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REVIEWS

Urban Water Supply and Management

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Abstract | Population growth and rapid urbanization lead to considerable stress on already depleting water resources. A great challenge for water authorities of urban cities is to supply adequate and reliable safe water to all consumers. In most of the developing countries water scarcity and high demands have led the water authorities to resort to intermittent supplies. Surface and groundwater are the major sources of supply in urban cities. The direct consequences of intermittent supplies and poor sanitation practices are several incidences of water borne diseases posing public health risk. In order to minimize the supply-demand gap and to assure good quality of water, new techniques or models can be helpful to manage the water distribution systems (WDS) in a better way. In the present paper, a review is carried out on the existing urban water supply management methodologies with a way forward for the proper management of the water supply systems.

Keywords: *urban water supply, water distribution network, water quality, sensor, modeling techniques.*

1 Introduction

Management of water supply has become a challenging task owing to population growth, expansion in industrial and agricultural activities, changing climatic scenarios, rapidly depleting water resource, increased demand for water, deteriorating infrastructure and water quality. In 2010, about 85% of global population (6.74 billion people) had access to piped water supply while 14% (894 million people) had to use unprotected sources for their water needs.[1] One of the eight Millennium Development Goals (MDGs) of United Nations is to reduce by half the proportion of population without sustainable access to safe drinking water and basic sanitation by 2015. A reliable supply of high quality water at a reasonable cost is of utmost importance for all types of consumers.

The two important sources of water in most of the urban cities are piped water and groundwater. In the developing countries piped water supply is intermittent with unacceptable pressures, high leakage rates, and poor maintenance of the system from source to consumer with large gap between supply and demand. Further, this inadequate quantity of water is not distributed equitably among consumers of different categories. A clean water supply is the single most important determinant of public health. However, the contamination of sources, aging infrastructure of WDS, leakages, cross contamination and poor sanitation practices have caused water quality deterioration. Globally, diarrhoea is the leading cause of illness and death, and 88% of diarrhoeal deaths are due to inadequate availability of water for hygiene and unsafe drinking water.[1] India has been well endowed with large freshwater reserves, but poor management practices of these resources have resulted in water scarcity. Hence, the focus is to improve the quantity and quality of water supply through improved water management techniques.

Traditional management tools and policies have, to some extent, achieved the required efficiency in this current scenario; however, they are not completely foolproof in making the network more reliable. A smart water network is one which is transparent and flexible in meeting future challenges, and carries out efficient asset management; as a whole it provides a reliable source of water to the consumer. Remote detection of leaks and water losses, early detection of contaminant events, real time data acquisition, data analysis, demand forecasting, energy optimization etc. are the key features of a smart water network.

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This paper focuses on the different conventional and smart techniques to manage quantity and quality of water supplied to an urban city.

2 Approaches to Manage Water Quantity Supplied to an Urban Area

None of the 35 Indian cities with a population of more than one million distribute water for more than a few hours per day. In most of the cities, water is pumped from a large distance to a very high elevation and in this process huge amount of energy is used to move the water from source to consumer. Present scenario of city water supply of most of the developing countries is shown in Figure 1. It should be noted that all the components indicated in the flow chart may or may not be working leading to more problems. Depleting groundwater table and deteriorating groundwater quality are threatening the sustainability of both urban and rural water supply in many parts of India. According to the guidelines issued by the CPHEEO, 150 lpcd (liters per capita daily) is considered as allowable for consumption at locations (towns/cities) where there is access to public underground sewerage system and where there is no such system, the value is 70 lpcd.[2] To meet the water demand, several approaches should be looked in to by developing models and with the proper usage of modern techniques as discussed below.

2.1 *Equitable water supply*

In the urban cities of developing countries, often large quantities of water are supplied to only a few consumers, leading to inequitable water supply. Equitable water to different consumers can be provided by operating the system in an efficient manner. Basu and Main;[3] Asingwire and Muhangi;[4] Rode[5] carried out studies on equitable water distribution by proper management of water, using other sources of water, more provision of funds, using proper technologies and policies, revision of tariff structures and involvement of private sectors. Vairavamoorthy et al.[6] developed a modified network analysis procedure using formal optimization techniques to ensure the maximum uniformity in supply. Chandapillai et al.[7] developed a simple device with a rubber sheet as the flow control element which is capable of delivering almost desired flow rate for the common range of upstream pressure. Not much work has been carried out in this regard for supplying equitable water to different consumers in different categories. Most of the urban cities receive water from source to intermediate reservoirs and from these reservoirs to consumers. Therefore, to achieve

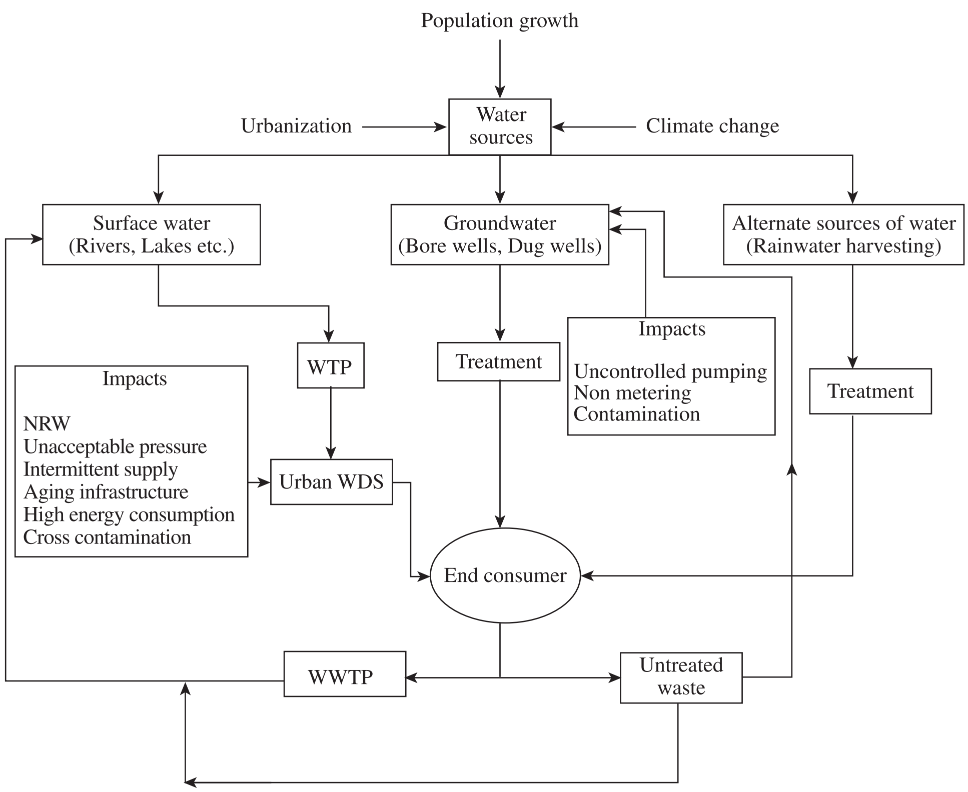


Figure 1: Present scenario of city water supply in developing countries.

equitable water supply these two supply steps have to be controlled by using different concepts/techniques. The water requirement of each of the reservoirs has to be calculated, which depends on the number of consumers and consumer category. Each reservoir should receive its share of water to satisfy its consumer demand and also there must be provision to accommodate shortages, if any.

2.2 *Controllers*

Controls can be applied to WDSs mainly to control flow in pipes (to achieve equitable water distribution or to get the target flow), level in tanks and for pump speed control. A control system compares measured value of the flow with the target value and gives the error, which is the difference between the two. There are different types of controls that can be used to arrive at the desired solution. Prasanna Kumar and Mohan Kumar[8] compared the application of linear (PID) and nonlinear (DI) control technique in WDS and concluded that nonlinear control technique is a powerful tool for achieving the target flow.

2.3 *Pressure and leakage management*

Pressure management in a WDS is of utmost importance for the optimal operation of the system. Pressure management can reduce the leaks and quantity of consumption, reduce the number of bursts, energy minimization and related costs. Zhang and Huang[9] proposed the pressure similarity method to get the optimal distribution of pressure measurement points for water distribution networks.

Leakage is the largest component of Unaccounted For Water (UFW). The loss of water due to leakage is a major problem in WDS. Aged and poorly maintained pipe lines, corrosion of the pipe lines, improper maintenance of the joints (like valves and bend), and mechanical damages are some of the major factors contributing to leakage in a WDS. Every year, more than 32 billion cubic meters of treated water physically leak from urban water supply systems around the world, while 16 billion cubic meters are delivered to customers for zero revenue.[10] In most of the developing countries leakage is about 20% to 50% of the total supplied quantity of water. By detecting the leaks in a pipe line, service can be improved to the existing customers and it can be extended to the population not served. Detecting leakage points is the first step towards minimizing the leakage in a WDS. Researchers have carried out number of works by using various techniques to minimize the leakage in WDS.

Studies on the optimal location and operation of control valves are carried out to minimize the leakage in WDS.[11,12] Several researchers have successfully developed an automatic leakage logger which monitors the continuous acoustic signals from leaking pipes in the middle of the night, when the water usage is minimal. Leakage control through pressure management is carried out by many researchers, for example, Ulanicki et al.;[13] Marunga et al.;[14] Poulakis et al.[15] proposed a Bayesian system identification methodology for leakage detection in water pipe networks. Based on information from flow test data, this model provides estimates of the most probable leakage events (magnitude and location of leakage) and the uncertainties in such estimates. Xu et al.[16] describe the application of belief rule based expert systems for pipe line leak detection by proper training and fine tuning of pipeline operating data. A water balance analysis has to be carried out at different levels from source to consumer by using modern tools/techniques to identify the location and quantity of leaks in a WDS. Leakage control is a regular maintenance activity and needs to be given priority, and should be included in the routine maintenance activities. Different types of valves (like pressure regulating, pressure control, pressure sustaining, throttle control, sluice valves) by proper analysis can also be used to manage pressure or to minimize the leakage in a WDS.

2.4 *Water Demand Management (WDM)*

Dedicated source of supply to cities is essential to meet the water demand. Demand is the major uncertainty in the WDS, which varies daily, in different seasons and for different types of consumers etc. It is difficult to investigate probable nature of demand in the WDS. Urban WDS demand management involves two measures - supply side management and consumer demand management. The supply side management involves infrastructure optimization, preventative maintenance, minimization of UFW and other water losses, metering of all connections, pressure management and energy efficient system. The consumer demand management involves social awareness and effective usage of water supplied, pricing, billing and minimization of losses due to overflow of tanks. A good relationship should be maintained between supply and demand for an efficient system whereby the quality can be maintained by reducing the residence time of water in the storage structures.[17] Water pricing is often recommended to reduce demand. Ruijs et al.[18] analysed demand and distributional effects of water pricing policies in a block pricing model that is applied to the metropolitan region of Sao Paulo. If there is shortage of water, the solution should not be limited to supply options alone (an alternate source of water), but also consider demand-side options, such as minimising water losses, and influencing demand to more desirable levels through structural modifications, retrofitting of water appliances, recycling and re-use, leak detection and repair, conducting educational and awareness campaigns.[19]

2.5 *Pump scheduling*

Pump operation plays a major role in WDS. Most of the urban cities receive water from long distance which is pumped to a higher elevation. High energy is consumed in this process, which can be minimized by proper pump scheduling. Different types of optimization techniques are used in this regard. Savic et al.[20] used multi objective genetic algorithms for pump scheduling to minimize the energy and maintenance cost. Six different types of multi objective evolutionary algorithms are implemented and compared by Baran et al.[21] to solve an optimal pump-scheduling problem with four objectives to be minimized: electric energy cost, maintenance cost, maximum power peak, and level variation in a reservoir. Ant colony optimization technique is used by Ibanez[22] for optimal control of pumps in a WDS. Zhuan[23] proposed an extended reduced dynamic programming algorithm to optimize pump scheduling of a pumping station with multiple pumps. Without making any changes to the basic operation pattern of a WDS, remarkable reductions in operation costs can be achieved by proper pump scheduling. Pump scheduling by using modern techniques is necessary in all the urban WDS where reasonable quantity of energy can be saved, thus the operation becomes economical.

2.6 *Reliability, resilience and vulnerability of the system*

Reliability considerations for WDS are an integral part of all decisions regarding the planning, design and operation phases. WDS operation is uncertain due to random change in demand, flow pattern, pressure head, and pipe roughness and therefore, knowledge of reliability, resiliency and vulnerability is important in understanding the system behavior for different scenarios in a better way. These three aspects can be defined as the probability that the system can provide the required flow rate at the required pressure (or how likely a system will fail), how quickly it can recover from failure, and the severity of failure respectively. Bao and Mays[24] developed a model based on Monte-carlo simulation to estimate the nodal and system hydraulic reliabilities of WDS that accounts for the uncertainties. Ciaponi et al.[25] developed a simple procedure for the analysis of WDS reliability during failure states resulting from the unavailability of a pipe (maintenance or repair), taking into account the probability of the failure events. Henry and Marquez[26] proposed generic metrics and formulae for quantifying system resilience, and they proved that it is possible to analyse resilience as a time dependent function. Bentes et al.[27] described the theory of vulnerability of WDS by tracing the vulnerable parts of the system, consequently giving guidance to increase its robustness. For any WDS, reliability, resilience and vulnerability calculations by developing/using a proper method are of utmost importance to operate the system in an efficient manner in any type of situation.

2.7 *Asset management*

Ensuring protection of the existing system and management of the assets for the future use requires analysis of the system for wider set of parameters, analysis of risk-assessment scenarios with all contributing factors, supplemented with real-time data collection, visualization and simulation for the sustainable management of the WDS. As the assets get older, the number of pipe failures increase. Therefore, an efficient failure management strategy becomes important. Two types of failure management strategies can be applied: proactive asset condition assessment to prevent a failure and reactive failure detection and location to minimize the reaction time and losses associated with a failure.[28] Christodoulou et al.[29] developed a neurofuzzy decision support system for performing multi-factored risk-of-failure analysis and asset management that capture the underlying knowledge and transform the patterns of the network behavior in to a knowledge repository and a decision support system. Misiunas[28] developed a technique that would utilise available measurement, data analysis, modeling and optimisation methods to reduce the risk of failure, minimize losses associated with the failure and improve the reliability, safety and efficiency of the urban water supply system. Proper asset management of the WDS is essential to meet the consumer demand.

Decentralized water supply for the economical and easy operation of the system, proper sewage treatment for dual quality water supply for potable and non-potable use, the concept of zero discharge, use of modern techniques/tools (like EPANET developed by Rossman[30]) for detailed modeling of different water supply scenarios are need to be looked in to. Disaster management scenarios for different cases should also be analysed to handle the system during abrupt change in the system behavior.

2.8 *Groundwater management*

More than 2 billion people worldwide depend on groundwater for their daily water supply. Groundwater is a highly useful and often abundant resource, but water levels are considerably decreasing in urban areas due to over extraction of groundwater for prolonged periods. Shi et al.[31] developed an integrated evaluation model for a series of purposes including the maximal efficiency of water use, the integral benefit of development and utilization, the optimized environmental water demand and the minimal anthropogenic influence on groundwater system. Camp et al.[32] derived simple indicators from meteorological data, in which abstraction rates and piezometric time series are compared with the groundwater storage depletion as obtained from a calibrated groundwater flow model. Managed Aquifer Recharge (MAR) has become an increasingly important component of integrated water management over recent years, in particular, for assistance in replenishment of depleted aquifers and storage of water for later extraction and use. Several studies are carried out in this regard to augment the groundwater resource.[33,34] Sustainable allocation of groundwater resource requires catchment and aquifer management plans that clearly integrate groundwater and surface water systems. This requires an accurate surface and groundwater balance to develop management plans which can recognise the interaction between the two.

2.9 *Rainwater harvesting and lake development*

Rain water can be used as a potential resource in water scarce areas. It can be used as an independent source of water supply during regional water restrictions, and in some areas it is used to supplement the main supply. A rainwater harvesting system comprises various components—transporting rainwater through pipes or drains, filtration, and storage in tanks for reuse or recharge. Large amount of work is carried out in this regard (Domenech and Sauri 2011; Ward et al., 2012) to reduce the stress on surface and groundwater.[35,36] In most of the cities, surface water bodies like lakes may occupy large areas, but severe ecological and environmental consequences can arise if they are given insufficient weightage in planning and development process. Proper maintenance of these surface water bodies will be an added advantage to meet the consumer demand.

Water balance study in a city scale will be useful to account for all the components of water and to manage the resource in a better way. An integrated urban water supply management approach is needed to meet the water demand of a city. The quality of the supplied water (surface and groundwater) at different stages till it reaches the consumer is also very important, and is discussed in the next section.

3 Approaches to Water Quality Management

Human health and well being depends on the water quality that is supplied. The increased dependence on bottled water or treatment at point of use in recent years throws light on the deficiencies of WDSs in supplying safe drinking water to the end consumer. The WDS constitutes an important component of every drinking water utility from catchment to consumer. But the contamination of sources due to point and non point pollution loads, inefficient treatment and storage, varying hydraulic conditions, leaky pipes/joints resulting in intrusion events, pose serious public health risk. Waterborne diseases are a major concern all over the world causing disease, loss of life and economic burden on individuals, communities and the government. Therefore, better management strategies along with latest tools and techniques are required for improving water quality which will be reviewed in the following sections.

3.1 *Source protection*

Rivers, streams and lakes are reliable water sources for supply of piped drinking water to communities. However, direct discharge of domestic, agricultural and industrial wastes has contaminated the surface water bodies making them unfit for use. In developing countries 70% of untreated industrial wastes are dumped into waters where they pollute the usable water supply (World Water Assessment Programme (WWAP)).[37] As a result, surface waters are contaminated with hazardous organic and inorganic chemicals, heavy metals, pesticides, radiological and bacteriological contaminants. Raw waters are treated at the treatment plants where strict water quality standards are enforced by regulatory mandates. In order to comply with microbial and disinfectant-by-product (DBP) regulations, water utilities can invest in advanced treatment processes like enhanced coagulation, carbon adsorption or reverse osmosis that achieve greater levels of microbial inactivation and DBP precursor removal.[38,39] With fast depletion of surface water bodies, ground water has become a reliable source of supply to many small communities and individual homeowners. However, there is an increasing concern over the quality of this untreated source owing to microbial and chemical contamination. A survey of 448 wells in 35 states of

US reported that 31% of the sites were positive for at least one virus.[40] Fourteen states in US reported 28 waterborne disease outbreaks (WBDOs) that occurred during 2005–2006, of which 20 were associated with drinking water coming mainly from ground water sources.[41] Owing to geogenic and anthropogenic activities high levels of nitrates (beyond the permissible limit of 45 mg/l) fluoride (greater than 1.5 mg/l) and arsenic (in excess of 0.05 mg/l) have been found in many parts of India, posing health risks.[42–44] Excessive withdrawal of water from coastal and inland aquifers has led to saltwater intrusion (CGWB).[45] Hence, there is a need to protect the sources of drinking water. Substantial research on chemical and microbial transport in natural subsurface systems is being carried out in order to have a better understanding of the various physical, chemical and biological factors involved in the contaminant transport, developing improved models and overcoming the inherent weaknesses of traditional approaches, and for devising better management practices and remedial measures of such polluted sources.[46–49]

3.2 *Water Distribution System (WDS) integrity*

The WDSs constitute a major infrastructure asset to water utilities all over the world, supplying treated water from the treatment plant to various consumers. There are many issues and concerns regarding the water quality supplied by the distribution networks. Most distribution systems' infrastructure is reaching the end of its expected life span.[50] The varying hydraulic conditions further add stress to the aging infrastructure leading to pipe breaks and leaks. Substantial changes occur during the transit owing to complex physical, chemical and biological reactions within the distribution systems. Therefore there is a need to address the WDS integrity. WDS integrity can be described as having three components (1) physical integrity-refers to the maintenance of a physical barrier between the distribution system interior and the external environment, (2) hydraulic integrity-refers to the maintenance of a desirable water flow, water pressure and water age and (3) water quality integrity-refers to the maintenance of finished water quality via prevention of internally derived contamination.[51] Intentional sabotage and deliberate contamination of WDS have been emphasized in recent reports by United States Environmental Protection Agency (USEPA). Water quality monitoring and contamination event detection throughout the WDS pose a technical challenge to every water utility but are essential in ensuring safe drinking water supply in addition to the maintenance of WDS integrity. Not maintaining the WDS properly can lead to disaster management situation that could be either due to man-made or natural causes.

3.3 *Disinfectant barrier*

Disinfection is the final barrier to protect consumers from waterborne diseases once the water has been released into WDS from the treatment plant. USEPA requires a minimum chlorine residual of 0.2 mg/l to be maintained throughout the WDS. Though large doses are applied to water leaving the treatment plant, these disinfectants decay as they travel within the WDS because of various hydraulic, chemical and microbiological factors. Vasconcelos et al.[52] noted that disinfectant decay in WDS is due to reactions occurring within the bulk flow and with pipe wall. The factors influencing bulk phase chlorine decay are the presence of total organic carbon (TOC), initial chlorine concentration, temperature and pH and can be determined by laboratory bottle tests. Many predictive models like single constituent (chlorine) decay model, two component (chlorine and fictitious reactant) decay model and multiple reactive component model were developed and investigated for the bulk disinfectant decay.[53–55] The model parameters are either single or multiple, based on the decay model and are functions of initial chlorine concentration, TOC, ultraviolet spectral absorbance (UVA), temperature, bromide concentration and alkalinity. The above models are useful in predicting chlorine decay and DBP formation studies. Pipe wall reaction rates are affected by the pipe material, nature and amount of deposits attached to or released from the wall (biofilms, scales and tubercles), rate of mass transfer from the bulk to the wall and corrosion rates.[56–58] There are no direct methods to determine wall decay rates and must be deduced from field measurement by comparison with simulation results. Optimization techniques can be used which prevent the tedious trial and error approach for parameter estimation, and serve as a good tool to calibrate the water quality model following either a first order or a non-first order chlorine reaction kinetics.[59,60]

3.4 *Controlling DBPs*

The interaction of chemical disinfection with natural organic matter (NOM) within the WDS, leads to the formation of harmful DBPs, namely trihalomethanes (THMs) and haloacteic acids (HAAs). Though a few of these are regulated, recent studies emphasize the potential health hazards when exposed to the unregulated emerging

DBPs (EDBPs) like iodinated trihalomethanes and acids, haloacetonitriles, halonitromethanes (HNMs), haloacetaldehydes, and nitrosamines, which are formed due to inorganic precursor like halide ions in the drinking water supplies.[61] Alternative treatment processes like lime softening or disinfection processes like UV radiation, ozonation or use of chloramines or chlorine dioxide, can aid in removal of precursor or lower the formation of regulated DBPs but increase the formation of EDBPs. Therefore, such processes should be optimized so that the formation of both regulated DBPs and EDBPs could be controlled.[62,63]

3.5 *Booster chlorination*

It is necessary to maintain free chlorine residuals between a specified minimum and maximum range so as to control the growth of pathogens and formation of DBPs throughout the WDS. However, it is difficult to maintain free chlorine residuals owing to the reactions occurring in bulk and wall phase of the WDS. Tryby et al.[64] explained the importance and effectiveness of booster chlorination a conceptual strategy, where disinfectant is reapplied in the network in the context of a distribution system for maintaining chlorine residuals. A nonlinear optimization problem was formulated to determine the chlorine dosage at the water quality sources subjected to minimum and maximum constraints on chlorine concentrations at all monitoring nodes.[65] A reactive species efficiency model was investigated for chlorine decay and total THM under rechlorination events and discontinuities associated with them.[66]

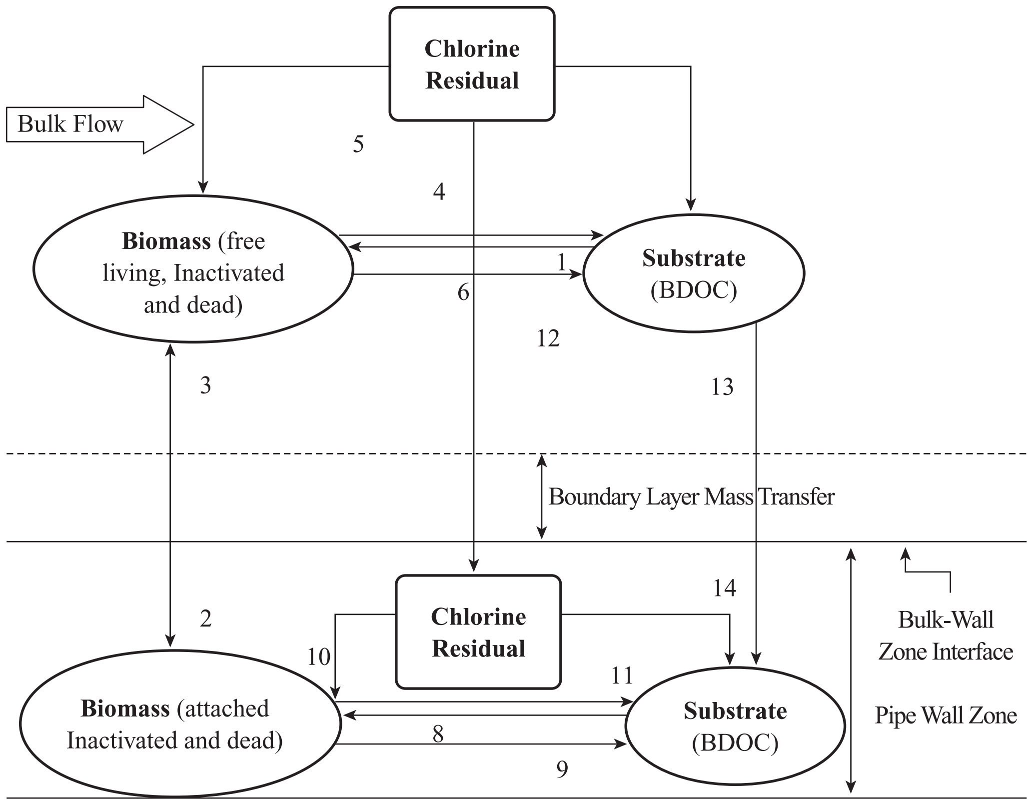
3.6 *Bacteriological studies*

Of the various causes of water quality deterioration in networks, bacteriological parameters are the most closely studied and monitored because of the short term risks to public health. Field and experimental studies by various investigators have established microbial ecosystems in the networks. The factors influencing bacterial re-growth are presence of nutrients, corrosion and sediment accumulation in pipes, hydraulic effects, disinfectant residuals, long residence time and age of biofilm. Mathematical modeling is used to predict and control bacterial growth in WDS. Two types of deterministic models have been prominent from earlier studies, namely SANCHO (Servais et al., 1992) and PICCOBIO (Dukan et al., 1996) models. While the former dealt with the adsorption-desorption of bacteria, the latter dealt with concept of biofilm.[67,68] Also, it had an advantage of having a hydraulic model thereby predicting dynamic nature of the system. However, the mathematical descriptions of the bacterial growth processes were complex with large number of parameters to be specified. Munavalli and Mohan Kumar[69] developed a multicomponent reaction transport model (Figure 2) which is governed by the relationship of bacterial growth in the presence of substrate (organic carbon) and disinfectant (chlorine).

This model uses simplified expressions for the basic processes like bacterial growth and decay, attachment to and detachment from the surface, substrate utilization and disinfectant action both in the bulk flow and at pipe wall. The developed model is useful in identifying the potential locations of bacterial re-growth and simulating contaminant intrusion events in the WDS.

3.7 *Modeling methodologies and tools*

Mathematical models can supplement monitoring as an effective tool for understanding the dynamics of water quality variations and complex processes occurring within the large networks of pipes. They help in predicting the spatial-temporal distribution of constituents in WDS. These models help in assessing alternative operational and control strategies for improving and maintaining water quality, optimize disinfection processes, design water quality sampling programs and help in evaluating water quality improvement projects for distribution networks.[70] EPANET, PICCOBIO, H2ONET, DWQM are some of popular water quality models used. The water quality models are formulated to determine the constituent concentration (conservative/reactive), water age and source trace at the nodes within the distribution system. Rossman et al.[71] compared two Eulerian and two Lagrangian methods for dynamic water quality, and found that the latter are more efficient for simulating chemical transport though the accuracies of the methods were comparable. These models, however, contrasted with respect to analytical solutions under varying concentration tolerance and water quality time step values. In order to overcome these limitations and improve the accuracy, Munavalli and Mohan Kumar[72] developed a hybrid model which simulates nodal concentrations accurately with least maximum segmentation of network and reasonable computational effort. These models have been extended to analyze hydraulic transients owing to the growing awareness that they can cause pathogen intrusion into WDS with disastrous consequences to public health. Wood et al.[73] compared two transient models namely method of characteristics (MOC) and wave characteristic method (WCM), and concluded that though the results were comparable,



Process Description

1. Substrate utilization and bacterial cell growth in bulk water
2. Bacterial cell attachment from bulk to biofilm
3. Bacterial cell detachment from biofilm to bulk water
4. Bacterial mortality in bulk water (natural)
5. Bacterial mortality in bulk water (chlorine induced)
6. Contribution of dead bacterial cell in bulk to BDOC (lysis)
7. Chlorine decay in bulk water
8. Substrate utlization and bacterial cell growth in biofilm
9. Bacterial mortality in biofilm (natural)
10. Bacterial mortality in biofilm (chlorine induced)
11. Contribution of dead bacteria cell in biofilm to BDOC (lysis)
12. Chlorine mass transfer across boundary layer
13. Substrate (BDOC) mass transfer across boundary layer
14. Chlorine decay in biofilm

Figure 2: Multicomponent reaction transport model.

WCM was computationally more efficient for large WDSs. Further, most water quality models developed were limited to tracking of the dynamics of single chemical component or water age within the WDS. Shang et al.[74] developed a general frame work for modelling the reaction and transport of multiple, interacting chemical species in WDS. The framework has been implemented as an extension to the well known EPANET programmer's toolkit. It employs several different numerical methods along with EPANET transport algorithm to solve the reaction/equilibrium system throughout the pipe network.

3.8 *Data driven modeling techniques*

Recent trends in the management of water supply have increased the need for modeling techniques that can provide reliable, efficient and accurate representation of the complex, non-linear dynamics of water quality within WDS. Statistical models based on Artificial Neural Networks (ANNs) have been found to be highly suited to this application, and offer distinct advantages over more conventional modeling techniques. Based on the representative data of WDS, ANN models developed were based on back propagation and General Regression Neural Network (GRNN) algorithms. Bowden et al.[75] used GRNNs for forecasting chlorine residuals in the Myponga WDS, South Australia, by addressing several critical model issues. The GRNN models are able to forecast chlorine levels to a high level of accuracy, up to 72 h in advance. D'Souza and Mohan Kumar[76] incorporated ANN to predict temporal chlorine residual and biomass concentrations at different nodes for five WDSs. Munavalli and Mohan Kumar[77] found genetic algorithm (GA) as a potential tool for estimating the kinetic parameters of a previously developed multicomponent reaction transport model consisting of substrate, biomass and disinfectant.

3.9 *Experimental studies*

Water quality monitoring on various networks is usually done through sampling. However, experimentation on networks is difficult owing to the lack of accessibility, few available representative sites and changing flow conditions. In order to study water quality deterioration and calibrate water quality models, experimental set up like pilot pipe loop is useful as it offers the possibility to work in conditions similar to those of actual network and to control the various parameters which affect water quality. Piriou et al.[78] used pilot pipe loop facility to validate the PICCO-BIO model under controlled conditions for various water quality scenarios, and found it to be a useful tool complementary to field experiments for studying and modeling water quality evolution in WDS. The pilot pipe loop facility consists of one or more pipe loops supplied with a feed tank, recirculation pump, flow and temperature controls and representative sampling of inner surface of pipes by PVC coupons. Boe-Hansen et al.[79] used a similar pilot loop facility to study the bacterial growth dynamics at low nutrient conditions and quantify the effect of retention times at hydraulic conditions similar to those in WDS. The microbial quantification was done by a range of methods like total direct counts through Acridine Orange Direct Count (AODC), Heterotrophic Plate Count (HPC), leucine incorporation and Adenosine Tri-Phosphate (ATP), and the bacterial growth rates thus determined were compared for the bulk phase and biofilm. Butterfield et al.[80] developed heterotrophic biofilms in rotating annular reactors to investigate the influence of chorine on biomass and kinetic parameters for biofilm growth in low carbon environment. Yang et al.[81] used pilot scale pipe flow experiments for a non reactive sodium fluoride tracer and the fast reacting aldicarb in order to validate a modified one dimensional Danckwerts Convection-Dispersion-Reaction (CDR) model developed by them to explain the chlorine residual loss for a slug of reactive contaminants introduced into the WDS. These studies help in analyzing and determining disinfectant efficiency and bacterial growth kinetic parameters thereby help in calibrating water quality models. Helbling[82] and VanBriesen,[83] investigated the efficiency of free chlorine residual as a surrogate indicator of pathogenic contamination in a chlorine demand free media in batch reactors, and later in laboratory-scale drinking WDS equipped with online free chlorine sensors by measuring chlorine decay kinetics and cell survival of dense microbial suspensions, and showed that free chlorine could be a suitable indicator of microbial contamination even for chlorine resistant organisms, which remain viable and infective within the WDS. Modeling the propagation of chlorine demand signals generated by specific pathogens could aid in the assessment of distribution system vulnerability.

3.10 *Public health risk and water safety*

Loss of WDS integrity makes the system vulnerable to external contamination through main breaks/repair sites, unprotected storage tanks, cross connections, improperly installed backflow prevention devices, leaking pipes/joints, back flow events due to loss of pressure. The most vulnerable systems are those with intermittent water supply often found in developing countries where the risk of contamination is higher with several incidents of waterborne disease outbreaks. In contrast, the developed countries deliver water at sufficient pressure on a continuous basis. However, unacceptable pressure conditions may still prevail owing to pressure transients associated with sudden pump shutdowns or pressure losses occurring from system failures

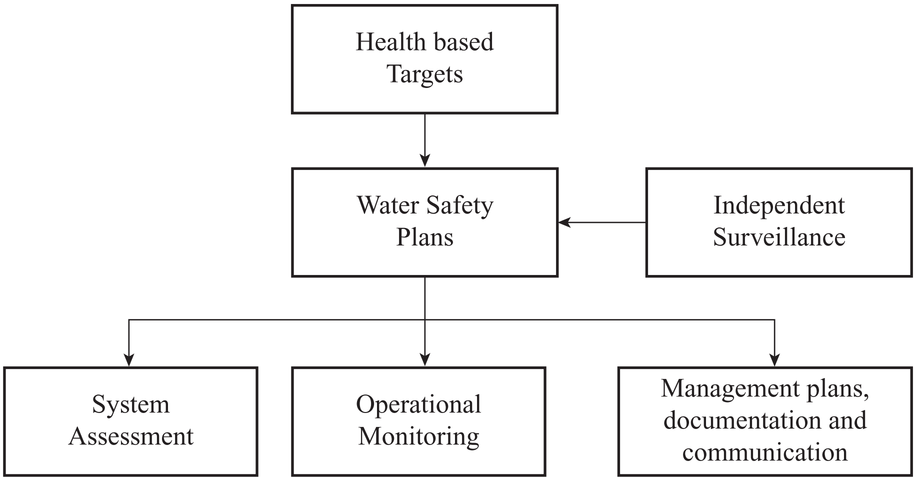


Figure 3: Frame work for safe drinking water.

resulting in contaminant events. While the public health risk associated with such events is not well understood, attempts have been made to estimate such risk either through quantitative microbial risk assessment (QMRA) (Schijven et al., 2011) or through conceptual models providing state of knowledge, current assumptions and challenges associated with model parameters (Besner et al., 2010) or through the development of software tools like GIS based improved risk assessment of WDS (IRA-WDS) for intermittent supplies, which are risk maps showing the risk of contaminant intrusion into various parts of WDS (Vairavamoorthy et al., 2007).[84–86] In addition to microbial risks, water safety may be compromised by chemical and radiological contaminants. The most effective means of consistently assuring a supply of acceptable drinking-water is the application of some form of risk management based on sound science and by appropriate monitoring. It is therefore important to include risk management that covers the whole system from catchment to consumer. The multi barrier approach is an important strategy where the WDS serves as a barrier against contamination at every step right from source, treatment, storage, distribution and treatment at point of use and ensures water safety at every step. The WHO Guidelines for Drinking-water Quality (GDWQ) aim to protect public health through the adoption of a Water Safety Plan (WSP). WSPs are comprehensive management strategies that prevent outbreak of disease with the objective of protecting water flow from catchments to consumer from contamination, optimization of treatment plants, prevention of contamination during storage, distribution and handling of drinking water.[87] The framework for safe drinking water is given in Figure 3.

3.11 *Case study*

A case study on Bangalore WDS is dealt with, which is an application of equitable water supply and water quality predictions using data driven modeling techniques as discussed in the previous sections.

Bangalore city receives about 910 Million liters of water per day (MLD) from Cauvery River which is distributed to an area of about 758 km^2. The present network consists of 350 junctions, 55 GLRs (distributed in six zones), 247 pipes, 85 pumps and 156 valves. The WDS is shown in Figure 4.

3.11.1 Equitable distribution of water using control algorithms: Usha Manohar and Mohan Kumar[88] used Dynamic Inversion based controller approach to achieve equitable distribution of water to different zones of Bangalore city. The Bangalore WDS has large undulating terrain with different capacity of reservoirs in different zones which bring inequality in water supply in these zones. The unequal distribution of water and the large variation in system parameters makes the WDS highly nonlinear. Bangalore WDS is very complex with many inter connected variables, and hence controlling the same is a challenging task. In this study, a Dynamic Inversion (DI) nonlinear controller (to remove the nonlinearity in the system) with Proportional Integral and Derivative (PID) features (to minimize error) is applied to WDS to analyze different flow scenarios. This network is modeled by using EPANET and is calibrated for valve throttling by minimizing the error between the observed (flow meter reading) and simulated flows using appropriate roughness and demand values. Sensitivity analysis is also carried out to understand the system behavior by changing the roughness values. By using the number of

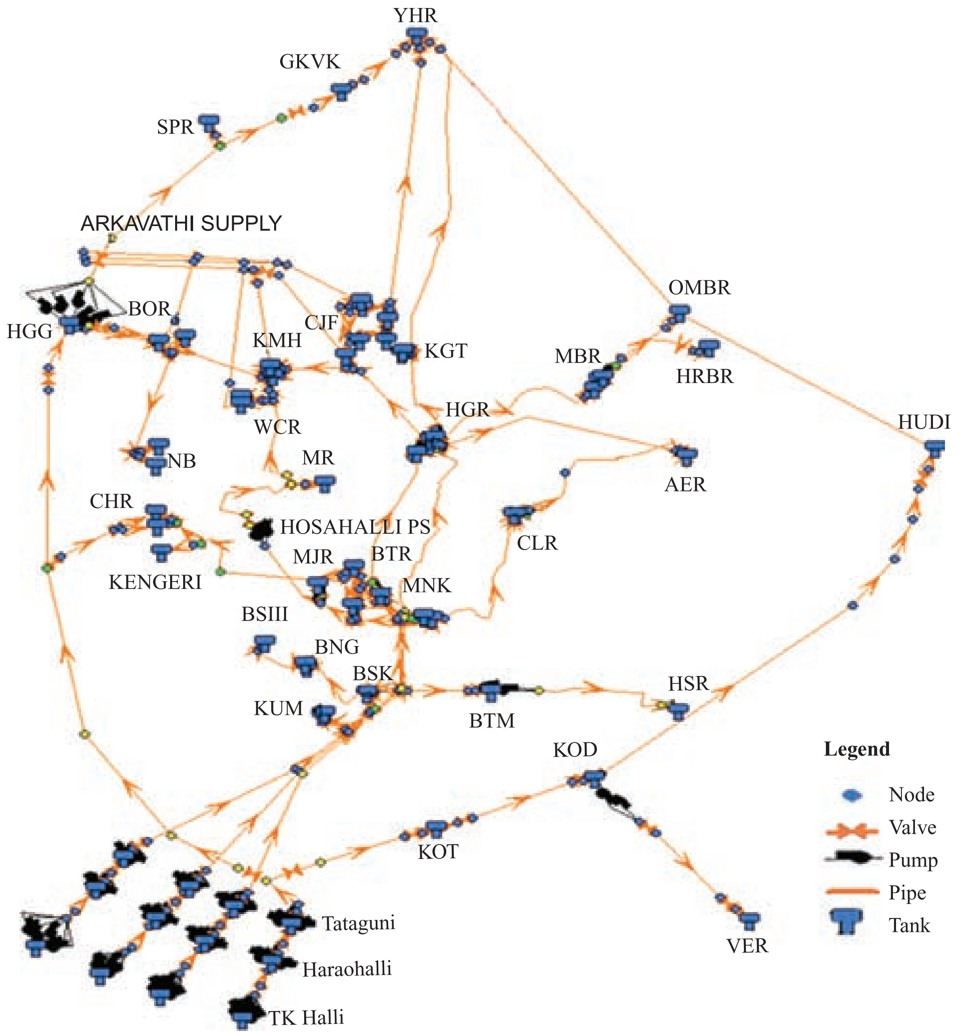


Figure 4: Bangalore WDS.

connections and consumptions, equitable water supply quantity is calculated for each zone. Controllers were effective in achieving the target flow at different levels in all the zones. The calibration and sensitivity analysis plot for the selected GLRs are shown in Figure 5.

3.11.2 Water quality prediction using data driven modeling techniques: D'Souza and Mohan Kumar[76] developed an ANN model to predict temporal chlorine residual and biomass concentrations for randomly chosen nodes for Bangalore WDS as shown in figure 6. The network shown is old Bangalore network comprising of 87 pipes, 7 pump elements, 70 nodes, 15 reservoir nodes and 3 supply source nodes. The authors tested three algorithms of feed-forward neural networks: resilient back propagation (RP), Levenberg-Marquardt (LM) and general regression (GR). The performance of each algorithm was determined on the basis of mean absolute error (MAE) and coefficient of correlation (R) and the best models were identified. The data used in the development of the ANN models were obtained from an earlier developed multi-component reaction transport model (Munavalli and Mohan Kumar (2004)) which determines chlorine residual, substrate and bacterial re-growth both spatially and temporally.[69] Because the inputs to the model were very large, principal component analysis (PCA) was carried out to reduce the dimensionality of the input vector and eliminate highly correlated inputs. The three algorithms were compared on the basis of R and MAE values; higher the value of R and lower the value of MAE, the better the performance of the algorithm. Table 1 shows the final architecture, R and MAE values for Bangalore WDS. To determine the robustness of the developed models, the ANN models for each of the algorithm were tested for noisy measurements. 10% of error was introduced into three inputs-source chlorine, source substrate and source biomass concentrations

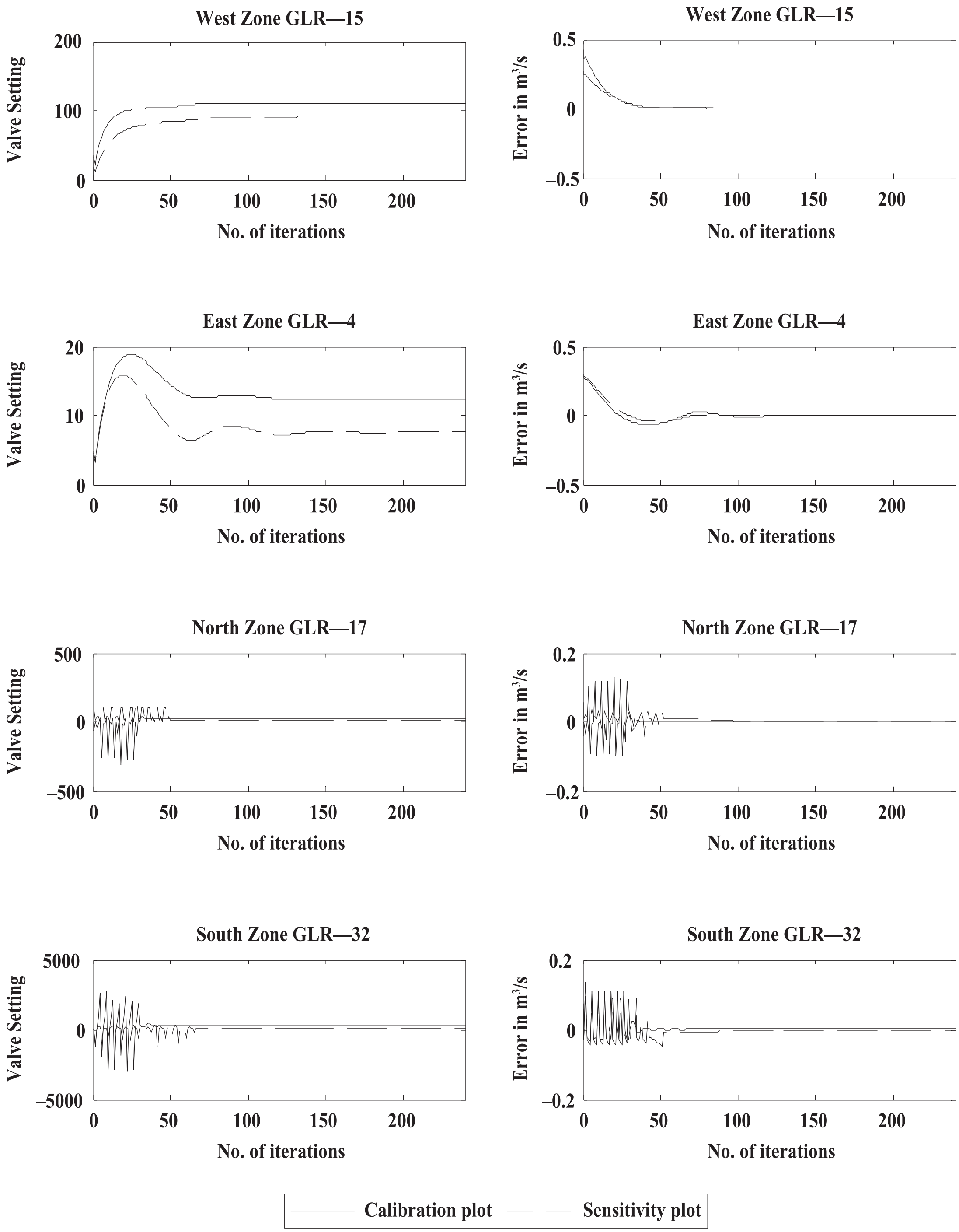


Figure 5: Calibration and sensitivity analysis plot for the selected GLRs. (Reproduced with permission from ASCE).

which were assumed to be normally distributed. The quality prediction for chlorine and biomass concentrations with and without the noisy data for the selected node is given in Figure 7. The observations led to the conclusion that the LM algorithm performed better than the other two in predicting temporal chlorine residual and biomass concentration.

4 Smart Water Networks

Collecting and analyzing water network data enables better understanding of the dynamics of the system and helps in improving system operations and the control on the system. Data can be collected from the source to the consumer points, and it can be analyzed to understand its change in hydraulics and quality. Just like every other physical system,

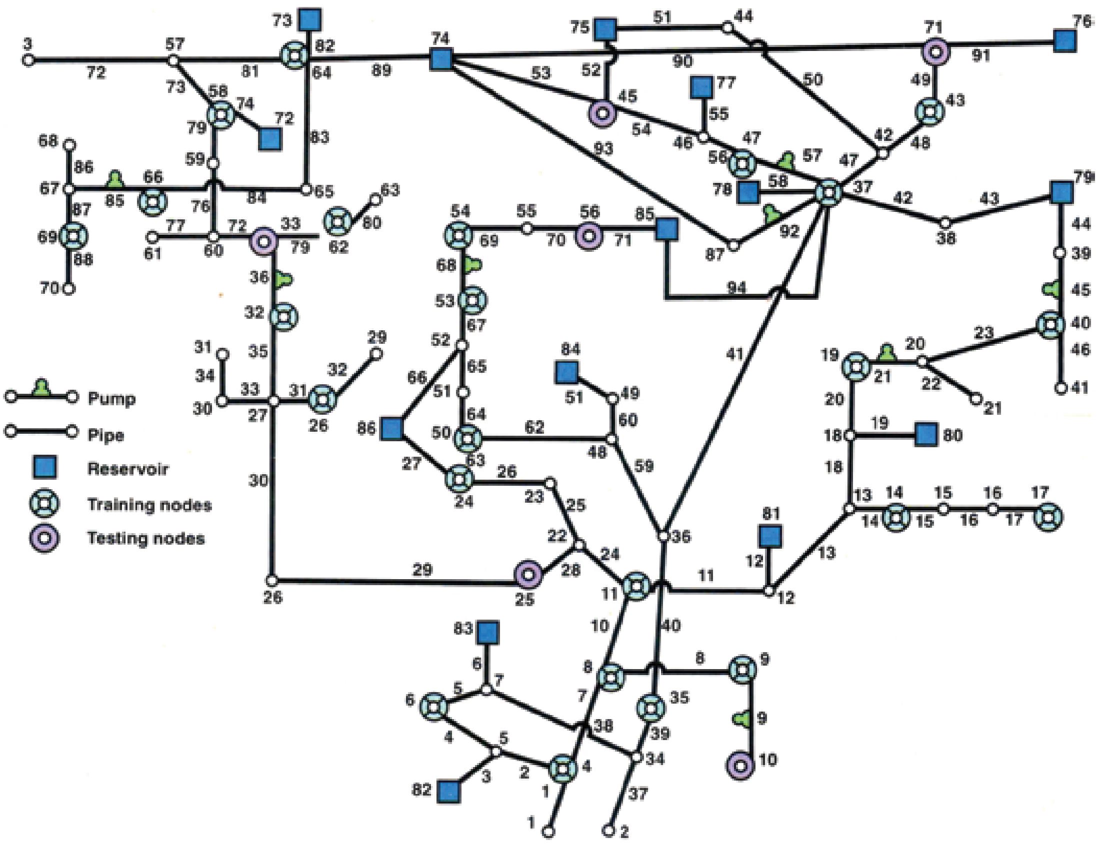


Figure 6: Schematic drawing of old Bangalore Water distribution System.
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Table 1: Model results of testing nodes for the prediction of temporal chlorine residual and biomass concentration for Bangalore WDS.

		Chlorine residual		Biomass	
Algorithm	Architecture	R	MAE	R	MAE
Resilient back propagation	6-10-5-2	0.935	0.0542	0.864	0.0128
Levenberg-Marquardt	6-8-5-2	0.961	0.0482	0.89	0.0123
General regression	NA	0.932	0.0464	0.8181	0.0190

MAE—mean absolute error, NA—not applicable, R—coefficient of correlation.
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Smart water network also has different interconnected tiers. First and the foremost is the data collection setup—Sensors. Sensor nodes continuously collect data from the system and transmit it to a database where it will be analyzed or modeled. Data transmission, archival and analysis form the other tiers of smart water networks. Figure 8 shows the components of a fully automated WDS.

Sensors can be used not just for monitoring water distribution networks, but also for monitoring river water quality and determining catchment health. It is essential for optimizing water treatment process and ensuring healthy aquatic life.[89] In WDS, sensors serve multiple uses like i) Continuous monitoring of WDSs, both quality and quantity of water; ii) Quality sensors can be deployed to ensure better quality drinking water; it is deployed for monitoring residual chlorine, turbidity etc. (key quality parameters of the system); iii) Leak detection in pipe lines can be done using sensors; iv) Contamination warning system which enables early detection of accidental as well as intentional contamination of WDSs. Flow and pressure sensors are used for continuous monitoring of water

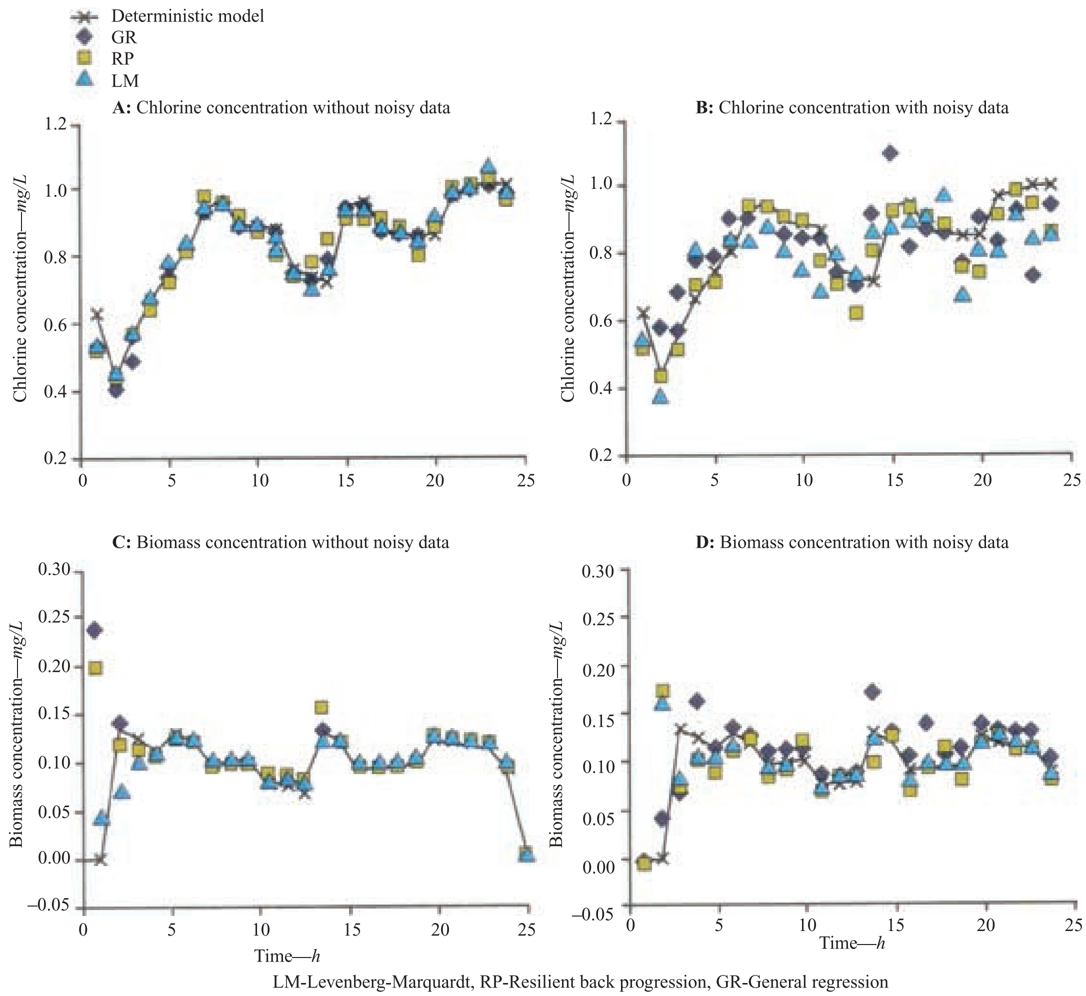

Figure 7: Variation in chlorine concentration and biomass concentration for the selected node of Bangalore WDS with and without the noisy data.
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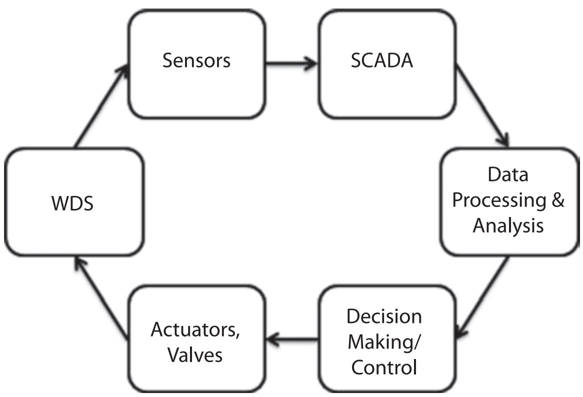

Figure 8: Components of an automated WDS.

distribution system hydraulics. Quality sensors like chlorine sensors, turbidity sensors, bacteriological sensors and other chemical sensors like fluoride, arsenic etc. determine the quality of water. Ground penetrating radars, moisture sensors, optical sensors, pressure sensors, sound sensors, acoustic sensors etc. help in leak detection. Corrosion sensors, stress sensors, tank and reservoir level indicators help in condition assessment of the system. These are a few ways in which sensor network can help in better water distribution management. However, sensors are expensive. To make them a viable option, there is a clear need to minimize the investment. And one of the ways to minimize the cost is by optimizing the number of sensor nodes. Non-optimal design choices lead to poor performance of the sensor system and also will compromise any system which relies on its information.

4.1 *Sensor placement optimization*

Different algorithms for sensor node optimization were being developed from early 20th century onwards. But little was known about how these design algorithms compared from one design methodology to another, and thus, what advantages they provided for practical design of sensor networks. To explore these issues, the Battle of the Water Sensor Networks (BWSN) was held as part of the 8th Annual WDSs Analysis Symposium, in Cincinnati, on August 27–29, 2006. All the teams were asked to develop designs according to a set of rules, which defined the design performance metrics and the characteristics of the contamination events. Table 2 shows the details of the algorithms presented at BWSN. Even though the teams were free to develop their designs and methodologies, yet, for comparison, all outcome designs were evaluated using identical procedures.[90] The main design objectives for the optimization of sensor network were: 1) Minimization of time of detection; 2) Minimization of expected population affected prior to detection; 3) Minimization of the volume of contaminated water consumed; 4) Maximization of detection likelihood. Thus, the BWSN was inherently a multi-objective problem. Over 15 groups of scientist and engineers put forward their designs during BWSN. It was found out that only compromised non-dominated solutions can be defined in a multi-objective space, and that determination of the "best" received solution was not possible. BWSN could assimilate all the techniques for sensor network optimization available in literature till date, but it failed to put forward a best solution from these. Also, the objective of optimizing the number of sensors required for securing a water distribution network was neglected during the problem formulation. Number of sensors used for the design purpose was fixed. It was later found out that the network used in this study was not as complex as a real world network. The average plume size over the possible set of injection was very small for the network because of largely homogeneous flow pattern over a 24-h period.

Hart and Murray[91] reviewed the optimization-based sensor placement strategies for contaminant warning systems in WDSs that were available in literature. This literature discussed gaps in the existing drinking water sensor placement algorithms and recommended directions for future research. They recommended that water security applications may require a higher degree of accuracy than traditional modeling applications, as well as multiple versions of models that reflect seasonal operational patterns and planned future improvements. Till date, no consensus has been achieved on what contaminants are most likely to be used in contaminating distribution systems or how one can model these contaminant incidents, the likely concentrations and volumes of the same, the injection durations, or the probable attack locations etc. Ambiguity still persists in deciding the number of potential contaminant incidents that need to be modelled to generate high performing sensor network designs (higher the number of contaminant incidents, higher the reliability of sensor design and higher computational time). But even in this review they couldn't come up with a unique solution for this multi-

Table 2: The table shows the details of the different approaches presented at BWSN conference in Cincinnati, 2006.

Authors	Method
Alzamora and Ayala	Topological algorithms
Berry et al.	*p*-median formulation to define sensor location
Dorini et al.	Constrained multi-objective optimization (noisy Cross-Entropy Sensor Locator (nCESL) algorithm)
Eliades and Polycarpou	Iterative deepening of Pareto solutions algorithm. (Multi-Objective)
Ghimire and Barkdoll	Demand based approach for sensor placement
Guan et al.	GA based single objective method
Gueli	Predator-prey model for multi-objective optimization
Huang et al.	Multi objective GA based framework with data mining

objective problem. Also, all the methods were unable to decide the optimal number of sensors required for a network. Table 3 shows a synopsis of different literature available as given in the review paper.[91]

In 2010, Aral et al.[92] proposed a methodology in which the objective function used in the model considers the effect of the four measures in one objective function there by transforming a multi-objective problem into a single objective problem. The proposed model also introduced the reliability constraint solution to determine the minimum number of sensors necessary, thus ending the continual ambiguity on the number of sensors optimal for a distribution network. Using this model, one can obtain the minimum number of sensors needed and their placement while satisfying a specified reliability for the system. The algorithm proposed in this study was able to overcome the computational time requirements constraint through the application of the PGA (Progressive Genetic Algorithm) based sub-domain approach. The water sensor network designed by the model was found to yield good performance in comparison with the other solutions provided to the BWSN session.

Table 3: Summary of Sensor Placement Optimization Literature, (1) Whether contaminant transport simulations were used to compute risk; (2) Whether sensor failures were modelled; (3) Whether multiple design objectives were used during optimization; (4) Type of optimization objective; and (5) Whether data uncertainties were modelled.[91] (Reproduced with permission from ASCE).

Citations	Risk calculations with simulation	Imperfect sensors	Multiple objectives	Optimization objective	Data uncertainties
Al-Zahrani and Moeid (2001, 2003); Kessler et al. (1998); Kumar et al. (1997, 1999); Lee et al. (1991); Lee and Deininger (1992); Ostfeld and Kessler (2001); Uber et al. (2004)	N	N	N	Cover	N
Berry et al. (2003, 2005); Krause and Guestrin (2009); Rico-Ramirez et al. (2005); Shastri and Diwekar (2006)	N	N	N	Mean	N
Carr et al. (2004, 2006)	N	N	N	Robust	Y
Watson et al. (2004)	N	N	Y	Mean	N
Chastain (2004, 2006); Cozzolino et al. (2006); Ostfeld and Salomons (2003, 2004, 2005)	Y	N	N	Cover	Y
Berry et al. (2004, 2005, 2006, 2007, 2008); Hart et al. (2008); Kızıleniş (2006); Propato et al. (2005); Propato (2006); Romero-Gomez et al. (2008); Watson et al. (2005)	Y	N	N	Mean	N
Aral et al. (2008); Berry et al. (2008); Dorini et al. (2006); Eliades and Polycarpou (2006); Guan et al. (2006); Gueli (2006); Hart et al. (2008); Huang et al. (2006); Krause et al.(2006, 2008); Krause and Guestrin (2009); Leskovec et al. (2007); Preis and Ostfeld (2006, 2008); Wu and Walski (2006)	Y	N	Y	Mean	N
Krause and Guestrin (2009); Watson et al. (2006, 2009)	Y	N	N	Robust	N
Berry et al. (2006); Preis and Ostfeld (2008); Wu et al. (2008)	Y	Y	N	Mean	N

4.2 *Data analysis*

Application of real time data for model generation can reduce the stochastic nature of the problem immensely. Once the network is secured using sensors, the next step is data collection and its transmission to a central data base where it can be analysed using different algorithms. Sensors collect the real time data which are to be transmitted to a central data base where it is fed into the hydraulic model of the network at each time step, and thus the system can be calibrated in real time. Different algorithms are available in literature that allows for remote detection of leaks, contaminant event detection, demand forecast etc.

4.3 *Demand forecast*

Alvis et al.[93] proposed a pattern based demand forecast method for prediction of monthly, daily and hourly forecast. In this, the changes due to climatic patterns were ignored. Availability of real time data can increase the accuracy of these models. Later, a predictor-corrector methodology was proposed to predict statistical hydraulic behaviour based on prior estimation of water demands, and then correct this prediction using new, real-time measurements. The problem was solved using the extended Kalman filter, which is a linear algorithm that calculates the estimate of water demands and their uncertainties.[94] In 2011, Preis et al.[95] employed an online predictor-corrector (PC) procedure for forecasting future water demands using real time data. A statistical data-driven algorithm (M5 Model-Trees algorithm) was applied to estimate future water demands, and an evolutionary optimization technique (genetic algorithms) was used to correct these predictions with online monitoring data. The calibration problem was solved using a modified least-squares (LS) fit method (Huber function) in which the objective function was the minimization of the residuals between predicted and measured pressure at several system locations, with the decision variables being the hourly variations in water demands. To meet the computational efficiency requirements of real-time hydraulic state estimation for prototype urban networks that typically comprise tens of thousands of links and nodes, a reduced model was introduced using a water system–aggregation technique. The reduced model achieves a high-fidelity representation for the hydraulic performance of the complete network, but greatly simplifies the computation of the PC loop and facilitates the implementation of the online model. ANNs were also used in view of their enhanced capability to match or even improve on the regression model for demand forecast.[96] The ANN models tested in this work were based on MLP-BP (Multilayer Perceptron-Back Propogation) and DAN2 (Dynamic Artificial Neural Network), and the proposed hybrid neural networks consisted of modeling the difference between the Fourier series forecasts and the observed consumption data together with weather variables.

4.4 *Real time leak detection*

Another main advantage of real time data collection is leak detection in WDSs. Different algorithms for leak detection are available in literature since early 20th century. Poulakis et al.[97] proposed a methodology for leakage detection which was based on single/double pipelines formulation and hence cannot be directly applied to network situation.[15] Analysis of the burst induced waves can also be used for localization of bursts. From Bayesian formulation, leak detection algorithms have evolved to GA formulation and ANN based model development. In 2006, Wu et al.[98] formulated an optimization-based approach for quantifying and locating water losses via the process of hydraulic model calibration. The model calibration was done as a nonlinear optimization problem that was solved using genetic algorithm. The method was developed as an integrated framework of hydraulic simulation and optimization modeling. In 2010, Christodoulou et al.[99] proposed a methodology that focused on sustainable management of water networks through real time data acquisition and processing of sensor network data collected from the distribution network. The report was based on the research conducted by Cyprus Research Promotion Foundation. They developed GIS based maps that shows the risk of failure for each segment of the network based on historical data. It uses ANN for data pattern analysis. In 2010, Romano et al.[100] proposed a methodology for real time leak detection in networks. The methodology made use of several Artificial Intelligence techniques including Wavelets for de-noising of the recorded pressure and/or flow signals, ANNs for the short-term forecasting of future pressure and/or flow signal values, Statistical Process Control for the analysis of discrepancies between the predicted and the actually observed signal values, and finally, the Bayesian Network based inference system for classification of discrepancies and raising of alarms. The method was tested on real-life DMA in the United Kingdom. Sun et al.[101] introduced system architecture and operational framework by using magnetic induction based wireless sensor network for underground pipe line monitoring for real time leakage detection. Li et al.[102] used data mining and genetic programming techniques to develop a model for leak detection, early warning and control of pipeline leakage in drinking WDS. Goulet et al.[103] proposed a leak detection and sensor placement methodology based on leak scenario falsification. The method of support vector machine learning is also employed to develop the algorithm for Negative pressure wave (NPW) which could be an indication of leakage in pipelines.[104,105]

4.5 *Real time near optimal control*

Real time, near optimal control of WDS is one field in which prominent research is being carried out recently. It has evolved to be an area of utmost importance as different water authorities around the world have started using sensors which made real time data mining possible. In 2007, Rao et al.[106] proposed a methodology for near optimal control of water networks using real time data. The methodology adopted for rapidly predicting the consequences of different control settings on the performance of the network, was based on replicating a detailed hydraulic simulation model by means of ANN. The objective was to meet the current and forecast demands on the study network at minimal operating cost, without violating any of the physical or standards-of-service constraints. Following the next update of the SCADA facilities, which defines the current state of the network, the whole process was repeated to accommodate any amendments to the demand forecasts. Rolling the process forward at short, regular time intervals gave an approximation to real-time control. This paper describes and demonstrates an efficient method for online hydraulic state estimation in urban water networks.

4.6 *Event detection*

Event detection (contamination) is also an important factor in WDS management; it allows for the identification and localization of accidental and intentional contamination of water networks. There are namely two types of sensors: i) Direct sensors which measure a particular type of contaminant and ii) Surrogate sensors which indirectly detect the presence of one or more contaminants through changes in basic water quality values such as pH, residual chlorine, electrical conductivity, total organic carbon etc. These water quality values change with variation in day to day operation of the system as well as with seasonal changes in source water quality. Event detection systems are used to distinguish between periods of normal and anomalous water quality variability from measures made with surrogate water quality sensors. Online event detection systems mainly consist of two stages: i) the first stage predicts the water quality value for the next time step (*state estimation*) and ii) the second stage compares the real time data with the predicted data and the difference between the two (i. e., *residual*) is used to determine whether the water quality is anomalous or not. In 2010, EPA developed a software named CANARY for event detection in water systems.[107] It can be used to analyze data from sensors in real-time to detect anomalous changes from the baseline of a particular parameter (example: residual chlorine) and provide an indication of potential contamination. CANARY provides a platform within which different event detection algorithms can be developed and tested. Three different state estimation models are implemented in the prediction algorithms used in CANARY, namely time series increments, a linear filter, and a multivariate nearest neighbour algorithm. The linear filter and multivariate nearest neighbor algorithms have proven to be more effective than time series increments. In 2012, Perelman et al.[108] proposed a method for event detection from multivariate time series data. The method utilizes ANNs for studying the interplay between multivariate water quality parameters and detecting possible outliers. The analysis is followed by updating the probability of an event, initially assumed rare, by recursively applying Bayes' rule. The model is assessed through correlation coefficient (R^2), Mean Squared Error (MSE), confusion matrix, Receiver Operating Characteristic (ROC) curves, and True and False Positive Rates (TPR and FPR). These are just a few of the methodologies currently used for WDS analysis and management using sensor data and real time data mining.

The above case study of Bangalore WDS can be further extended by deploying sensors at strategic locations to address key issues like leakage, cross contamination or any other sort of contamination. Data analysis will enable real time control of the system, thereby improving the overall efficiency of Bangalore network. Smart water systems can, in a way, ease the stress on the WDS due to population growth and water scarcity by minimizing leaks, minimizing health impacts due to contamination etc.

5 Way Forward

The urban water supply system is constantly reeling under the stress of supplying adequate reliable safe drinking water. This paper reviews various issues of the urban water supply system and different models/methodologies/tools/algorithms to address the same. Some of the major issues to be addressed to satisfy consumer demand in an urban water supply system are

- Equitable supply of water at different levels
- Leakage and energy minimization
- Pressure and asset management
- Analysis for reliability, resilience and vulnerability of the system
- Managed ground water pumping
- Virus transport and contaminant modeling studies
- Chlorine attenuation under varying flow dynamics
- Sensor placement algorithms for intermittent supply
- Real time control of WDS in case of contaminant intrusion

These issues can be addressed by developing new algorithms or by comparing and re-evaluating the existing models/methodologies/tools/algorithms for different scenarios. By conducting extensive field/laboratory pilot loop and other analytical studies along with development of reliable predictive models, water quality issues can be addressed. Models developed for water quantity and quality management can be coupled with real time data to achieve real time control of the system resulting in increased reliability of the same. An integrated urban water supply management is needed to meet the water demand of a city.

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