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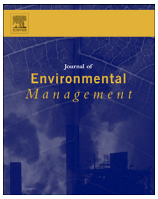

Review

Energy and water quality management systems for water utility's operations: A review

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ABSTRACT

Holistic management of water and energy resources is critical for water utilities facing increasing energy prices, water supply shortage and stringent regulatory requirements. In the early 1990s, the concept of an integrated Energy and Water Quality Management System (EWQMS) was developed as an operational optimization framework for solving water quality, water supply and energy management problems simultaneously. Approximately twenty water utilities have implemented an EWQMS by interfacing commercial or in–house software optimization programs with existing control systems. For utilities with an installed EWQMS, operating cost savings of 8–15% have been reported due to higher use of cheaper tariff periods and better operating efficiencies, resulting in the reduction in energy consumption of ~6–9%. This review provides the current state-of-knowledge on EWQMS typical structural features and operational strategies and benefits and drawbacks are analyzed. The review also highlights the challenges encountered during installation and implementation of EWQMS and identifies the knowledge gaps that should motivate new research efforts.

1. Introduction

The water and energy sectors are being inextricably linked through a co-dependent and complex relation of mutual exchange of resources often referred as the Water-Energy Nexus (Raucher et al., 2008). High volumes of water are required to generate energy and conversely, water abstraction, treatment and distribution are highly energy-intensive processes [Rothausen and Conway, 2011; Griffiths-Sattenspiel and Wilson, 2009]. Water and energy are critical resources, and their integrated management can provide important economic and environmental benefits in both sectors [Wilkinson, 2008; Kanakoudis et al., 2012].

Over the past several decades, water organizations have been challenged by new stringent regulatory requirements, increasing energy costs and demands, and decreased availability of high quality source water [Sovacool and Sovacool, 2009]. As freshwater becomes scarce, more energy is required to extract water from aquifers, process saline water into potable drinking water and deliver freshwater over long distances [Wilkinson, 2008].

Water utilities have become increasingly energy intensive and responsible for an approximate 3% share of U.S. annual electricity consumption, which increase to as high as 13% when residential water use is included [Boulos and Bros, 2010; U.S. EPA, 2012; Sanders and Webber, 2012]. Future projections estimate this percentage to double to 6% due to higher water demand and more energy intensive treatment processes [Chaudhry and Shrier, 2010]. Estimates indicate that approximately 90% of the electricity purchased by U.S. water utilities, US$10 billion per year, is required for pumping water through the various stages of extraction, treatment, and final distribution to consumers [Bunn, 2011; Skeens et al., 2009]. Further, the energy use in water utilities, with the exclusion of energy use for water heating by residential and commercial users, contributes significantly to an increasing carbon footprint with an estimated 45 million tons of greenhouse gas (GHGs) emitted annually in U.S. into the atmosphere [Griffiths-Sattenspiel and Wilson, 2009; Wallis et al., 2008; Kanakoudis, 2014].

In anticipation of federal and state legislation that may impact future GHG emissions from water facilities, it is important that

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energy management practices become an integral part of effective water utility management. Current management strategies, often, pose complex coordination issues between energy savings, water quality concerns, and operational and maintenance issues [Barry, 2007; Jentgen et al., 2003]. For water utilities, source supply and distribution systems control and operations have typically followed consumption [Jentgen et al., 2003] and have mostly aimed to solely achieve water quality goals with less attention oriented towards energy costs and carbon footprint reduction [Bunn and Hillebrand, 2008; Kanakoudis and Gonelas, 2014]. Recently, smart water grid concepts have been developed to enable better management of the water network by leakage and pressure management, capital spending optimization, streamlined water quality monitoring, and network operations and maintenance, however without addressing energy management issues.

The concept of an integrated Energy and Water Quality Management System (EWQMS) was introduced in the early ‘90s to provide water utilities with the foundation for a systems control management tool for simultaneously achieving energy efficiency and water quality objectives [Jentgen et al., 2003]. An EWQMS is a collection of individual application software programs, user–developed or commercially available, that allow the implementation of an array of energy cost reduction strategies operating within designated constraints. Real–time communications with pre–existing SCADA (Supervisory Control and Data Acquisition) systems allow the EWQMS software to monitor and proactively provide recommendations regarding system operation (e.g., pumping, storage tank turnover, etc.) based on time–of–day electrical use and associated tariff, forecasted demand and pump scheduling [Barnett et al., 2004].

Two decades after the EWQMS concept was first introduced, approximately twenty drinking water utilities across the world (US, New Zealand, Canada, Australia, South Korea) have installed the EWQMS architecture at their facilities, confirming an increasing interest in EWQMS as energy prices and demand continue to increase [Badruzzaman et al., 2014].

Although design and implementation of this platform are characterized by numerous challenges, EWQMS provides a number of economic, environmental and operational benefits, such in more effective risk management for maintenance of water quality objectives and favorable cost–benefit solutions. Utilities with installed EWQMS have opportunities to better manage their water supply portfolios and their local water resources. EWQMS can be employed as a system simulator for decision making that assists engineers and planners in understanding the impact of water demand patterns and energy market profiles on their water resources management. EWQMS also assists water utilities in monitoring the water balance, identifying water losses in the distribution systems, thus reducing overall water consumption. Water leakage from aging infrastructure poses a challenge for water supplies, particularly in areas that are struggling to support the growing demand [Kanakoudis et al., 2013a; Kanakoudis et al., 2014]. The daily water loss through leakage, which is estimated to represent about 40%–50% of the total daily water consumption [Tucciarelli et al., 1999], is associated to the waste of a large amount of energy [Nasirian et al., 2013].

To date, there is no comprehensive review paper on EWQMS in the peer–reviewed literature; there exists only sparse and fragmented documentation of EWQMS practices within the water industry. Because this field of study and implementation is growing rapidly, a review of the various aspects of EWQMS is warranted. Thus, this review aims to collectively integrate the fundamental concepts of energy, water demand and supply, and water resources management to provide a more perspicuous understanding of the structure of the EWQMS platform at drinking water utilities. The specific objectives of this review are to:

- Discuss the historical development and modules of EWQMS;
- Assess the major optimization strategies for EWQMS operation;
- Illustrate typical mathematical models used for the system optimization;
- Identify the benefits of EWQMS installation at selected water utilities;
- Analyze the challenges encountered by water utilities during EWQMS implementation and operation; and
- Identify the knowledge gaps and future research needs for more effective EWQMS practices.

2. Historical development and structure of EWQMS

2.1. Historical development of EWQMS

Pump energy management systems have been investigated by the water industry and academic researchers for more than two decades. In the early 1990s, the AWWA Research Foundation, Electric Power Research Institute's Community Environmental Center and the East Bay Municipal Utility District (California, US) (EBMUD) funded the first EWQMS project in the U.S. [Morley et al., 2009] and outlined the key components of a practical EWQMS for water facilities. In 1996, a group of water and electric utilities, academics and consulting engineers began developing the functional specifications of a more formalized EWQMS prototype followed by the software installation at EBMUD. However, the difficulties encountered during the implementation required additional research efforts. In 2003, Colorado Springs Utilities developed an off–line EWQMS by building on the lessons learned from the EBMUD prototype, creating a customized Operations Planning Scheduler and related organizational processes [Jentgen et al., 2003]. This off–line study demonstrated the feasibility of an EWQMS for control of the system's daily operations. In the years 2000–2004, the installation of commercially developed software at Wellington (New Zealand) and EBMUD were the first of several EWQMS implementations at other water utilities across the world (e.g., UK, Canada, Australia, Korea), as shown in Fig. 1.

Both commercial software and research–grade optimization techniques from various academic efforts have been developed over the years. Finesse [Rance et al., 2001], POWADIMA [Salomons et al., 2007], and Neptune [Morley et al., 2009] are software applications principally developed with government (e.g., European Union) and water industry funding. These efforts focused on developing suitable algorithms for management of real, complex water supply systems by undertaking proof of concept studies using either off-line post processing or limited on-line real time control. Few academic software applications have been used for full-scale operation of major supply systems. However, commercial software suppliers, such as Derceto's Aquadapt, have achieved some success with real, extended operational examples [Derceto, 2013]. In addition to Derceto's Aquadapt, Schneider Electric's Aquis, Tynemarch's MISER–PSL [Fowler and Main, 2010; Woodward and Fowler, 2011] and Innovyze's IWLive [Innovyze, Inc., 2013] are other commercial software products that are marketed as EWQMS packages that typically interface with commercial hydraulic models. These products use different programming options to optimize pump scheduling. While Project Neptune pump optimization is formulated on Model Predictive Control, MISER-PSL, Aquadapt and Aquis employ linear, mixed integer linear and dynamic programming respectively to control pump operations (Skworcow et al., 2009; Fowler and Main, 2010; Derceto, 2013). BalanceNet, an add-on module of IWLive, overcomes the problem