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Influence of flow rate variations on chemistry change of pumped Disi water to Amman/Jordan: a laboratory simulation approach

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ABSTRACT

In order to monitor the change in the Disi water chemistry that is pumped from the Disi aquifer to Amman city along the 345 km pipeline, the changes in chemistry and surface precipitation of scale were investigated using simulated plumbing system. The influence of flow rate variation was investigated since Disi water usually pumped using different flow rates along the pipeline. Disi water was pumped through 20.0 m steel pipes at different flow rates (5, 10, 15, 25, and 35 L/min) with circulation time of 5 h for each run. Water quality parameters, for example, temperature, pH, electrical conductivity, calcium, magnesium, carbon dioxide, total alkalinity, and total hardness, were determined every hour using standard methods of analysis. The results showed that pipes that transport Disi water suffers from calcium carbonate scale deposition as the water is pumped with different flow rates. It was found that the scale deposition increased by increasing the flow rate and the surface roughness of the metal.

Keywords: Disi aquifer; Water chemistry; Flow rate; Scale deposition; Plumbing system

1. Introduction

Availability of drinking water with acceptable quality is one of the most important human rights. Drinking water should be free from contaminates and its quality should obey the applied national drinking water standards. Factors that affect the quality of drinking water include but not limited to water sources, type of water purification, and storage tanks. Water reaches consumers using different types of distribution systems. Pumped water usually suffers from diverse problems due to different factors, for example, scale formation and corrosion. Piped water classified into three categories: scaling, corrosive, and neutral water. Scaling water results from the supersaturating of water with calcium carbonate, while corrosive water shows ability to dissolve calcium carbonate [1].

There are increasing concerns with the behavior and transport of chemical species in a water distribution system. Water quality can greatly change from the resource to the consumer, throughout the distribution system [2]. Conveying water through long distance causes several changes in its chemistry, such as pH, alkalinity, total hardness (TH), and concentration of common ions (Ca^{2+}, Mg^{2+}, CO_3^{2-}, and HCO_3^-) [3]. This change is caused due to diverse reasons, including the change in carbon dioxide concentration, which affects the concentrations of both calcium and magnesium, where the increasing CO_2 concentration leads to the formation of carbonate ion which precipitates with Ca^{2+} and Mg^{2+} as $CaCO_3$ and $MgCO_3$, which is known by scale formation. The following chemical equations illustrate the process [4]:

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$$CO_{2(g)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3(l)} \rightleftharpoons HCO^-_{3(aq)} + H^+_{(aq)} \rightleftharpoons CO_3{}^{2-}{}_{(aq)} + 2H^+_{(aq)} \tag{1}$$

$$Ca^{2+}{}_{(aq)} + CO_3{}^{2-}{}_{(aq)} \rightarrow CaCO_{3(s)} \tag{2}$$

$$Ca^{2+}{}_{(aq)} + 2HCO_3{}^-{}_{(aq)} \rightarrow CaCO_{3(s)} + H_2O_{(l)} + CO_2 \tag{3}$$

One of the factors that lead to the change of concentration of carbon dioxide is the change in flow rates. Some previous studies were concerned with factors affecting scale formation such as flow rate. The effect of flow rate, temperature, and maleic acid as additives on the mass and morphology of the scale formation in pipes was studied by Muryanto et al. [5]. As a result of this study, it was found that higher flow rates lead to more calcium carbonate scale deposition, which indicates that the fluid flow enhances the scale formation. The effect of flow rate and copper ion concentration on calcium sulphate scale formation was studied [6]; it was found that the gypsum scale mass generated can be reduced to 61% depending on the flow rates and the Cu^{2+} concentrations as impurities.

Simulation plays an important role in understanding the change of water chemistry when transport occurs through plumbing systems. Simulation serves to understand systems behavior, determines water supply problems, as well as studying complex systems. The models used for simulation can provide quantitative information which leads to choosing the optimum flow and cost minimization [7]. Several simulation works were performed to study the behavior of water or to solve some problems in drinking water distribution systems [5]. In Turkey, simulation was utilized to manage the water transport from resources to consumers [8]. Nonlinear modeling and simulation were performed on the city of Gaziantep city [9] water supply systems to practice water management. The nonlinear system was simulated to obtain the flow rates, the reservoir heads and the head loss caused by friction, which helped understanding the behavior of a water supply system in Gaziantep. Al-Rawajfeh [10] had used a simulation system to study factors that influence $CaCO_3$ scale precipitation and the CO_2–H_2O system for flowing water in steel pipes. It has been found that the concentration of HCO_3^- and CO_3^{2-} decreases by increasing the flow rate, as well as the possibility to precipitate $CaCO_3$ increases due to the increase in pH.

Disi water conveyance project was inaugurated in 2013 to bridge the gap in water supply in the capital city (Amman), which resulted from the high population growth. Disi water is of high quality with TH of 140 ppm as $CaCO_3$, alkalinity of 170 ppm as $CaCO_3$, and pH of 8.03. Disi water transported through about 345 km steel pipes from Disi aquifer in the south of Jordan to Amman city is shown in Fig. 1.

Disi water is pumped to Amman city with different flow rates, one of them is under gravity as illustrated in Fig. 1 [11]. Simulation is one of the methods that used widely to study water chemistry changes. The long-term simulation of water quality within a distribution system becomes possible with the advancement in dynamic hydraulic simulations.

In this study, an experimental setup of 20.0 m pipe line was used to study the influence of flow rate on Disi water chemistry, and suggestions to reduce scale deposition using nanofiltration and some chemical additives.

2. Experimental setup

2.1. Materials and methods

2.1.1. Water sampling

The experimental work has been conducted using a controlled pump (Schneider Electric C60HC, C10. 240/415v) as shown in Fig. 2. This setup is used to simulate the pumping system of Disi water that conveyed through steel pipelines of about 345 km length to Amman city. About 20.0 L of Disi water was pumped into steel pipeline with length of 20 m and diameter of 15.0 mm. Water was pumped for 5 h. Samples were taken every hour and subjected to physiochemical analysis. The water samples were collected in

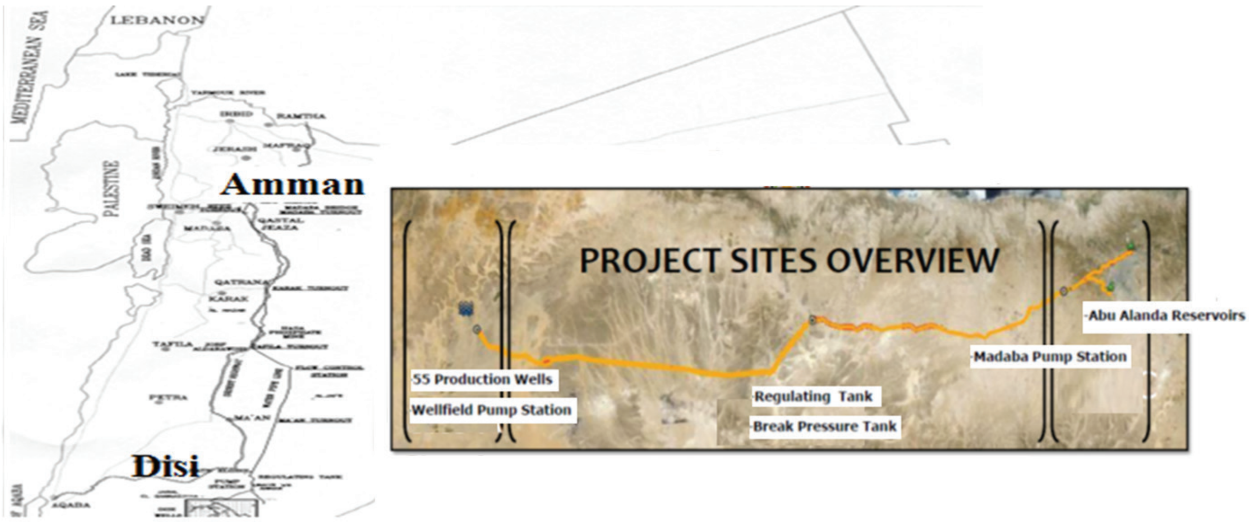

Fig. 1. Disi water conveyance project to transport water from Disi aquifer to Amman city.

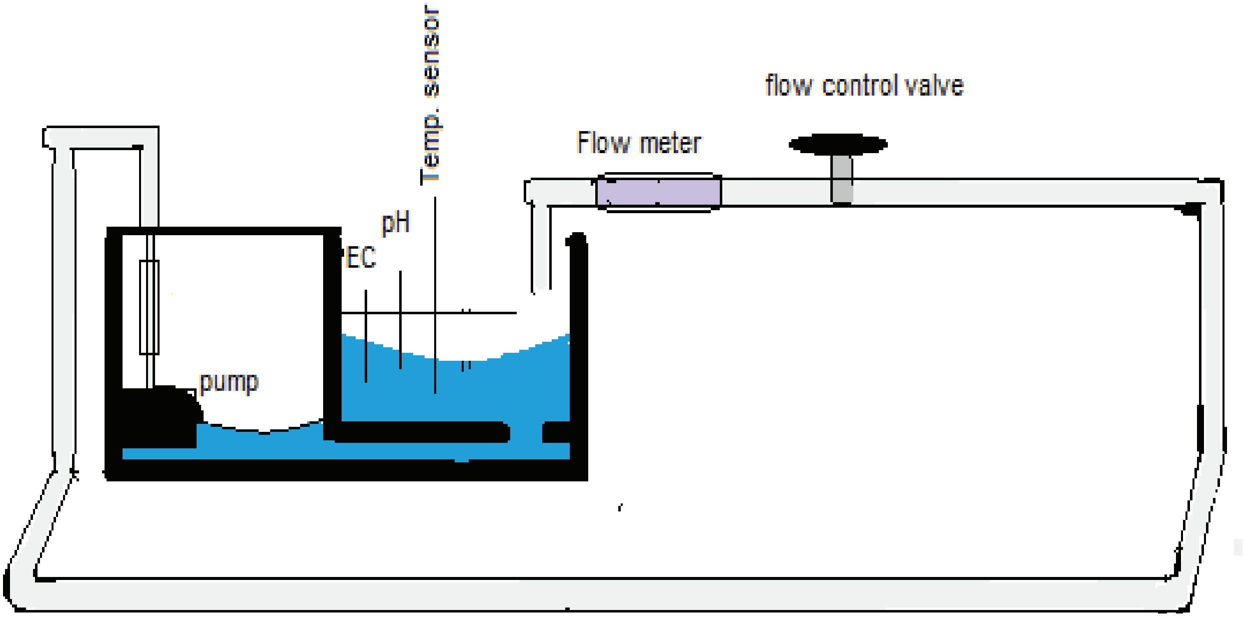

Fig. 2. Experimental setup for simulating the pumped Disi water.

100.0 mL polyethylene bottles. The pumping process was repeated with a new sample using different flow rates (5, 10, 15, 25, and 35 L/min). Coupons of halves-tubes were placed in the tank with different surface roughness to investigate the influence of roughness on the scale deposition.

2.1.2. Chemicals and reagents

All salts utilized for the preparation of all solutions were of analytical reagent grade and anhydrous with reported purities of +99%. Deionized water was used in all experiments. EDTA, $AgNO_3$, KNO_3, Na_2SO_4, NaH_2PO_4, NaOH, KCl, NaCl, $BaCl_2$, K_2CrO_4 were purchased from AVONCHEM (UK). Murexide, Eriochrome Black T, methyl red, and phenolphthalein indicators were purchased from Alfa Aesar (USA). All salts were dried in an oven at 120°C as required and used without further purifications. Stock solutions were prepared by using double distilled water (DDW).

2.1.3. Physical and chemical analysis

Based on standard methods of analysis [8], all samples were tested for physical and chemical parameters. pH was measured using HI 254 pH/ORP meter, pH/ION/Cond 750 m was used to measure electrical conductivity (EC). Total dissolved solids (TDS) parameter was calculated on the bases of EC values. Total alkalinity (TA) was measured by HCl titrimetric method. Total hardness (TH), calcium, and magnesium ions were measured by EDTA titrimetric method. Carbon dioxide was measured by NaOH titrimetric method. Argentometric titration was used in chloride determination. Sulphate and nitrate concentrations were assessed by using UV-1800 Shimadzu Spectrophotometer. Sodium and potassium ions were determined using flame emission photometric method (Jenway PFP7 Flame photometer).

3. Results and discussion

3.1. Physico-chemical characteristics

Disi water was subjected to pumping through 20.0 m long steel pipes connected to a tank. Different flow rates were investigated. Temperature, pH, and EC were measured directly in the collecting water tank. A sample has been collected each hour. For all collected samples, TH, TA, and TDS were measured immediately. All measured and calculated parameters are tabulated in Table 1.

Studied characteristics (temperature, pH, TA, EC, TDS, and TH) were plotted against time, separately in order to illustrate their behavior during pumping. Fig. 3(A) displays the increase in temperature with time for each run. The increase in temperature becomes larger as the flow rate increases. The temperature change was found to be 7.5°C at a flow rate of 5.0 L/min, while the change at 35.0 L/min was 12.7°C. As it can be expected, the temperature increases during the pumping process; this can be explained by the movement of water molecules and the friction in the internal walls of the pipes.

As shown in Table 1, pH values increase from 8.03 to 8.15, 8.18, 8.22, 8.24, and 8.32 at flow rates of 5, 10, 15, 25, and 35 L/min, respectively. All pH values remain within both the Jordanian standards and WHO guidelines for drinking water (6.5–8.5) during pumping at all stages of the process. Fig. 3(B) shows that the increase in pH values with time for the same flow rate. This can be explained due to the fact that the solubility of gases decreases as the temperature increases. The concentration of dissolved carbon dioxide is expected to decrease during the pumping process and hence increase the pH value. From Fig. 3(C) it is noticeable that as the flow rate of pumping increases, the change in pH value of pumped water also increases. For example, at 5.0 L/min the pH value changed by 0.12, while for the highest studied flow rate (35.0 L/min), the pH changed by 0.29. The rise of temperature, or a sharp rise in pH, will cause bicarbonate to decompose

Table 1
Physico-chemical characteristics (temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness as CaCO$_3$ (TH), and total alkalinity (TA)) of all samples from simulation

Run no./ flow rate	Time (h)	Physico-chemical characteristics					
		Temperature (°C) ±0.01	pH ±0.001	EC (µS/cm) ±0.1	TDS (mg/L) ±0.1	TH (mg/L)	TA (mg/L)
1st run 5.0 L/min	1	25.50	8.030	328.0	210.6	139.40 ± 0.05	170.00 ± 0.10
	2	26.00	8.060	322.0	206.1	139.40 ± 0.08	173.00 ± 0.20
	3	28.00	8.100	318.0	203.5	138.50 ± 0.05	174.00 ± 0.11
	4	30.50	8.130	315.0	201.6	136.20 ± 0.05	178.00 ± 0.10
	5	32.00	8.150	310.0	198.4	134.80 ± 0.02	180.00 ± 0.05
2nd run 10.0 L/min	1	25.00	8.030	329.0	210.2	139.10 ± 0.10	172.00 ± 0.10
	2	27.50	8.100	321.0	205.4	139.20 ± 0.10	173.00 ± 0.13
	3	30.00	8.140	317.0	202.9	138.00 ± 0.05	177.00 ± 0.00
	4	33.50	8.160	315.0	201.6	135.70 ± 0.05	179.00 ± 0.05
	5	34.00	8.180	309.0	197.8	134.60 ± 0.00	181.00 ± 0.11
3rd run 15.0 L/min	1	25.20	8.030	327.0	210.0	139.20 ± 0.10	170.00 ± 0.07
	2	28.00	8.130	321.0	205.4	139.00 ± 0.26	174.00 ± 0.02
	3	31.00	8.160	316.0	202.2	137.80 ± 0.10	177.00 ± 0.02
	4	33.50	8.190	313.0	200.3	135.10 ± 0.10	180.00 ± 0.01
	5	36.00	8.220	307.0	196.5	134.00 ± 0.05	183.00 ± 0.03
4th run 25.0 L/min	1	25.00	8.030	329.0	210.4	139.40 ± 0.02	169.00 ± 0.05
	2	29.00	8.150	319.0	204.2	138.40 ± 0.06	176.00 ± 0.04
	3	32.50	8.170	313.0	200.3	137.20 ± 0.10	180.00 ± 0.09
	4	34.00	8.210	311.0	199.0	134.30 ± 0.02	182.00 ± 0.10
	5	37.00	8.240	303.0	193.9	133.70 ± 0.05	184.00 ± 0.01
5th run 35.0 L/min	1	25.30	8.030	330.0	210.1	139.50 ± 0.05	171.00 ± 0.08
	2	29.50	8.160	317.0	202.9	137.90 ± 0.02	178.00 ± 0.06
	3	33.00	8.210	310.0	198.4	136.60 ± 0.04	181.00 ± 0.03
	4	35.00	8.260	307.0	196.5	133.60 ± 0.01	185.00 ± 0.15
	5	38.00	8.320	298.0	190.7	132.80 ± 0.04	186.00 ± 0.08
JDWS*		–	6.5–8.5	750–2,300	500	300–500	300
WHO**		–	6.5–8.5	300–750	300–500	100–500	–

*JDWS: Jordan Water Standard (Js no:286/2008).
**WHO: World Health Organization Guidelines (2011).

and form carbon dioxide and carbonate leading to CaCO$_3$ deposition.

Alkalinity level also increases with time as shown in Fig. 3(C) due to the decrease in carbon dioxide concentration. TA increased by 10-fold at 5.0 L/min flow rate, while the value increased to 16 at a flow rate of 35.0 L/min. Measured EC values ranged from about 329 to 310, 309, 307, 303, and 298 µS/cm at flow rates of 5, 10, 15, 25, 35 L/min, respectively. EC decreases with time as shown in Fig. 3(D), which is considered as an indicator of ionic concentration in water. This decrease in the EC can be explained by the decrease in ionic concentrations such as calcium, magnesium, and carbonate (ions participating in scale formation).

TDS and TH display the same behavior as time passes and with flow rate of pumping (Figs. 4(A) and (B)). This decrease in both TDS and TH is explained for the same reasons as for the EC reduction. Raise in calcium carbonate precipitation with time involved decreasing in calcium ions in water (i.e., decrease in hardness). Decreasing in TDS also is explained by the same way, in addition to the decreasing in carbonate ions and magnesium ions when contribute in scale formation. From the above results, it can be concluded that there is a remarkable correlation among most measured parameters.

Table 2 shows the concentrations of calcium, magnesium, and carbon dioxide in all water samples.

The concentrations of calcium, magnesium, and carbon dioxide vs. time are plotted at all flow rates of the study. There is a decrease in the concentration of calcium and magnesium ions with time which indicates the possibility of scale deposition (Figs. 4(C) and (D)).

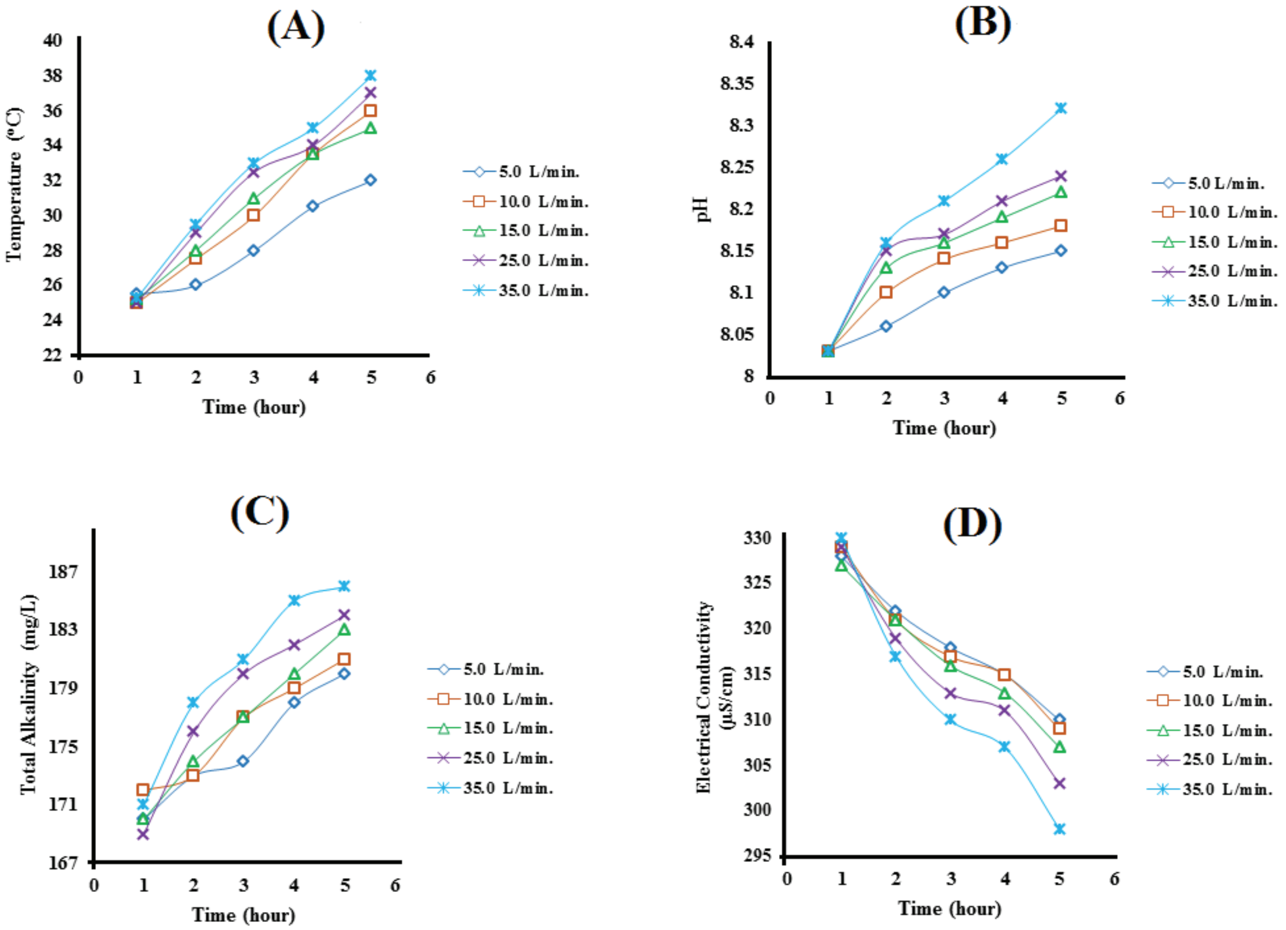

Fig. 3. The change in: (A) temperature, (B) pH, (C) total alkalinity, and (D) electrical conductivity of pumped Disi water with time at five different flow rates (5.0, 10.0, 15.0, 25.0, and 35.0 L/min).

Scale formation is from the release of carbon dioxide gas from water, which makes a shift in the reaction direction according to the Le Chatelier's principle. The following chemical equations indicate the equilibrium between carbon dioxide and calcium carbonate precipitation. When CO_2 is released, the equilibrium shifts to the right to compensate for the loss of carbon dioxide pressure/concentration.

$$Ca^{2+}_{(aq)} + 2HCO_3^-{}_{(aq)} \rightleftharpoons CaCO_{3(s)} + H_2O_{(l)} + CO_2 \qquad (4)$$

Figs. 4(D) and (E) display the behavior of ions with time at all studied flow rates. The flow rate enhances the magnitude of decreased ions and carbon dioxide concentration increase. At a flow rate of 5.0 L/min, the change in calcium, magnesium, and carbon dioxide concentrations was: 1.68, 0.09, and 0.04 mg/L, respectively. While at a flow rate of 35.0 L/min, the change in concentration was: 2.45, 0.13, and 1.86 mg/L, respectively. That means that the produced scale becomes denser as the flow rate of pumping is raised. The conversion rate of carbonic acid to bicarbonate then to carbonate ions increases with pH rise. Produced carbonate then deposits with calcium as $CaCO_3$.

As seen in Fig. 4(E), there is a considerable decrease in CO_2 concentration which agrees well with the previously discussed pH and temperature results. Finally, a decrease in carbon dioxide concentration strongly suggests a decrease in the concentration of carbonate and bicarbonate ions according to following equilibria:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^{2-} + 2H^+ \qquad (5)$$

$$Ca^{2+}_{(aq)} + 2HCO_3^-{}_{(aq)} \rightleftharpoons CaCO_{3(s)} + H_2O_{(l)} + CO_2 \qquad (6)$$

The loss rate of CO_2 increases as the flow rate increases due to the rise in all temperature, pH, and alkalinity parameters [12].

3.2. Correlation

Correlation is calculated by what is called coefficient of correlation (r). Its numerical value ranges from –1.0 to +1.0. Coefficient of correlation (r) gives an indication of the strength of relationship between two parameters. In general, $r > 0$ indicates a positive relationship, $r < 0$ indicates a negative relationship while $r = 0$ indicates no relationship (or that the variables are independent and not related). A perfect positive correlation indicated when $r = +1.0$ (when one

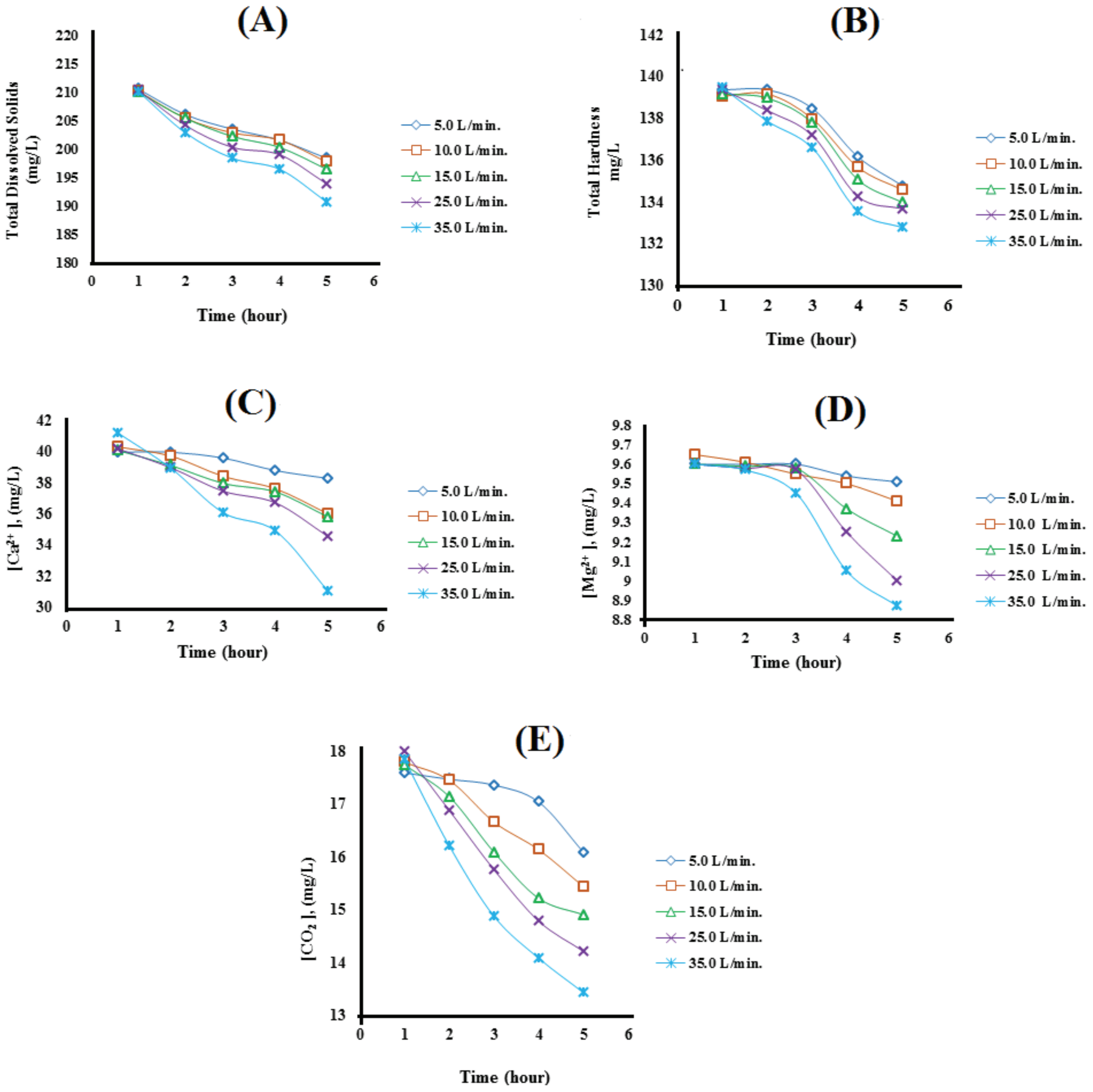

Fig. 4. The change in: (A) total dissolved solids, (B) total hardness, (C) $[Ca^{2+}]$, (D) $[Mg^{2+}]$, and (E) $[CO_2]$ of pumped Disi water with time at five different flow rates (5.0, 10.0, 15.0, 25.0, and 35.0 L/min).

variable increases as the other increases), and a perfect negative correlation indicated when $r = -1.0$ (when one decreases as the other increases). As the coefficient is close to +1.0 and –1.0; the strength of the relationship between the variables is greater. The interpretation of correlation coefficient value; for absolute values of r, 0–0.19 is regarded as very weak, 0.2–0.39 as weak, 0.40–0.59 as moderate, 0.6–0.79 as strong, and 0.8–1 as very strong correlation. Excel Microsoft Office was used to calculate the correlation between measured parameters. Table 3 displays the calculated correlation coefficients between all water qualities measured parameters. It is evident that there is a strong positive correlation between EC and TDS ($r = 0.967$), TH and $[Ca^{2+}]$ ($r = 0.9998$), TH and $[Mg^{2+}]$ ($r = 0.982$), $[Mg^{2+}]$ and $[Ca^{2+}]$ ($r = 0.979$), temperature and TA ($r = 0.975$), pH and TA ($r = 0.\ 973$), temperature and pH ($r = 0.950$), TH and $[CO_2]$ ($r = 0.946$), $[Mg^{2+}]$ and $[CO_2]$ ($r = 0.937$), EC and $[Ca^{2+}]$, TDS and $[Ca^{2+}]$, EC and TH ($r = 0.924$), TDS and TH ($r = 0.923$), EC and $[Mg^{2+}]$ ($r = 0.894$), TDS and $[Mg^{2+}]$ ($r = 0.894$), and finally pH with $[CO_2]$($r = 0.798$). All additional parameters show a strong negative correlation with each other according to Table 3.

3.3. Calculation of water stability indices

Water stability/saturation indices provide an indication about the tendency of water to deposit or to dissolve scale which is mainly consisting of calcium carbonate. In order to examine the effect of flow rate on Disi water chemistry, Langelier saturation index (LSI), Ryznar stability index (RSI), Puckorius scaling index (PSI), and Aggressive Index (AI) were calculated for all samples. Water stability indices and their interpretation have been explored in the introductory part. All results are presented in Table 4 and Fig. 5.

Table 2
Concentrations of calcium and magnesium ions and dissolved CO_2

Run no./ flow rate	Time (h)	Concentration		
		$[Ca^{2+}]$ (mg/L)	$[Mg^{2+}]$ (mg/L)	$[CO_2]$ (mg/L)
1st run 5 L/min	1	40.00 ± 0.05	9.60 ± 0.08	17.60 ± 0.10
	2	40.00 ± 0.18	9.60 ± 0.02	17.48 ± 0.02
	3	39.62 ± 0.02	9.60 ± 0.02	17.37 ± 0.05
	4	38.82 ± 0.09	9.54 ± 0.04	17.05 ± 0.03
	5	38.32 ± 0.02	9.51 ± 0.04	16.10 ± 0.04
2nd run 10 L/min	1	40.33 ± 0.01	9.65 ± 0.03	17.80 ± 0.06
	2	39.75 ± 0.08	9.61 ± 0.04	17.46 ± 0.06
	3	38.45 ± 0.05	9.55 ± 0.03	16.67 ± 0.03
	4	37.65 ± 0.05	9.50 ± 0.10	16.15 ± 0.05
	5	36.05 ± 0.10	9.41 ± 0.03	15.45 ± 0.07
3rd run 15 L/min	1	40.10 ± 0.11	9.60 ± 0.20	17.75 ± 0.05
	2	39.15 ± 0.13	9.59 ± 0.02	17.15 ± 0.10
	3	38.00 ± 0.16	9.58 ± 0.08	16.10 ± 0.07
	4	37.45 ± 0.08	9.37 ± 0.03	15.23 ± 0.05
	5	35.85 ± 0.01	9.23 ± 0.03	14.92 ± 0.02
4th run 25 L/min	1	40.20 ± 0.05	9.60 ± 0.20	18.00 ± 0.05
	2	39.00 ± 0.10	9.58 ± 0.05	16.89 ± 0.04
	3	37.50 ± 0.06	9.57 ± 0.03	15.77 ± 0.02
	4	36.75 ± 0.05	9.25 ± 0.02	14.80 ± 0.09
	5	34.60 ± 0.05	9.00 ± 0.07	14.23 ± 0.03
5th run 35 L/min	1	41.20 ± 0.02	9.60 ± 0.17	17.85 ± 0.08
	2	38.97 ± 0.16	9.57 ± 0.05	16.22 ± 0.20
	3	36.12 ± 0.02	9.45 ± 0.05	14.89 ± 0.04
	4	34.95 ± 0.10	9.05 ± 0.05	14.10 ± 0.20
	5	31.10 ± 0.07	8.87 ± 0.06	13.45 ± 0.10
JDWS*		100–500	100–500	–
WHO**		100–300	150	–

*JDWS: Jordan Water Standard (Js No:286/2008).
**WHO: World Health Organization Guidelines (2011).

Table 3
Correlation matrix for all samples

Parameters	Temperature (°C)	pH	EC (μS/cm)	TDS (mg/L)	TH (mg/L)	TA (mg/L)	$[Ca^{2+}]$ (mg/L)	$[Mg^{2+}]$ (mg/L)	$[CO_2]$ (mg/L)
Temperature (°C)	1								
pH	0.950	1							
EC (μS/cm)	–0.968	–0.963	1						
TDS (mg/L)	–0.968	–0.963	1	1					
TH (mg/L)	–0.950	–0.963	0.923	0.922	1				
TA (mg/L)	0.975	0.973	–0.978	–0.978	–0.942	1			
$[Ca^{2+}]$ (mg/L)	–0.951	–0.890	0.924	0.924	0.9998	–0.944	1		
$[Mg^{2+}]$ (mg/L)	–0.923	–0.844	0.894	0.894	0.982	–0.901	0.979	1	
$[CO_2]$ (mg/L)	–0.916	0.798	0.932	0.932	0.946	–0.926	0.946	0.937	1

Table 4
LSI, RSI, PI, and AI indices

Run no./ flow rate	Sample no.	Scale saturation indices			
		LSI	RSI	PSI	AI
1st run 5 L/min	1	0.49	7.04	7.28	12.40
	2	0.53	7.00	7.26	12.44
	3	0.57	6.96	7.25	12.48
	4	0.60	6.93	7.23	12.51
	5	0.62	6.91	7.22	12.53
2nd run 10 L/min	1	0.49	7.04	7.28	12.40
	2	0.57	6.96	7.26	12.51
	3	0.61	6.91	7.23	12.55
	4	0.63	6.90	7.23	12.58
	5	0.65	6.87	7.21	12.61
3rd run 15 L/min	1	0.49	7.04	7.28	12.40
	2	0.60	6.93	7.25	12.44
	3	0.63	6.89	7.23	12.48
	4	0.66	6.87	7.22	12.51
	5	0.70	6.83	7.20	12.53
4th run 25 L/min	1	0.49	7.04	7.28	12.40
	2	0.62	6.90	7.24	12.54
	3	0.65	6.87	7.21	12.56
	4	0.68	6.84	7.21	12.60
	5	0.72	6.81	7.19	12.63
5th run 35 L/min	1	0.49	7.04	7.28	12.40
	2	0.64	6.89	7.22	12.55
	3	0.69	6.83	7.20	12.60
	4	0.74	6.78	7.19	12.65
	5	0.80	6.73	7.18	12.71

3.3.1. Langelier saturation index

Positive value of LSI indicates that water has a tendency to deposit calcium carbonate. While negative value of LSI indicates that water has a tendency to dissolve calcium carbonate. Zero value of LSI means that water is at equilibrium [13]. From an analysis based on Langelier saturated index, it is found that all samples showed a positive value at all times and at all studied flow rates. This result indicates that Disi water has a tendency to deposit calcium carbonate while pumping. Fig. 5(A) represents the change in LSI with time and at all the studied flow rates.

At the same flow rate, value of LSI increased and becomes more positive with time. This is comparable with the results mentioned above. The change in LSI value is increased by the increase in the flow rate. The change is raised from 0.13 at 5.0 L/min flow rate to 0.31 at 35.0 L/min which indicates that the tendency of water to deposit calcium carbonate increases as flow rate rises.

3.3.2. Ryznar stability index

RSI value below 5 indicates that water tends to form heavy scale. If RSI value lies between 5.0 and 6.0, then it indicates that water tends to form some scale. If RSI value lies between 6.0 and 7.0, then water is considered to be non-scaling. If RSI

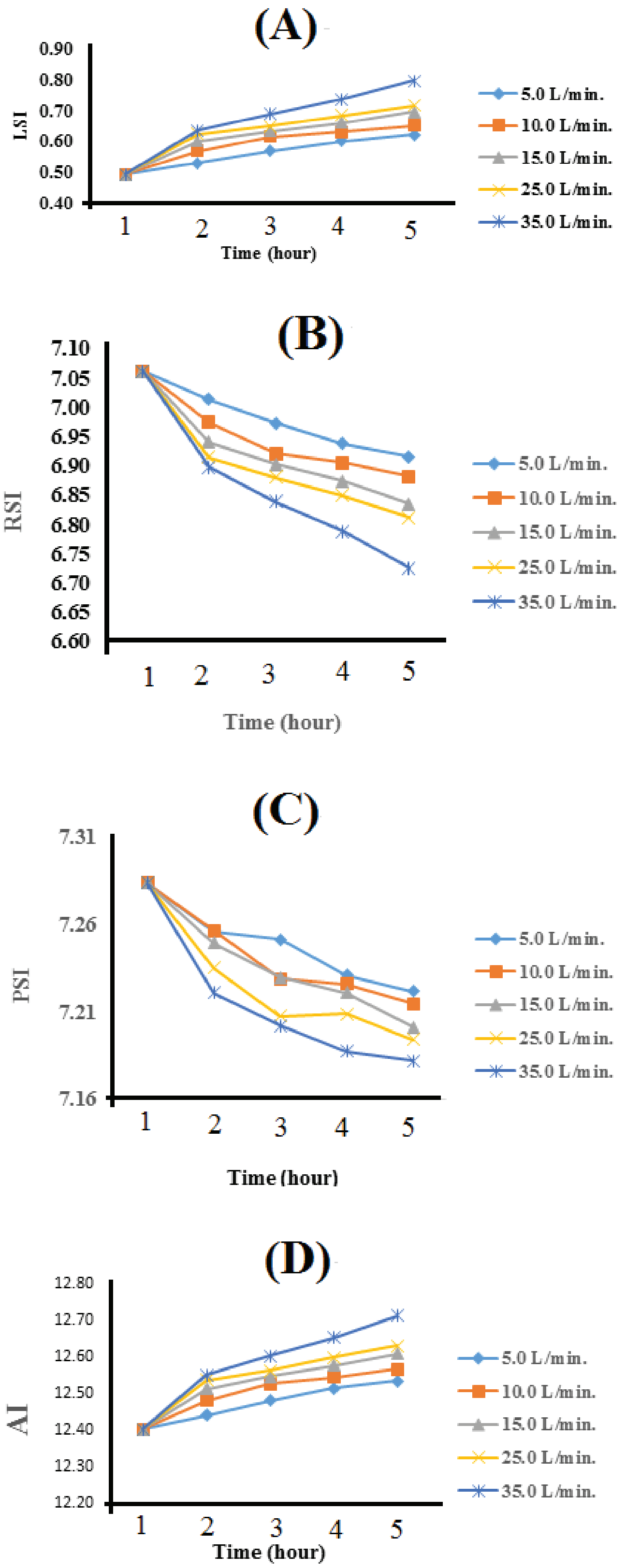

Fig. 5. The change in (A) Langelier saturation index (LSI), (B) Ryznar stability index (RSI), (C) Puckorius scaling index (PSI), and (D) Aggressive Index (AI) of pumped Disi water with time at five different flow rates.

value lies in the range of 7.0–8.0 then water starts to be corrosive. Finally, if RSI value lies above 8.5 then water tends to be heavy corrosive [14]. Fig. 5(B) and Table 4 illustrate the results of RSI for all samples.

3.3.3. Puckorius scaling index

PSI has the same numbering systems and descriptions as for the RSI. PSI considers scaling as unlikely to take place if the value is <6.0. It is considered as likely to dissolve scale if >7 [13]. All samples have values greater than 7. Fig. 5(C) shows how PSI changed with time at different flow rates.

3.3.4. Aggressive index

Water with AI less than 10 is considered highly aggressive, while 10–12 indicates moderate corrosion and above 12 indicates scaling [15]. Calculations showed that all samples have AI greater than 12 which agreed with the results of ability of scale formation. Fig. 5(D) represents the relationship between flow rate and aggressive index.

Though Disi water has a high quality with TH of 140 ppm as $CaCO_3$ (considered to be hard), alkalinity of 170 ppm as $CaCO_3$, and pH of 8.03, this study proved that Disi water has a tendency to deposit calcium carbonate when pumped through the conveyed pipes and network distribution systems. The deposition of calcium carbonate causes the formation of a thin film on the internal walls of pipes. Initially, this formed film was considered as an advantage because it protects pipes against corrosion. But over a long period of usage clogging of pipes become a problem, as it affects the efficiency of flow through the pipes. Therefore, the consumption of energy was expected to grow. To solve or to prevent the occurrence of the problem, the accumulated scale should be removed from pipes from time to time, or by finding a suitable and efficient method that reduces the scale formation during pumping. This will be discussed in the last section of this study.

3.4. Surface roughness

The effect of surface roughness on scale deposition on steel pipes was investigated using roughness measurements of the scaled surfaces. The roughness of the scaled surfaces increases by increasing the amount of deposited scale. Scale deposition increases by increasing the surface roughness. Fig. 6 shows photos of the coupon with 0.3 and 0.24 μm roughness, respectively. The scale consists of calcium carbonate, magnesium hydroxide, calcium sulfate, and some tube's metals such as Fe and Zn.

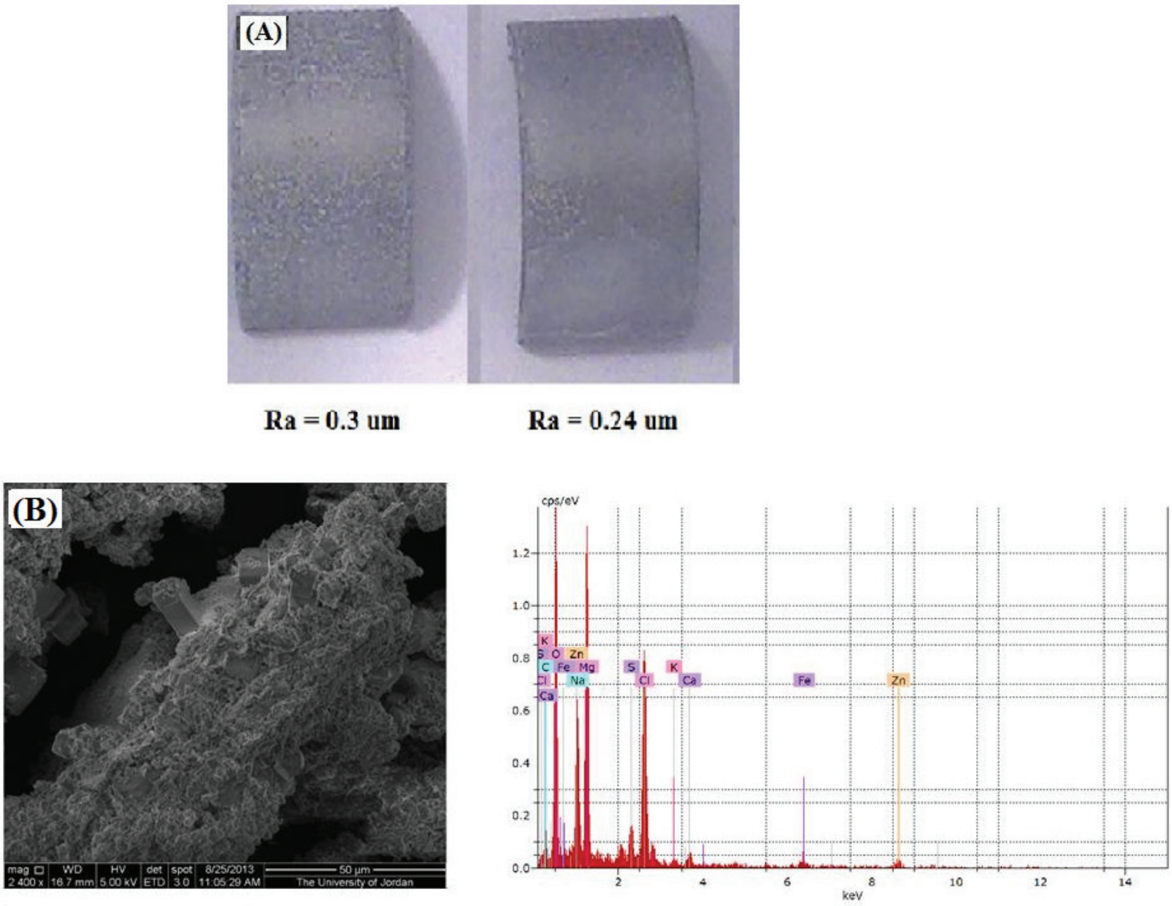

Fig. 6. The influence of surface roughness on the scale deposition.

4. Conclusion

Chemistry of the pumped Disi water has been changed when pumped from the south of Jordan to the north. The influence of using different flow rates for pumping process has been investigated. It was found that by raising the flow rate there was more scale deposition on the inner walls of distribution system pipes. The change in Disi water chemistry because of pumping was explored based on exchangeable dissolved carbon dioxide concentration in water. The results showed that Disi water suffers calcium carbonate scale deposition as it is pumped with different flow rates. It was found that the scale deposition increased by increasing the flow rate and surface roughness.

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