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Chlorine residual management for water utilities using GIS, SCADA and modeling tools

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ABSTRACT

The aim of the current study is to demonstrate that managing chlorine in a water distribution network (WDN) can be done using GIS, SCADA and hydraulic/water quality modeling. For this purpose, EPANET hydraulic and water quality software was applied to a certain section of Antalya WDN using data sets obtained from SCADA and GIS. The model calibration and verification were carried out using both on-site manual and online measurements of flow rates, water pressures and free residual chlorine concentrations. Comparison of modeling results with field measurements in the study area showed that model predictions are in line with field measurements. Based on this study, the developed system can be considered as a useful tool for water utilities, planners and decision makers for similar applications in other regions.

Keywords: Chlorine; Drinking water distributions network (WDN); GIS; Modeling; SCADA

1. Introduction

Chlorination is a widely common practice for disinfection in drinking water distribution networks (WDN) [1,2]. The free residual chlorine concentration (FRC) in WDN is an important parameter for deciding if water disinfection is enough or not. Although chlorine is very effective against diseases and pathogens in water, it interacts with natural organic compounds and results in harmful chemicals (disinfection by products—DBPs) that may cause detrimental effects on health at the same time [3–5]. Specialized clinic research results indicated that DBPs must be blamed for cancer risks [4,6,7].

On the other hand, having low and insufficient chlorine concentrations in a WDN may not adequately disinfect the water, while it poses public health risks. Consequently, providing certain level of chlorine concentration in a WDN requires efficient monitoring systems and careful management of the WDN. Generally, a FRC concentration exceeding 0.2 mg l^{-1} must be maintained all over the distribution system, thus reducing the likelihood of possible contamination [8–10].

The US-EPA EPANET software is widely used in the WDN modeling studies [11–14]. Accurate definition of chlorine bulk decay (K_b) and chlorine wall decay (K_w) coefficients are important factors to chlorine modeling. Also, determination of K_b and K_w coefficients and accurate hydraulic modeling are crucial to improve prediction accuracy of chlorine modeling [15,16]. The calibration of the WDNs with different types and ages of pipes is rather difficult [17].

K_w coefficient depends on pipe material, size and service age [18,19]. The coefficient is higher for older pipes than younger pipes due to corrosion and deposition. K_b coefficient is affected by organic and inorganic contents of water [18]. Therefore, both coefficients and related factors have been investigated in numerous studies [15, 20–26]. The impact of water demand was much less than the impact of K_b coefficient in the study conducted by Blokker et al. [20]. Several chlorine decay model and coefficients were investigated for various hydraulic conditions by Kim et al. [21]. K_b and K_w coefficients were found as 0.13156 d^{-1} and 0.01 m.d^{-1} at 20°C for Antalya Konyaaltı WDN [22] while K_b values ranged between 0.09 and 0.53 d^{-1} in the

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study carried out by Cooper et al. [23]. Also, the impacts of water quality, pipe material, pipe size and flow conditions on K_b and K_w coefficients were investigated by Arevalo [24]. K_b values varied from 0.0301 to 1.23 d^{-1} while temperatures varied from 0 to 30°C in the study conducted by Xin et al [25]. Chlorine decay was also investigated in details in the study carried out by Kowalska et al. [26]. K_b and K_w change widely with temperature changes. Therefore, the impact of temperature on the levels of K_b and hence chlorine decay was considered for chlorine dosing management by Karadirek et al. [22].

Antalya is one of the most important touristic cities in Turkey along the Mediterranean coast. Groundwater is the only drinking water resources in Antalya that has high water quality. Antalya water and wastewater administration (ASAT) is responsible to provide water and wastewater services to the city. The WDN in the city has good monitoring and control by supervisory control and data acquisition (SCADA) system. The on-line data sets obtained from the monitoring stations are transferred through a wireless connection to the SCADA control center for analyses and storage. ASAT is interested in achieving good management of chlorine disinfection all over Antalya city WDN. A recent study was conducted to manage chlorine dosing rates at Antalya Konyaaltı WDN [22]. In this current study, management of chlorine residual was carried out for another different WDN than Konyaaltı WDN in terms of water source, hydraulic conditions, operation and network size.

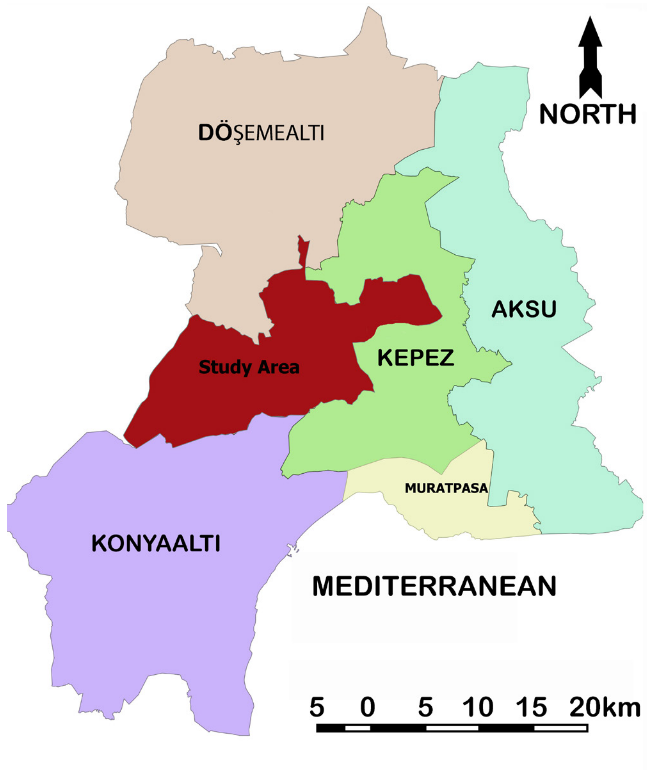


Fig. 1. PSA and surrounding districts.

2. Materials and methods

2.1. Pilot study area

Fig. 1 depicts the pilot study area (PSA) which is nearly 10% of whole Antalya City WDN in terms of total pipe length. Total pipeline network within the study areas is calculated as 285 km while types of pipe material vary between PVC, Steel and HDPE. The PSA consists of three district metered areas (DMAs) which are *Yeşilbayır* (YDMA), *Odabaşı–Kirişçiler* (OKDMA) and *Duacı* (DDMA). The PSA covers 91 km² land surface housing around 40,000 persons.

2.2. SCADA system

There are four SCADA measurement points in the PSA named 1, 7, 8 and 11 (Fig. 2). These points are equipped with online flow meters and pressure meters. Also, online continuous pH, EC, turbidity and FRC levels are being monitored at the SCADA Stations 1, 7 and 11. Values of monitored parameters are being transferred through a wireless connection to the SCADA control room. Fig. 2 presents SCADA and manual measurement points covered in the current study.

The PSA is fed only from *Yeşilbayır* reservoir. Based on the 2011 SCADA data sets for 11 months, average water output from the reservoir was 821.48 $m^3 h^{-1}$ while average water output from the PSA to other different pressure regions was 457.06 $m^3 h^{-1}$. These values are average and change depending on variations in water demands.

2.3. GIS and modeling

The EPANET modeling software is a useful tool for hydraulic and water quality analyses for WDNs. Elevations and coordinates of all nodes, pipe types, materials, diameters and other information about the pipe network in the PSA were updated with the support of ASAT personnel. GIS provides accurate spatial information, such as the general shape of the network, coordinates of pipe, pipe connections and pipe material etc. which are used to develop the network's hydraulic simulation [27,28]. Thus, GIS is considered as an important key element supporting modeling studies. Using the GIS data sets, the input file to the EPANET software could be precisely prepared.

In general, the flow distributed per unit pipe was found by dividing the flow rate of each DMA to the total length of pipes. Half the total length of pipes connected to that node was used for the calculation of the water demand at each node. However, nodal demand was adjusted for large users based on the monthly customer water bills recorded by ASAT. 5 min interval of SCADA data was used to calculate flow rate and FRC patterns in the EPANET input file. *Yeşilbayır* Reservoir which supplies water to the PSA is the only reservoir in the model input file. Kanakoudis et al. developed accurate water demand spatial allocation for water networks [29,30].

2.4. Determination of chlorine decay coefficients

In order to investigate the water quality characteristics of the region, raw water samples, and chlorinated water samples collected from the outlet of *Yeşilbayır* reservoir

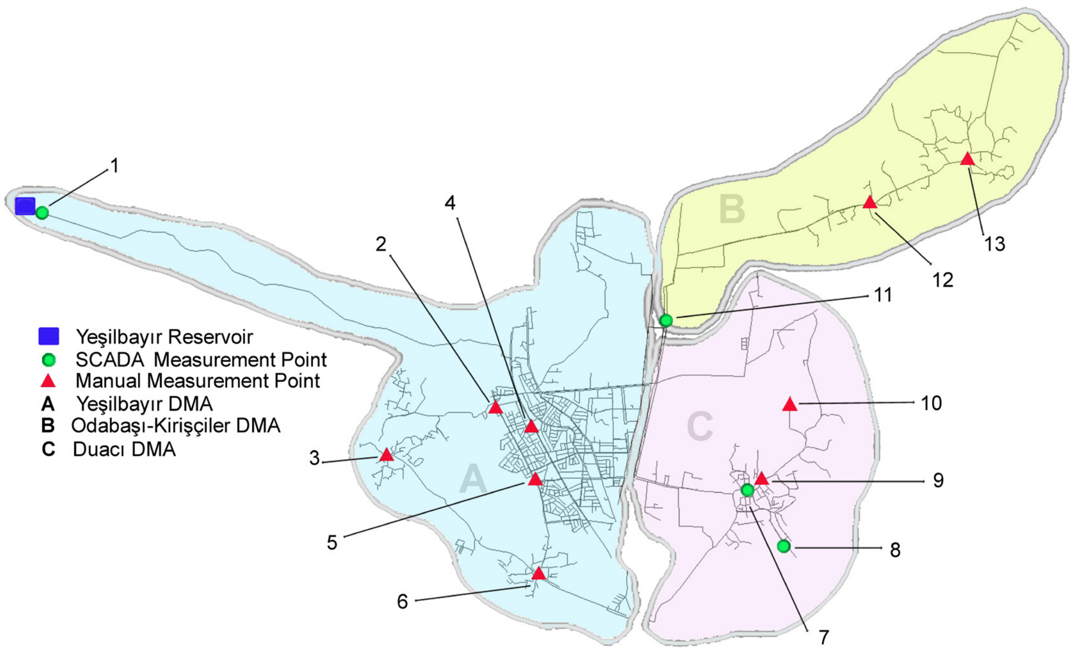


Fig. 2. SCADA and manual measurement points in the PSA.

were analyzed for many physical, chemical and biological water quality parameters. Table 1 gives the average analysis results and guidance values in the related legislation [8,9,31,32]. The results show that the water has very low TOC and complies well with the related standards.

K_b value is easily determined in the lab [18]. K_b was measured once in September 2010 as the seasonal raw water quality revealed marginal changes. To determine the K_b, FRC and total residual chlorine levels were measured in predefined intervals on prepared samples and blank samples. The results of K_b values for FRC are given in Table 2. Chlorine measurements were carried out using DPD (N,N diethyl-1,4 phenylenediamine sulfate) method on HACH DR5000 Spectrophotometer.

2.5. Model calibration and verification

Pipe friction coefficient which is a key parameter for hydraulic modeling studies was determined separately for each DMA by trial and error throughout the hydraulic model calibration studies. This is accomplished by comparing the model predictions with field measurements of pressures under different pipe friction coefficients. The final values of friction coefficients are being determined by choosing the coefficient giving the least prediction error. Also, K_w value was determined by chlorine model calibration using trial and error. The applied method has side effects such as improper determination of K_w which in turn causes insufficient model outputs [29,30].

For model calibration and verification studies, SCADA data and manually measured field values were used. Flow rates, water pressures and FRC levels at each DMA inlet and also at the storage facility were provided by ASAT SCADA Center as 5-min-interval-measurements. All measurement devices were calibrated before carrying out field measurements for the calibration periods (CP) and the verification periods (VP) given in Table 3.

3. Results and discussion

3.1. Hydraulic model calibration and verification

Hydraulic model calibration studies showed that the values of the calibrated pipe friction coefficient of Hazen-Williams were 135 for YDMA, 100 for DDMA and 110 for OKDMA. Conditions of pipes in water distribution systems are subjected to change as they age in time. An increase of pipe roughness as well as a decrease of pipe diameter may occur due to the accumulation of suspended particles and byproducts originating from corrosion of the inside wall of aged pipes. Pipe ages in OKDMA and DDMA are greater than the YDMA. Fig. 3 depicts calibrated model predictions and field measurements of water pressures at YDMA, as an example. Based on the comparison of all model predictions with SCADA measurements and field measurements during the verification period, model predictions were as accurate as 0.17 bar for water pressure values and 1.09 m^3 h^{-1} for water flow rates.

3.2. Chlorine model calibration and verification

The calibrated and verified hydraulic model for the PSA was used for the calibration and verification of the chlorine model. Model calibration and verification periods are given in Table 3. Lab studies showed that K_b at 20°C is –0.1610 d^{-1} [32]. This value was directly used since water quality measurements showed that the average water temperature was very close to 20°C in WDN of the PSA.

K_w values range between 0.0–1.524 m.d^{-1} depending on the age and conditions of pipe walls [33]. For the calibra-

Table 1
Raw and chlorinated water quality analyses results

Parameters	Observed average values in raw water samples (for 24 samples on June, August, September 2010 and January 2011) [32]	Observed average values in Yeşilbayır reservoir (for 9 samples from July to December 2010) [31]	Turkish legislation of water intended for human consumption [8]	WHO guidelines for drinking water quality [9]
Temperature, °C	19	19		
pH	7.23	7.08	6.5-9.5	
EC, µS cm^{-1}	839	836	2500	
Turbidity, NTU	0.50	0.31		
FRC, mg l^{-1}		0.39	0.2–0.5 in dead ends	min 0, 2 in dead ends
Fluoride (F), mg l^{-1}		0.37	1.5	1.5
Chloride (Cl), mg l^{-1}		27.17	250	Above 250 cause taste problems
Nitrite (NO_2), mg l^{-1}	<0.01	<0.01	0.5	3
Nitrate (NO_3), mg l^{-1}	2.21	2.52	50	50
Sulfate (SO_4), mg l^{-1}		44.81	250	
Sodium (Na), mg l^{-1}		22.75	200	
Ferrous (Fe), µg l^{-1}	<3.01	3.20	200	
Manganese (Mn), µg l^{-1}	<2.42	<2.42	50	
TOC, mg l^{-1}		0.12	No abnormal changes	
Total coliform, (CFU/100 ml)	11	0	0	
Fecal coliform, (CFU/100 ml)	0	0	0	

Table 2
Results of lab studies for Kb value (FRC)

Temp.	Period		K_b (d^{-1})	R^2
	Start date	End date		
20°C	24.09.2010	28.09.2010	–0.1610	0.9199
30°C	24.09.2010	28.09.2010	–0.2490	0.9611

tion periods of EPANET runs, values between 0.00 and 0.30 m.d^{-1} were tested for K_w with an interval of 0.01 m.d^{-1}. Trial and error method is used with the least average absolute errors to assess the calibrated K_w value that reached 0.02 m.d^{-1} [32]. Impacts of temperature variations on K_w were neglected in this study due to the fact that the calibrated K_w is extremely low. Fig. 4 presents model predictions and observations of FRC at YDMA, as an example. In Fig. 4, the

Table 3
Calibration and verification periods of EPANET model

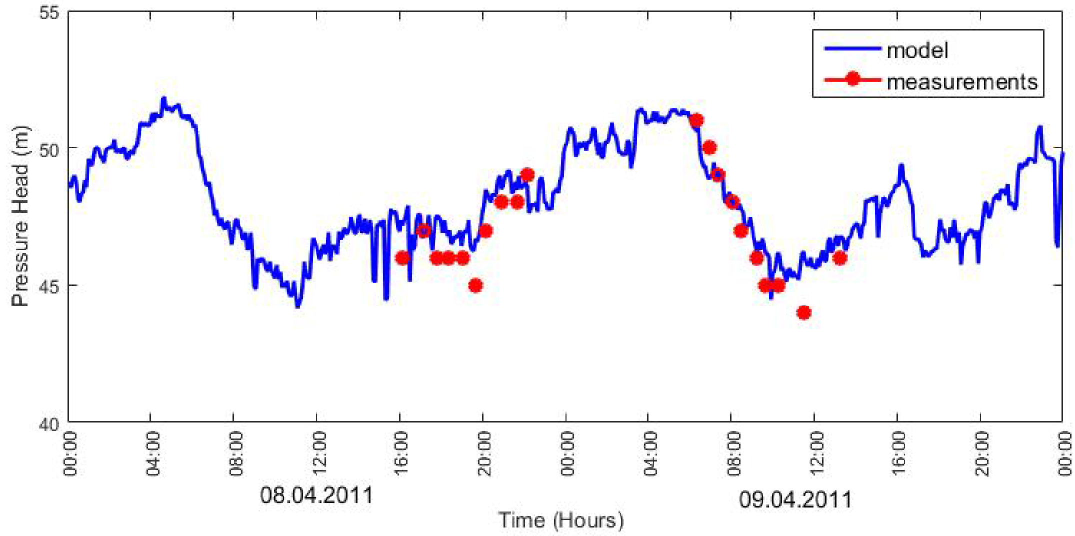
Period	Area	Start time	End time	Total duration (h)
HMCP* (1)	YDMA	19.03.2011 00:00	20.03.2011 23:55	48
HMCP* (2)	YDMA	08.04.2011 00:00	09.04.2011 23:55	48
HMCP*(3)	DDMA, OKDMA	19.04.2011 13:00	21.04.2011 12:55	48
HMVP**(1)	All DMAs	07.04.2011 00:00	09.04.2011 23:55	72
CMCP***(1)	All DMAs	19.04.2011 13:00	21.04.2011 12:55	48
CMCP***(2)	All DMAs	05.05.2011 00:00	06.05.2011 23:55	48
CMVP****(1)	All DMAs	07.04.2011 00:00	09.04.2011 23:55	72

*HMCP Hydraulic Model Calibration Period,

**HMVP Hydraulic Model Verification Period

***CMCP Chlorine Model Calibration Period,

**** CMVP Chlorine Model Verification Period



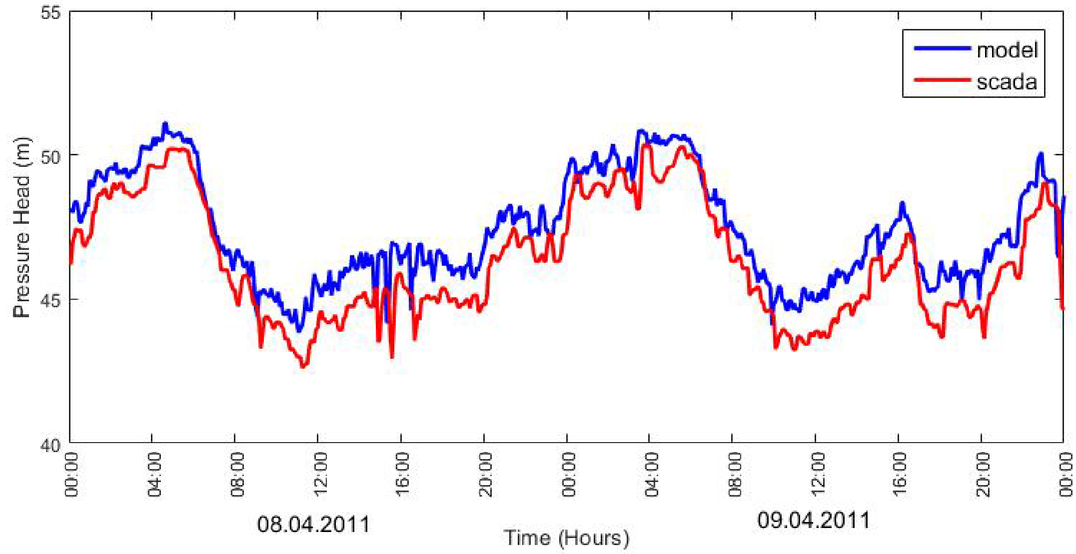


Fig. 3. Model pressure predictions and observations at YDMA (08- 09.04.2011) (a) Node 2 MAE: 0.83 m; (b) Node 11 MAE: 1.06 m

peaks of chlorine concentrations were resulted from the manual application of chlorine dosage where the chlorine dosing pumps operated at constant rates during night but the flow rates dropped to low levels at the same time.

Based on the comparison of all model predictions with SCADA measurements and site sampling values during the chlorine verification period, model predictions are as accurate as 0.06 mg l^{-1} for FRC concentrations.

3.3. Chlorine residual management

The recommended minimum FRC concentration in WDNs is 0.2 mg l^{-1} according to the WHO [9]. Therefore, the aim of chlorine residual management in this study was to keep the FRC at the minimum level of 0.2 mg l^{-1} and to define the required FRC at the chlorine dosing station by trial and error. Chlorine consumptions in a WDN are affected by many parameters such as temperature, K_w, K_b, water age and chlorine concentration at source. K_b values at 20 and 30°C were determined as –0.1610 and –0.2490 d^{-1}; respectively for the PSA by lab studies.

Water age in a WDN is affected by the water demand. During the periods of low water demand, water velocity decreases. Consequently water age and chlorine degradation increase. Similarly, during the periods with high temperature, chlorine degradation rate increases. Therefore, period of low water demand associated with high water temperature are considered as the critical condition with regards to chlorine residual management scenarios. A water temperature as high as 30°C associated with relatively low flow rates occurs only in early summer season (e.g. in May). Therefore, base chlorine simulation is carried out in the PSA in May 2011. Based on the 5th and 6th May 2011 SCADA data, average water output from the reservoir was 768.58 m^3 h^{-1} while average water output from the PSA to other different pressure regions was 495.56 m^3 h^{-1} [32].

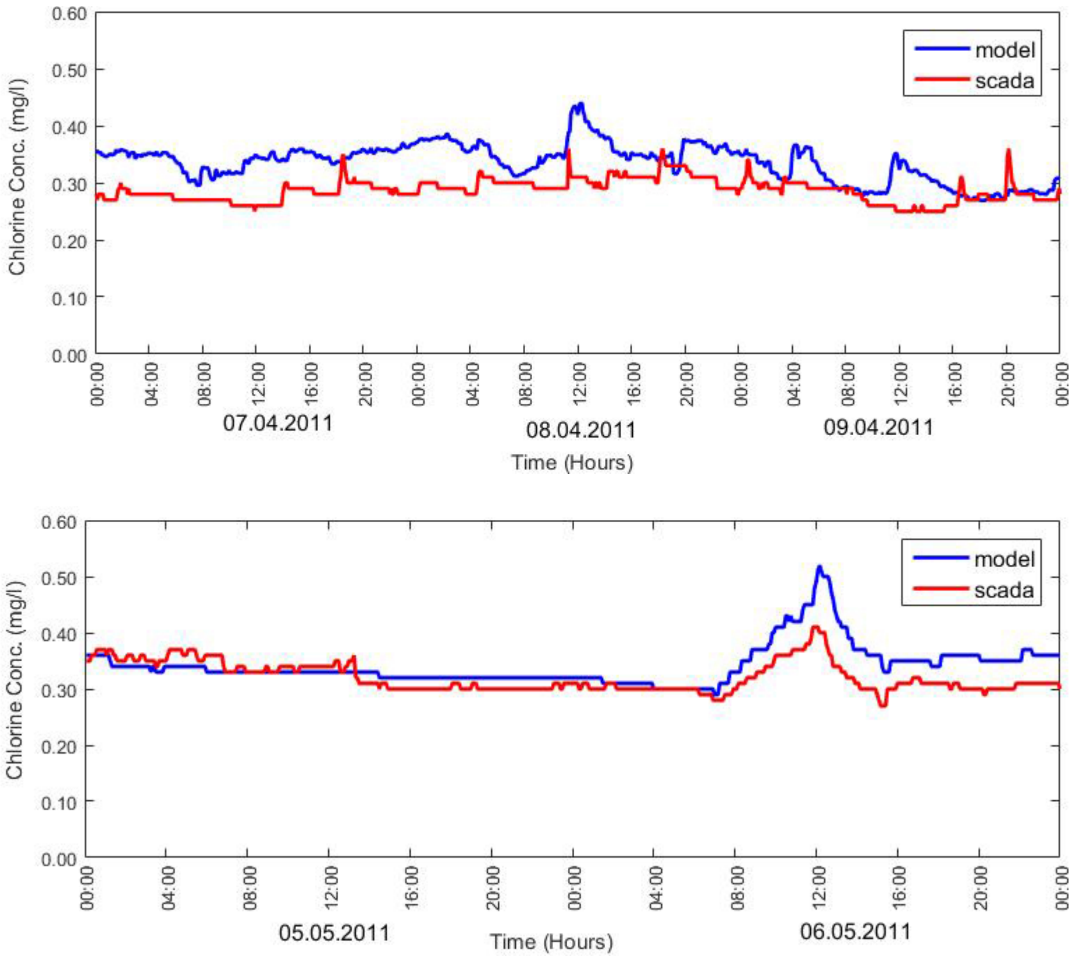


Fig. 4. Model FRC predictions and observations at YDMA (a) Node 11 (07- 09.04.2011, MAE: 0.05 mg l^{-1}) and (b) Node 7 (05- 06.05.2011, MAE: 0.03 mg l^{-1}).

Table 4
Chlorine residual management scenarios in the PSA

Management scenarios	Flow (cm h)	Water temperature (°C)	K_b value (d^{-1})	Explanations
1	768.58	20	–0.1610	Average water temperature associated with low water consumptions
2	768.58	30	–0.2490	Extreme high water temperature associated with low water consumptions
3	614.86	20	–0.1610	Average water temperature associated with 20% reduction of water consumption
4	614.86	30	–0.2490	Extreme high water temperature associated with 20% reduction of water consumption
5	461.15	20	–0.1610	Average water temperature associated with 40% reduction of water consumption
6	461.15	30	–0.2490	Extreme high water temperature associated with 40% reduction of water consumption
7	922.30	20	–0.1610	Average water temperature associated with 20% increase in water consumption
8	922.30	30	–0.2490	Extreme high water temperature associated with 20% increase of water demands

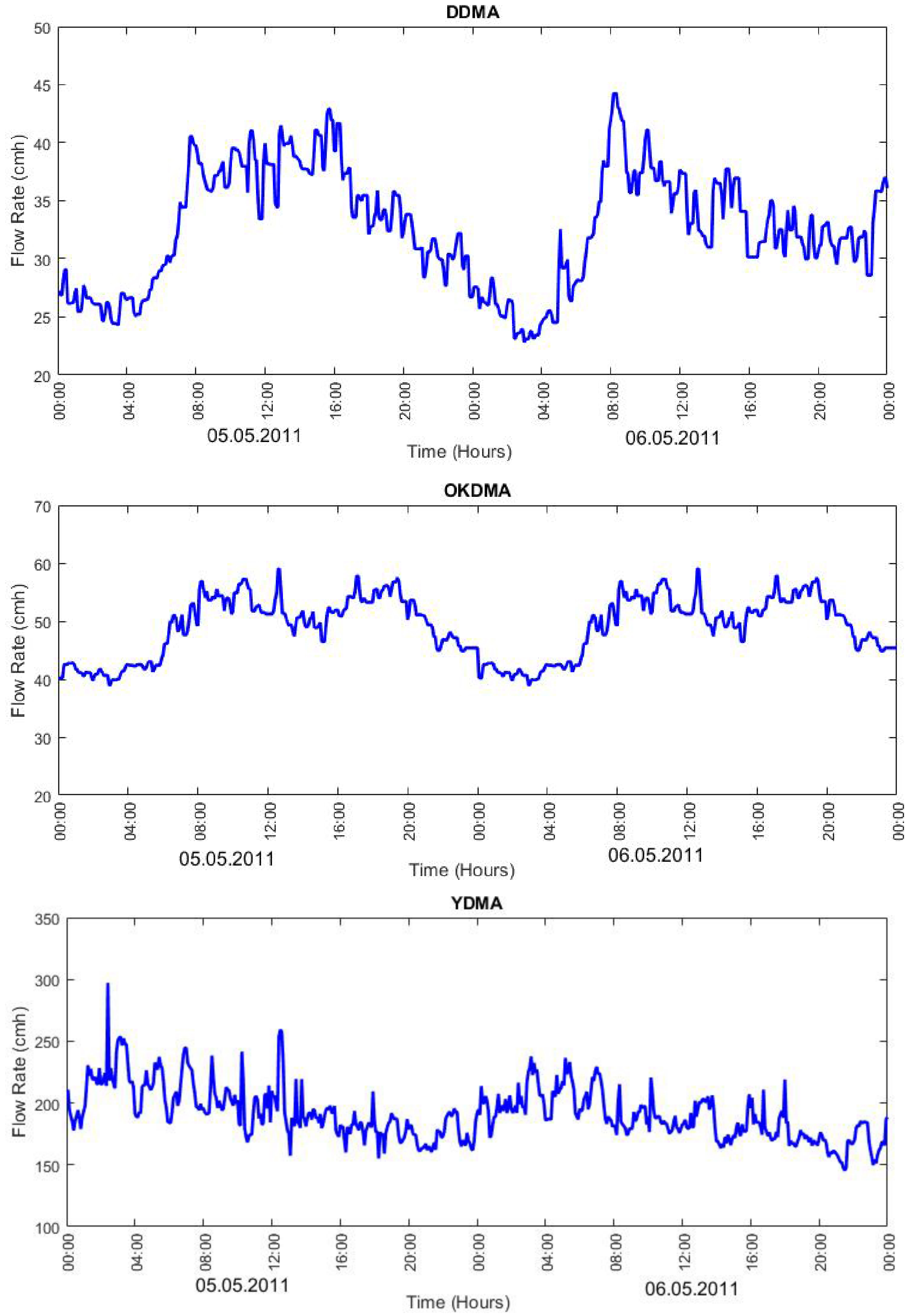


Fig. 5. Profiles of flow rates for scenario 1 and 2 in the PSA.

Table 5
FRC concentrations at the source in PSA for management scenarios

Scenarios	FRC (mg l^{-1})
1	0.65
2	0.80
3	0.80
4	1.10
5	1.00
6	1.60
7	0.55
8	0.65

Different scenarios were tested considering different water temperatures and changes in water demands. In future, the current efforts to reduce the existing high physical water losses in the PSA may decrease the present water demand rates. However, water demand rates may also increase due to increasing water usage in the PSA and possible failure of water losses reduction efforts. Table 4 lists the details of the tested management scenarios in the PSA.

Fig. 5 presents the profiles of flow rates used in the first two scenarios. The required FRC at the dosing station to maintain a minimum level of 0.2 mg l^{-1} FRC all over the PSA were determined using the verified chlorine model. Epanet software was run for different chlorine concentration at the dosing station and the FRC levels were checked at all nodes. Table 5 presents the results obtained for the checked management scenarios.

The most realistic scenario in the PSA that occurs currently for most of the year is represented by the first scenario. In that scenario, 0.65 mg l^{-1} FRC at the chlorine dosing station is enough to keep the minimum FRC all over the WDN in the PSA as 0.2 mg L^{-1}. Fig. 6 presents the areal concentrations of FRC in the PSA for scenario 1.

In scenarios 3 and 4, total flow rate was reduced by 20% while in scenarios 5 and 6, total flow rate was reduced by 40%. When the flow rate decreases, water age and chlorine consumption rate increase. Thus, the required FRC at the dosing station increases. On the contrary, flow rates were increased in scenarios 7 and 8 which lead to decreasing the required FRC at the chlorine dosing station.

4. Conclusions

Management of chlorine residuals in WDN is crucial for efficient water disinfection. Within this respect, chlorine levels should be kept within certain limits all around the year. Manual management of chlorine residuals is impossible and therefore dynamic hydraulic and chlorine models should be used for accurate management of chlorine concentration, and to maintain chlorine residual in WDN within the required levels spatially and temporally. However, well calibrated and verified models are a prerequisite to achieve reliable results. In this respect, online measurements of water quantity and quality such as flow rates, water pressures, temperature and FRC provided by the SCADA system beside the GIS data play

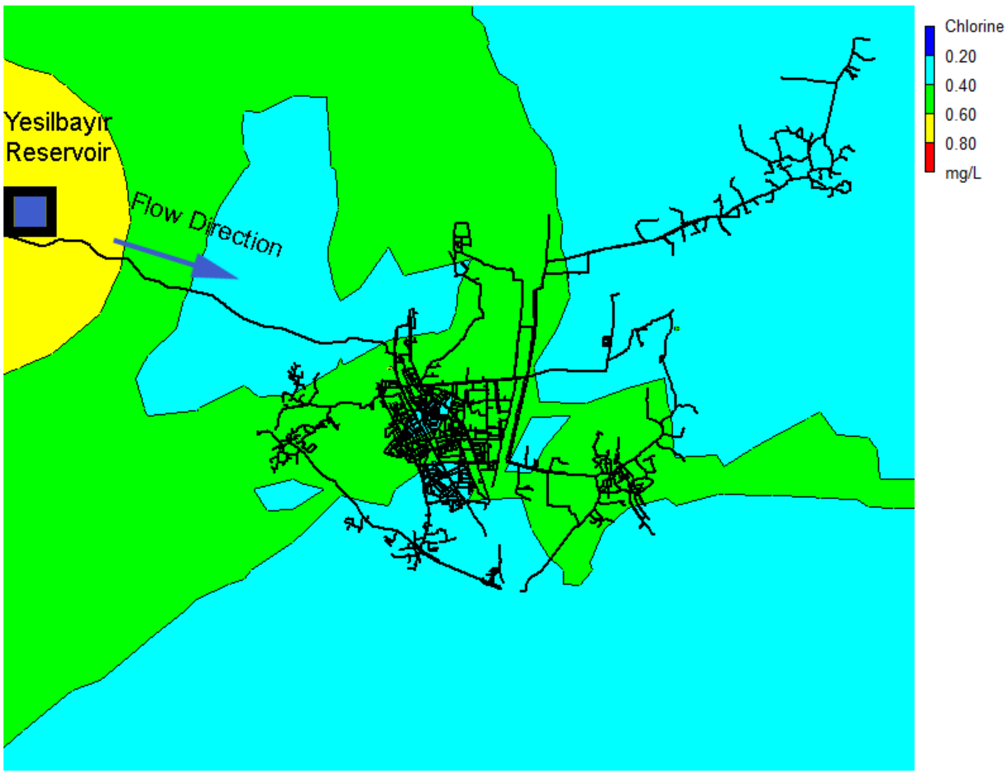


Fig. 6. Spatial changes of chlorine concentrations for Scenario 1 (06.05.2011, 02:00)

an important role for model calibration and verification. Moreover, lab determination of chlorine bulk decay coefficient at different temperatures is necessary for setting model kinetics. Although water losses reduction involves many advantages, it entails serious concerns about chlorination. Reducing water losses leads to reducing flow rates and hence increasing water ages that result in increasing the required chlorine dosing rates to comply with the relevant chlorine standards in WDN. Consequently, chlorine management scenarios should take into consideration the possible changes of water demand changes in the future beside the impacts of temperature variations on chlorine bulk and wall decay coefficients.

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