Chapter 1

Introduction

1.1 General

Water is considered as synonymous with life as it is the most essential ingredient for survival. To cater various human needs due to overpopulation, industrial and irrigation demand overexploitation of this precious water resource has resulted into a scarce commodity today. At the same time its quality is being deteriorated due to polluted sources. It is very essential to provide the safe water free from pathogenic organisms for urban and rural drinking water requirement. But unfortunately in many developing countries safe drinking water is not available for human consumption and poor water quality is one of the causes of increasing health problem. In order to ensure the safe drinking water for all, it is a prime requirement to manage this valuable natural resource from both the aspect of quantity and quality for the sustainable development. Thus, the prime objective of any Drinking water distribution system (DWDS) is to make water available to all consumers in proper quantity ,pressure and with acceptable quality in terms of flavour, odour, and appearance and free from microbial contamination to safeguard the community against waterborne diseases. The quality of drinking water supplied to consumers depends on quality of raw water, application of appropriate treatment technology/disinfection, and monitoring of treated water within the water distribution system network. When clean and pure water leaves the treatment facility, it can be degraded due to chemical and biological transformations that take place within the distribution system. Disinfectant like chlorine can decay and may generate harmful side effects as its reaction with natural organic matter (NOM) results in harmful disinfection by-products (DBP), some of which are potential carcinogens (USEPA 2005). Drinking water utilities in throughout the world face the challenge of providing water of good quality to their consumers as significant water quality changes can occur within drinking water distribution systems. These changes can make it challenging for water utilities to provide expected levels of service and to comply with regulatory requirements & to maintain a desired disinfectant residual (0.2 mg/L as per IS 10500 – 2012) in DWDS. Although water may look safe, it may be impure and contain microorganisms that cause waterborne diseases like cholera, dysentery, typhoid fever, hepatitis-A etc. Therefore it is very essential for any water supply authority to manage the chlorine disinfection within lower and upper limits of residual chlorine to safeguard the consumers from water borne diseases and harmful disinfection by products (DBPs) simultaneously.

The present study aims to implement the advanced methods of water quality modelling and optimization methods for water quality management with specific focus on management of chlorine disinfection in drinking water distribution system (DWDS). The optimization methods such as linear programming (LP) and particle swarm optimization (PSO) are used to couple the water quality model for scheduling and managing optimum level of chlorine mass rate application to maintain it between the lower and upper limit of residual chlorine within DWDS. Further the study is extended for the optimal location and selection of number of booster stations to check the effectiveness of booster chlorination approach to justify its use for the crucial task of protecting water from microbial contamination by managing sufficient level of chlorine at the same time limiting the harmful DBP in the drinking water distribution system (DWDS). Impulse response coefficients obtained from simulation model is used to develop the impact matrix for rapid estimation of impact of chlorine injection at various locations. The cost analysis is carried out to check the economic feasibility of installing the booster stations.

1.2 Chlorine Disinfection

Drinking water treatment plays an important role in maintaining public health. Disinfection of drinking water is considered to be one of the major public health advances of the 20^{th} century. The successful application of chlorine as a disinfectant was first demonstrated in England. In 1908, Jersey City (NJ) initiated the use of chlorine for water disinfection in the U.S. This approach subsequently spread to other locations, and soon the rates of common epidemics such as typhoid and cholera dropped dramatically. Today, disinfection is an essential part of a drinking water treatment train. Chlorine, chlorine dioxide, and chloramines are most often used because they are very effective disinfectants, and residual concentrations can be maintained in the water distribution system (USEPA 2005). Chlorine, dissolved in liquid, is one of the most effective and economical germ-killers for the treatment of water to make it potable or safe to drink. Chlorine’s powerful disinfectant qualities come from its ability to bond with and destroy the outer surfaces of bacteria and viruses. Drinking water chlorination is one of the most widely used methods to safeguard drinking water supplies. Due to reactive nature of chlorine the chlorine decay takes place as the time passes which may be critical while using less dose of chlorine applied as source chlorination alone. To compensate the losses due to chlorine decay if higher doses are applied it results in harmful disinfection by-product formations.

1.2.1 Chlorine Decay

Once water has exited the treatment plant and entered the distribution system, it cannot be assumed that the chlorine residual will remain constant. As chlorine is reactive, it reacts with natural organic and inorganic matter in water which decreases the chlorine concentration with time called chlorine decay (Males et al. 1988; Rossman et al. 1994; Clark et al. 1994, 1995,1996; Boccelli & Try by 2003; Courties et al. 2009). Chlorine residual will decay "naturally" within the system as a result of reaction of chlorine with materials in or on the pipe wall. This can be either the pipe material itself or bio films or sediment at the pipe surface. This loss of disinfectant residual can weaken the barrier against microbial contamination which can occur within the distribution system. To guarantee the water supply system's disinfection, we need certain residual concentration of disinfectant to prevent recontamination by pathogenic or indicator micro-organisms, which can originate in the bio film formed inside the system, as well as in negative pressure areas (created by pipe cracks, fissures, etc.). Controlling and maintaining chlorine residual within DWDS can be challenging due to chlorine decay. In India as per IS 10500- 2012, the minimum residual chlorine to be maintained at the consumer's end is 0.2 mg/L to ensure the microbial free water. To maintain this minimum residual chlorine at locations in DWDS, the source concentration of chlorine is kept high which results in many problems.

1.2.2 Problems Associated with Excess Chlorination

The application of disinfection agents to drinking water reduces the microbial risk but the excess chlorination to compensate the losses due to chlorine decay results in taste and odour problems. As chlorine is a strong oxidizer, it reacts with a wide range of chemicals and naturally occurring organic (and/or inorganic) matter (NOM) in the treated and/or distributed water to form potentially harmful Disinfection by-products (DBPs). More than 250 different types of DBPs have already been identified (Sadiq & Rodriguez 2004). Some of these DBPs have cancer risks as well as other acute and chronic effects to human health. Toxicological and epidemiological studies have characterized the effects of approximately thirty DBPs to human and animal health (Chowdhury et al 2009)

DBPs can be controlled by several means, by modifying the chlorination strategy, changing disinfectants, lowering mass rate of chlorine application or removing the DBP itself. Because DBPs are difficult to remove once they are formed, control strategies typically focus on the first three methods. The modification in chlorine application strategy by application of booster chlorination may be one of the options to control the harmful disinfection by products.

Carrico & Singer (2009) stated that the THM formation can be modelled solely as a function of chlorine decay (Clark 1998; Clark & Sivaganesan 1998). Boccelli et al. (2003) tested the relationship between THM formation and chlorine consumption from model predictions and experimental data under various chlorination scenarios, observes a strong linear relationship between THM formation and chlorine decay. Thus if we reduce the mass rate of chlorine within lower limit of residual chlorine the less reaction of chlorine will automatically results in less formation of DBP. To cope up with DBP problems water supply authorities may target to minimize the less mass rate of chlorine application and booster chlorination approach.

The management of residual chlorine and DBP using mathematical Modelling coupled with optimization technique is very essential to correctly design new systems or make changes in existing ones to maintain a desired level of residual chlorine to avoid recontamination in distribution system. Booster Chlorination strategies may help to balance between Chlorine residual and DBP formation.

1.3 Booster Chlorination

Due to the large size of the water distribution systems, and physical, chemical and biological reactions in pipes, the disinfectants usually run out before reaching the far ends of the network (Powell et al. 2000 a, b; Hallam et al. 2002; Boccelli et al. 2003; Meng et al. 2013). Breakthrough of organisms increases if inadequate chlorine residual is found (less than 0.2 mg/L as per IS 10500-2012) in drinking water distribution system. This can ultimately result in public health and regulatory compliance problems. But maintaining sufficient residual, especially in outlying areas of a system, often presents major difficulties for water utilities. In conventional methods utilities simply increase underground sump’s chlorination to meet the demand of chlorine at the farthest point of distribution network. But this can generate higher disinfection by products (DBPs), plus bring odour and taste complaints. Due to chlorine decay it is very difficult to maintain a desired residual chlorine concentration at all the consumer’s nodes if less chlorine is supplied in storage reservoirs. To overcome the conditions of imbalance in maintaining the desired residual chlorine can be achieved by applying the strategy called booster chlorination to maintain the balance between lower and upper limit of the residual chlorine concentration. Booster chlorination is the application of disinfectant at strategic locations within the distribution system to compensate for the losses that occur as it decays over time. It helps to minimize the dosage required to maintain chlorine residuals throughout the distribution network, reduction in DBP formation and more even distribution of disinfectant concentration. The booster chlorination strategy allows the water utilities to meet disinfection goals by providing proper balance between the minimum and maximum concentration of chlorine (Boccelli et al. 1998; Tryby et al. 2002; Carrico & Singer 2009). The use of advanced method of water quality modelling is useful tool for the prediction of residual chlorine in DWDS for maintaining the desired level of chlorine at all the locations of DWDS. The coupling of such water quality model with advanced optimization methods can serve as an important decision support model for the water supply authority for scheduling and mass rate application of chlorine at storage reservoir for maintaining chlorine with range in DWDS at all the nodes.

1.4 Need for Water Quality Modelling

Maintaining water quality in a drinking water distribution system while assuring adequate disinfection and reducing DBPs is a significant challenge for many drinking water utilities. Research are being conducted to explore the feasibility of employing "targeted" distribution system treatment systems to manage the chlorine disinfection in conjunction with a water quality/hydraulic model which would be used to predict the residual chlorine at various locations of the distribution system. The alternate chlorine application strategy such as booster chlorination can be applied based on model predictions to locations where violations are likely to occur in maintaining the desired level of residual chlorine. Nowadays water distribution system models have become widely accepted within the water utility industry as a mechanism for simulating the hydraulic and water quality behaviour in water distribution system networks. Water distribution system models are used to replicate the behaviour of a real or proposed system by simulating the hydraulic and water quality behaviour in water distribution system network. Early network models were used to simulate only steady-state hydraulic behaviour. In the 1970s, modelling capability was expanded to include extended period simulation (EPS) models that could accommodate time-varying demand and operations. In the early 1980s, water quality modelling developed to incorporate water quality simulation capability. By mid 1980s, water quality models were developed to incorporate the dynamic behaviour of water network. (Grayman et al. 1988 in USEPA, 2005). The usability of these models was greatly improved in the 1990s with the introduction of the public domain EPANET model (Rossman 2000) and other Windows-based commercial water distribution system models. The costs associated with constructing and maintaining a distribution system model may be more easily justified if it is used for a variety of applications by a water utility (Grayman 2000 in USEPA 2005). Hydraulic simulation model computes junction heads and link flows for a fixed set of reservoir levels, tank levels, and water demands over a succession of points in time. Water quality models use the output of hydraulic models in conjunction with additional inputs to predict the temporal and spatial distribution of a variety of constituents like water age, loss rate of chlorine or chloramines, concentration of DBP within a water distribution system. Water quality modelling techniques can be used to identify points in the distribution system that experience long retention times, which can in turn represent locations in the system that may experience chlorine residual loss, excessive formation of DBPs, and the formation of bio films. The coupling of such models with optimization methods can serve as a decision support models (DSM) for managing the chlorine disinfection to determine the optimum location of booster chlorination station along with scheduling and operation of chlorine dose in DWDS.

1.5 Optimization Techniques

Optimization tools allow the user to evaluate a large number of options and to select the specific alternative that gives the best results in terms of predefined objective functions. In the area of water distribution system analysis, optimization models are used for calibration, design, and operational purposes. The most common areas of operation where such models have been applied are in energy management and water quality

Boccelli et al. (1998) was the first who applied the linear superposition theory and linear programming models for optimal scheduling of booster disinfection doses in water distribution systems for minimization of total disinfectant mass. Tryby et al. (2002) extended the linear programming (LP) booster disinfection scheduling model presented by Boccelli et al. (1998) to incorporate booster station location as a decision variable within the optimization process. Propato & Uber (2004 a, b) used optimization techniques to determine optimal location and operation of chlorine booster stations. Munavalli & Kumar (2003) formulated optimal scheduling model in terms of a nonlinear optimization problem to determine the chlorine dosage at the water quality sources using GA approach in which decision variables (chlorine dosage) were coded as binary strings and solved by linking EPANET with a genetic algorithm (GA). Ucaner & Ozdemir (2003) studied, the locations, injection rates and scheduling of chlorine booster stations using genetic algorithms by coupling the hydraulic solution and chlorine concentration distribution using EPANET software. Prasad et al. (2004) investigated the booster facility location and injection scheduling problem formulated as a multi objective genetic algorithm optimization model using the theory of linear super position in water quality modelling for calculating concentration profiles at network nodes. Propato and Uber (2004 a) formulated a linear least-squares problem to determine the optimal disinfectant injection rates that minimize variation in the system residual space-time distribution with assumption of known location of booster stations. Propato and Uber (2004 b) extended their previous work to include the locations of the booster stations as decision variables and formulated a mixed-integer quadratic programming (MIQP) problem to locate booster stations and to identify their dosage schedules for maintaining disinfectant residual in DWDS. Ostfeld & Salomons (2006) presented two different optimization objectives for optimal pump operation and booster disinfection. Gibbs et al. (2010 a) studied the booster disinfection dosing problem, including daily pump scheduling, for a real system in Sydney, Australia using GA to optimize the operation of the Woronora WDS. Kang & Lansey (2010) formulated a real-time optimal valve operation coupled with booster disinfection problem as a single objective optimization model. The problem was solved using a GA linked with EPANET. Ohar & Ostfeld (2010) worked on the chlorine-TTHM multi species model for optimal design and operation of booster chlorination stations. Ohar & Ostfeld (2014) formulated and solved model to set the required chlorination dose of the boosters for delivering water at acceptable residual chlorine and TTHM concentrations for minimizing the overall cost of booster placement, construction, and operation under extended period hydraulic simulation conditions through utilizing a multi-species approach. Thus, the use of coupled simulation optimization model is used by many researchers to maintain the quality of water within DWDS using booster chlorination. The coupled model can serve as a decision support model for managing chlorine disinfection in DWDS. In the present study the coupled simulation –optimization model is developed for the management of chlorine disinfection in DWDS using LP and PSO.

1.6 Motivation for the Study

Water supply authorities must supply the water to the entire distribution system as per the compliance with drinking-water standards. Clark et al (1995) states that various factors that affect water quality in distribution systems include chemical and biological quality of source water; effectiveness and efficiency of treatment processes; adequacy of the treatment facility, storage facilities, and distribution system; age, type, design, and maintenance of the distribution network; and quality of treated water (Clark & Coyle 1990). A factor, infrequently considered, that may influence water quality in a distribution system is the effect of mixing of water from difference sources. Water-distribution systems frequently draw water from multiple sources, such as a combination of wells and/or surface sources. The mixing of waters from different sources takes place within a distribution system and is a function of complex system hydraulics (Clark et al. 1991; Grayman et al. 1988 in USEPA 2005). Distribution systems are frequently designed to ensure hydraulic reliability, which includes adequate water quantity and pressure for fire flow as well as domestic and industrial demand. To meet these goals large amounts of storage are usually incorporated into system design, which results in long residence times, which in turn may contribute to deterioration of water quality.

Maintenance of chlorine or other disinfectant residual is generally considered to be a water-quality goal in most water systems attempt to maintain a detectable residual (0.2 mg/L as per IS 10500, 2012) throughout the distribution system. Before leaving the treatment plant, water is generally chlorinated in a final disinfection step and then stored in a storage tank. When the water is discharged from the storage tank it is transported through the distribution system and home plumbing to the consumer. It is presumed that detectable chlorine residual will minimize the potential for waterborne disease and bio film growth in the system. As dissolved chlorine travels through the pipes in the network it reacts with natural organic matter in the bulk water and with bio film and tubercles on the pipe walls or the pipe wall material itself. This reaction results in a decrease in chlorine residual and a corresponding increase in DBP depending on the residence time in the network pipes and holding time in storage facilities. Understanding these reactions will assist water utility managers in delivering high-quality drinking water and in meeting regulatory requirements (Clark et al. 1995).

Drinking water utilities focused on meeting drinking water standards at the treatment plant, even though the water quality can deteriorate in a distribution system due to chlorine decay and formation of harmful DBP which may be a carcinogen. The modern water treatment must maintain an acceptable balance between the microbial safety of potable water supply and formation of potentially harmful DBP. In order to achieve the optimum balance, it is essential to understand and predict both the formation of DBP and chlorine decay in DWDS. So it is very essential to understand the impact of the distribution system on water quality with special reference to effective management of chlorine disinfection for health aspect of consumers. Water distribution system models have become increasingly accepted within the water utility industry as mechanism for simulating the hydraulic and water quality behaviour in water distribution system network. The water quality models use the output of hydraulic models in conjunction with additional input to predict the temporal and spatial distribution of variety of constituents like water age, residual chlorine and TTHM. The prediction of the residual chlorine by applying such models is very essential for maintaining the quality of water in DWDS. The recent development in optimization methods can provide an opportunity to combine with water quality model prediction of residual chlorine to support decisions for suggesting optimal locations of booster chlorination stations along with scheduling of chlorine injection for maintenance of desired residual chlorine. By selecting appropriate optimization method in conjunction with water distribution model can result in reduction in overall mass rate of chlorine, reduction in cost of chlorine application at the same time assuring the safety of water from waterborne diseases and harmful DBPs. Thus the collective knowledge from this research can be applied to improve the quality of water delivered to the consumer especially from safety point of view of microbial contamination and DBP using booster chlorination strategies.

1.7 Objectives and Scope of Study

The main objective of the present study is to develop the decision support models (DSM) by developing hydraulic and water quality model using EPANET software to predict various hydraulic parameters and residual chlorine at various locations of branch network of DWDS. The model is coupled with optimization methods like linear programming and modern method of optimization such as particle swarm optimization (PSO) for optimal scheduling of mass rate of chlorine application for managing chlorine disinfection within desired range. The optimization model is further used to decide the optimum location and number of booster stations to be installed for efficient management of chorine in DWDS.

The specific objectives and scope of study with water quality concerns of drinking water distribution system of the research study are as follows:

- Development of hydraulic and water quality model for a branch network of DWDS.
- Analysis of hydraulic and water quality parameter (residual chlorine) for field networks.
- Investigation of bulk coefficient of chlorine decay using field measurements.
- Evolving methodology to determine the scheduling of dosing of chlorine in booster chlorination station to maintain desired residual chlorine to protect water against microbial contamination and DBP formation simultaneously.
- Evaluation of proposed booster chlorination system using optimization method for the placement of appropriate locations of booster stations within analysed drinking water distribution network.
- Development of impact matrix for rapid conclusions regarding impact of addition of chlorine on concentration of residual chlorine at various locations in DWDS.
- Development of coupled simulation optimization model for overall management of chlorine disinfection in DWDS.
- Cost analysis to check the economic feasibility of installation of booster stations.

This study will provide a very useful decision support models (DSM) to the water supply managers for effective management of chlorine disinfection in DWDS. It will provide improved tools for decision support system to the water supply managers for the crucial task to maintain balance between lower and upper limits of residual chlorine and DBP formation by managing sufficient level of residual chlorine in treated water by applying booster chlorination strategies. Thus, it will help to safeguard water against microbiological recontamination in the drinking water distribution system (DWDS) and ultimate benefits to the consumers by supplying safe drinking water and protection against various waterborne diseases and harmful effects of DBP formation due to excess chlorination.

1.8 Methodology Adopted

To achieve the above stated objectives the following methodology are adopted.

(1) Hydraulic simulation of Drinking Water Distribution System: Drinking water distribution system simulation model for example problem and study area are developed using EPANET simulation model. The EPANET model is used to predict the pressure and discharge at different locations in DWDS.

(2) Simulation of Water Quality in DWDS: EPANET is further used to study and predict the concentration of residual chlorine at different locations in various DWDS. It is further used to check the effect of conventional and booster chlorination on chlorine residuals and DBP formation in drinking water distribution systems.

(3) Development of optimization Model: Optimization methods such as linear programming (LP) and particle swarm optimization (PSO) techniques are used to evaluate a large number of options and to select the specific alternative that gives the best results in terms of predefined objective of minimizing the mass rate of chlorine.

(4) Coupling of Simulation and Optimization Models: Simulation model and optimization model are coupled to determine optimal location, operation and scheduling of chlorine for booster chlorination stations for overall management of chorine disinfection in DWDS.

1.9 Inferences

This chapter gives the brief introduction of the present study which includes the use of chlorine as disinfectant in DWDS and importance of managing it in DWDS with the help of water quality modelling and optimization technique. The subsequent chapter 2 gives a comprehensive literature review on process of chlorine disinfection and problems associated while using it, detailed review on various chlorine decay models for prediction of residual chlorine as well as work done on modelling of DBP. It also reviews the use of optimization methods using booster chlorination approach over conventional approach of chlorination. The development of explicit equations in terms of flow and chlorine mass rate for quick computation of the residual chlorine concentration at various nodes to check the effect of booster chlorination on residual chlorine concentration is presented in Chapter 3. Chapter 4 gives the simulation of residual chlorine using EPANET for example problem real DWDS network of Vadodara city. Development of coupled simulation optimization model for chlorine management in drinking water distribution systems (DWDS) using linear programming (LP) and particle swarm optimization (PSO) technique is presented in Chapter 5. Finally, Chapter 6 summarizes the present work with extensive discussion and brings out the important conclusions drawn from the present study. Research contributions and further scope of the present study are also highlighted in this chapter.