Integration of quality control and GIS to improve water network in the city of Sharjah

Adil K. Al-Tamimi and Mayada Bardan

ABSTRACT

A quality control process has been applied to improve the water quality in the network of Sharjah city in the United Arab Emirates. The process capability of the network is measured in terms of pH and residual chlorine using the 6-sigma method. The sources of problems in this network are investigated and identified and corrective and preventive actions for each type of quality nonconformity are suggested. A geographic information system (GIS) is utilized to enhance managerial skills in supervising and improving the system. GIS maps allow remote and instantaneous monitoring of water quality in the network based on laboratory tests. Water quality in 38 locations of Sharjah city are classified according to their sources and located on GIS maps. Nonconformities are also classified according to their severity and located on the same maps to identify problematic areas. The Al-Nahda sampling point is selected as a sample location to test the process. The research showed that real time data gathered from different locations and embedded on GIS maps would provide an effective and immediate decision tool for technical managers in monitoring and improving the system.

Key words | capability index, GIS, quality control process, water network, WHO standards, X-chart

Adil K. Al-Tamimi (corresponding author)
Institute of Materials Systems,
School of Engineering,
The American University of Sharjah,
SharjahPO Box 26666,
United Arab Emirates
E-mail: *atamimi@aus.edu*
www.aus.edu/engr/ims/
Tel.: ++971 6 5152958
Fax: ++971 6 5152979

Mayada Bardan
Sharjah Electricity & Water Authority,
SEWA,
SHARJAH,
United Arab Emirates

INTRODUCTION

The main source of water supply in Sharjah city is sea desalination, which provides 80%; the remaining 20% comes from ground water. There are four pumping stations supplying the water:

1. Falaj pumping station (mixed desalinated sea water plus natural ground water), produces 33 million gallons per day (MGD)
2. Layyah plant (sea water thermal desalination), produces 14 MGD
3. Bedai pumping station (atural ground water), produces 7 MGD
4. Sajaa plant (reverse osmosis desalination – brackish water), produces 6 MGD

In the current research only Falaj and Layyah water sources were analysed because they are the major supply of water. The General Directorate of Water (GDW) has been established to produce and distribute fresh and safe water to the city of Sharjah. The GDW has developed a quality management system based on ISO 9001/2000. The main objective of this system is to make sure that the distributed water follows the international standards set by the World Health Organization (WHO 2003).

The quality control system is required to test and monitor the quality of water during transportation and distribution before reaching the consumer. Water nonconformities are raised when at least one water property does not comply with WHO standards; these standards are shown in Table 1. Monthly water data were collected and checked for any inconsistency with the standards and nonconformities were identified and tabulated in Table 2. In this paper, statistical process control is performed on

doi: 10.2166/aqua.2006.027

Table 1 | WHO standards for drinking water

Water parameter	WHO standards	GDW standards	Unit
pH	Optimum 7.0–8.5 Acceptable 6.5–9.2	6.5–9.2	
Chlorine residual	<0.6	0.15–0.6	ppm

the current quality control system, control charts have been prepared and process capability is measured using the 6-sigma method.

A geographic information system (GIS) is a computer-based tool that helps visualize information and identifies patterns and relationships. It links information stored in a database about places – such as streets, buildings, water features and terrain – with their locations in the real world. The GDW started to apply a GIS system in 2004 to store network data, to produce digital maps, and share information with the information technology (IT) section, which digitizes and updates the current network.

Several electricity and water utilities rely on GIS in managing and maintaining their distribution network (Horsburgh and Ames 2000). GIS-based software known as BASINS was developed to facilitate the examination of the environmental information, provide an integrated watershed framework, and to support the analysis of point and non-point source pollution management. East Bay municipal utility district operates a complex water distribution system and recently converted its system from using free chlorine to monochloramines as a secondary disinfectant of water (Swain and Erkkila 1998). This conversion promoted the development of a water quality monitoring system and GIS database to collect and analyse the required data to optimize the operations of the distribution system. A total of 77 sample points were selected at the pipeline locations and 59 samples were selected at the reservoir locations. Monthly water samples from these locations were collected and analysed in the field and in the laboratory. The field data were entered into an Oracle database using a web-enabled data management system while the laboratory analyses results were entered into a separate Oracle database due to operational constraints. The system offered many major benefits such as reducing the cost of developing new data and avoiding the duplication of data entry and data maintenance.

Table 2 | Types and frequency of water nonconformities in the Sharjah network from January 2004 to March 2005

Type of nonconformity	Frequency	%
High pH value	16	70
High chlorine value	0	0.0
Low chlorine value	7	30
Total	23	100

The development of the new GIS for water quality improved four main functions: 'mapping of customer complaints, mapping of water quality analysis results, production of water quality parameter time series charts, and output automation' (Swain and Erkkila 1998). Development of the water quality monitoring system with the GIS database enabled East Bay municipal utility district to monitor water quality throughout its distribution system, and identify areas that had water quality problems.

In the UK, the performance of water distribution networks has come under increasing scrutiny in recent years as supply companies strive towards higher levels of operational efficiency. Viable methods of network analysis and reporting from these data streams have been utilized, employing conventional network (flow/pressure) modelling solutions in combination with GIS (Burrows *et al.* 2000).

Interactive analysis has been applied by Adrians *et al.* (2003) in order to assess the vulnerability of potable water supplies and water quality. It created close integration of human and natural systems information derived from online and offline point measurements with GIS. The study suggested that point measurements need to be integrated with GIS layers to develop a risk framework applicable to local or regional scales.

Geographic information systems were used in central Kansas to ensure a balanced use of groundwater resources (Chang & Hoover 1998). Many water utilities rely on their own laboratories to monitor water quality in the systems (Sweeney 1999). However GIS was applied to access the data and immediate remedy would be taken whenever required.

METHODS

Monthly water reports were collected from Falaj Pumping Station laboratory, which performed quality checks on the network. Two specific parameters were analysed: the pH or the acidity factor and the residual chlorine (Cl), which is a measure of the free chlorine in water. Fifteen subgroups of data were available for the pH and Cl parameters.

Identification of sampling point location

The previous water quality check was based on monthly collection of samples taken from different locations and analysis at the Falaj pumping station laboratory. The position of the sampling points and their locations were not fixed. During this study, a new system was developed to permanently locate these points and provide a systematic approach for collecting samples and comparing analysis results. Sample points were selected and identified in order to represent an exact location that can be easily accessed and permanently located. The 33 kW electrical substations were mainly selected for this purpose. Water valves have been installed on the service line that supplies these stations. The number of sample points was increased from 27 to 38 in November 2004 in order to cover a large area of Sharjah city.

Sampling points digitizing

The global positioning system (GPS) instrument was used to measure X and Y coordinates of each sample point to locate them on the GIS map. The maps enabled the mainline personnel to identify the location of the points where problems occur and perform the required corrective actions.

Specifications and tolerance

The World Health Organization (WHO 2003) standards for drinking water are applied at GDW water laboratories and are shown in Table 2.

Process capability

Process capability was measured for the entire network of Sharjah city supplied from four different water sources. One section in Layyah zone was investigated using the 6-sigma method to measure the process capability. Capability index, C_p, was measured using the following equation (Besterfield 2001):

$$C_p = \frac{USL - LSL}{6\sigma_o} \quad (1)$$

Where C_p = capability index
$USL - LSL$ = upper specification – lower specification, or tolerance
σ_o = population standard deviation
$6\ \sigma_o$ = process capability

There are three categories for C_p:

1. $\mathbf{C_p > 1}$ Case 1: when the process capability is less than the tolerance. This is the most desirable case. In this case, no nonconforming water is produced even when the process does not meet the control requirements. However, corrective actions are required to remain in control conditions.
2. $\mathbf{C_p = 1}$ Case 2: when the process capability is equal to the tolerance. In this case, no nonconforming water will be produced if the process remains in control. However, when the process does not meet the control requirements due to natural variation or any assignable cause, nonconforming water is produced. Therefore, assignable causes of variation must be corrected as soon as they occur.
3. $\mathbf{C_p < 1}$ Case 3: when the process capability is greater than the tolerance. This is an undesirable situation. Even when the process is in control, nonconforming water is produced. In this case the process is not capable of producing or supplying water that meets the required standards or specifications. The minimum desirable capability index is established at 1.33 by most companies. This value gives a safe margin for process variation and natural deviation before producing nonconforming products. This value was selected in this study in measuring the process capability.

Creating sample point features from tabular data

GPS was used to record the location of each sample point. The longitude and latitude coordinates (x-y) were added to the GIS map, creating a point feature class, and saved in a geodatabase. Table 3 shows the attributes that were created to identify each sample point.

Classifying data

There are four standard classification methods available in GIS: natural breaks, equal interval, quantile and manual (Beckford 2002). In this study, the manual classification method was used to classify water quality in the network according to the water sources. This method was selected because it provides flexibility in specifying the desired range of values and break points. Six class groups were defined; each class represents water quality range in relation to its source. After setting the classes and their corresponding ranges, a GIS water quality map was created relating each sample point area to its water source as shown in Figure 1. The legend on the map shows the sampling point symbol, the pumping stations symbol and the classes of water sources.

RESULTS AND DISCUSSION

Analysis of source water

Table 4 shows the four sources of Sharjah water with their distribution capacities and percentages. In the current research only Falaj and Layyah water sources were selected and analysed because they are the major supply of water in the city.

Falaj pumping station

Falaj water is a mixture of desalinated water (about 70%) and natural ground water (about 30%). It is located in the Halwan area in the centre of Sharjah city and distributes around 30 to 37 MGD. Table 5 shows the average values for electrical conductivity (EC) and pH for Falaj water in each month during 2004. The values of the pH varied from 7.65 to 7.89, whereas the value for residual chlorine was about 0.36, yielding a very slight deviation.

Layyah pumping station

Layyah pumping station distributes thermally desalinated seawater (multi stage flash evaporation (MSF) and multi effect desalination (MED)). It is located in the Al-khan area and produces about 35 MGD. It transmits 21 MGD to Falaj pumping station, and 14 MGD to the city. Table 6 shows the average values of water parameters during 2004.

The values in bold exceed the applied WHO standard for residual chlorine in drinking water.

Analysis of pH values in the network

The pH value changes during transportation as a result of the following factors:

- Material of pipeline
- Flow rate and speed of water in the pipeline
- Age of pipeline and fittings

Table 3 | GIS sample point attributes

No.	Point name	Area type	No.	Point name	Area type
1	Al Noof	Residential	9	Al Qurain 3	Residential
2	Ind. Area 15	Industrial	10	Al Qurain 5	Residential
3	Ind. Area 13	Industrial	11	Al Ramaqiya	Residential
4	Ind. Area 14	Industrial	12	Al Ramth	Residential
5	Ind. Area 16	Industrial	13	Al Muwafjah	Residential
6	Ind. Area 17	Industrial	14	Al Qadisiya	Commercial
7	Al Turfa	Residential	15	Al Sabkha	Commercial
8	Falah Gardens	H.H palace			

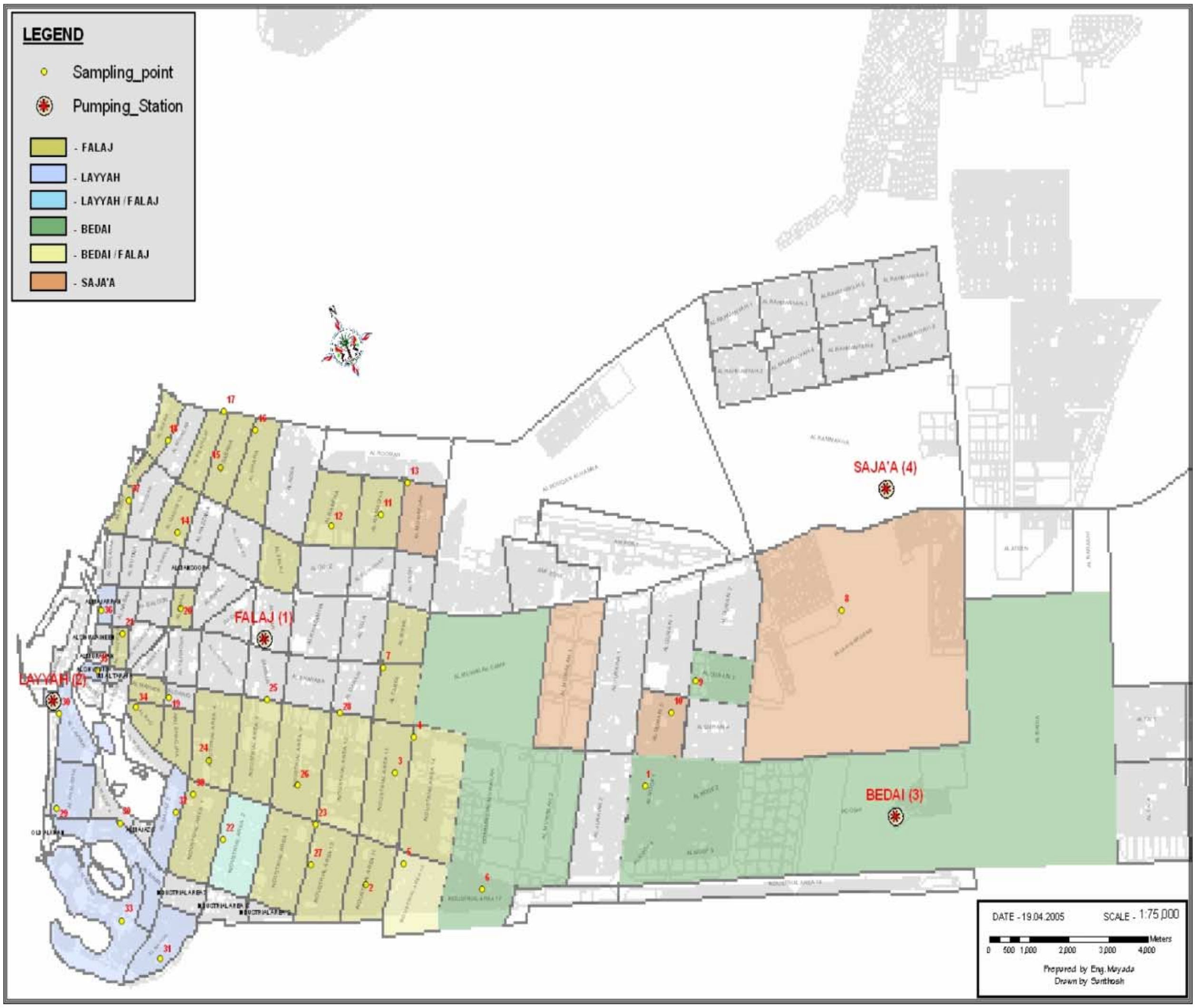


Figure 1 | Water source classification map for the Sharjah areas.

The pH values of the source water are described in Table 7. Data for pH values of water samples taken from 27 different locations in the network from January 2004 to March 2005 are shown in Table 8. These data were analysed in order to measure the process capability and establish the control charts. The frequency distribution histogram shown in Figure 2 has approximately a normal distribution shape with the peak value at the middle class (8.00–8.25). Of the pH values, 96.1% are between 7.0 and 8.5, which is the optimum range for pH according to WHO standards. Of these values, 99.8% are between 7.0 and 8.75, which is within the acceptable range of pH.

Table 4 | Sources of Sharjah Water

		Distributed water	
No.	**Sources of water**	**Amount (MGD)**	**%**
1	Falaj	33	55.00
2	Layyah	14	23.33
3	Bedai	7	11.67
4	Sajaa	6	10.00
	Total	60	100.00

Table 5 | Average chlorine residual and pH value for Falaj water in 2004

Month	Av. Cl (ppm)	Av. PH
January	0.38	7.89
February	0.35	7.70
March	0.36	7.72
April	0.37	7.80
May	0.37	7.84
June	0.35	7.85
July	0.37	7.81
August	0.38	7.83
September	0.35	7.84
October	0.35	7.76
November	0.35	7.77
December	0.35	7.65
Average	0.36	7.79
St. Dev.	0.01	0.07
Range	0.35–0.38	7.65–7.89

Table 6 | Average chlorine residual and pH value for Layyah water in 2004

Month	Av. Cl (ppm)	Av. PH
January	0.55	7.41
February	0.55	8.37
March	**0.65**	7.50
April	**0.65**	7.48
May	**0.9**	7.53
June	**0.65**	7.73
July	0.55	7.59
August	**0.65**	7.60
September	**0.75**	7.78
October	0.45	7.37
November	**0.9**	7.56
December	**0.75**	7.23
Average	**0.67**	7.60
St. Dev.	0.14	0.29
Range	0.45–0.9	7.23–8.37

Control charts and state of control

A process is said to be not efficient when there are one or more measurements fall outside its control limits, or when unnatural runs of variation are present in the process. These measurements should be studied for any assignable causes that are not part of the natural variation of the process. These measurements should be analysed using X chart (the Mean of measurements) and R chart (the Range of the measurements). Referring to the mainline section and obtaining data about the network condition and maintenance work should provide information about any assignable causes that contribute to the nonconformity. The values of X and R that contributed to the nonconforming points are discarded from the data and new revised central lines and control limits are calculated.

The central line of pH values is the average of each subgroup average and equals 8.00. The control limits are established within three standard deviations from the central line. The upper control limit is 8.2, and the lower control limit is 7.79.

Analysis of the X chart for the pH values in Figure 3 shows that the process does not meet the control requirements.

Process capability

There are two ranges for pH standard according to WHO: optimum (7.0–8.5), which is mostly applied for drinking

Table 7 | Average and range of pH values of source water for 2004

No.	Water sources	Average pH	pH range
1	Falaj	7.79	7.65–7.89
2	Layyah	7.60	7.23–8.37

Table 8 | Frequency distribution of pH values for the Sharjah network

No.	pH value	Frequency	Accumulated freq.	%	Accumulated %
1	<7.0	0	0	0	0.0
2	7.0–7.5	21	21	5.17	5.2
3	7.5–7.75	37	58	9.11	14.3
4	7.75–8.0	132	190	32.51	46.8
5	8.00–8.25	162	352	39.90	86.7
6	8.25–8.50	38	390	9.36	96.1
7	8.50–8.75	15	405	3.69	99.8
8	8.75–9.00	0	405	0.00	99.8
9	>9.00	1	406	0.25	100.0
	Total	406	406	100.00	100.00

water, and acceptable range (6.5–9.2). Outside these boundaries, water will be unsuitable or even harmful for consumption. The values were classified according to their ranges and process capability. The optimum pH range (7.0–8.5) is: USL − LSL = 1.5

$C_p1 = 0.98$: this is Case 2 where the process capability is approximately equal to the specification limits or tolerance. In this case water with pH > 8.5 is produced or supplied while the process is still in control. Therefore, the process does not meet the control requirements and some nonconforming products are produced. The frequency distribution histogram shows that 3.9% of water pH values exceed 8.5, which proves this result.

The acceptable pH range (6.5–9.2) is: USL − LSL = 2.7

$C_p2 = 1.76$: this is Case 1 where the process capability is less than the tolerance. This is the most desirable case. This shows that the process is in good control. The process

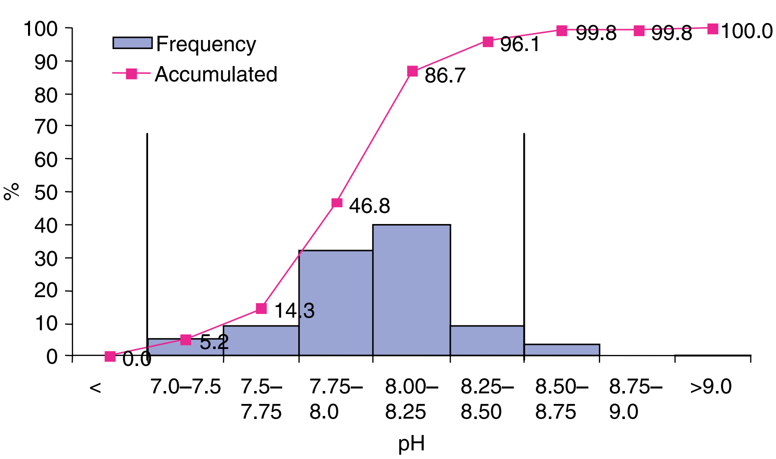


Figure 2 | Frequency distribution histogram for pH values.

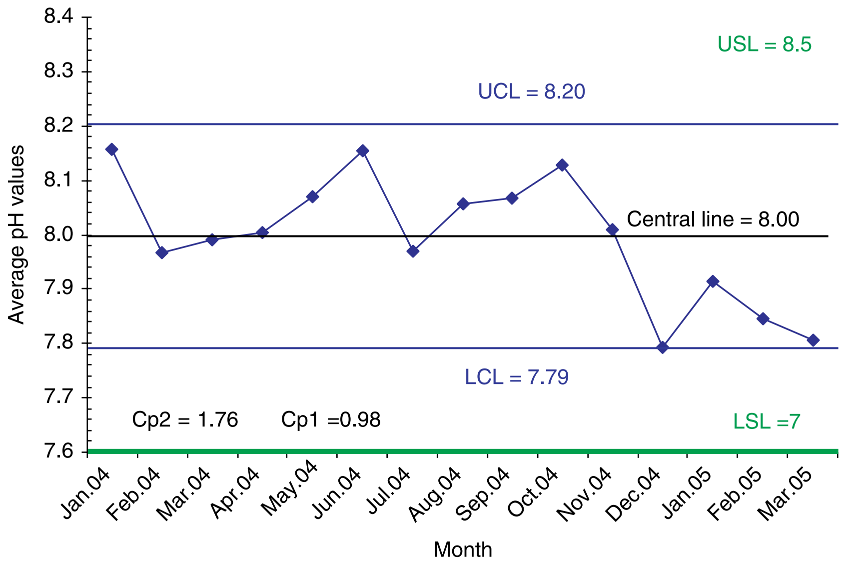


Figure 3 | X chart for pH values.

capability is much higher than the acceptable standard 1.33. This states that no nonconforming product (water having pH > 9.2) is supplied even when the process does not meet the control requirements and some assignable causes of variation exist. Figure 3 shows some recurring cycles and periodic high and low points that show an increase in value starting from February to June, and a second increase from July to October 2004. Seasonal effects and water temperature might be the cause of the nonconformity.

Analysis of residual chlorine in network

Chlorine is the sterilizing chemical that is added to water before its distribution to control microbiological growth and disinfect water during transportation until it reaches the customer. The dosing rate should be controlled in order to maintain a chlorine residual of not less than 0.15 ppm along the network while not exceeding a rate of 0.6 ppm at the dosing location. Table 9 shows the chlorine average and range values at the four distribution plants during 2004. Layyah water has the highest chlorine dosing rate; this might be due to the rapid deterioration of chlorine concentration in water during distribution which is caused by the high temperature of Layyah water. The frequency distribution histogram shown in Figure 4 has a normal distribution shape with a peak value of 0.35 ppm. All of the values are beyond the maximum limit 0.6 ppm, whereas 2.2% are less than the minimum limit of 0.15 ppm.

The X chart of chlorine values in water is established for 15 subgroups and shown in Figure 5. The central line of chlorine values is the average of each subgroup and is equal to 0.262 ppm. The control limits are established at three standard deviations from the central line. The upper control limit is 0.31 ppm, and the lower control limit is 0.21 ppm. The upper specification limit for chlorine is 0.6 ppm, and the lower specification limit (LSL) is 0.15 ppm. Although there are no signs of nonconforming points and no abnormal run of variation that divert the state of control, there are long runs at one side of the central line (six points in a row fall below the central line),

Table 9 | Average and range values for chlorine in source water for 2004

No.	Sources of water	Average chlorine	Chlorine range
1	Falaj	0.36	0.35–0.38
2	Layyah	0.67	0.45–0.9

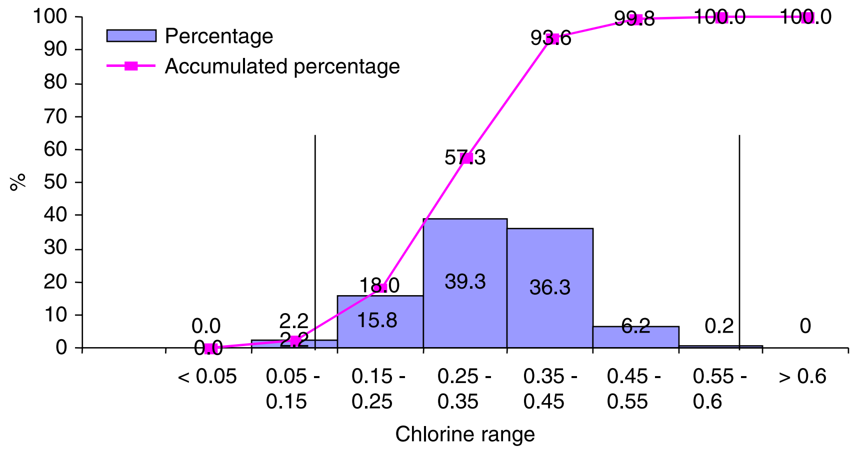


Figure 4 | Frequency distribution histogram for chlorine.

and one point falls exactly on the UCL. Considering these observations together would put the process close to a nonconforming state.

The capability index is 0.88, which indicates that the process capability is greater than the tolerance. This implies that, even when the process is in control, a nonconforming product is produced. This is shown in the frequency histogram where about 2.2% of the values of chlorine concentrations lie below the lower specification limit. There is a high value of 0.55 ppm in the Al-Noaf area which is supplied from Bedai pumping station and a low value of 0.05 in the Al-Nahda area which is supplied from Layyah. An analysis of the X chart for Sharjah zone excluding Layyah shows that there were two nonconforming points in May 2004 and February 2005. The first point is slightly above the upper control limit, and the second point is just below the lower control limit. Although the X chart shows that the process is still not conforming, the process capability increased to 1.11 as shown in Figure 6. This indicates that no nonconforming water was found in Sharjah network even though the process does not meet the control requirements.

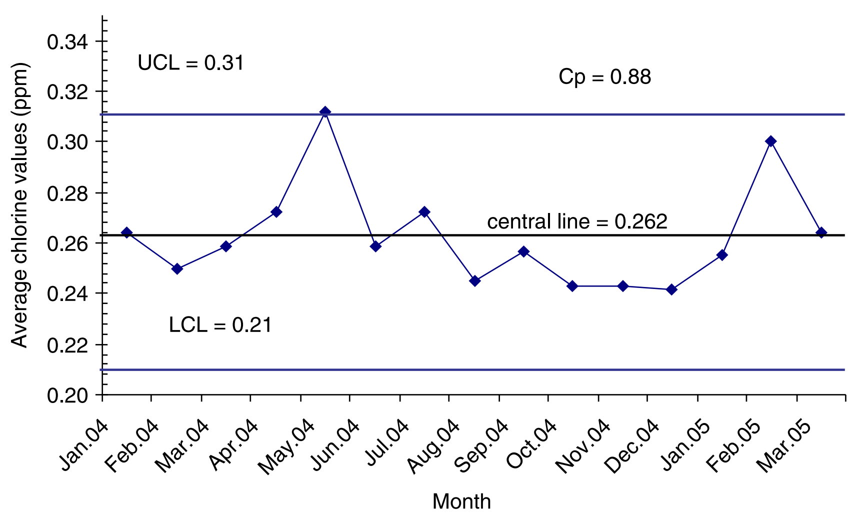


Figure 5 | X chart for chlorine values.

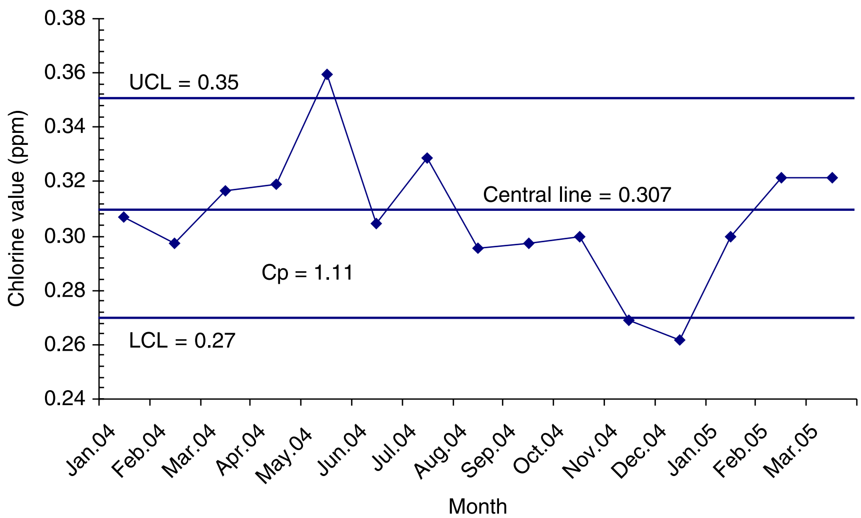


Figure 6 | X chart values excluding Layyah.

The chart shown in Figure 7 is the X chart for the chlorine values for Layyah zone only. A nonconforming point is shown in February 2005. However the process capability increased from 0.88 to 0.96 indicating that the process capability is equal to the tolerance. Nonconformity results were manually tabulated in Figure 8 in order to test the process and a map was created for this area with a 500 metre buffer around the sampling point. The selection of the 500 metre buffer was based on an arbitrary assumption that the nonconformity points would extend into a circular area of 1,000 m diameter surrounding the sample point.

A semi-transparent circle shape was selected to represent the buffer zone in order to show the pipeline network in that zone. It shows the exact location of the contaminated area so that maintenance and corrective actions can be taken accordingly. Additionally, the buffer zone can be used to investigate the network condition and the possible changes that might cause the water

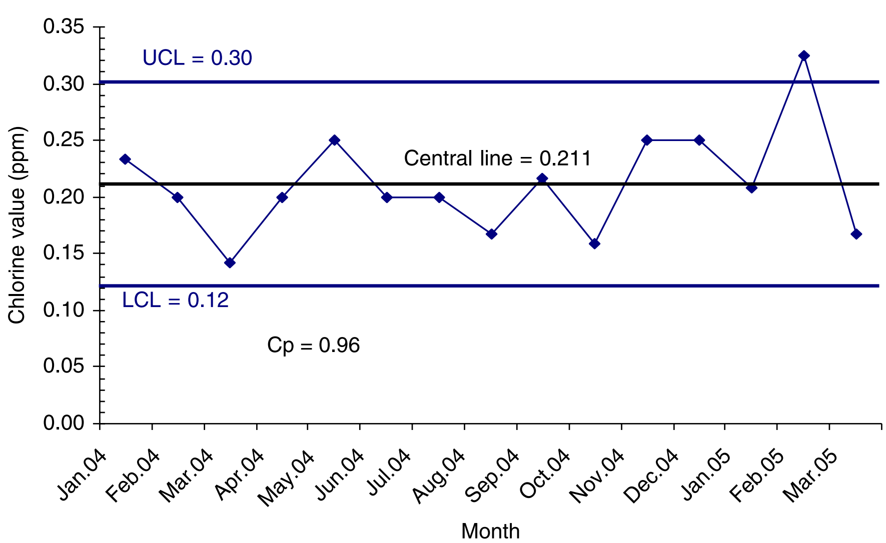
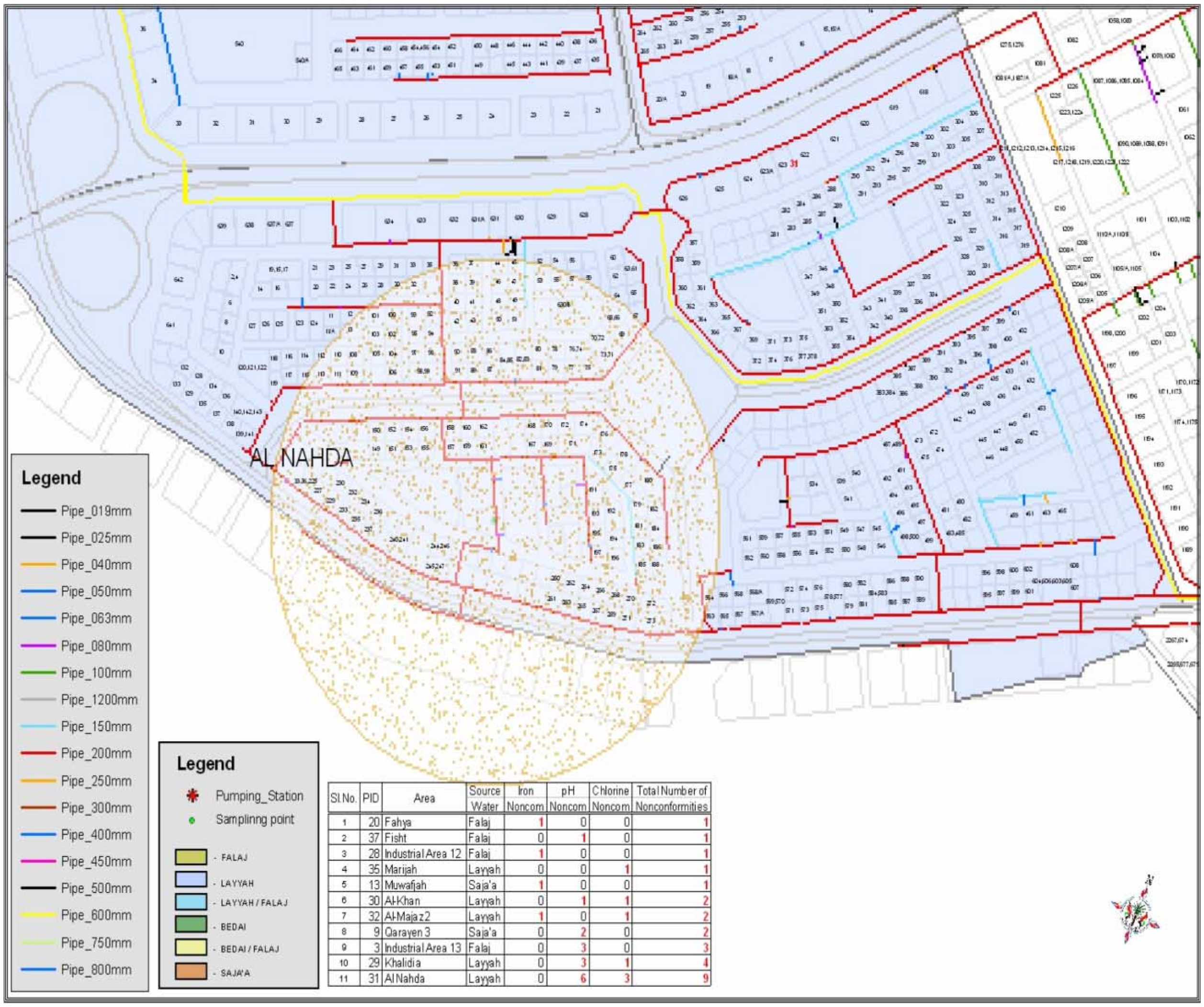


Figure 7 | X chart for chlorine values from Layyah only.



Sl.No.	PID	Area	Source Water	Iron Noncom	pH Noncom	Chlorine Noncom	Total Number of Nonconformities
1	20	Fahya	Falaj	1	0	0	1
2	37	Fisht	Falaj	0	1	0	1
3	28	Industrial Area 12	Falaj	1	0	0	1
4	35	Marijah	Layyah	0	0	1	1
5	13	Muwafjah	Saja'a	1	0	0	1
6	30	Al-Khan	Layyah	0	1	1	2
7	32	Al-Majaz 2	Layyah	1	0	1	2
8	9	Qarayen 3	Saja'a	0	2	0	2
9	3	Industrial Area 13	Falaj	0	3	0	3
10	29	Khalidia	Layyah	0	3	1	4
11	31	Al Nahda	Layyah	0	6	3	9

Figure 8 | Analysis results for Al-Nahda sample point.

quality problem in that area. Finding the root cause of water nonconformity will provide a good tool to rectify the problem, optimize the system and control the overall state of the network.

CONCLUSIONS

A high pH value was the most frequent water nonconformity type found in the network during the 15-month study period. Of the total water nonconformities, 59% were high pH values, 26% were low chlorine residuals and 15% were high iron values.

The Al-Nahda area, which is supplied from Layyah pumping station, had the highest number of water nonconformities. About 60% of total water nonconformities were found in this area.

Water nonconformities occurred mainly in the Layyah zone. Of the total water nonconformities, 67% were found in this zone, which supplies 23% of the distributed water. However, only 18% of sampling points are located in this zone. Therefore, increasing the number of sample points in Layyah zone is recommended in order to comply with its distribution capacity.

All chlorine nonconformities were found in the Layyah zone. Water temperatures for the four sources of water and the Langelier saturation index (LSI) were measured. The measurements show that Layyah water has the highest temperature values among the four sources of water in Sharjah city, and the highest negative LSI, which makes it more aggressive to pipeline surfaces.

Using GIS has enabled prompt action to identify problems in the system followed by quick solutions to optimize network maintenance work, and provide a framework for continuous improvement.

GIS was used to store water quality data in order to create many informative maps. Two useful maps were created during this study: a water classification map and a water quality map. The water classification map is used to identify causes of water quality nonconformities that are related to the source water. The water quality map is used to determine the exact locations of water nonconformities, identifying areas of water quality problems, and viewing quality trends and historical data.

REFERENCES

Adrians, P., Goovaerts, P., Skerlos, S., Edwards, E. & Egli, T. 2003 Intelligent infrastructure for sustainable potable water. *Biotechnol. Adv.* **22**, 119–134.

Beckford, J. 2002 *Quality* (2nd Edition), Routledge, Oxford.

Besterfield, D. 2001 *Quality Control* (6th edition), Prentice Hall, New York.

Burrows, R., Crowder, G. & Zhang, J. 2000 Utilization of network modeling in the operational management of water distribution systems. *Urban Water* **2**, 83–95.

Chang, T. & Hoover, M. 1998 Spatial investigation of water quality in Lake Erie using GIS method. *International Water Resources Engineering Conference*, Memphis, USA, 1464–1474.

Horsburgh, J. & Ames, D. 2000 Water quality estimation from regional characteristics. *ESRI Conference*, July 2000, San Diego, USA.

Swain, C. & Erkkila, R. 1998 Development of an integrated water quality database/GIS. *ESRI Conference*, October 7–9, 1998.

AlexandriaSweeney, M.W. 1999 Geographic Information Systems. *Wat. Environ. Res.* **71**(5), 551–556.

WHO 2003 *Standards for Drinking Water, 2003*, WHO, Geneva.

First received 17 November 2005; accepted in revised form 12 May 2006