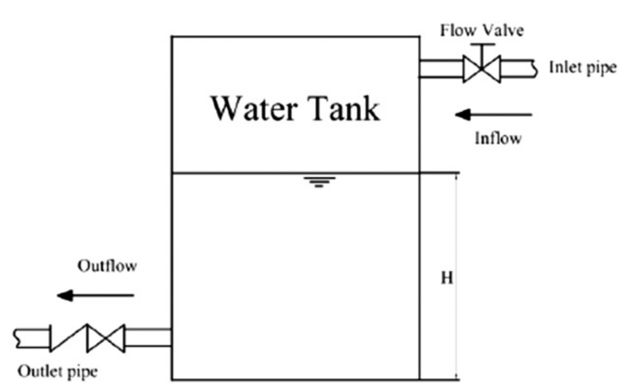


**Fig. 1.** Diagram of tank regulation.