Sustainable water management with multi-quality recycled water production: the example of San Luis Potosi in Mexico

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ABSTRACT

This paper presents and discusses the performance, reliability of operation, socio-economic and environmental aspects and benefits of the Tenorio Project in San Luis Potosi. This is the first project in Mexico making possible the production of multi-quality recycled water for planned water reuse for different purposes, including industrial cooling in a power plant, agricultural irrigation, groundwater restoration and environmental enhancement. Long-term water quality monitoring demonstrated the reliability of operation of the selected treatment trains, which were well adapted to local conditions and the given reuse application. The major challenge was the control of the conductivity and silica content in recycled water for industrial reuse, which needed complementary investigations and the implementation of an additional treatment by ion exchange. The reliable operation of the power plant with recycled water encouraged other industries to explore water reuse as an option, as well as the possibility of improved treatment. Once the main technical and social challenges of the original project were overcome, the project acquired a new dimension with the request of the industrial client to improve water quality by means of reverse osmosis. In return, the power plant proposed giving their right for water withdrawal from the aquifer to the City of San Luis Potosi, allowing thus the availability of freshwater for augmentation of the potable water supply.

Key words | agricultural irrigation, environmental enhancement, industrial reuse, water reuse

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INTRODUCTION

San Luis Potosi is the eleventh most populated metropolitan area in Mexico with more than 1.3 million inhabitants, and is situated in a semi-arid region with less than 400 mm of annual rainfall. The intensive industrial and economic development of this city has always been related to water availability and water conservation efforts. Since 1961, the water withdrawal from the two main aquifers has been strongly restricted and poor quality wastewater has been used for irrigation purposes (Diario Oficial de la Federación 2009). In the late 1990s, the State Water Commission (CEA), the Government of San Luis Potosi, decided to implement an Integral Plan for Sanitation and Water Reuse aiming to substitute groundwater resources by recycled water for a number of non-potable uses, including agricultural irrigation, urban reuse (recreational parks, sport and golf courses, recharge of artificial lakes, fountains) and industrial reuse mainly for cooling (Olivo & Martínez 2000). In consequence, seven wastewater treatment plants (WWTPs) were built for this purpose with an additional one under construction. At present, 70% of the wastewater of San Luis Potosi is treated and 100% of treated wastewater is recycled (Equihua 2006; Rojas 2011).

In this context, the main objective of this paper is to present and discuss the performance, reliability of operation, socio-economic aspects and benefits of Tenorio – Villa de Reyes, the largest WWTP, which has operated since 2006 and treats 45% of the total wastewater of the city of San Luis Potosi. This project, known as the Tenorio Project, is the first one in Mexico making possible the production of multi-quality recycled water for planned water reuse for different purposes,

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including industrial use, agricultural irrigation, groundwater restoration and environmental enhancement.

MATERIAL AND METHODS

The Tenorio WWTP was designed for a total capacity of 1,050 L/s (90,720 m^3/d) and it uses the following treatment steps (Figure 1):

- Screening, grit and grease removal and advanced primary treatment in lamellar clarifiers enhanced with chemicals for the total capacity. The main objective of this treatment is the removal of suspended matter before discharge into the Tenorio Reservoir, a wetland.
- Natural engineered treatment and polishing for at least 51,840 m^3/d in a constructed wetland, with a semi-rectangular shape, a total surface of 179 ha and a storage capacity of 2.65 Mm^3, named Tenorio Reservoir, for agricultural reuse. The main objective of this treatment is the removal of organic matter and faecal coliforms before the water is pumped for irrigation of fodder crops.
- Secondary treatment for up to 38,880 m^3/d by activated sludge with nitrogen removal, followed by tertiary treatment with lime, sand filtration, ion exchange softening and chlorine disinfection for industrial reuse. The main objective of this treatment is the reduction of nutrients, organic and suspended matter, silica, calcium hardness and phosphate content, as well as the removal of bacteria in order to avoid scaling, biofouling and algal development in the cooling towers of the power plant of Villa de Reyes.

Water quality has been monitored daily over 6 consecutive years by means of composite 24 h sampling of the activated sludge and the advanced treatment for industrial reuse and monthly sampling of the treatment line for agricultural reuse and environmental enhancement. Results from the first year of operation (2006) were not considered for this paper as several adjustments were made to the process in that year. Physical-chemical parameters were measured according to the Standard Methods (2005). Microbiological parameters were measured in grab samples. On-line monitoring of recycled water was implemented at the inlet to the industrial end-user, the power plant.

Observation of birds at 10 set-points around the Tenorio Reservoir was used to evaluate the positive impact of the improved recycled water quality on this confined ecosystem. At each observation point, five counts were performed at two different periods in 2011 and at the beginning of 2012. In total, 100 counts were carried out to determine the total number of birds and to identify different species.

RESULTS AND DISCUSSION

Recycled water quality and quantity

The results of water quality monitoring during the whole operating period 2007–2012 are summarised in Table 1.

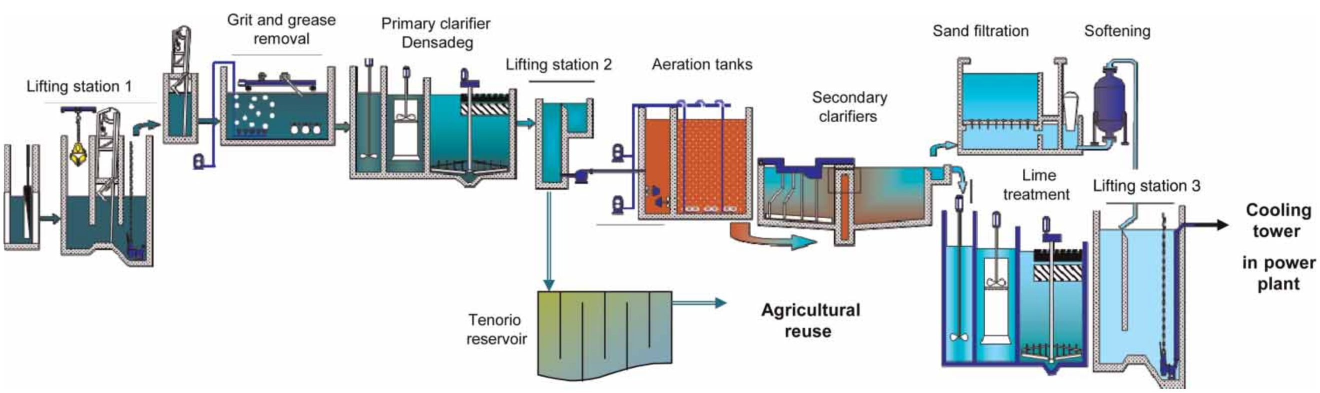

Figure 1 | Flow diagram of the treatment process.

Table 1 | Characteristics of raw sewage and recycled water with different quality for agricultural irrigation and industrial uses by the power plant (January 2007–April 2012)

Parameter	Raw wastewater[a]	Primary effluent[a]	Tenorio Reservoir effluent to reuse in agriculture[b]	Reclaimed water to power plant[a]
TSS (mg/L)	188.96 (±72.78)	33.18 (±20.82)	25.83 (±10.73)	3.30 (±2.71)
BOD_5 (mg/L)	286.49 (±93.73)	36.8 (±21.85)	31.4 (±13.96)	2.96 (±2.1.83)
COD (mg/L)	524.1 (±226.46)	99.7 (±51.81)	81.2 (±28.9)	16.2 (±13.07)
P_{TOTAL} (mg/L)	8.5 (±3.38)	6.2 (±1.91)	6.2 (±1.20)	1.2 (±0.8)
Total Kjeldahl nitrogen (mg/L)	34 (±8.91)	26.8 (±8.94)	22.3 (±5.1)	1.6 (±3.59)
Faecal coliforms /100 mL	4.57×10^9 ($\pm 1.33 \times 10^2$)	8.72×10^2 ($\pm 2.21 \times 10^2$)	240 (±189)	18.56 (±16.6)
Total hardness (mg/L)	115 (±29.86)	Not measured	Not measured	109.3 (±23.42)
Silica (mg/L)	104.3 (±20.69)	Not measured	Not measured	64.5 (±7.82)

TSS: total suspended solids; BOD_5: biological oxygen demand; COD: chemical oxygen demand.
[a]Average (standard deviation) from 1945 daily composite samples.
[b]Average from 54 monthly composite samples.

The annual consumption of each type of recycled water is shown in Figure 2. The major reuse applications and the associated volumes of recycled water are as follows:

- Industrial reuse of up to 9.9 Mm^3/yr in the 700 MW Power Plant Villa de Reyes for cooling purposes, saving currently 7.9 Mm^3/yr of potable water (average daily flow of 21,600 m^3/d).
- Agricultural irrigation with up to 23.9 Mm^3/yr (average daily flow of 52,785 m^3/d) for fodder crops, such as fodder, corn, barley and alfalfa.
- Environmental enhancement with the restoration of the wetland for wildlife habitat.

Water quality for agricultural reuse

Despite the strong variations in raw wastewater quality, advanced primary treatment ensured good removal of suspended solids to an average value of 82.2 mg/L (Figure 3(a)) preserving the fertilising capacity of treated effluents by maintaining its nutrient content. The additional polishing in the wetland (Tenorio Reservoir) ensured good additional removal of suspended solids to an average value of 28.2 mg/L. The observed high values above 35–40 mg/L are due to microalgae development. The average concentration of organic matter in the recycled water for irrigation is BOD_5 (biological oxygen demand) 31.4 mg/L, total phosphorus 6.2 mgP_{tot}/L and nitrogen 22.3 mgN/L as total Kjeldahl nitrogen.

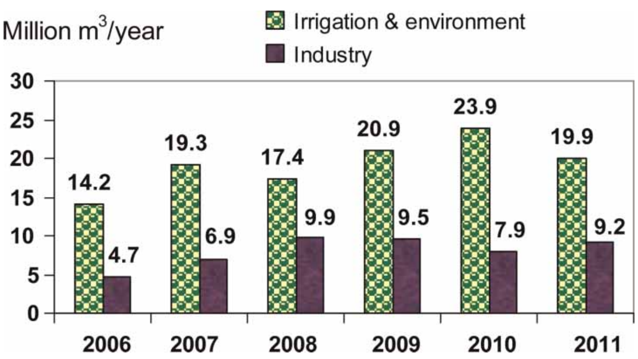

Figure 2 | Evolution of the annual production of the two qualities of recycled water of the Tenorio WWTP.

The high residence time of the primary effluent in the Tenorio Reservoir with an average value of 40 days ensures good disinfection of the effluent with about 7.3 log removal of faecal coliforms. The mean concentration of faecal coliforms in the outlet was 240 MPN/100 mL (MPN: most probable number) for the 2-year period of 2010–2011 (Figure 3(b)), which is largely below the WHO guidelines (2006) of 1,000 *Escherichia coli*/100 mL despite the very high inlet values of up to 9 to 11 log.

Salinity is one of the most important agronomic parameters as high salinity can damage salt-sensitive plants and decrease crop yields. As shown in Figure 4, average salinity remains below 900–1,000 μS/cm, with periodic increases to 1,300–1,400 μS/cm, which is within the range of tolerance of irrigated crops. More stringent requirements apply to the recycled water for industry with a permitted value of 1,200 μS/cm.

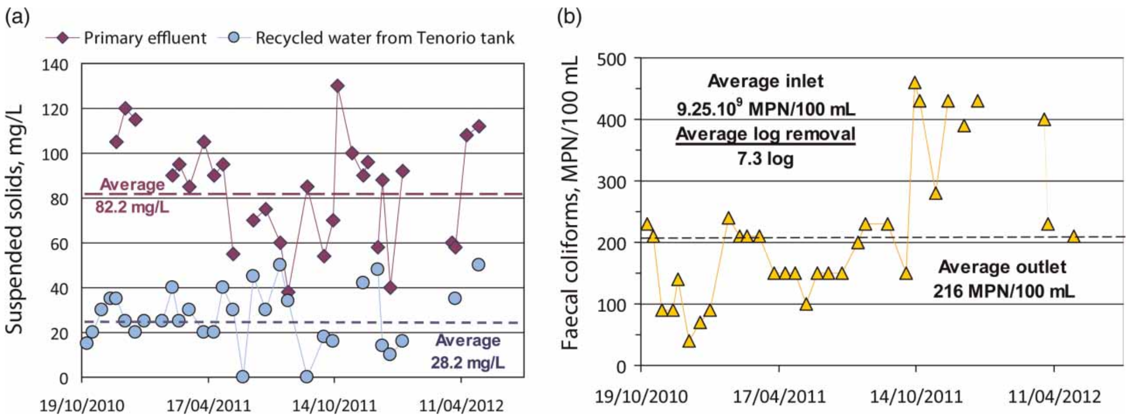

Figure 3 | Evolution suspended solids (a) and faecal coliforms (b) in the outlet of the Tenorio Reservoir before the use for agricultural irrigation.

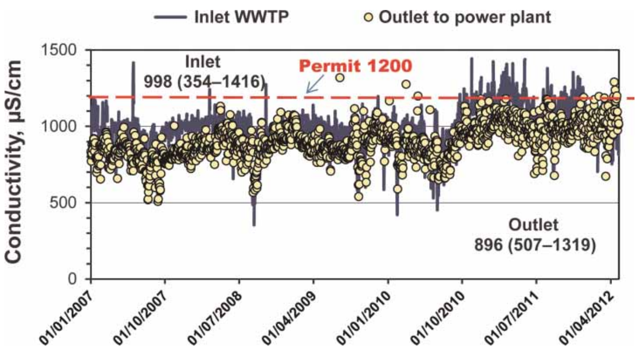

Figure 4 | Evolution of the conductivity in secondary effluent for a 6-year period (2007–2012).

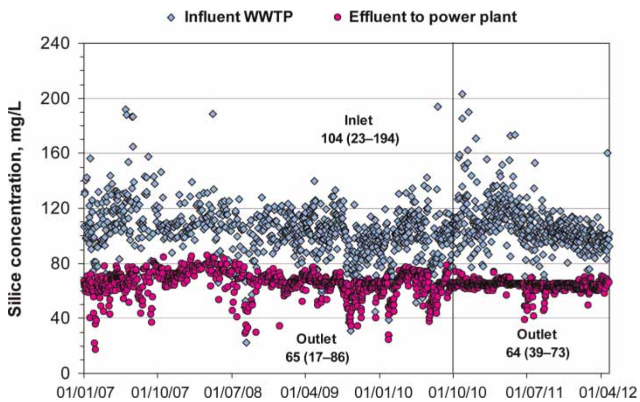

Figure 5 | Evolution of the silica in secondary effluent for a 6-year period (2007–2012).

Water quality for industrial reuse

The major challenge for operation of the Tenorio WWTP was the compliance and the reliability of the recycling plant for the supply of recycled water to the industrial user, the power plant. In this respect, the major problem was the average value of the conductivity, which was 5 to 10% above the 800 μS/cm contract guarantee. After several months of investigation, a higher conductivity limit of 1,200 μS/cm was accepted in exchange for a lower silica content of 65 ppm instead of the initial guarantee of 85 ppm (Figure 5).

In order to meet this new guarantee level, over a 6-month test period, several combinations of chemicals were used to increase the removal of silica (sodium hydroxide and lime, sodium aluminate and lime, etc.) and ion exchange softening was implemented in order to treat the hardness increase as a consequence of the silica removal process.

The Villa de Reyes power plant is, at present, the main consumer of high quality recycled water for cooling purposes. After 6 years of operation and demonstrated reliability of operation, the power plant has evaluated the overall benefits of the use of treated water and has requested that the treatment level be increased in order to reduce silica and dissolved solids content. The main objective is to produce demineralised water, which will allow complete elimination of their groundwater consumption. In order to avoid increasing the unitary cost of recycled water, the power plant management has proposed transferring their groundwater extraction rights to the State Water Commission, and thus, augment the drinking water resources of the Metropolitan Area by up to 13.8 Mm^3/yr at a reasonable cost for the population.

Water quality in distribution network

Another significant challenge was bacterial control in the conveyance system to the industrial end-user (40 km of pipe and 4,000 m^3 of intermediate storage). Due to the large flow variations associated with daily and seasonal energy production, total residence time varied from 16 to 60 h. This increased significantly the chlorine demand and made the residual chlorine control very challenging. As a result, the problem of bacterial regrowth in the pipe and intermediate tank became an issue for the power plant operation. The solution came after several weeks of tests with a non-oxidant biocide and dispersant agents that were applied in combination with chlorine. Finally, the bio-monitoring allowed establishment of the basis for biofilm control and fine tuning came as a second priority to optimise doses, while maintaining the guaranteed bacterial count and residual chlorine at the end of the pipe.

Environmental enhancement and preservation of biodiversity

An ecosystem monitoring programme has been launched for the Tenorio Reservoir that had deteriorated in the past due to the discharge of untreated wastewater. In 2006, the reservoir was modified to perform as a wetland. As a consequence of the improved water quality, a large diversity of migratory birds has been encountered in recent years.

During the period from December 2011 to April 2012, three surveys to monitor the bird population, flora and fauna on the Tenorio Reservoir. The major objectives of this study were to:

- produce a baseline of information on the diversity of resident and migratory birds;
- identify indicator species of environmental quality;
- determine values of ecological importance with distribution patterns and temporal dynamics;
- propose guidelines for management and conservation of the environment to regulate land use in the catchment area (control of the urban and industrial growth in the area);
- determine the importance of wetlands as a basis for protection of biodiversity and the ecological status of the area, in accordance with state or national environmental policy.

As shown in Figure 6, the reservoir was surveyed from 10 observation points. During each of the three surveys, a total of 100 counts were performed. The results enabled the identification of 56 species of birds: 23 aquatic, 28 terrestrial and five predators. The 56 species belong to 23 families, the families with larger number of species were *Anatidae* (9), *Ardeide* (6) and *Tyrannidae* (5) (Figure 7). Four species have been classified as protected birds by the Mexican Government. The polishing wetland is located in the route of several migratory species that have colonised the site for regular nesting. Consequently, 48 of the observed species are migratory birds. The average total number of birds counted in the area surveyed (2,703 m^2) was 1514 birds.

This study demonstrated the role of the Tenorio Reservoir in the enhancement of biodiversity, in terms not only of the increase of the bird population, but also for the floral diversity and small mammals. The birds are essential for maintaining the health of the surrounding ecosystem. Some species also contribute to controlling pests and vectors of several diseases by eating insects and rodents. As a result of this study, the creation of a protected area with a mitigation zone in the surroundings is under consideration by local authorities.

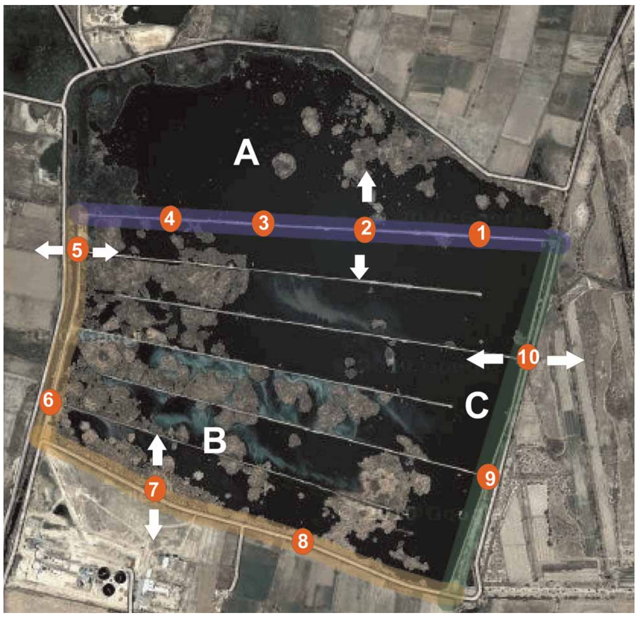

Figure 6 | Location of the ten birds observation points in the Tenorio Reservoir.

Figure 7 | Views of the bird populations of American black-winged stilt *Himantopus mexicanus* and white-faced ibis *Plegadis chihi* (left) and *Anatidae* family (right).

Costs and benefits of the Tenorio recycling scheme

The Tenorio WWTP was built under a BOT (Build, Operate and Transfer) contract with 18 years of operation and maintenance. BOT contracts in Mexico have become a very important tool to finance projects with long-term contracts that guarantee reliable operation and maintenance of the facilities during the life of the contract. The cost of Tenorio-Villa de Reyes project was $585,277,351 (May 2000); 40% was subordinated support or non-refundable from the trusteeship for infrastructure in charge of Banco Nacional de Obras y Servicios and the 60% left risk capital comes from private funds.

The most important benefits of this first large water reuse project in Mexico, widely recognised by all stakeholders, can be summarised as follows:

- Strong social benefits, as the production of recycled water with fit-for-purpose water quality enabled resolution of the existing conflicts for water supply between the agricultural and industrial sectors.
- Health benefits have also been significant because the mortality rate caused by gastrointestinal diseases that existed in the zone irrigated with raw wastewater was reduced.
- Economic benefits for industry and farmers have been acknowledged due to the reliable supply of a drought-proof alternative water resource.
- Environmental benefits consisted in the rehabilitation of the stabilisation pond into a natural wetland, preserving biodiversity and providing habitat for wild birds and other animals.
- A programme to implement a protected area with a mitigation zone is in progress to assure the long-term preservation of the restored micro-ecosystem.
- The population established near the plant improved their living standard as the ecological environment of the zone was enhanced.
- In addition, the existing two aquifers were preserved from pollution with untreated wastewater and the water balance has been re-established for one of them.
- Indirect augmentation of drinking water resources has been possible due to the saving of 48 Mm^3 that were not extracted from the aquifer for industrial uses by the power plant in the past 6 years, as well as due to a new project that is in progress which will allow provision of an additional volume of 13.8 Mm^3/yr of potable water to the City of San Luis Potosi if the power plant transfers its rights for extraction of groundwater.

CONCLUSIONS

The long-term water quality monitoring and performance analysis demonstrated the feasibility and economic viability of integrated water management with multi-quality recycled water by means of the implementation of appropriate treatment technologies well adapted to local conditions. The two treatment trains of the Tenorio WWTP in San Luis Potosi consistently produced recycled water of the quality required for agricultural irrigation, environmental enhancement and industrial uses.

The major challenge was the investigation and the improvement of recycled water quality for industrial reuse. Conductivity, silica and hardness were the mean parameters to be improved and a good balance was achieved by lowering silica level, which allowed increase of the number of concentration cycles in the cooling towers, in order to compensate the slightly higher salinity observed during certain periods.

At the present, after 6 years of operation, the power plant management consider that the operation with recycled water is reliable, and have also expressed their desire to prepare a feasibility study to evaluate the installation of reverse osmosis units to reduce silica levels to 10 ppm which will allow them to stop using groundwater and replace it 100% by recycled water.

The irrigation of 500 ha with good quality recycled water reduced water-related diseases and increased the public acceptance of the crops. The aquifer balance of one of the aquifers has been recovered by the substitution of the groundwater with recycled water for industrial and agricultural uses.

The satisfactory operation of the power plant with recycled water encouraged the industry to explore new possibilities of improved treatment. Finally, other industries are interested in substituting their groundwater consumption with recycled water given the economic benefits and the demonstrated reliability of this water reuse system.

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