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RESEARCH ARTICLE

Management of chlorine dosing rates in urban water distribution networks using online continuous monitoring and modeling

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The aim of this study is to present the results of a research which was undertaken to manage chlorine dosing rates in a real water distribution network using online continuous monitoring and modeling. The study area was divided into 18 district metered areas (DMAs) where the water pressure and flow rate measurements to each DMA were online and continuous. Besides, online water quality sensors were installed at eight different locations and a bimonthly water quality measurement and sampling program was carried out. The data sets required to set, calibrate and verify the hydraulic and chlorine models were derived from the online continuous monitoring and sampling program. Eight chlorine management scenarios that take into consideration the extreme conditions found out during the online monitoring and sampling were utilized. The study revealed that online monitoring provides excellent data sets for chlorine modeling and management that enables automatic application of chlorine dosing.

Keywords: chlorine modeling; management of chlorine dosing; online continuous monitoring; urban water distribution networks

1. Introduction

Chlorine is the most common disinfectant for drinking water as it is cheap, effective, widely available and easy to apply. Application of chlorine as a disinfectant has eliminated many waterborne diseases resulting from drinking water consumption (USCDC, 1997). The aim of disinfection in a water distribution network (WDN) is not only inactivating pathogens but also providing residual against possible contamination of water. Chlorine reacts with both organic and inorganic compounds in water. Inorganic substances such as iron, manganese, sulphide, bromide and ammonia are most reactive with chlorine leading to relatively quick reactions, while reactions of organic substances with chlorine usually proceed at slower rates. As a result of these reactions, chlorine decay in WDNs can be classified under the name of bulk decays (K_b). The bulk decay rates depend on concentrations of both organic and inorganic substances (Clark & Sivaganesan, 2002). Chlorine also reacts with pipe walls, which is known as chlorine wall decay (K_w), and it depends on pipe material as well as attached biofilm, corrosion products if corrosion exists and accumulated sediments (Vasconcelos et al., 1997). A trial and error method for the determination of K_w does not identify the pipes that affect chlorine decay but adjusts wall demand coefficients for each pipe (Shank, 2004). On the other hand, K_w can be precisely determined by in-system measurements in cases of accurate determination of chlorine bulk decay (Liu et al., 2014).

As a result of low chlorine concentrations in WDNs, the risk of waterborne diseases increases in the presence of contamination in water. The presence of high chlorine concentrations in WDNs is associated with the formation of disinfection by-products (DBPs) and some of these DBPs may cause cancer. Further, they may have other chronic and acute adverse health effects to human beings and animals (King & Marrett, 1996). As the cause of aforementioned reasons, chlorine concentrations should be kept within certain limits to minimize health risks. According to the Turkish Standards (CWIHC, 2013), free residual chlorine (FRC) concentrations must be kept between 0.2 and 0.5 mg/L at end points of water distribution network and the concentrations of total trihalomethanes (TTHM) must not exceed the value of 100 μg/L. The standards do not specify any value for FRC at locations other than end points.

Several models have been developed to quantify chlorine decay in WDNs since 1951. Chlorine decay is generally assumed to follow first order reaction with respect to chlorine concentrations (Biswas et al., 1993; Chambers et al., 1995; Haas & Karra, 1984; Rossman, 1993; Rossman et al., 1994; Vasconcelos et al., 1997). In 1980, Wood (1980) developed the first water quality

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model and Males et al. (1985) used his formulation to determine spatial changes determined as a function of travel time and concentration.

In 1988, a water quality model using a dynamic algorithm was developed (Grayman et al., 1988). Following these studies, researchers started to couple water quality and hydraulic simulations for WDNs. The model EPANET, which is capable of performing extended period simulation of hydraulic and water quality behaviors in water distribution networks, was developed by United States-Environmental Protection Agency (US-EPA) in 1993 (Rossman, 1993). Many hydraulic and water quality models which are in use nowadays have been led by the development of EPANET (Grayman, 2006). Chlorine prediction models use hydraulic modeling results, chlorine bulk and wall decay rates as inputs. Therefore, a well calibrated hydraulic model is required for water quality modeling (Males et al., 1988). Water quality models should be calibrated to verify chlorine bulk decay rates which can be determined by laboratory studies. However, chlorine wall decay rates are usually estimated during the calibration steps.

Several processes affect water quality during its distribution. These processes and factors are little known. Therefore monitoring of drinking water quality in WDNs becomes an important issue to ensure compliance with national standards and WHO guideline values (Aisopou et al., 2012). Chang et al. (2012) mentioned about the importance of continuous monitoring of drinking water quality in WDNs and developed a new method for sensor deployment. Szabo and Hall (2014) carried out a study focusing on the benefits and gaps of total organic carbon (TOC) and total/free chlorine which are presented as the most effective online monitoring parameters. Yamanaka et al. (2012) carried out a modeling study using stochastic demand determination. They compared the results with field observations and the results from deterministic models. In their study, applied models to the drinking water system in the city of Culiacan, Sinaloa were supplied with online measurements of flow rate at the water sources and internal points of supply system. Water quality measurements and quantitative flow measurements were carried out for seven days at water sources and the distribution network. Afshar and Marino (2012) set up a multi objective ant colony optimization algorithm to determine the optimal location of monitoring stations in WDNs.

The chlorine dosing rates for drinking water are generally determined from the experiences of water operators and the monitoring results of residual chlorine concentrations in the WDN. This method of operation is inappropriate because insufficient chlorine dosing rates

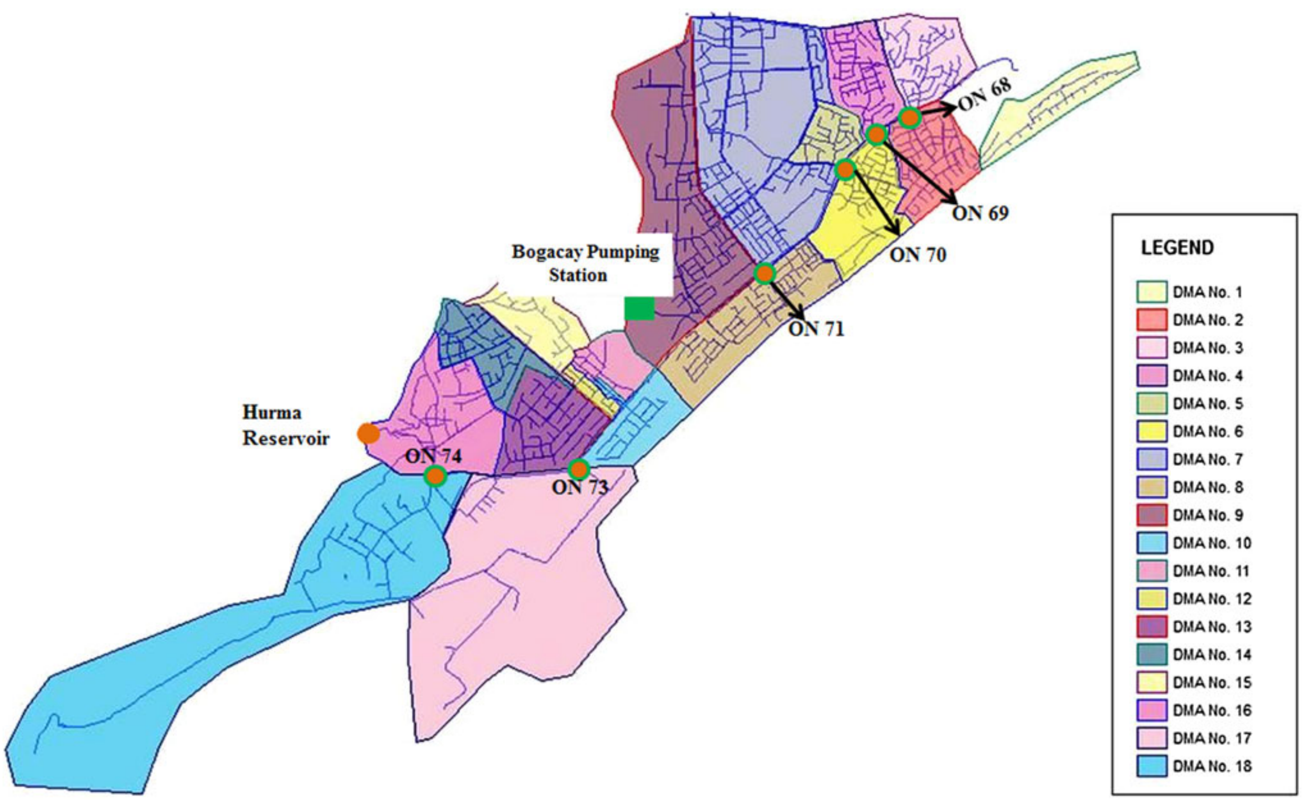

Figure 1. Map showing Konyaalti water distribution system with SCADA water quality monitoring stations (ON), district metered areas (DMAs), reservoir and pumping station.

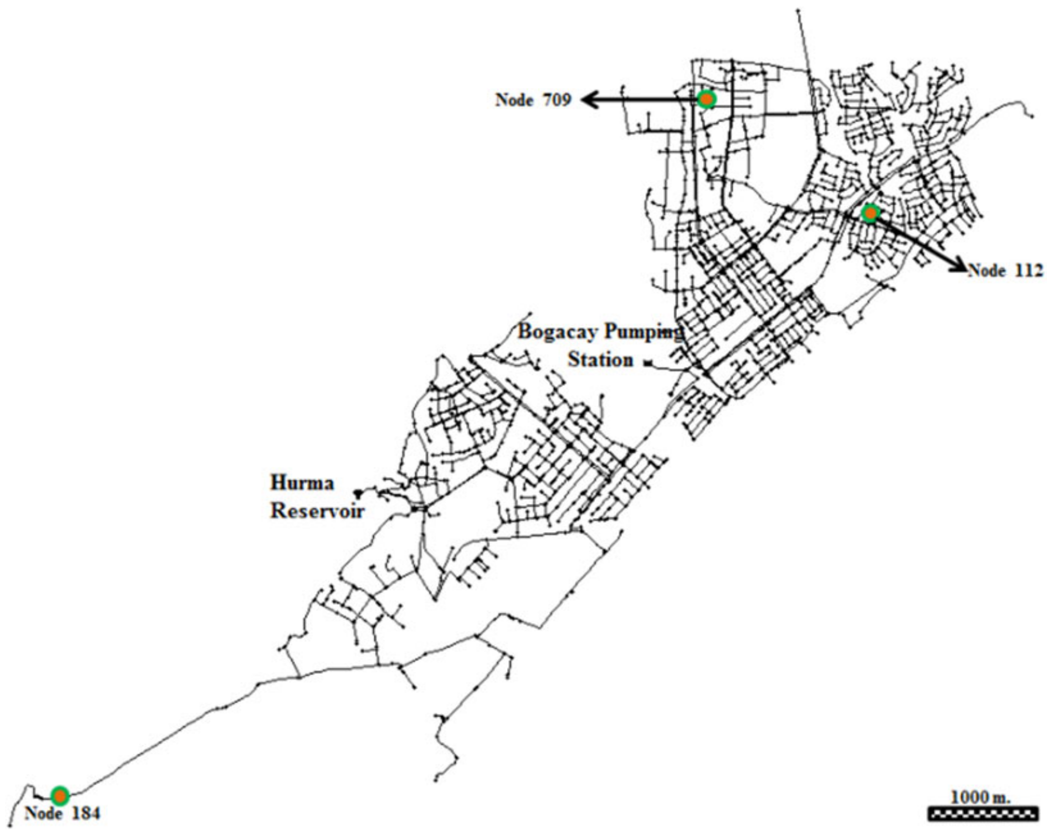

Figure 2. Water distribution network of the pilot study area and locations of nodes used for description.

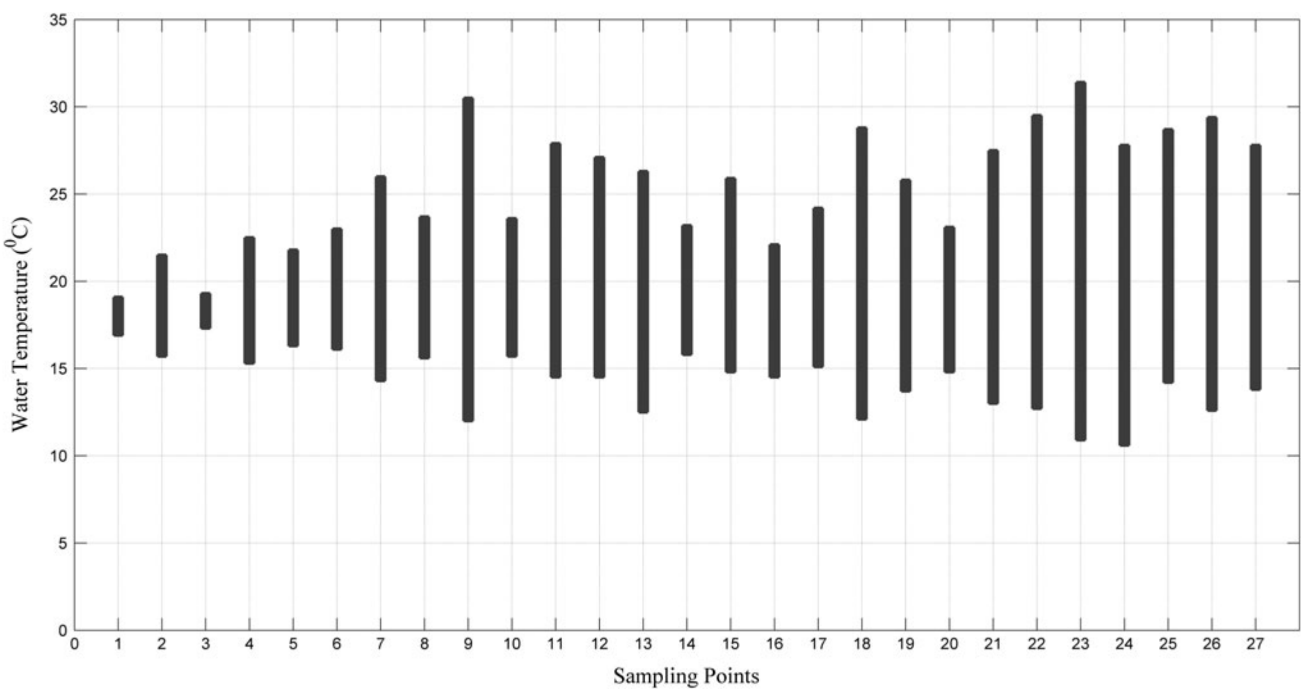

Figure 3. Measured water temperature values in the pilot study area.

Table 1. A comparison of Konyaalti water distribution system water quality with WHO guidelines and Turkish standards (updated from Soyupak et al., 2011).

Parameter	Unit	Observed Range			Ministry of Health Regulation Concerning Water Intended for Human Consumption (2013)	WHO Guidelines for Drinking Water Quality (2011)
		Min	Average	Max		
Temperature	°C	10.6	20.18	31.4		–
pH		7.29	7.51	7.95	6.5 and 9.5	–
DO	mgO2/L	3.95	5.70	9.15	–	–
EC	µS/cm	547	593	651	2500	–
Salinity	‰	0.1	0.1	0.1	–	Recommended chloride concentration,250 mg/L
Turbidity	NTU	0.08	0.2	0.55	–	–
FRC	mg/L	0.06	0.33	0.78	0.2 and 0.5 on dead point	Min. 0.2 on dead point (recommendation)
Total Chlorine	mg/L	0.08	0.36	0.80	–	–
NH_4	mg/L	0.00	0.02	0.38	0.50	–
NO_2	mg/L	0.002	0.017	0.055	0.5	3
NO_3	mg/L	3.05	9.82	17.8	50	50
Total Kjeldahl N	mg/L	0.28	1.09	5.60	–	–
Ortophosphate-P	mg/L	<0.01	<0.01	0.15	–	–
Total-P	mg/L	<0.01	<0.01	0.43	–	–
Fe	mg/L	0.01	0.02	0.07	0.2	–
Mn	mg/L	0.001	0.017	0.038	0.05	0.05
TTHM	µg/L	10	15	23	100	Chloroform 300, Bromoform 100, Dibromochlorometan 100, Bromodichlorometan 60
TOC	mg/L	0.10	0.34	1.02	No abnormal change	–
Bromide	mg/L	<0.02	<0.02	0.0539	–	–
Total coliform	CFU/100 ml	0	0	0	0	0
Fecal coliform	CFU/100 ml	0	0	0	0	–

could be adjusted only sometime after the residual chlorine concentration in the network is detected to lie outside a desirable range. Therefore, it would be useful to predict the right dosing rates that always keep residual chlorine levels within the required range. In this study, EPANET model was used as a decision tool for the determination of optimum chlorine dosing in a real WDN to achieve FRC that comply with the Turkish Standards. The input data sets required for modeling and management of chlorine were collected from a number of on-line continuous monitoring stations and from sampling and measurement sessions.

1.1 Basis for modeling chlorine kinetics by EPANET

Although the reactions of chlorine with other constituents present in water are extremely complex, literature offers simplistic modelling approaches for decision makers and planners. The general equation for one dimensional advection-dispersion mass transport along with reaction for dissolved substances in water is given in Equation (1). EPANET (Rossman, 2000) assumes any dissolved substance will travel along the length of pipes of networks with the same average velocity of bulk fluid flow with some given reaction rate and it neglects transport due to the longitudinal dispersion. Therefore, EPANET assumes a simplified version of general one dimensional advection-dispersion and reaction as given in Equation 2.

$$\frac{\partial C_i}{\partial t} = D\frac{\partial^2 C_i}{\partial x^2} - u_i\frac{\partial C_i}{\partial x} - r(C_i) \tag{1}$$

$$\frac{\partial C_i}{\partial t} = -u_i\frac{\partial C_i}{\partial x} - r(C_i) \tag{2}$$

where C_i = concentration of dissolved matter (mass/volume) in pipe i (in our case it is FRC); t = time; D = dispersion coefficient (length^2/time); u_i = velocity (length/time) in pipe i; x = distance (length); $r(C_i)$ = reaction rate in pipe i (1/time) as a function of concentration C_i.

A detailed review of formulations of chlorine decay kinetics is given by Rossman (2000) within the EPANET user's manual. A summary of formulations pertaining to the first order kinetics assumption applicable for this specific study is presented here. Research on reactions of FRC of water transporting in network pipes revealed two major types of chlorine decay: a) Bulk flow reactions (K_b) and, b) Pipe

Table 2. Statistical analysis for the results of chlorine bulk decay coefficient experiments.

Season	May 2009			August 2009			March 2010
Water Temperature (°C)	15	20	30	15	20	30	20
Number of samples	21	36	21	36	31	26	15
Regression equation	Y = 0.0588 − 0.06758.X	Y = −0.0121 − 0.06808.X	Y = −0.0113 − 0.16098.X	Y = −0.0561 − 0.06082.X	Y = 0.0237 − 0,16296.X	Y = −0.0572 − 0.23696.X	Y = −0.1380 − 0.16365.X
K_b (day^{-1})	0.06758	0.06808	0.16098	0.06082	0.16296	0.23696	0.16365
R^2	0.956	0.985	0.972	0.987	0.968	0.981	0.958
Adjusted R^2	0.954	0.984	0.970	0.987	0.966	0.980	0.955
Standard error of the estimates	0.03434	0.03922	0.06174	0.03908	0.11515	0.10718	0.06940
Total sum of squares	0.510	3,436	2.550	4,016	11,858	14,296	1,493
Mean squares	0.487	3,383	2,478	3,964	11,473	14,020	1,430
F test statistics	413.242	2198.91	650.113	2596.11	865.287	1220.54	296.94
Significance degrees of regressions (Sig. or P value)	Very High (0.000)	Very High (0.000)	Very High (0.000)	Very High (0.000)	Very High (0.000)	Very High (0.000)	Very High (0.000)

wall reactions (K_w) that occur while chlorinated water flows within pipes. The reaction rate term for K_b can be expressed in the following most general form:

$$r(C_i) = K_b C_i^n \tag{3}$$

where C_i^n = reactant concentration in the pipe (mass/volume); K_b = bulk rate of reaction; n = reaction rate order. EPANET assumes the following general equation for the rate of water quality reactions near or at pipe wall as a function of bulk flow concentration of dissolved reactant:

$$r(C_i) = (A/V) K_w C_i^n \tag{4}$$

where K_w = a wall reaction rate coefficient; (A/V) = the surface area per unit volume within pipe (= $2/R_i$); R_i = pipe diameter (length). The software EPANET has two options for the order n: either 0 or 1. Therefore, K_w assumes the units of either (mass/length^2/time) or (length/time). The literature cites K_w to range in between 0 to 1.52 m/day, depending upon the condition and age of the pipe.

The rate of a pipe wall reaction can be re-formulated by Equation (5) under the assumption of first order kinetics (Rossman et al., 1994) considering the mass transfer limitation:

$$r(C_i) = \frac{2 K_w K_f C_i}{R_i (K_w + K_f)} \tag{5}$$

where K_w = wall reaction rate constant (length/time); K_f = mass transfer coefficient (length/time). EPANET calculates K_f value internally as a function of Sherwood number which is a function of Reynold's number, pipe diameter and molecular diffusivity. EPANET assumes the magnitude of molecular diffusivity to be 1.

2. Materials and methods

2.1 Pilot study area

Konyaalti water distribution network (KWDN), which serves nearly 60 thousand people and operated independently from the rest of Antalya city, was chosen as a pilot study area for applying this study. KWDN has reliable network information and is one of the major sub-networks of Antalya WDN. The network has approximately 200 km pipe network with different pipe materials such as iron, PVC and HDPE. There is one balancing reservoir namely Hurma balancing reservoir with 15,000 m^3 storage capacity which is used to balance supply with demand.

Extracted water from five groundwater wells is pumped to the KWDN after chlorination at Bogacay pumping station using sodium hypochlorite solution (Karadirek et al., 2012a, 2012b). There is no need for water treatment as the abstracted water has high water quality (Kitis et al., 2010; Soyupak et al., 2011;

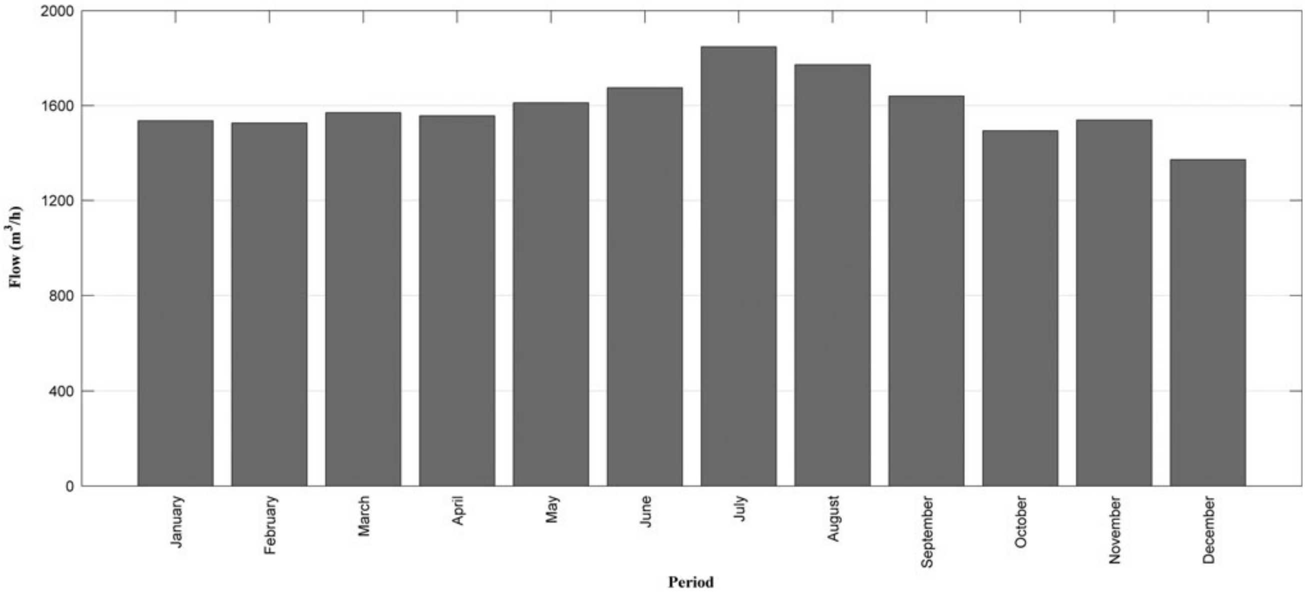

Figure 4. Average monthly flow rates supplied to the pilot study area.

TUBITAK, 2011). The purpose of chlorination is to protect the potable water from any possible contamination during its distribution to the customers.

Total water losses which consist of physical and apparent losses in KWDN are around 45% of system input volume (SIV). This percentage is very close to the experienced average percent for Turkey. Physical water losses are mainly due to leakages from transmission and distribution mains along with leakages on service connections and are summed up to 30% of SIV in KWDN (Kanakoudis & Muhammetoglu, 2013). The pilot study area has been divided into 18 district metered areas (DMAs) to manage both water losses and water quality (Karadirek et al., 2012a; TUBITAK, 2011). The DMAs and main components of KWDN are also depicted in Figure 1.

2.2 Online continuous monitoring and sampling

There is an efficient supervisory control and data acquisition system (SCADA) infrastructure in the study area which facilitates online continuous monitoring and control of physical components of WDN such as pumps, balancing reservoir, valves and water mains. In the pilot study area, each DMA is equipped with sensors for the online continuous measurements of flow rates, and water pressures. Moreover, water levels in *Hurma Balancing Reservoir* and the flow rates entering the reservoir are continuously measured. Additionally, there are water quality sensors for the online continuous measurements of FRC, pH, water temperature, turbidity and electrical conductivity at the entrance to six DMAs located at ON 68, ON 69, ON 70, ON 71, ON 73, and ON 74, Bogacay pumping station and Hurma balancing reservoir, as depicted in Figure 1. The measured data sets are sent wirelessly to the SCADA center at Antalya Water and Wastewater Authority (ASAT) for evaluation and storage for further analyses.

Besides the online continuous measurements, an extensive field and lab sampling and analyses sessions were conducted bimonthly for 30 months starting from July 2008 to December 2010 at a total of 27 sampling and measurement stations representing the WDN in the study area both before and after the chlorination process. *In situ* measurements of water temperature, pH, dissolved oxygen (DO), salinity, turbidity, electrical conductivity, FRC and total residual chlorine concentrations were realized at all the measurement and sampling stations. Chlorine measurements were conducted using HACH DR/890 portable colorimeter.

Parallel to the field measurements, water samples were collected from the same stations bimonthly for 30 months and analyzed for many parameters such as nitrogen and phosphorus compounds, iron, manganese, TOC, trihalomethanes (THM), UV_{254}, bromide, total and fecal coliforms.

2.3 Hydraulic modeling

The EPANET 2.0 hydraulic and water quality model developed by US-EPA (Rossman, 2000) was applied to the pilot study area to predict water velocities, flow rates and water pressures. Physical configuration of the study area such as pipe diameters, coordinates of nodes, balancing reservoir, pipe lengths and vertexes were obtained from ASAT Geographical Information System (GIS). Nodal demands were calculated taking into consideration the online continuous flow rate measurements and the water

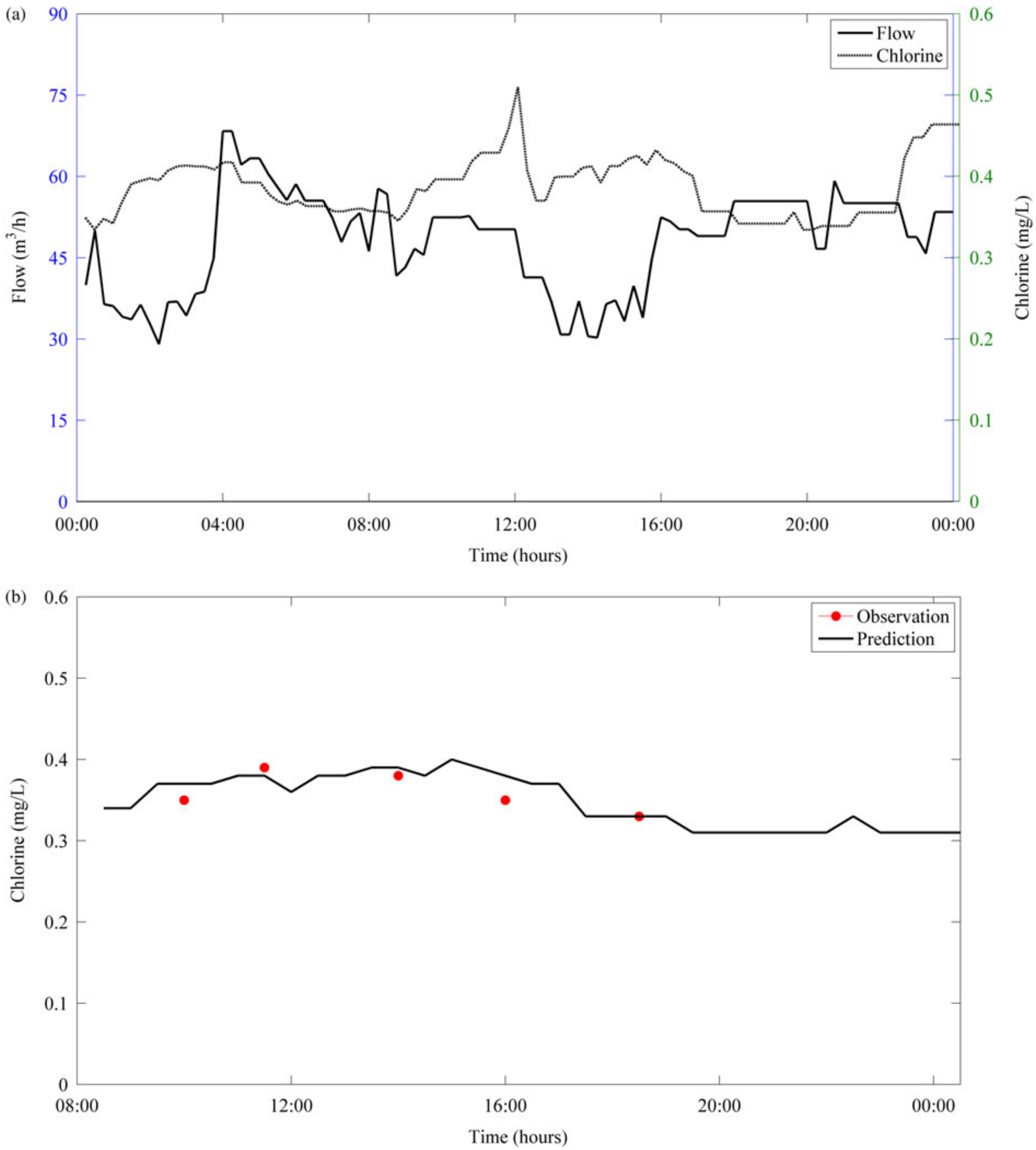

Figure 5. a) Measured chlorine concentrations and flow rates at the entrance to DMA 6 (ON 70) between February 22nd and 23rd, 2010, b) Model predictions and observations of chlorine concentrations at Node-112 on February 23rd, 2010 (MAE = 0.014 mg/L).

bills of subscribers which are recorded monthly. Temporal and spatial changes in flow rates which help in estimating demand patterns were obtained from the online continuous monitoring of flow rates. Configured hydraulic model for the pilot study area in EPANET 2.0 model is depicted in Figure 2. Hydraulic model calibrations and verifications were conducted by comparing online continuous water pressure measurements with model predictions. Additional *in situ* measurements of water pressures were conducted at different points using accurate portable pressure meters. Moreover, fire hydrants were also opened to create additional flow rates and the changes in water pressures were monitored and compared with model predictions. Further details of hydraulic model calibration, verification and application to the pilot study area are given elsewhere (Karadirek et al., 2012a).

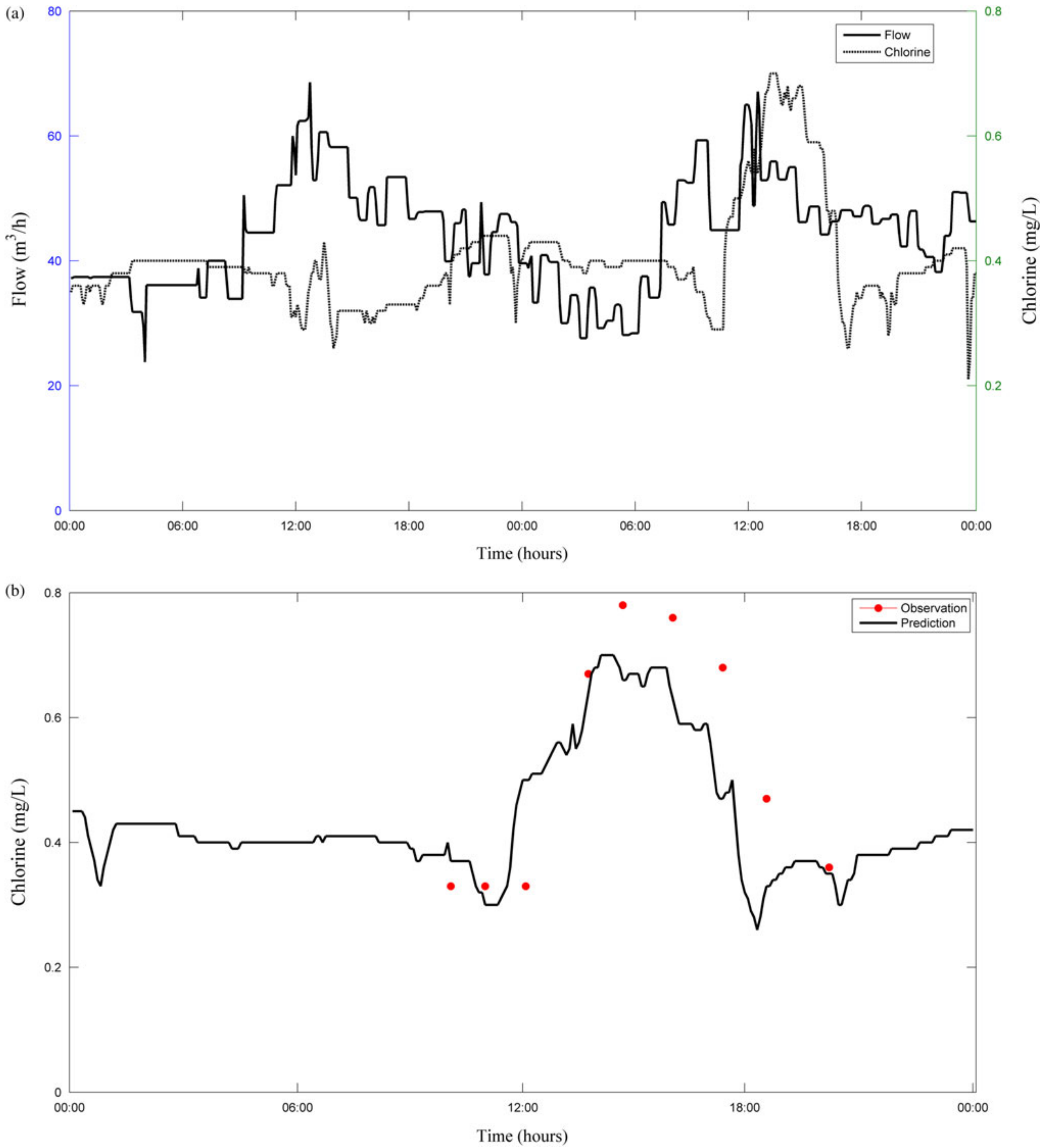

Figure 6. a) Measured chlorine concentrations and flow rates at the entrance to DMA 6 (ON 70) between Dec 6th and 7th, 2009 b) Model predictions and observations of chlorine concentrations for node-112 during perturbation period on December 7th, 2009 for 24 hours (MAE = 0.098 mg/L).

2.4 Chlorine modeling

2.4.1. Determination of chlorine bulk decay coefficient

Modeling of chlorine in WDNs requires input of two chlorine decay coefficients; namely chlorine bulk decay coefficient (K_b) and chlorine wall decay coefficient (K_w). K_b can be easily determined in the lab whereas K_w is usually determined by estimation and calibration. K_b is affected by factors such as water temperature, initial chlorine concentration, types and concentrations of

Table 3. Management scenarios applied in the study area to determine chlorine dosing rates.

Management scenarios	Application period	Flow rate (m^3/h)	Water temperature (°C)	K_b (day^{-1})
Scenario 1	July 2010 (max. water consumption with max. water temperature)	1847.75	30	0.19897
Scenario 2	June 2010 (min. water consumption with max. water temperature)	1674.64	30	0.19897
Scenario 3	December 2010 (min. water consumption)	1372.54	20	0.13156
Scenario 4	July 2010 (with reduction of physical water losses)	1478.20	30	0.19897
Scenario 5	June 2010 (with reduction of physical water losses)	1339.71	30	0.19897
Scenario 6	December 2010 (with reduction of physical water losses)	1098.03	20	0.13156
Scenario 7	July 2010 (with K_b multiplied by five)	1847.75	30	0.99485
Scenario 8	December 2010 (with K_b multiplied by five)	1372.54	20	0.65780

organic and inorganic substances present in water that react with chlorine.

As an initial step before the modeling study of chlorine concentrations in KWDN, K_b values of the distributed water were determined in the lab. Raw water samples were collected from Bogacay pumping station in the pilot study area, before chlorination. The water samples were dosed with sodium hypochlorite dispensed into opaque glass bottles which do not react with chlorine leaving no headspace. Afterwards, the samples were stored in three different incubators at the same initial time set at 15, 20 and 30°C. These temperatures represent the average water temperature (20°C) and the extreme water temperatures (15°C and 30°C) of the distributed water in KWDN as determined by the accomplished *in situ* measurements. Total and FRC analyses were conducted at short intervals where analyses were carried out in duplicate and the average values were used. Determination of K_b was repeated at three different periods namely in May 2009, August 2009 and March 2010 to examine the impacts of seasonal water quality variations on the magnitudes of K_b. First order decay kinetics was used for the determination of K_b.

2.4.2. *Model calibration and verification*

In this study, EPANET 2.0 was used to model and manage chlorine concentrations in the pilot study area. Model calibration was performed to estimate chlorine wall decay coefficient, K_w, by trial and error. Both online continuous and numerous *in situ* measurements of FRC were used to compare with model predictions of FRC. The model was first calibrated to the DMAs that were equipped with online continuous monitoring of both flow rates and FRC. Afterwards, the calibration was extended to include the whole network of KWDN. The calibrated K_w value was verified using different data sets of FRC measurements obtained from the online continuous monitoring and additional *in situ* measurements. Additionally, a chlorine perturbation was applied by increasing the chlorine dosage at Bogacay pumping station above the normal level deliberately for a short period to increase FRC levels and examine the prediction capabilities of the hydraulic and water quality model, as explained in the following sections.

3. Results and discussions

3.1 Field and lab measurement and analyses

Average tap water temperatures obtained from the bimonthly monitoring study at 27 sampling and measurement stations of the study area are depicted in Figure 3. The average measured tap water temperature was around 20°C and the minimum tap water temperature was somewhat below 15°C in winter season while the maximum tap water temperature slightly exceeded 30°C in summer season. Accordingly, these three temperatures of 15, 20 and 30°C were used for determination of K_b in the lab and for chlorine management scenarios as explained in the next sections.

The results of the lab analyses of the water quality parameters in KWDN and their comparison with the related standards are presented in Table 1. The levels of TOC, bromide, Fe, NH_4 and turbidity are very low which implies low chlorine demand, and hence low K_b values.

K_b values were examined at three different temperatures and three different periods namely May 2009, August 2009 and March 2010. The results show minor variations between the three different periods. Average K_b value at 20°C was determined as 0.13156/day while it was determined as 0.19897/day at 30°C and 0.06420/day at 15°C (Altindal, 2010). Statistical analysis for the results of chlorine bulk decay coefficient experiments is given in Table 2. The results of statistical analysis support the assumption of chlorine first order decay kinetics. K_b values reported in the literature at 20°C vary from 0.082/day to 17.7/day (Tiryakioglu, 2005) and therefore the determined K_b values of KWDN are very low. Low K_b values are justified by the bimonthly lab analyses results which proved that the drinking water at KWDN has very high quality, as presented in Table 1.

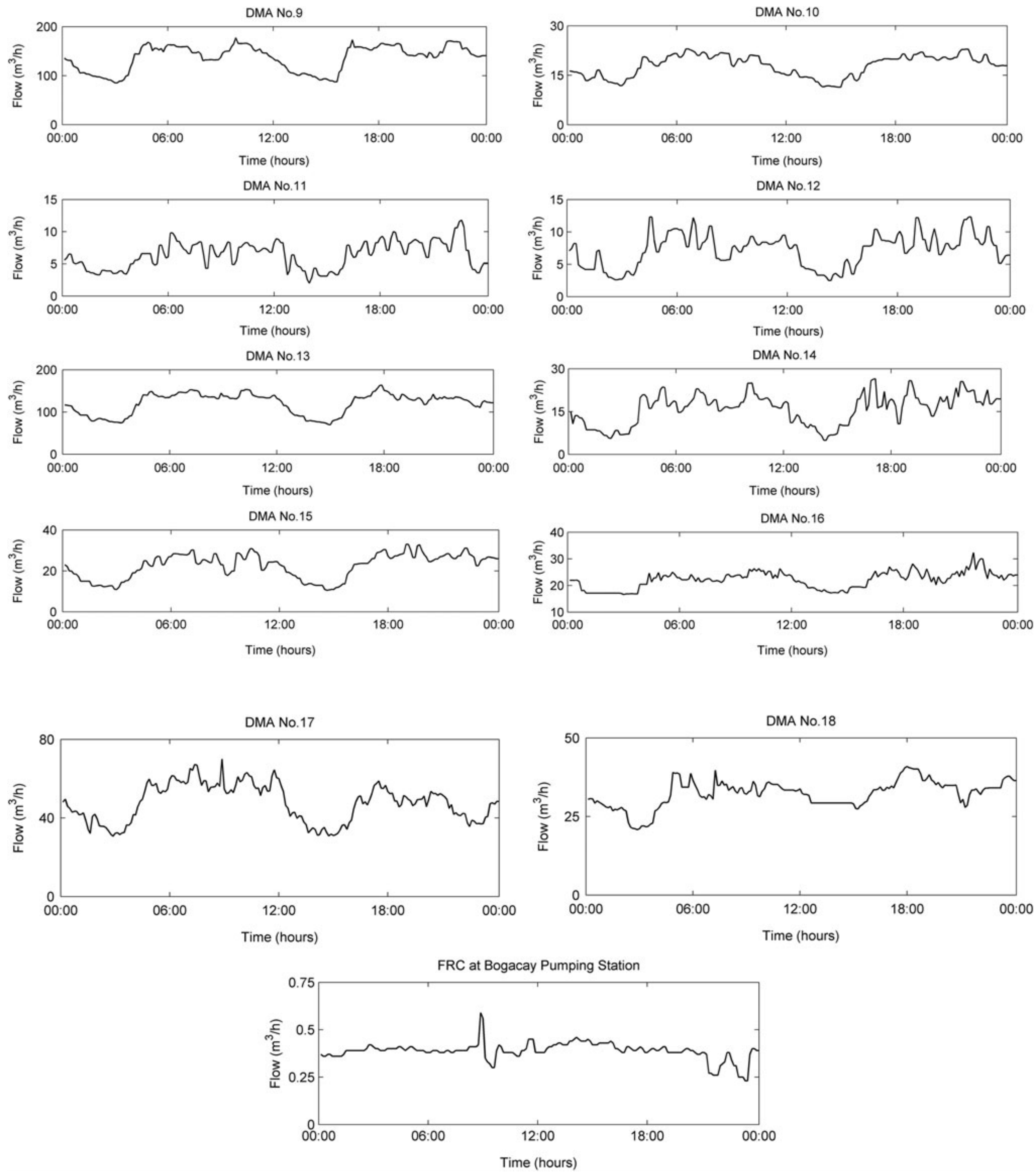

Figure 7. Profiles of flow rates and chlorine concentrations at the chlorine injection station for Scenario 1 between July 20th and 21st, 2010.

The water supplied to KWDN is continuously measured online and recorded by the SCADA system. The monthly average flow rates of water supplied to KWDN in 2010 is depicted in Figure 4. The maximum averaged monthly flow rate in KWDN was around 1800 m^3/h as measured in July, while the minimum averaged monthly flow rate was measured around 1400 m^3/h in December.

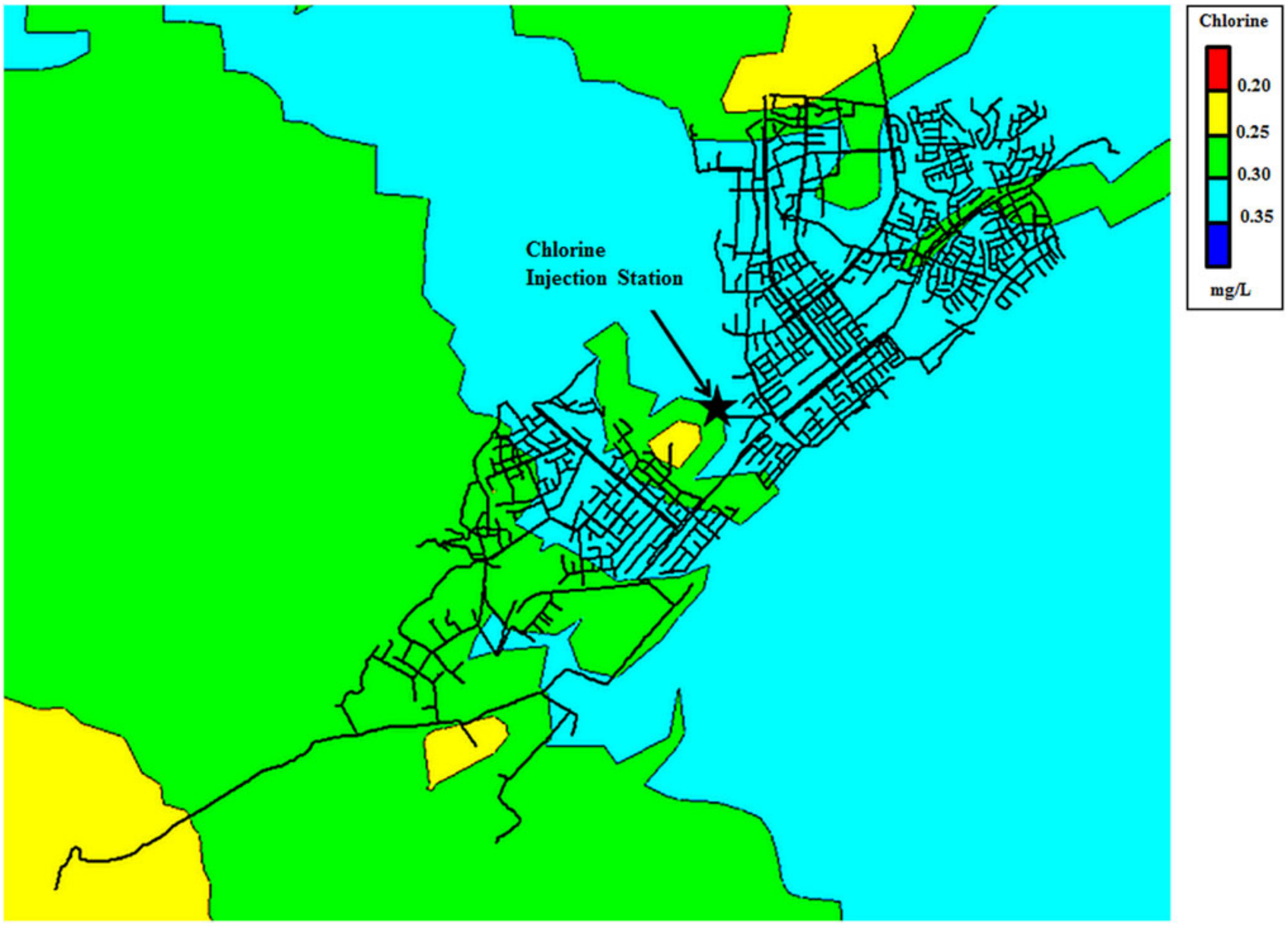

Figure 8. Spatial changes in chlorine concentrations for Scenario 1 at 11:00 pm on July 21st, 2010 (Scenario 1, chlorine dosage 0.35 mg/L at *Bogacay Pumping Station*).

3.2 Chlorine management

In the study area of KWDN, the aim of chlorine management was (i) to determine chlorine dosing rates at the chlorine injection station of the pilot study area which is Bogacay pumping station, (ii) to predict the spatial and temporal changes in chlorine concentrations all over KWDN, (iii) to apply the minimum possible chlorine dosing rates while always complying with the related Turkish standards for chlorine disinfection, and keeping a minimum FRC above 0.2 mg/L all over the KWDN as recommended by WHO (WHO, 2011).

3.2.1. Chlorine modeling

K_w was determined through model calibration by comparing a series of model predictions with field observations of FRC. K_w of 0.01 m/day resulted in the least mean absolute error (MAE) and was found by trial and error. Figure 5 shows a comparison between model predictions and observations at Node 112 in DMA 6. A chlorine perturbation was performed by increasing chlorine dosing rate above normal values at the chlorine injection station (Bogacay pumping station) for a short period. A comparison of chlorine predictions and observations at Node 112 in DMA 6 during the perturbation period is depicted in Figure 6 as an example. In Figure 6b, model predictions exhibited a discrepancy with observations particularly for higher values of FRC due to response time of the online FRC analyzers and relatively long time step of 15 minutes used for both hydraulic and chlorine models. Moreover, a model verification process was applied using different data sets than the data sets used for calibration process. Model predictions of FRC showed good agreement with observations.

3.2.2. Chlorine management scenarios

FRC levels in WDNs are affected by a number of factors such as chlorine dosage applied at the source, water age, chlorine bulk decay coefficient (K_b) and chlorine wall

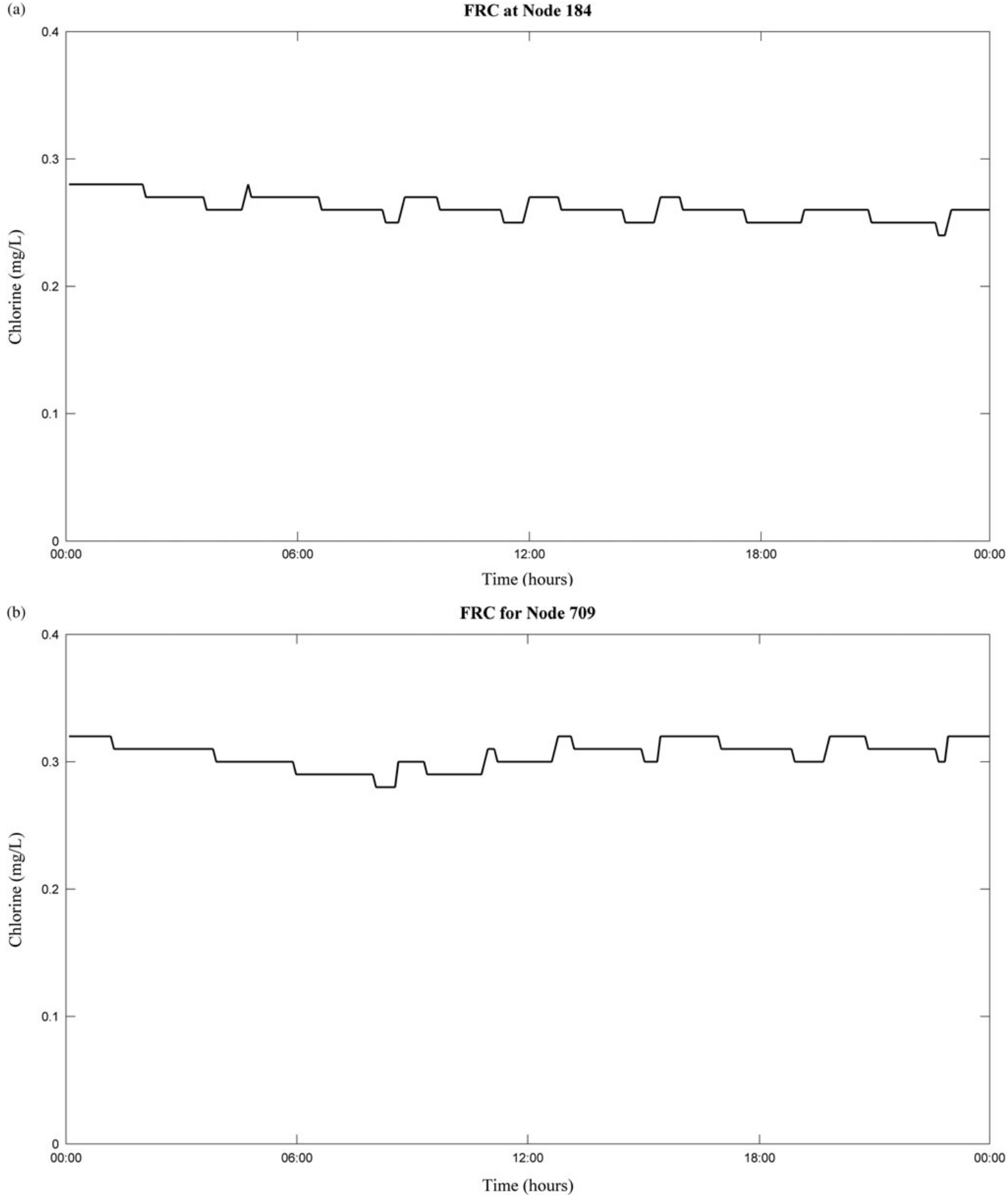

Figure 9. Temporal variations of FRC on selected nodes of the study area on July 21st, 2010 (Scenario 1, chlorine dosage 0.35 mg/L at *Bogacay Pumping Station*).

Table 4. Required FRC concentrations at the source (*Bogacay Pumping Station*) for the chlorine management scenarios.

Scenario	1	2	3	4	5	6	7	8
FRC (mg/L)	0.35	0.45	0.35	0.35	0.45	0.35	0.60	0.45

decay coefficient (K_w). Water age is determined by water velocity or flow rate. In the study area, there were minor seasonal changes of K_b at a fixed temperature as mentioned previously. However, water temperature exhibited wide yearly variations from 15°C to 30°C which affects the value of K_b. At higher water temperatures, higher K_b values occur. Therefore, the maximum K_b value was obtained at 30°C in KWDN. Accordingly, the impact of water temperature changes on the value of K_b was considered in chlorine management scenarios. Although K_w is temperature dependent, impacts of temperature variations were neglected in this case study because the calibrated K_w is extremely low.

Eight management scenarios taking into consideration the extreme conditions of flow rates, water temperature and possible reduction in physical water losses were adopted in KWDN to manage chlorine concentrations and to determine chlorine dosing rates, as listed in Table 3. It can be seen that the maximum daily flow rate in 2010 was recorded as 1847.75 m^3/h while the minimum daily flow rate was measured as 1372.54 m^3/h in the same year.

Scenario 1 takes into consideration the maximum daily flow rate which occurs in July. In this month, water temperature is measured as 30°C. Scenario 2 takes into consideration the minimum flow rate that occurs when the water temperature is 30°C, which occurs in June. Scenario 3 takes into consideration the minimum daily flow rate which occurs in December. In this month, water temperature was measured as 20°C. Scenario 4, 5 and 6 are similar to Scenarios 1, 2 and 3; respectively but physical water losses were reduced to 10% of SIV. Scenarios 7 and 8 take into consideration possible contamination of water supply. Therefore, K_b values of Scenarios 1 and 3 were increased five-fold to represent possible contamination impact on chlorine decay.

3.2.3. Chlorine management results

Following calibration and verification steps, the model was applied to the whole KWDN as needed for management purposes. In this application, the online continuous measurements of flow rate at 18 locations (at the entrance of each DMA) in KWDN and the online continuous measurement of FRC only at Bogacay pumping station were used as input values for the model. The model could predict the spatial and temporal variations of FRC all over the KWDN.

Figure 7 gives an example for the profiles of flow rates and FRC concentration at Bogacay pumping station which are used as input values to develop Scenario 1. FRC concentrations at Bogacay pumping station were changed by trial and error until a minimum value of FRC as 0.2 mg/L was achieved in KWDN. In this scenario, the required FRC at Bogacay pumping station was found as 0.35 mg/L. Figure 8 shows the spatial changes in chlorine concentrations all over KWDN for Scenario 1, while Figure 9 shows the temporal variations of FRC at two nodes, as an example.

Similarly, the calibrated and verified chlorine model was used to determine the required FRC concentrations at Bogacay pumping station for each chlorine management scenario. For each management scenario, FRC concentrations at Bogacay pumping station were changed by trial and error until a minimum value of FRC as 0.2 mg/L in KWDN was achieved. The results show that the required FRC concentrations at Bogacay pumping station range between 0.35 and 0.45 mg/L for all the scenarios when there is no water contamination, as given in Table 4. For the sake of easy application and considering the measurement error of the online chlorine analyzers, it was decided to apply chlorine dosage that leaves FRC as 0.40 mg/L in winter season, 0.50 mg/L in summer season and between 0.40 and 0.50 mg/L in other seasons. Consequently, the responsible managers of the water authority (ASAT) have installed automatic chlorine dosing equipment to replace the manual application, according to the results of this study.

4. Conclusion

This paper presents a real case application of a combined hydraulic and chlorine modeling study where both online continuous hydraulic and water quality monitoring data sets and subsequent bimonthly water quality monitoring results were utilized for model calibration and verification purposes in addition to evaluation of water quality. Determination of both bulk decay and wall decay rates of chlorine were presented and discussed which are important model input parameters to predict chlorine concentrations in WDNs. Accurate determination of chlorine dosing rates is essential to keep FRC concentrations within the required limits in water distribution networks and to comply with the related standards. This can be achieved only by dynamic hydraulic and chlorine modeling. A well calibrated and verified model is crucial for efficient chlorine management. Online continuous monitoring facilitates excellent data sets for model calibration and verification. Additionally, the presence of DMAs helps to calibrate and verify the model, as the application starts from small scale with controlled data sets and later it extends to the whole network. Chlorine management should take into consideration extreme conditions of flow rate, impacts of water temperature on chlorine decay rates, possible reduction of water losses and possible contamination of the distributed water. Water authorities should adapt modeling for chlorine management and should benefit from the monitored data sets in calibrating and verifying the model and for establishing valid chlorine management scenarios. This study is expected to contribute to the literature by presenting a viable approach for better management of chlorine levels in water distribution networks.

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