IMPACT OF OPERATIONAL STRATEGIES TO PREVENT SILICA FOULING IN REDUCING COSTS IN BWRO SYSTEMS: CASE STUDY FOR ARICA 18,000M3/DAY BWRO PLANT IN CHILE

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ABSTRACT

Minimizing fouling and scaling problems in RO facilities has been reported as one of the main issues for an affordable desalination for all water types. Fouling can be simply described as an undesirable deposition of deposits in a surface (membrane). In RO systems fouling problems mean higher working pressures, higher energy consumption rates, frequent cleaning and unscheduled plant downtime, making it difficult to comply with contractual water production targets

Silica has been reported as one of the most undesirable foulant in membrane systems. Due to a shortage of good quality water in many regions of the world, RO plants are forced to operate with very high levels of silica. Silica chemistry is complex; deposits can be found on the surface of reverse osmosis membranes in a polymeric or crystalline form, and can also reach the membranes as colloidal particles. Traditionally reverse osmosis systems have been operated at low recoveries with frequent cleaning and reduced membrane life as conventional antiscalants are limited in their ability to inhibit silica fouling.

Arica Desalination plant, has a capacity of 750 m^3/h, and started its operation in 1998. The plant is fed from several wells located at Lluta Valley, characterized by high chloride levels (average concentration over 800 mg/L) and dissolved solids (average concentration over 3.000 mg/L). Feed water quality is variable as the wells have differing geology and chemistry and extraction is dictated by availability not quality. Silica levels in the feed water have increased from the design level of 196 mg/L silica in reject to as high as 300 mg/L of silica in reject. This paper describes the analytical and on-site research work carried out to better characterize factors negatively affecting plant performance. Silica inhibition and cleaning strategies adopted in this plant to minimize the fouling problems identified are explained. The effectiveness of different strategies adopted is reviewed using real operational data available from 1999 to 2011.

In this paper cost savings of operational strategies adopted in Arica Desalination plant are calculated and presented. The importance of operational practices in reducing energy consumption is demonstrated. The use of actual silica inhibition and cleaning strategies shows that membrane desalination in very poor quality waters can be a cost effective affordable solution. Results show a significant reduction in cleaning frequency from more than six per year to once per year and reductions in energy consumption of 0.06kWh/m^3.

1.- Introduction

Arica city, in Chile, is geographically located as a point of convergence between the countries comprising the Andean Macro region, bounded on the north by Peru and Bolivia to the east. This situation makes it a strategic area to meet the logistical needs of Asia Pacific, among many other markets that would require port services, transport and storage. According to the Chilean National Statistics Institute in 2002, its population exceeded 175,000 habitants, with expectative for fast growing in next years due to the development of trade and tourism related activities. Weather conditions (coastal desert climate) and soil characteristics determine water scarcity conditions, which has forced the construction of water infrastructures to ensure water supply in sufficient quantity and quality.

Arica Desalination Plant, designed and built by OHL Medio Ambiente INIMA SA, was commissioned in April 1998. This plant was designed for a maximum production capacity of 18,000 m^3/day and company Desalari Ltd. has been in charge for exploitation since 1998. The plant is supplied from 11 wells located in the Valley of Lluta, with average depths around 130 meters and occur in most cases high levels of chlorides (average value exceeding 800 mg / L) and dissolved solids (average value exceeding 3,000 mg / L). These characteristics require desalination processes, having been selected for this reverse osmosis technology. Feed water quality is extremely variable, depending on the operating conditions of the different well since they have very heterogeneous water quality.

2.- Plant description

An 11 Km collector is used for transporting water from different wells to the treatment plant, with a storage tank of 2.000 m^3 capacity. Pre-treatment design of this facility is composed of sand filtration (4+1 sand filters) followed by security filtration (4 +1 filter housings with a total of 175 units of 40” 5 micron cartridge filters). Dosage of sodium hypochlorite, acid and coagulant was before sand filters and sodium bisulphite and antiscalant were scheduled, all currently out of use except for the antiscalant. The reverse osmosis system consists of 4 racks in 2 stages, with 24 pressure vessels in first stage (144 membrane elements Hydranautics CPA3) and 12 pressure vessels in second stage (72 membrane elements Hydranautics ESPA2). The total design capacity of this facility is 750 m^3 / h, with a conversion rate of 75%. The facility has a Pelton turbine to recover energy from reject. Permeate water is aerated to promote the elimination of CO_2 and then mixed with other types of water in the Chuño pond and ETAP Stadium, to guaranty regulatory values for potable supply.

Figure 1.- Plant overview

3.- Problems/failures detected in performance and strategies suggested for operation optimization

3.1 .- Problems and failures detected in plant operation. Diagnosis of plant performance.

The review of different analyses and tests performed before and during the commissioning of the plant shows that the main risks associated with water quality in this facility are related to high concentrations of silica and the variable and usually high concentration in metals (iron and manganese). Also a significant variability in the content of suspended solids and colloidal matter has been detected. Feed (mixture) water quality data from physico-chemical analyses from different samples taken during the period 2006-2009 (monthly averages) is shown in Table 1. Heterogeneity of data is associated with use of a large number of wells with different water characteristics and irregular operations regime depending on water availability and production needs. Table 2 summarizes quality related data for feed (mixture) and some of the wells in operation during a sampling campaign in July 2005 for those parameters considered to be critical.

Table 1.- Feed (mixture) water analyses. Monthly average values for 2006 – 2009.

	2006				**2007**				**2008**				**2009**	
	Jan	**Apr**	**July**	**Oct**	**Jan**	**Apr**	**July**	**Oct**	**Jan**	**Apr**	**July**	**Oct**	**Jan**	**Apr**
Turbidity (UNF)	7	3	1,0	5	0,34	0,38	0,49	0,53	0,55	3,95	4,04	4,45	3,25	3,06
Conductivity	4529	4500	4697	4517	4590	4570	4610	4540	4570	4510	4400	4450	4430	4410
Clorides (mg/L)	913	927	969	920	925	918	920	906	921	877	867	860	874	863
Hardness (mg/L)	-	-	-	1301	1242	1266	1268	1200	1205	1178	1155	1152	1144	1053
Bicarbonates (mg/L)	-	-	-	-	110	111	112	122	124	121	125	125	116	110
Calcium (mg/L)	323	332	329	323	318	334	327	316	324	312	306	308	304	299
Magnesium (mg/L)	-	-	106	102	94	104	99	98	97	93	93	92	91	80
Barium (mg/L)	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1
Sílica (mg/L)	57,5	57,1	59,5	56,0	56,1	54,4	57,4	55,0	56,4	57,9	57,1	57,6	56,2	56,4
Sulphates (mg/L)	1037	1061	1180	1058	1085	1044	1044	1034	1019	1010	1020	1028	1042	1040
Manganese (mg/L)	-	-	0,90	0,69	0,65	0,65	0,65	0,28	0,85	0,99	0,98	1,03	1,12	1,04
Iron (mg/L)	-	-	0,05	0,15	0,04	0,05	0,05	0,05	0,06	0,09	0,12	0,13	0,14	0,20
Strontium (mg/L)	-	-	2,29	2,15	2,19	2,29	2,29	2,21	2,25	2,19	2,12	2,15	2,12	2,07

Table 2.- Feed (mixture) water analysis for a punctual sampling campaign in July 2005. Water characteristics for individual wells.

	Well 3	**Well 10**	**Well 23**	**Well 16**	**Well 18A**	**Feed water (mixture)**
Turbidity (UNF)	1,02	5,5	**35**	0,61	1,76	0,75
pH (u.pH)	7,05	7,08	6,80	6,76	6,89	7,39
Conductivity (µS/cm**)**	4050	5340	4220	4420	4840	4710
TDS (mg/L)	2909	3722	2779	2967	3290	3325
Total iron (mg/L)	0,08	1,26	**2,75**	0,19	0,49	0,08
Dissolved iron (mg/L)	0	0,09	0,14	0,04	0,01	0,03
Total Manganese (mg/L)	0,12	**1,81**	**1,41**	0,28	**3,16**	0,09
Diss. manganese (mg/L)	0,10	1,81	1,41	0,28	1,55	0,05
Silica (mg/L)	56,7	60,2	62,7	61,3	59,0	**74,4**

Despite the observed variability in the turbidity of the water supply, the values obtained for the Silt Density Index SDI_{15} in raw water and feed water (pre-treated) are always lower than 3. Operational historical data review indicates average values of SDI_{15} of 2.91 for raw water and 1.05 for feed water (after microfilters) for a period of six years (Sept 2003-Sept 2009).

Moreover, the concentration of silica in the water supply has increased from the beginning of operation due new wells commissioning to ensure contracted production. Figure 2 summarizes the monthly average values for the concentration of silica in the period 1998-2008, although in the individualized review of monitoring data peaks concentrations above 75 mg / L are (As shown in Table 2, sampling data in July 2005). Several studies indicate that the solubility of silica is of 120-150 mg / l at 25 ° C and pH <8 [1], much lower than the design concentration of silica in the rejection (196 mg / L). The presence of iron in the water promotes the formation of iron silicates while the ratio of magnesium to calcium, the presence of manganese, barium and aluminium are factors influencing the catalysis of the polymerization reaction of silica [2] [3].

The usual recommendation in these systems has been operating with maximum concentrations of silica in the concentrate of 120-150 mg/L, depending on pH and temperature values [4], but case studies with plants operating with rejection silica concentrations higher than 180 mg/L in certain operating conditions has been also reported[5].

During 1998-2008 period, the plant operates on a regular basis, although the fouling problems associated with silica were higher than anticipated. The fouling of silica has been described in different works as one of the major unsolved problems in reverse osmosis systems, and its main direct consequence of increased energy costs [2]. They must be also considered the maintenance costs associated with a greater frequency of cleaning, basic equipment and chemicals as well as those associated with production losses during plant stops.

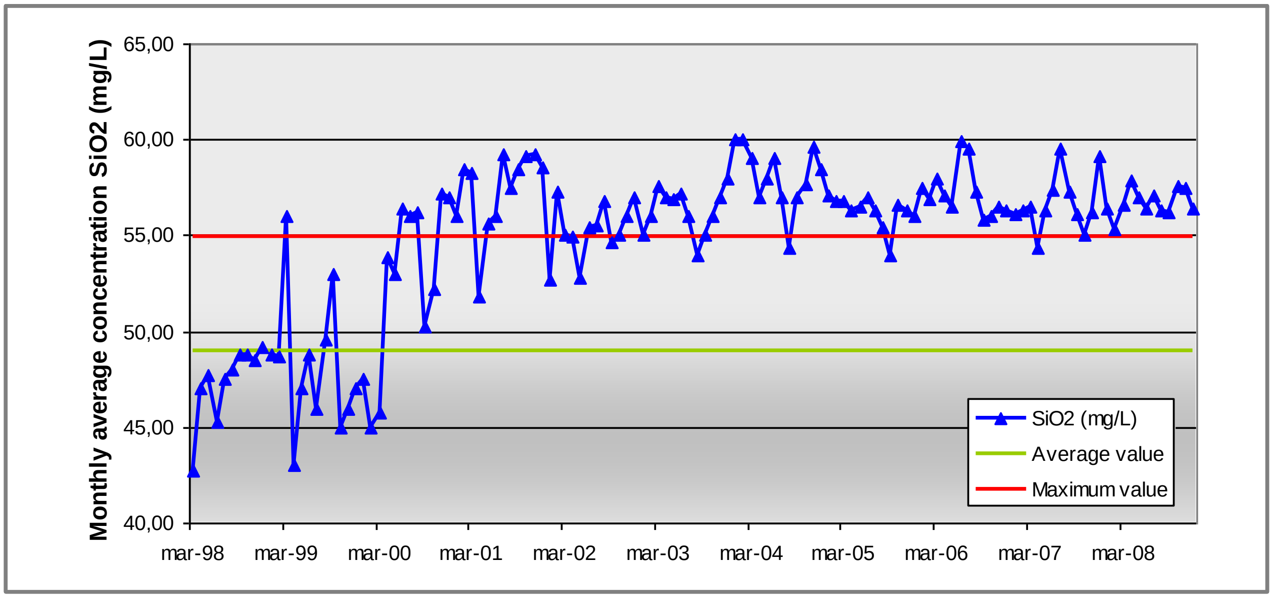


Figure 2.- Monthly average concentration for Silica (mg/L SiO_2) in feed water for 1998-2008 period. Comparison with average and maximum contractual values.

The revision of standard operating data recorded in the period 2005-2008 show dramatic decreases in production flows and increases in operating pressures, especially for second stage. These translate into frequent chemical cleaning in the two stages of this plant.

Figure 3 shows normalized data for production and salt passage in rack 1, second stage during 2006. During this 12 months period, 10 chemical cleanings were scheduled as indicated on the graph (red arrows). Besides the high frequency of cleaning, it is observed that sometimes the protocols and products used are ineffective as no significant increases in flow are achieved.

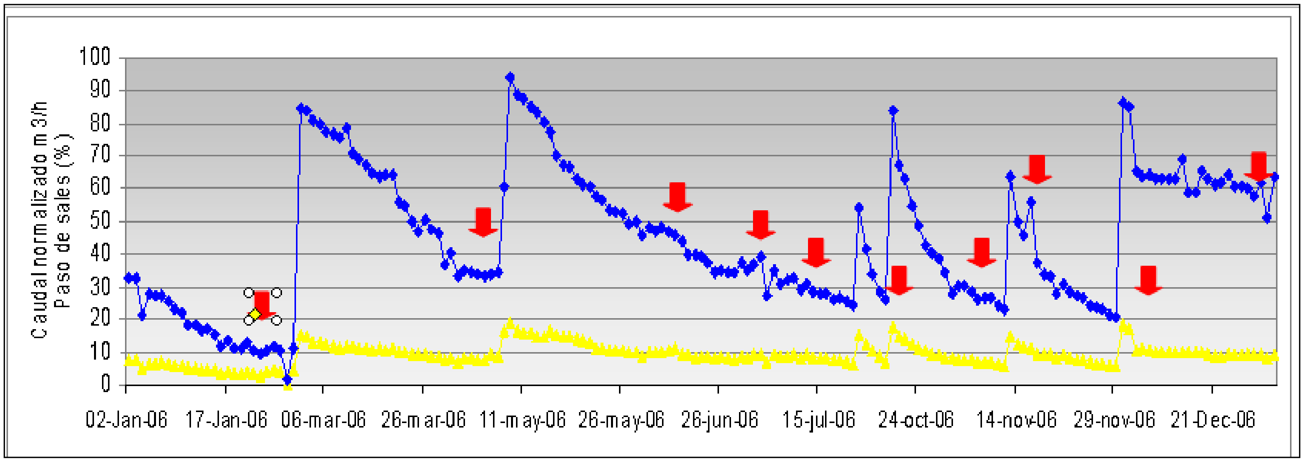
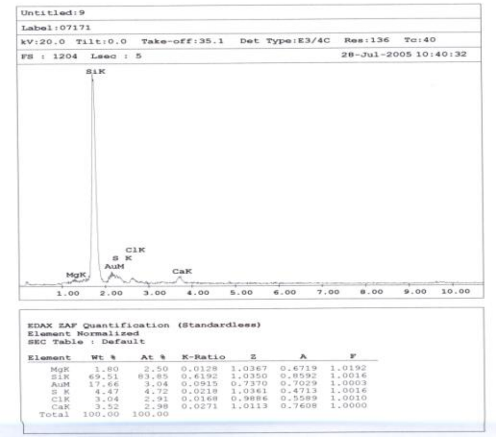


Figure 3.- Normalized permeate flux (m^3/h), rack 1, second stage. Chemical cleaning frequency.

In order to more accurately characterize membranes condition and fouling problems suspected from operational data, four membrane elements were autopsied in 2005 at Genesys Membrane Products laboratories in Madrid (Spain). First and last position elements for first and second stage, at the same production line, were selected. The most significant results in terms of silica fouling phenomena are summarized below:

- Silica deposits are detected in all autopsied elements. In second stage membranes, silica deposits are almost its entire surface. In membranes from the first stage, the deposits are concentrated in spacer-membrane contact areas (lower speed zones). Additional studies on SDI membrane filters and cartridge filters using electron microscopy coupled with energy dispersive detector X-ray (SEM-EDX) confirm presence of silica deposits on their surface. This confirms that, in addition to precipitation processes occurring on the surface of the membrane, there are contributions of colloidal silica in feed streams.
- In the first stage membranes, a significant presence of iron is detected, in addition to aluminosilicates. No other compounds are identified in second stage membranes.
- Salt rejection values are in all cases below 96%. Flow rate is characterized using a test rig device finding in all cases values below 25 % of design (<34 L / m^2 h). Even for one of the elements from second stage flux is lower than 10 L/m^2 h.

Figure 4.-SEM Micrograph. SDI membrane used for filtering 100 mL pre-treated water.



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Untitled:9
Label:07171
kV:20.0  Tilt:0.0   Take-off:35.1   Det Type:E3/4C   Res:136   Tc:40
FS : 1204   Lsec : 5                              28-Jul-2005 10:40:32

EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Element    Wt %     At %    K-Ratio     Z       A        F
   MgK     1.80     2.50    0.0128   1.0367  0.6719   1.0192
   SiK    69.51    83.85    0.6192   1.0350  0.8592   1.0016
   AuM    17.66     3.04    0.0915   0.7370  0.7029   1.0003
   S K     4.47     4.72    0.0218   1.0361  0.4713   1.0016
   ClK     3.04     2.91    0.0168   0.9886  0.5589   1.0010
   CaK     3.52     2.98    0.0271   1.0113  0.7608   1.0000
 Total   100.00   100.00
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Figure 5.- EDX Spectrum. Analysis for SDI sample shown in Figure 5.

These data, along with comprehensive studies to characterize the different sources of water supply and operation of pre-treatment made possible to determine the proposals described in the following section.

3.2.- Optimization strategies proposal

The proposed optimization actions are focused on following aspects:

3.2.1.- Pre-treatment optimization

Despite the low values obtained for Silt Density Index (SDI) on the membranes feed water, complementary studies carried out (as discussed in Section 3.1) confirm the presence of silica in the membranes in first positions and in cartridge filters that arrives in colloidal form and is not effectively retained in the pre-treatment.

After operation, maintenance and cleaning practices in pre-treatment review, changes are proposed in the tasks of washing filters. Sand filters are washed out with reject water, stored in a 30 m ^{3} tank. To avoid using water stored in this task during high periods (silica precipitation problems), system is modify for emptying the tank before the start of each cleaning, which is then made fresh reject water.

The dosage of flocculant (compatible with polyamide membranes) prior to the sand filters to optimize the retention of colloidal silica has also been considered (positive results in laboratory testing), although not yet tested on the plant.

3.2.2.- Silica fouling prevention by dosing a specific antiscalant

In reverse osmosis systems specific products to inhibit scale formation and fouling deposits, known as antiscalants, are commonly used. Unfortunately traditional methods of fouling control apply to crystalline minerals (calcium carbonate, calcium sulfate, barium sulfate and strontium, etc.) but they are not valid for silica because of its amorphous structure. This topic has been covered in numerous investigations in recent years [6].

GENESYS SI is a formulated antiscalant product that combines scale inhibitors and dispersants for operating systems with high concentrations of silica. This product was selected to be dosed in Arica desalination plant as an alternative to other previously proven treatments. The dosage was set at an average value of approximately 4 mg / L, although this value is adjusted regularly based on changes in pH, temperature and composition of the water mixture (concentration of silica, mainly) using scaling prediction software. The dosage of silica antiscalant in Arica plant started on 09/09/2008.

3.2.3.- Optimization of cleaning practices and protocols.

In addition to preventing membrane fouling, one of the goals of this proposal was to optimize the cleaning practices implemented on the plant so far. Included on autopsy procedures of membrane elements described in section 3.1, several cleaning tests were also carried out to compare cleaning procedures used at the moment in the plant and to evaluate other alternatives that could reduce costs associated costs with reducing downtime (cleaning of shorter duration) and increases in the lifetime of the membrane elements (effective cleanings at temperatures below 40 º C and pH <12.5).

According to results in these laboratory scale tests, an optimized cleaning protocol in 3 steps (details in Table 3) alkaline-acid-alkaline was designed to be effective in removing both silica and metal oxides and / or other possible scaling and appropriate for both stages. This cleaning sequence allows increases in flux reaching design values established by membrane manufacturer. Although salt rejection is also improved, reference values can not be reached as membranes have been irreversibly damaged during operation due to severe fouling conditions as it was demonstrated during integrity tests conducted in membrane autopsy trials (out of the scope of this work).

Table 3.- Cleanup program recommended according to laboratory testing

Proposed cleanup program				
Step 1	**Alkaline cleaning**	**2% Genesol 40 (4 hours)**	**pH ≤ 12**	**35 ºC**
Step 2	**Acid cleaning**	**1% Citric acid (2 hours)**	**pH ≤ 4**	**25 ºC**
Step 3	**Alkaline cleaning**	**2% Genesol 40 (4 hours)**	**pH ≤ 12**	**35 ºC**

4.- Discussion of results

Figures 6 and 7 show normalized permeate flux (in m^3/h) data, for rack 1, first and second stages respectively. On 09/09/2008, chemical cleaning was scheduled according to protocol described in section 3.2.3. for membranes in both stages. The objective of this cleaning procedure is to start the evaluation period of optimization actions with the membranes clean and evaluate its efficiency in preventing silica deposits by monitoring changes (decreases) in production rate.

Data collected for the 1st stage (Figure 6) show that the production rate since September 2009 has remained more stable than in previous operation periods, with values ranging around 150-160 m ^{3}/h. In the period September 2008 – September 2009 no chemical cleaning has been scheduled, which represents more than a year of non-stop operation. For second stage, a progressive decrease in permeate flow has been observed for a 6 months period (September 2008 – March 2009) after optimization strategies were adopted. When permeate flux decreases to values close to 30 m^3/h, membrane cleaning was scheduled (in previous operational cycles, cleaning practices were adopted when flux decreased to values close to 20 m ^{3}/h). Flow values keep stable until October 2009 with no fouling symptoms and no cleanups foresee in the short-term. These data confirm a significant decrease in the frequency of cleaning in the second stage exceeding 6 months non-stop operation.

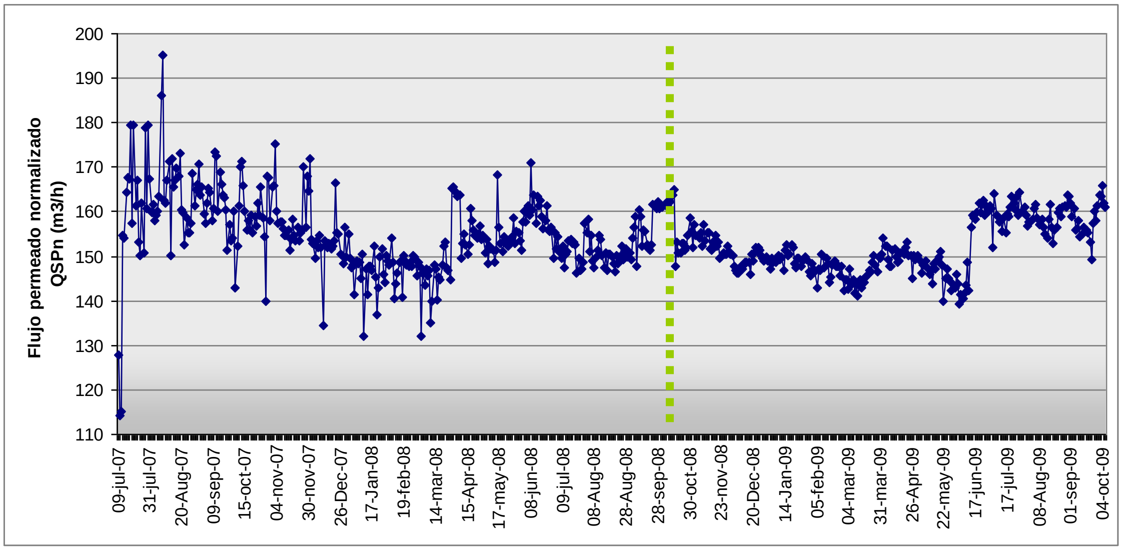

Figure 6.- Normalized permeate flow (m^3/h) in stage 1 – Rack 1 (July 2007-October 2009)

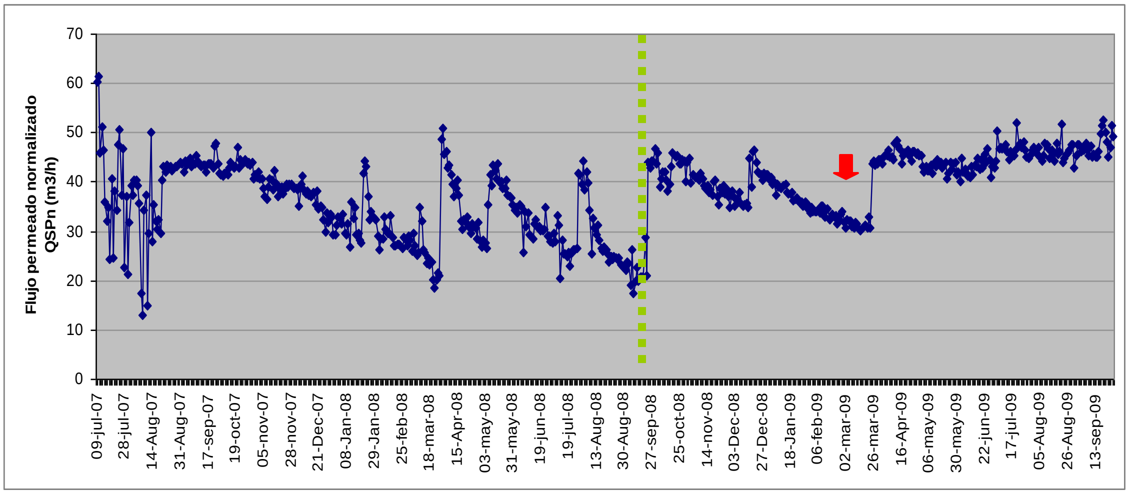

Figure 7.- Normalized permeate flow (m^3/h) in stage 2 - Rack 1 (July 2007 – October 2009)

5.- Conclusions

Evaluation of historical operating data and optimization actions taken in Arica Desalination Plant as described above allow us to conclude that:

- This facility has been operating successfully for the design conversion value of 75% (representing an average concentration of silica in the rejection of 230-240 mg / L) since September 2008, using a specific silica antiscalant. Punctual control analyses of feedwater indicate silica in the water supply above 75 mg / L (representing concentrations of silica in the rejection over 300 mg / L)
- The frequency of membrane cleaning has been reduced significantly by adjusting and optimizing the pre-treatment. Since the beginning of the dosage of a silica specific antiscalant the periods between cleaning operations have come to exceed 6 months of continuous operation.

One of the main obstacles to the use of specific antiscalants in reverse osmosis systems is the higher cost compared with conventional ones, but it is usual to not take into account the associated savings in operating costs. In the case presented in this article we have observed the reduction of problems of precipitation and/or fouling detected at this facility, which translates into lower operating pressures (average specific consumption has been reduced by 0.06 kWh/m$^{3)}$ and reduced cleaning frequency (a reduction from 12 to 1 annual maintenance cleanings at second stage). Also should be taken into account in this calculation other indirect benefits such as reducing personnel costs in cleaning operations, increased total production by reducing maintenance stops as well as an increased membrane elements life difficult to quantify.

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