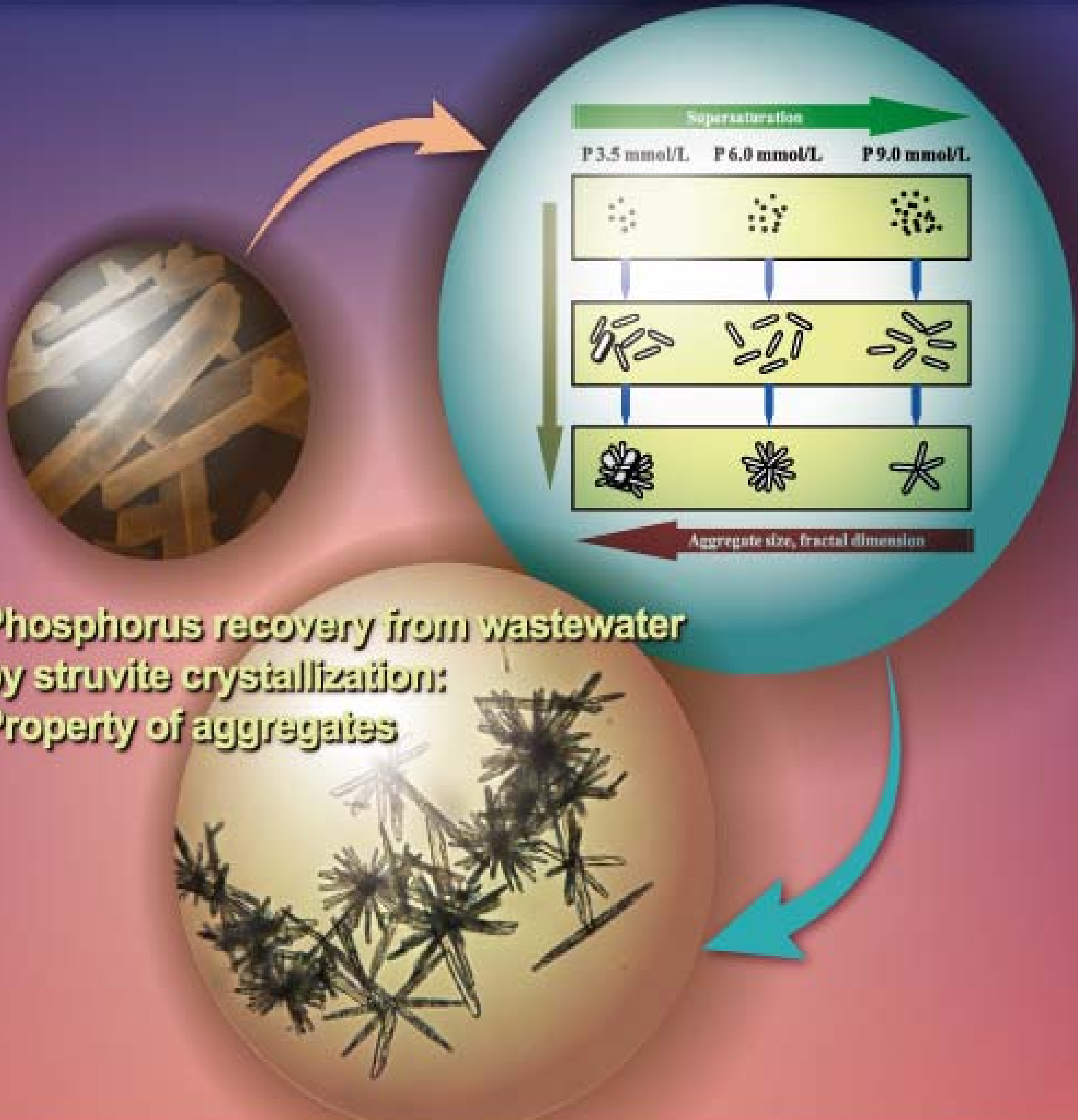
JES

JOURNAL OF ENVIRONMENTAL SCIENCES

ISSN 1001-0742
CN 11-2629/X

May 1, 2014 Volume 26 Number 5
www.jesc.ac.cn



Phosphorus recovery from wastewater by struvite crystallization: Property of aggregates

ELSEVIER
Science Press

Sponsored by
Research Center for Eco-Environmental Sciences
Chinese Academy of Sciences

ISSN 1001–0742 **Journal of Environmental Sciences** Vol. 26 No. 5 2014

CONTENTS

Aquatic environment

Atmospheric environment

Terrestrial environment

Environmental biology

Environmental health and toxicology

Environmental catalysis and materials

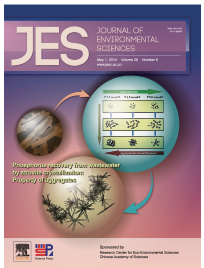
Serial parameter: CN 11-2629/X*1989*m*277*en*P*29*2014-5

Journal of Environmental Sciences 26 (2014) 955–961

Available online at www.sciencedirect.com

Journal of Environmental Sciences

www.jesc.ac.cn



Review on water leakage control in distribution networks and the associated environmental benefits

Qiang Xu[1], Ruiping Liu[1], Qiuwen Chen[1,2,3,*], Ruonan Li[1]

1. Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China. E-mail: qiangxu@rcees.ac.cn
2. Center for Eco-Environmental Research, Nanjing Hydraulics Research Institute, Nanjing 210029, China
3. China Three Gorges University, Yichang 443002, China

ARTICLE INFO

Article history:
Received 20 August 2013
revised 27 January 2014
accepted 11 February 2014

Keywords:
water leakage control
water distribution system
environmental benefits
DOI: 10.1016/S1001-0742(13)60569-0

ABSTRACT

Water supply is the primary element of an urban system. Due to rapid urbanization and water scarcity, maintaining a stable and safe water supply has become a challenge to many cities, whereas a large amount of water is lost from the pipes of distribution systems. Water leakage is not only a waste of water resources, but also incurs great socio-economic costs. This article presents a comprehensive review on the potential water leakage control approaches and specifically discusses the benefits of each to environmental conservation. It is concluded that water leakage could be further reduced by improving leakage detection capability through a combination of predictive modeling and monitoring instruments, optimizing pipe maintenance strategy, and developing an instant pressure regulation system. The environment could benefit from these actions because of water savings and the reduction of energy consumption as well as greenhouse gas emissions.

Introduction

Human civilization is closely related to water development, as observed by the one-dimensional system whereby major cities have mostly originated along rivers. The settlement and interaction of human beings are influenced by the spatial and functional characteristics of river basins, and the direction of flow of rivers affects the movement of civilization (Delli Priscoli, 2000). The inherent driver of this phenomenon is that people need water in every aspect of life, e.g. drinking, agriculture, industry, transportation, recreation, etc.

In the early stage of the water-human relationship, people passively adapted their behaviors to the water distribution. The situation was reversed, however, in the later stages, especially when cities emerged. In urban planning, one of the most important infrastructures is the design of water systems, including the water supply system and the sewerage system. The former distributes potable water to the city habitants and the latter collects the wastewater and conveys it out. They serve as the arteries and veins of the city. The sustainable development of a city must involve the sustainable use of water.

However, it is nowadays more and more challenging to satisfy the water demand of the city inhabitants following rapid urbanization, since the per capita water use of urban inhabitants is much higher than that of rural inhabitants. Access to reliable potable water is an increasing pressure for many water supply industries, especially in developing countries. Taking China, which is the world's largest developing country, as an example, the urban population has grown much faster than the total domestic water supply, as indicated by the growth rate during 2004 to 2012 (**Fig. 1**). The urban population increased by 35.2% (from 303.4 to 410.3 million) while the total amount of urban water supply increased only by 10.2% (from 23.3 to 25.7 billion m^3) during the period. There is no surprise that this gap will hamper urban development; therefore, it is essential to

* Corresponding author. E-mail: qchen@rcees.ac.cn

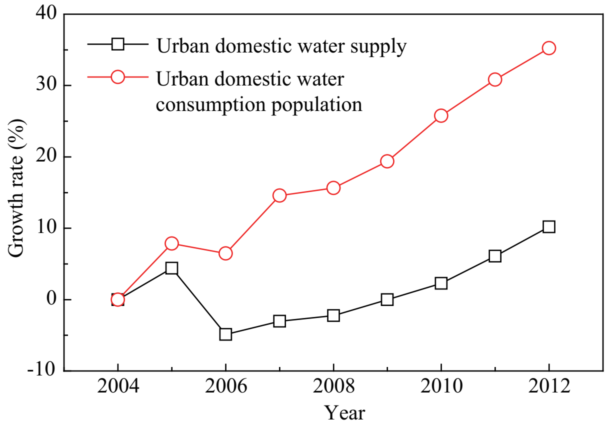


Fig. 1 Growth rates of urban domestic water supply vs. water consumption population of China from 2004 to 2012. Data from the National Bureau of Statistyics of China (http://www.stats.gov.cn/english).

bridge the growing gap between the demand and supply of water.

However, a large amount of water is lost during the delivery to customers in the meantime due to pipe failures. Each year more than 32 billion m^3 of potable water are lost from water distribution networks all over the world, which accounts for 35% of total water supplied (Farley et al., 2008). Therefore, control of water leakage is an effective measure to enhance water supply capability. The emergence of the concepts water sensitive urban development and water sensitive city demonstrates the willingness of utility managers to improve water use efficiency (Coombes et al., 2000; Ferguson et al., 2013; Morison and Brown, 2011; Wong and Brown, 2009).

In addition to the waste of potable water, there are several indirect effects of water leakage. Water supply is an energy-intensive industry, which consumes 2%–3% of the worldwide energy (James et al., 2002), thus the leakage of water is also the waste of a large amount of energy. The development of small breaks in pipes, if not detected, may lead to pipes bursting, incurring great socio-economic losses. At the same time, there is a risk of contaminating the water because pollutants may intrude into the pipe network through the breaks when negative pressure occurs.

Management of water leakage is seen to obviously benefit both the water utilities and the customers. The water utilities will get the cheapest additional water source without much investment, reduce the risk of pipe bursts, and ensure water quality for the end-users. The savings of water resources and the associated energy from water leakage control will support the sustainable development of cities. Therefore, many investigations and practices have been conducted to minimize water leakage from water distribution systems, including active leakage detection, optimal maintenance of deteriorated pipes, and water pressure regulation.

This article presents a comprehensive review on state-of-the-art water leakage control approaches, in particular the research hotspots and the associated environmental benefits.

1 Improvement of leakage detection by combining models and instruments

Leakage detection is the fundamental to control water leakage because only if the leak is located it is possible to fix it. As such, leakage detection has become routine work for the water supply industries. Efficiency of leakage detection can be significantly improved if an optimal leakage detection scheme is used, which demands a combination of detection instruments and pipe failure prediction models.

1.1 Leakage detection techniques

The available leakage detection approaches are usually classified into three categories: noise monitoring, flow and pressure monitoring, and the others. The first two categories are widely applied in water utilities.

Noise monitoring: leakage can generate noise when water flows out through a hole or fracture of a pipe and when water flows past substances outside the pipe. Noise can propagate along the pipe and the ground, thus capturing the noise will help in finding a leak. There are many kinds of acoustic equipment to capture this noise signal. The earliest form of such acoustic equipment is a stethoscope-like apparatus that connects a metal rod and earphones. Placing the metal rod in contact with a pipe, the noise can be transmitted to the listener's ears through the earphones (Babbitt, 1920). According to the sound heard, experienced workers can give a judgment as to whether a leak exists in the pipe and the leak location can approximately be given by repeating the process at different places. Although labor-intensive, this method has been used for many years and is still the main way to detect leaks for some water utilities. New acoustic techniques have also been applied to improve the efficiency. Devices have been developed to capture and/or record the signal of leakage noise, based on which the leakage information can be calculated. In essence, the theory is the same as that of the detection by human listening. But the machine-based techniques take advantage of the enhancement of hearing capacity and the improvement of leakage-locating accuracy and precision. Although broadly used, this kind of method suffers from the disadvantage of insensitivity to large leaks that do not generate vibrations at high frequencies (Colombo et al., 2009).

Flow and pressure monitoring: leakage is an additional, but unexpected, flow out of the pipe network, which means leakage can cause changes in the hydraulic characteristics, i.e. flow increase and pressure decrease, which are noticeable if the leak is large enough. Continuously monitoring the flow and pressure of a sectorized pipe network, e.g.

DMA (district metered area) can help to detect leakage. For example, if the minimal night flow (MNF, the flow when the normal water use is at its minimum) increases suddenly and keeps at this level for several consecutive days, it possibly indicates a new leak (Alkasseh et al., 2013). Besides the MNF, a leak can also be identified by analyzing the changes of flow pattern (Buchberger and Nadimpalli, 2004; Van Thienen, 2013) and the changes of water pressure, e.g. a sudden drop of water pressure may imply a big leak or a burst pipe. The method of transient pressure waves is also explored to identify leaks in pipe networks (Guo et al., 2012; Kapelan et al., 2003; Misiunas et al., 2005; Vítkovský et al., 2007; Wang et al., 2002). The existence of leaks can impose a wave reflection on an incoming transient signal and thus alter the system's pressure response, notably the singularities in the wave shape and the attenuation in the wave amplitude (Colombo et al., 2009). By measuring the characteristics of the transient pressure wave, the leak can be detected. Corresponding to these approaches, hydraulic models have been developed as an alternative to direct monitoring. The location and rate of leakage can be estimated by the models to obtain an acceptable fit to the monitoring data (Wu, 2009; Wu and Sage, 2006).

The other approaches: there are also some forms of visual evidence such as water seeping or gushing to the surface, anomalous vegetation growth, etc. These observations are usually reported by the public and play an important role in leak detection, especially in the developing countries. Usually the visual evidence arises only when the leak exists for a long time, so such passive leakage detections become less and less, following the improvement of the leakage management capability of water utilities.

1.2 Optimization of leakage detection scheme based on pipe leakage assessment

Although a variety of instruments are available to monitor and detect leaks, they are mostly expensive or labor-intensive. It is logical that water utilities want to find more leaks with limited labor force and investment. The straightforward solution is to assess the risk of pipe failure and prioritize the sections to be monitored. Therefore, pipe break assessment models are developed to analyze pipe failure risks. These models can be grouped into two categories: physically based models and statistical models. Physically based models aim to reveal the physical mechanism behind the pipe break behavior. The explanatory variables usually contain physical and chemical parameters describing how the pipe's structural resistance capacity decreases with chemical processes such as corrosion (Rajani et al., 2000), and how the pipe corrosion relates to the surrounding environment (Liu et al., 2010; Rajani and Kleiner, 2013).

Different from the physically based models, statistical models employ macro indicators to predict pipe breaks without much consideration of the physical mechanism. These indicators include both the properties of the pipe such as material (Kleiner and Rajani, 2002), age (Kettler and Goulter, 1985), diameter (Walski and Pelliccia, 1982), length (Le Gat and Eisenbeis, 2000) and number of service connections (Berardi et al., 2008) and the environmental variables such as soil type (Watson, 2005) and even earthquake interference (Fragiadakis et al., 2013; Ho et al., 2010).

Quantitative relationships between pipe leakage and selected explanatory variables have been established in the abovementioned studies. Although the models' structures and parameters are usually case-dependent because of the inherent complexity of pipe leakage, the difference in pipe networks and data availability, these models are successfully applied to assess the failure probability of pilot pipes (Xu et al., 2011), from which an optimal leakage detection plan or pipe rehabilitation strategy can be made (Xu et al., 2013).

2 Pipe repair, rehabilitation and replacement

Once pipe are deemed to be structurally or functionally deteriorated, decisions should be made to repair the breaks, rehabilitate the pipe or replace it. Pipe repair has the least impact on the pipe since it usually operates on a rather small fraction of pipe compared to the entire length. Pipe replacement replaces the old pipe with a new one and thus can completely restore the pipe's condition. Pipe rehabilitation can improve the pipe's condition to a level between the current status and new pipe. It should be noted that, in some circumstances, the term pipe rehabilitation is used as a generalized concept referring to a wide range of measures taken on the pipe, including pipe repair, pipe lining, pipe replacement, etc. In some other instances, it specifically refers to a variety of maintenance operations including, for example, spray-on lining, sliplining, etc., while excluding the measures of pipe repair and pipe replacement. This special meaning of pipe rehabilitation is adopted in this study.

It is obvious that pipe repair requires the least cost while pipe replacement requires the most. Therefore, careful consideration must be taken when making a decision whether to just repair the breaks or to rehabilitate or replace the pipe. Many researchers have studied the optimal pipe replacement strategies with the goal of achieving the largest benefit-to-cost ratio. These studies can be basically classified into two categories: models to calculate the optimal time to replace a pipe, and models to prioritize the pipes for replacement.

A notable model of the first category was presented by Shamir and Howard (1979), who established a pipe break prediction model and defined a cost function by adding up the total pipe repair cost and the pipe replacement cost. The optimal pipe replacement time could be quickly obtained by minimizing the cost function. Besides structural deterioration, functional deterioration was taken into consideration by Kleineret et al. (1998) to calculate the pipe's lifetime and thereafter to schedule the pipe replacement strategies. In some other studies, multi-objective models were established to account for both the maintenance cost and the effect of deteriorated pipes on the water pressure (Dridi et al., 2009; Halhal et al., 1997). Park and Loganathan (2002) introduced the concept of threshold break rate and when a pipe's actual break rate reached this value, it was economical to replace it. It should be noted that an essential step to optimize the pipe replacement strategy is to predict the pipe break probability (Xu et al., 2013).

The other category of optimal pipe replacement models focuses on sorting the pipes according to the assessment of priorities for replacement. The emergence of these models come about because usually water utilities have a pipe replacement plan, for example, replacing 1% of all the pipes per year. Rather than knowing exactly the most economical time to replace a pipe, they are more interested in knowing which pipes out of the whole network should be replaced first. Therefore, models were developed to assess the pipes' priorities for replacement, where different performance indicators were included and different methods were developed (De Oliveira et al., 2010; Ho et al., 2010; Luong and Fujiwara, 2002; Luong and Nagarur, 2005). The results of these studies help make efficient use of the funds invested in pipe replacement.

Although quite a few studies have been done to balance the benefits and costs of break repair and pipe replacement, little effort was taken to assess the benefits of pipe rehabilitation. The main difficulty may exist in the prediction of pipe break rate after rehabilitation. For pipe repair, the break rate can be assumed to be consistent before and after the repair; for pipe replacement, the break rate is the same as new pipes after the replacement. Therefore, in most studies only pipe repair and pipe replacement are considered to develop optimal pipe maintenance models.

3 Water pressure regulation

Water pressure management is an effective and efficient way to reduce the leakage of water distribution systems and actually is the only way to reduce the background leakage that cannot be detected using current techniques. Compared to a long-term pipe break detection and pipe maintenance strategy, water pressure management can reduce the water leakage in a much shorter period. Leakage is positively related to pressure, which means that reducing the water pressure can immediately incur water leakage reduction. **Figure 2** gives the response of MNF (often used to represent leakage) of a DMA to three pressure regulation regimes (the data is from a field experiment by the authors), which demonstrates the effectiveness of pressure management.

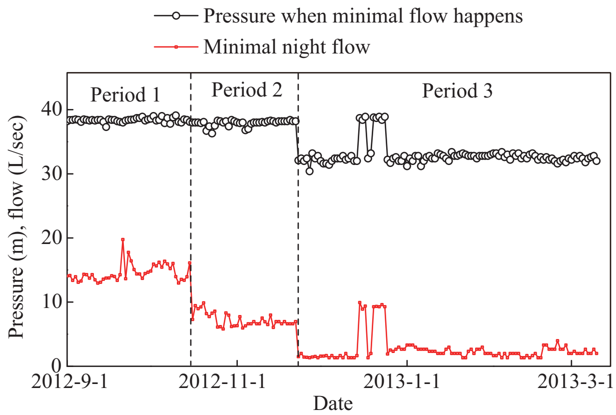


Fig. 2 Minimal night flow response to pressure regulation.

The leakage-pressure relationship is usually described by the following equation (Lambert, 2001; Thornton and Lambert, 2005; Thronton, 2003):

$$L = k \times P^n$$

where, L is the leakage rate, P is the average pressure of the network, and k and n are parameters to be calibrated. The exponent n ranges from 0.5 to 2.5 or even higher depending on the type of leak (Lambert, 2001; Thornton and Lambert, 2005). Obviously, leakage will be very sensitive to water pressure when $n > 1$.

Besides the reduced leakage from existing breaks, the water utilities can also benefit from pressure management by lowering pipe burst risks and extending the pipe's lifetime (Farley and Trow, 2003; Lambert and Thornton, 2011; Thornton and Lambert, 2006). Water pressure is usually controlled based on the partitioning management of the pipe network, such as the PMA (pressure management area) and DMA. PRVs (pressure reducing valves) are installed at the inlet of the PMAs or DMAs and the water pressure inside the zonal network can be regulated by operating the PRVs. To maximize the benefits of pressure management, the installation and operation strategies of PRVs, i.e. quantity, locations and opening adjustment, are optimized (Araujo et al., 2006).

Although the benefits of pressure management have been recognized for over 40 years in some countries, notably the UK and Japan (Thronton, 2003), and are more and more realized by water utilities (Girard and Stewart, 2007; Marunga et al., 2006; Soriano et al., 2012), it is still not applied in most developing countries. The two major reasons are: the lack of decision support tools that can accurately assess the benefits associated with pressure management and justify the investment; the fact that water distribution networks are usually not well configured for effective pressure management (Mutikanga et al., 2013).

4 Discussion

4.1 Benefits of water leakage control

Water availability significantly influences the development of a city, and at the same time, urbanization has great impact on the available water resources, resulting in reduced amount, changed spatio-temporal distribution and deteriorated water quality (Du et al., 2010; Lee et al., 2009; Marinoni et al., 2013).

Water leakage control in distribution systems is a valuable activity to preserve the water resources, especially in the situation of water scarcity and climate change. The direct benefit of water leakage control is that more people will be fed without the need for new water resource exploration. According to the work by Farley et al. (2008), the lost water from distribution systems over the world can meet the demand of 200 million people.

The benefits of water leakage control go far beyond the saved water itself. Associated benefits include the reduction of energy consumption and greenhouse gas emissions. The energy consumption for treating 1 m^3 of water is 2–42 MJ and varies depending on the source of water. Surface water and groundwater need 2–3 MJ of energy to treat 1 m^3 of water (Friedrich, 2002; Mo et al., 2011; Racoviceanu et al., 2007). Recycled water or imported water needs 3–18 MJ/m^3 of energy (Lyons et al., 2009; Stokes and Horvath, 2009), while the number for desalinated water is 42 MJ/m^3 (Stokes and Horvath, 2009). The reduction of energy consumption is accompanied by a decrease of greenhouse gas emissions. According to Stokes and Horvath (2009), 60.7 g of CO_2 is emitted for each 1 MJ of energy consumed in the process of producing and distributing imported water.

With rapid urbanization, new water plants and supply systems must be constructed to meet the increasing water demand, especially in the developing countries. In some cases when insufficient source water is available, long distance water transfer projects, such as the South-to-North Water Diversion Project in China, are required, which inevitably cause significant impacts. However, if the water leakage from the existing water distribution systems is reduced, the need to expand the water supply may be alleviated.

Besides the direct and associated benefits, water leakage control can create more jobs in pipe leakage detection, pipe maintenance, pressure regulation, and the related device design and manufacturing. From this aspect, water leakage control can stimulate economic growth and promote social interests. This point has been justified by a newly released report from United Nations Environment Programme, which states that a sustainable urban water infrastructure can boost economic growth and social stability in addition to environmental protection (Swilling et al., 2013).

Although the effects of water leakage control on water savings (Sun and Chen, 2012) and energy reduction for sustainable urban development (Dzidic and Green, 2012) have been appreciated, a precise quantification is still lacking. It is important to use life cycle analyses to establish a method to parameterize these values so as to persuade the policy makers and the public to invest in water leakage control.

4.2 Outlook of water leakage control

The current water leakage control actions are relatively comprehensive. There is still, however, great room for improvement. With respect to pipe break prediction, many models in the previous studies were developed to describe pipe break behaviors. These models are either weak at explaining the mechanism for pipe breaks (statistical models) or hard to implement in large-scale pipe networks (physically based models). Therefore, there is a need to bridge the two types of models in further studies. Besides, the existing models are usually case-specific; so that one model working well in a given pipe network may fail in another. Development of generic models should be emphasized in the future. Although some authors have made the attempt (Savic et al., 2009), it is still worthwhile to move forward by using more data from different cases.

In pipe leakage detection, low-cost devices with high accuracy should be invented because high cost is a big barrier for many water utilities for the use of efficient leakage detection devices at a large scale. The same situation applies for pressure control equipment. For pipe rehabilitation, the benefits and costs of different kinds of rehabilitation techniques need to be studied in the future to help the stakeholders make economically optimal pipe rehabilitation plans. With respect to pressure management, pressure is mostly regulated by PRVs nowadays. The mechanism of PRV-based pressure control is that a local energy loss is generated at the PRVs, which implies that the energy for pumping the water is not really saved. Therefore, there is a potential to further reduce the water leakage and energy consumption in water distribution networks by lowering the redundant water pressure at the pumping station. By combining PRVs and pump regulation, a two-level water pressure management scheme can be designed. The first level is large-zone pressure management regulating the pumps, and the second level is pressure reduction at the inlet of DMAs using PRVs.

Finally, decision support systems are required to support the water utilities to manage their pipe networks and improve their work efficiency. Although there are several such systems available (Li et al., 2011; Matthews et al., 2011; Stone et al., 2002), they should be updated in time when innovative water leakage control methods are available.

5 Conclusions

Water leakage control in distribution systems is essential to sustainable urban development. Although many measures are available for leakage management, there is still great room for improvement; in particular the development and application of more reliable pipe break prediction models in leakage monitoring, the invention of low cost leakage detection and pressure regulation devices, optimization of pipe maintenance strategies, and establishment of updated decision support systems. Sustainable urban development will be benefited not only by the water savings, but also by the associated reduction of energy consumption and greenhouse gas emissions. Precise quantification of these benefits should be emphasized in the future.

Acknowledgments

This work was supported by the National Natural Sciences Foundation of China (No. 51309216) and the Ministry of Sciences and Technology of the People's Republic of China (No. 2012ZX07408-002).

REFERENCES

Alkasseh, J.M., Adlan, M.N., Abustan, I., Aziz, H.A., Hanif, A.B.M., 2013. Applying minimum night flow to estimate water loss using statistical modeling: A case study in Kinta Valley, Malaysia. Water Resour. Manage. 27, 1439–1455.

Araujo, L., Ramos, H., Coelho, S., 2006. Pressure control for leakage minimisation in water distribution systems management. Water Resour. Manage. 20(1), 133–149.

Babbitt, H.E., 1920. The detection of leaks in underground pipes. J. Am. Water Works Ass. 7, 589–595.

Berardi, L., Kapelan, Z., Giustolisi, O., Savic, D.A., 2008. Development of pipe deterioration models for water distribution systems using EPR. J. Hydroinform. 10(3), 113–126.

Buchberger, S., Nadimpalli, G., 2004. Leak estimation in water distribution systems by statistical analysis of flow readings. J. Water Resour. Plann. Manage. 130(4), 321–329.

Colombo, A.F., Lee, P., Karney, B.W., 2009. A selective literature review of transient-based leak detection methods. J. Hydro. Environ. Res. 2(4), 212–227.

Coombes, P.J., Argue, J.R., Kuczera, G., 2000. Figtree Place: A case study in water sensitive urban development (WSUD). Urban Water J. 1(4), 335–343.

De Oliveira, D.P., Garrett Jr, J.H., Soibelman, L., 2010. A density-based spatial clustering approach for defining local indicators of drinking water distribution pipe breakage. Adv. Eng. Inform. 25(2), 380–389.

Delli Priscoli, J., 2000. Water and civilization: Using history to reframe water policy debates and to build a new ecological realism. Water Policy. 1(6), 623–636.

Dridi, L., Mailhot, A., Parizeau, M., Villeneuve, J.P., 2009. Multiobjective approach for pipe replacement based on bayesian inference of break model parameters. J. Water Resour. Plann. Manage. 135(5), 344–354.

Du, N., Ottens, H., Sliuzas, R., 2010. Spatial impact of urban expansion on surface water bodies–A case study of Wuhan, China. Landsc. Urban Plann. 94(3), 175–185.

Dzidic, P., Green, M., 2012. Outdoing the Joneses: Understanding community acceptance of an alternative water supply scheme and sustainable urban design. Landsc. Urban Plann. 105(3), 266–273.

Farley, M., Trow, S., 2003. Losses in water distribution networks: A practitioner's guide to assessment, monitoring and control. IWA, London, UK.

Farley, M., Wyeth, G., Ghazali, Z.B.M., Istandar, A., Singh, S., 2008. The manager's non-revenue water handbook: a guide to understanding water losses. Ranhill Utilities Berhad and the United States Agency for International Developement, Bangkok, Thailand.

Ferguson, B.C., Frantzeskaki, N., Brown, R.R., 2013. A strategic program for transitioning to a water sensitive city. Landsc. Urban Plann. 117, 32–45.

Fragiadakis, M., Christodoulou, S.E., Vamvatsikos, D., 2013. Reliability assessment of urban water distribution networks under seismic loads. Water Resour. Manage. 27(10), 3739–3764.

Friedrich, E., 2002. Life-cycle assessment as an environmental management tool in the production of potable water. Water Sci. Technol. 46(9), 29–36.

Girard, M., Stewart, R.A., 2007. Implementation of pressure and leakage management strategies on the Gold Coast, Australia: Case study. J. Water Resour. Plann. Manage. 133(3), 210–217.

Guo, X.L., Yang, K.L., Li, F.T., Wang, T., 2012. Analysis of first transient pressure oscillation for leak detection in a single pipeline. J. Hydrodyn. Ser. B 24(3), 363–370.

Halhal, D., Walters, G.A., Ouazar, D., Savic, D.A., 1997. Water network rehabilitation with structured messy genetic algorithm. J. Water Resour. Plann. Manage. 123(3), 137–146.

Ho, C.I., Lin, M.D., Lo, S.L., 2010. Use of a GIS-based hybrid artificial neural network to prioritize the order of pipe replacement in a water distribution network. Environ. Monit. Assess. 166(1), 177–189.

James, K., Campbell, S.L., Godlove, C.E., 2002. Watergy: Taking advantage of untapped energy and water efficiency opportunities in municipal water systems. Alliance to Save Energy, Washington DC, USA.

Kapelan, Z.S., Savic, D.A., Walters, G.A., 2003. A hybrid inverse transient model for leakage detection and roughness calibration in pipe networks. J. Hydraul. Res. 41(5), 481–492.

Kettler, A.J., Goulter, I.C., 1985. An analysis of pipe breakage in urban water distribution networks. Can. J. Civil Eng. 12(2), 286–293.

Kleiner, Y., Adams, B.J., Rogers, J.S., 1998. Selection and scheduling of rehabilitation alternatives for water distribution systems. Water Resour. Res. 34(8), 2053–2061.

Kleiner, Y., Rajani, B., 2002. Forecasting variations and trends in water-main breaks. J. Infrastruct. Syst. 8(4), 122–131.

Lambert, A., 2001. What do we know about pressure/leakage relationships in distribution systems. In: Proceedings of IWA Specialised Conference: System Approach to Leakage Control and Water Distribution Systems Management, Brno, Czech Republic. May 16–18.

Lambert, A., Thornton, J., 2011. The relationships between pressure and bursts - A 'state-of-the-art update'. Water 21. April 2011, 37–38.

Le Gat, Y., Eisenbeis, P., 2000. Using maintenance records to forecast failures in water networks. Urban Water J. 2(3), 173–181.

Lee, S.W., Hwang, S.J., Lee, S.B., Hwang, H.S., Sung, H.C., 2009.

Landscape ecological approach to the relationships of land use patterns in watersheds to water quality characteristics. Landsc. Urban Plann. 92(2), 80–89.

Li, W.F., Ling, W.C., Liu, S.X., Zhao, J., Liu, R.P., Chen, Q.W., et al., 2011. Development of systems for detection, early warning, and control of pipeline leakage in drinking water distribution: A case study. J. Environ. Sci. 23(11), 1816–1822.

Liu, Z., Sadiq, R., Rajani, B., Najjaran, H., 2010. Exploring the relationship between soil properties and deterioration of metallic pipes using predictive data mining methods. J. Comput. Civil Eng. 24(3), 289–301.

Luong, H.T., Fujiwara, O., 2002. Fund allocation model for pipe repair maintenance in water distribution networks. Eur. J. Oper. Res. 136(2), 403–421.

Luong, H.T., Nagarur, N.N., 2005. Optimal maintenance policy and fund allocation in water distribution networks. J. Water Resour. Plann. Manage. 131(4), 299–306.

Lyons, E., Zhang, P., Benn, T., Sharif, F., Li, K., Crittenden, J., et al., 2009. Life cycle assessment of three water supply systems: importation, reclamation and desalination. Water Sci. Technol. 9(4), 439–448.

Marinoni, O., Higgins, A., Coad, P., Garcia, J.N., 2013. Directing urban development to the right places: Assessing the impact of urban development on water quality in an estuarine environment. Landsc. Urban Plann. 113, 62–77.

Marunga, A., Hoko, Z., Kaseke, E., 2006. Pressure management as a leakage reduction and water demand management tool: The case of the City of Mutare, Zimbabwe. Phys. Chem. Earth 31(15-16), 763–770.

Matthews, J., Condit, W., McKim, R., 2011. Decision support for renewal of wastewater collection and water distribution systems. US Environmental Protection Agency.

Misiunas, D., Vtkovsk, J., Olsson, G., Simpson, A., Lambert, M., 2005. Pipeline break detection using pressure transient monitoring. J. Water Resour. Plann. Manage. 131(4), 316–325.

Mo, W.W., Zhang, Q., Mihelcic, J.R., Hokanson, D.R., 2011. Embodied energy comparison of surface water and groundwater supply options. Water Res. 45(17), 5577–5586.

Morison, P.J., Brown, R.R., 2011. Understanding the nature of publics and local policy commitment to Water Sensitive Urban Design. Landsc. Urban Plann. 99(2), 83–92.

Mutikanga, H., Sharma, S., Vairavamoorthy, K., 2013. Methods and tools for managing losses in water distribution systems. J. Water Resour. Plann. Manage. 139(2), 166–174.

Park, S.W., Loganathan, G.V., 2002. Methodology for economically optimal replacement of pipes in water distribution systems: 1. Theory. KSCE J. Civ. Eng. 6(4), 539–543.

Racoviceanu, A.I., Karney, B.W., Kennedy, C.A., Colombo, A.F., 2007. Life-cycle energy use and greenhouse gas emissions inventory for water treatment systems. J. Infrastruct. Syst. 13(4), 261–270.

Rajani, B., Kleiner, Y., 2013. External and internal corrosion of large-diameter cast iron mains. J. Infrastruct. Syst. 19(4), 486–495.

Rajani, B., Makar, J., McDonald, S., Zhan, C., Kuraoka, S., Jen, C.K., Viens, M., 2000. Investigation of grey cast iron water mains to develop a methodology for estimating service life. American Water Works Association Research Foundation, Denver, Colo.

Savic, D.A., Giustolisi, O., Laucelli, D., 2009. Asset deterioration analysis using multi-utility data and multi-objective data mining. J. Hydroinform. 11(3-4), 211–224.

Shamir, U., Howard, C., 1979. An analytical approach to scheduling pipe replacement. J. Am. Water Works Ass. 71(5), 248–258.

Soriano, R.N., Ramos, R.U., Padua, R.C., 2012. Introduction to Maynilad pressure management program. In: Proceedings of Water Loss 2012, Manila, Philippines. Feb 26–29

Stokes, J.R., Horvath, A., 2009. Energy and air emission effects of water supply. Environ. Sci. Technol. 43(8), 2680–2687.

Stone, S.L., Dzuray, E.J., Meisegeier, D., Dahlborg, A., Erickson, M., Tafuri, A.N., 2002. Decision-support tools for predicting the performance of water distribution and wastewater collection systems. US Environmental Protection Agency.

Sun, R.H., Chen, L.D., 2012. How can urban water bodies be designed for climate adaptation? Landsc. Urban Plann. 105(1), 27–33.

Swilling, M., Robinson, B., Marvin, S., Hodson, M., 2013. City-Level Decoupling: Urban resource flows and the governace of infrastructure transitions. United Nations Environment Programme.

Thornton, J., Lambert, A., 2005. Progress in practical prediction of pressure: leakage, pressure: burst frequency and pressure: consumption relationships. In: Proceedings of IWA Special Conference: Leakage 2005, Halifax, Nova Scotia, Canada. Sep 12–14.

Thornton, J., Lambert, A., 2006. Managing pressure to reduce new breaks. Water 21. December 2006, 24–26.

Thronton, J., 2003. Managing leakage by managing pressure: A practical approach. Water 21. October 2003, 43–44.

Vítkovský, J.P., Lambert, M.F., Simpson, A.R., Liggett, J.A., 2007. Experimental observation and analysis of inverse transients for pipeline leak detection. J. Water Resour. Plann. Manage. 133(6), 519–530.

Van Thienen, P., 2013. A method for quantitative discrimination in flow pattern evolution of water distribution supply areas with interpretation in terms of demand and leakage. J. Hydroinform. 15(1), 86–102.

Walski, T.M., Pelliccia, A., 1982. Economic analysis of water main breaks. J. Am. Water Works Ass. 74(3), 140–147.

Wang, X.J., Lambert, M.F., Simpson, A.R., Liggett, J.A., Vtkovský, J.P., 2002. Leak detection in pipelines using the damping of fluid transients. J. Hydraul. Eng. 128(7), 697–711.

Watson, T.G., 2005. A hierarchical Bayesian model and simulation software for the maintenance of water pipe networks. PhD Thesis. University of Auckland, Auckland, New Zealand.

Wong, T., Brown, R., 2009. The water sensitive city: Principles for practice. Water Sci. Technol. 60(3), 673–682.

Wu, Z.Y., 2009. Unified parameter optimisation approach for leakage detection and extended-period simulation model calibration. Urban Water J. 6(1), 53–67.

Wu, Z.Y., Sage, P., 2006. Water loss detection via genetic algorithm optimization-based model calibration. In: Proceedings of ASCE 8th Annual International Symposium on Water Distribution Systems Analysis, Cincinnati, Ohio, U.S. Aug 27–30.

Xu, Q., Chen, Q.W., Li, W.F., 2011. Application of genetic programming to modeling pipe failures in water distribution systems. J. Hydroinform. 13(3), 419–428.

Xu, Q., Chen, Q.W., Ma, J.F., Blanckaert, K., 2013. Optimal pipe replacement strategy based on break rate prediction through genetic programming for water distribution network. J. Hydro. Environ. Res. 7(2), 134–140.

JOURNAL OF ENVIRONMENTAL SCIENCES

环境科学学报(英文版)

(http://www.jesc.ac.cn)

Aims and scope

Journal of Environmental Sciences is an international academic journal supervised by Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. The journal publishes original, peer-reviewed innovative research and valuable findings in environmental sciences. The types of articles published are research article, critical review, rapid communications, and special issues.

The scope of the journal embraces the treatment processes for natural groundwater, municipal, agricultural and industrial water and wastewaters; physical and chemical methods for limitation of pollutants emission into the atmospheric environment; chemical and biological and phytoremediation of contaminated soil; fate and transport of pollutants in environments; toxicological effects of terrorist chemical release on the natural environment and human health; development of environmental catalysts and materials.

For subscription to electronic edition

Elsevier is responsible for subscription of the journal. Please subscribe to the journal via http://www.elsevier.com/locate/jes.

For subscription to print edition

China: Please contact the customer service, Science Press, 16 Donghuangchenggen North Street, Beijing 100717, China. Tel: +86-10-64017032; E-mail: journal@mail.sciencep.com, or the local post office throughout China (domestic postcode: 2-580).

Outside China: Please order the journal from the Elsevier Customer Service Department at the Regional Sales Office nearest you.

Submission declaration

Submission of an article implies that the work described has not been published previously (except in the form of an abstract or as part of a published lecture or academic thesis), that it is not under consideration for publication elsewhere. The submission should be approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out. If the manuscript accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

Submission declaration

Submission of the work described has not been published previously (except in the form of an abstract or as part of a published lecture or academic thesis), that it is not under consideration for publication elsewhere. The publication should be approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out. If the manuscript accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

Editorial

Authors should submit manuscript online at http://www.jesc.ac.cn. In case of queries, please contact editorial office, Tel: +86-10-62920553, E-mail: jesc@263.net, jesc@rcees.ac.cn. Instruction to authors is available at http://www.jesc.ac.cn.

Journal of Environmental Sciences (Established in 1989)

Vol. 26 No. 5 2014

Supervised by	Chinese Academy of Sciences	**Published by**	Science Press, Beijing, China
Sponsored by	Research Center for Eco-Environmental		Elsevier Limited, The Netherlands
	Sciences, Chinese Academy of Sciences	**Distributed by**	
Edited by	Editorial Office of Journal of	Domestic	Science Press, 16 Donghuangchenggen
	Environmental Sciences		North Street, Beijing 100717, China
	P. O. Box 2871, Beijing 100085, China		Local Post Offices through China
	Tel: 86-10-62920553; http://www.jesc.ac.cn	Foreign	Elsevier Limited
	E-mail: jesc@263.net, jesc@rcees.ac.cn		http://www.elsevier.com/locate/jes
Editor-in-chief	Hongxiao Tang	**Printed by**	Beijing Beilin Printing House, 100083, China

CN 11-2629/X **Domestic postcode: 2-580** **Domestic price per issue RMB ¥ 110.00**

ISSN 1001-0742

9 771001 074147 05>