A baseline analysis of the quality of water resources on San Cristóbal Island, Galápagos

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ABSTRACT

The population growth and the increase in tourist volume in the Galápagos Cristóbal could pose a risk to water resources. The objective of this research was to conduct a baseline analysis of the quality of drinking water in the primary reservoirs on San Cristóbal: Cerro Gato, La Toma y El Progreso and a sample of drinking water. Raw wastewater samples were also analyzed. In water samples from the sources, pH and dissolved oxygen were the only parameters that fell outside regulations. Fecal and total coliforms are of the greatest concern because both of these values were far above the recommendations made by the World Health Organization (WHO) and Ecuadorian environmental legislation (TULAS) for drinking water requiring only disinfection. Regarding drinking water, the sample is acceptable for human consumption. As expected, raw wastewater samples presented significant contamination. Finally, the information generated in this study could be employed to develop an integrated water management plan to protect water resources in Galápagos.

INTRODUCTION

The status of the water quality on San Cristóbal Island is a serious public health issue, due to rapid population growth and a boom in the tourism industry (Watkins & Cruz, 2007) (Epler, 2007) (Hennessy & McCleary, 2011). Water-borne diseases are the biggest health concern related to water quality and include a range of pathogens, from viruses to bacteria to protozoan parasites (Grabow, 1996). Nowadays, 2.5 billion people, including almost one billion children, live without even basic sanitation. According to UN statistics, a child dies every 20 seconds as a result of poor sanitation (http://www.unwater.org/statistics_san.html).

Few studies have been reported in the literature regarding the water quality in the Galápagos Islands. In 2006, Werderman published an article that analyzed the differences in macronutrients levels as well as in salinity, oxygen and temperature measurements in Academy Bay, Turtle Bay and Wreck Bay adjacent to the three most populated centers Puerto Ayora, Puerto Villamil and Puerto Baquerizo Moreno, respectively in comparison with Cartago Bay with no adjacent inhabitants (Werdeman, 2006). Although, the focus of the study was not drinking water, the quality tests are comparable to those within this study. The main findings were that human interference, due to a rise in tourism and population growth led to an increase in nutrient concentration in the water (Werdeman, 2006). In 2008, d'Ozouville published an article on water resource management, which highlights the different uses of water on Santa Cruz and implications for the future of water handling and analysis (d'Ozouville, 2008). A common issue that arose in that study was how much of the non-treated water was being used for domestic uses (d'Ozouville, 2008). On San Cristóbal, the quantity of non-treated water that is used for domestic purposes and how all water sources are being managed is unclear. Further inquiry will be needed to understand how the non-treated water is distributed throughout the town of Puerto Baquerizo Moreno. In 2010, López and Rueda reported a study on water quality monitoring in eight sites in Santa Cruz (4 sites), San Cristóbal (2 sites) and Isabela (2 sites) (López & Rueda, 2010). The results of the study showed that with the exception of fecal coliforms, all parameters tested fell within the maximum allowable limits for water used for human consumption established in the national environmental legislation TULAS (López & Rueda, 2010). In fact, information regarding the variance in fecal coliform within different sites in the three islands was provided and the concentrations were much higher than the regulations set by TULAS (MAE, 2003).

In many areas with population increase, wastewater management rapidly becomes one of the biggest challenges and can lead to environmental damage and widespread health concerns (Parkinson & Tayler, 2003). In the Galápagos, the tourism industry has created a spike in the population and, as a result, difficulty handling the waste produced. Wastewater treatment in the Galápagos is minimal at best and this water has the potential to contaminate water sources and affect public health (Moir & Armijos, 2007). Currently, diarrheal and similar diseases are the second leading cause of death in the Galápagos (Walsh, McCleary, Heumann, & Brewington, 2010). One major concern is the presence of fecal contamination in the wastewater. Pathogens associated with fecal contamination include various viral and bacterial agents that can cause diseases ranging from mild gastro-intestinal distress to diseases so severe that they can be fatal (Rose, 2006).

Throughout Latin America, there is a large gap between treatment and distribution of drinking water and treatment of wastewater (WW). Between 50 and 80% of people are connected to drinking water systems and sewer systems, but only about 5% of this wastewater is treated at any level (Idelovich & Ringskog, 1997). Often, raw sewage is pumped into rivers or the ocean, and Ecuador is not an exception. In San Cristóbal, the wastewater treatment plant (WWTP) is not completely operational and the untreated raw sewage is still pumped a couple miles off the shore of Playa Corolla, a beach popular amongst tourists (Flores, 2012).

The objective of this study was to perform a baseline analysis of the current status of water resources on the island of San Cristóbal. Water samples from drinking water sources were analyzed based on physical-chemical and microbiological parameters. A drinking water sample ready to be consumed was also analyzed. Raw wastewater samples were also characterized. The data obtained in this study can be used as a baseline of the state of water resources on the island. This information can be employed to make decisions to develop an integrated water management plan to protect water resources, the unique environment of the Galápagos Islands, and the wellbeing of the Galápagos human population.

MATERIALS AND METHODS

Sample Collection: water samples were taken at various points from the three water sources: Cerro Gato, La Toma and El Progreso using plastic bottles of 100 mL. A ready to be consumed drinking water sample distributed by tanker trucks was sampled at El Progreso. Four municipal wastewater samples were also taken of untreated sewage from the wastewater collection area using ambar glass bottles. All samples were taken in May of 2012.

Analytical Methods:

Ammonium, chloride and nitrate were measured using Orion ion-selective electrodes (ISE) (Thermo Scientific, Beverly, MA, USA). In the case of ammonium, a reference electrode was also employed. First, calibration curves were constructed for each ion in the low and medium concentration ranges by employing standards solutions prepared from stock solutions of 1000 mg L^{-1} of ammonium as ammonium chloride, chloride as sodium chloride and nitrate as sodium nitrate, respectively. For NH_4^+, 20 mL of each standard solution were mixed with 2.0 mL of ionic strength adjuster (ISA) freshly prepared in the laboratory. The ISA solution consisted of 0.25 M magnesium acetate and 0.5 M acetic acid. In the case of Cl^-, 10 mL of each standard solution were mixed with 0.2 mL of ionic strength adjuster (ISA) (Thermo Scientific, Beverly, MA, USA). For NO_3^-, 10 mL of each standard solution were mixed with 0.2 mL of ionic strength adjuster (ISA) (Thermo Scientific, Beverly, MA, USA). In each case, the response of the ISE was recorded in mV and plotted as a function of the natural log of the ion concentration. Then, samples were measured with the same procedure described for the standards and the voltage reading in mV was recorded. Finally, the concentration of each ion was calculated based on the calibration curves.

Biological oxygen demand (BOD_5) was determined with composites samples with a final volume of 432 mL. This procedure was conducted for samples from Cerro Gato, El Progreso and the WW sample. La Toma was excluded because there were not enough samples to yield the desired volume. The BOD_5 test consisted of 3 bottles, 2 of water samples and 1 standard within the OxiTop Box incubator (WTW, Weilheim, Germany). The bottles containing the water samples were diluted by adding 1 mL of each of the following solutions: phosphate buffer, calcium chloride and iron chloride. The bottles were incubated at 20°C for a 5-day period.

Chemical Oxygen Demand (COD) was determined by mixing 2.5 mL of sample, 1.5 mL of digestion solution and 3.5 mL of sulfuric acid reagent into culture tubes. The samples were analyzed in triplicates and each tube was vortexed, capped and placed in the oven. After a two hour digestion period at a temperature of 150°C and an appropriate amount of time for cooling, the absorbance was measured employing the Spectronic 20D+ spectrophotometer (Thermo Scientific, Madison, WI, USA) at a wavelength of 600 nm. A calibration curve was created to determine the concentration of COD in each sample.

Sulfate was measured using composite WW sample with a final volume of 25 mL. The pH of the samples was adjusted to 1 to 3. Each sample was then filtered and 25 mL of 0.1 M $BaCl_2$ solution was added and the samples were left for one hour for precipitation of sulfate as barium sulfate. Afterwards, each sample was then filtered through the vacuum filtration system and the filters that contained the samples were placed in the oven overnight at a temperature of 150°C. The filters were weighed again using an analytical balance.

Sulfide was analyzed colorimetrically by the methylene blue method at a wavelength of 670 nm (Truper & Schlegel, 1964). 5 mL of 2% zinc acetate solution and a determined volume of sample were added to a 25 ml volumetric flask. Sample volume was calculated so that the concentration of sulfide in the flask was less than 1 mg L^{-1}. Then, 2.5 mL of DMP solution, 0.125 mL of iron (III) ammonium sulfate solution and distilled water were added to fill the 25 mL volumetric flask. After 30 minutes, the absorbance was recorded using the Spectronic 20D+ spectrophotometer (Thermo Scientific, Madison, WI, USA).

Conductivity, dissolved oxygen (DO), pH and temperature were measured in-situ by a Thermo Scientific Orion 5-Star portable multiparameter (Thermo Scientific, Beverly, MA, USA). Each parameter was measured three times at each site.

Turbidity was measured in triplicates by an AQUAfast AQ4500 Turbidimeter (Thermo Scientific, Beverly, MA, USA).

Total solids (TS) and Total dissolved solids (TDS) were determined according to Standard Methods for Examination of Water and Wastewater (APHA, 1998)

Fecal and total coliforms were measured employing 3M Petri Film E. Coli/Coliform Count Plates (3M, St. Paul, Minnesota). 1 mL of each sample was taken and plated on the film. They were incubated at 37˚C and checked at 24 and 48 hours. The presence of coliforms was indicated by red or blue colonies that had associated gas bubbles. Both colors of colonies were counted to determine total coliforms, while the blue colonies were confirmed fecal coliforms.

RESULTS AND DISCUSSION

A baseline analysis of the quality of water resources on San Cristóbal Island, Galápagos was conducted in this study. Physical-chemical and microbial parameters were analyzed on water samples based on the guidelines of the Ecuadorian national environmental legislation (TULAS) (MAE, 2003) and World Health Organization (WHO) (WHO, 2011). Table 1 presents the maximum allowable limits for various water quality parameters based on the Ecuadorian legislation (TULAS) that includes parameters for water that requires only disinfection to be treated as well as standards for water that requires conventional treatment and the WHO recommendations.

Cerro Gato, La Toma and El Progreso are the three primary reservoirs of drinking water in San Cristóbal. All three of these reservoirs are located in the highland region of the island (López & Rueda, 2010). Cerro Gato is located the furthest from Puerto Baquerizo Moreno and has a waterfall as the main natural source. Two pipes at the base of the reservoir, lead source water to El Progreso. La Toma is characterized by a constant flow of water within the reservoir which is fed by a natural spring. There is a large vertical wall where source water flows down into a rocky bed and two main pipes carry source water to El Progreso. Finally, El Progreso, nearest to Puerto Baquerizo Moreno, is the principal and largest reservoir on San Cristóbal and is where the water is disinfected for consumption. For each sample location, water samples were pulled from various sites in duplicates. The sites were chosen to provide a representation of all accessible tanks and stages of water in the reservoirs. In Cerro Gato, samples were taken from the waterfall and pond area, as well as in each open tank, with a total of nine sample sites. At La Toma, two samples were taken from the top of the waterfall and one was taken at the bottom, for a total of three sample sites. At El Progreso, there were five sample sites in easily accessible tanks and one sample site at the source. In addition, ready to be consumed water was also sampled. All parameters analyzed were pretty consistent among all sampled sites within each water source; therefore, the physical-chemical and microbiological water quality parameters were averaged across each drinking water source site having only one averaged parameter for source: El Cerro Gato, La Toma and El Progreso.

Table 1. Maximum allowable limits for various water quality parameters based on the Ecuadorian legislation (TULAS) and the WHO recommendations.

Parameter	TULAS: Book VI, Annex 1, Table 2: Maximum allowable limits for water used for consumption and households uses, that only requires disinfection	TULAS: Book VI, Annex 1, Table 2: Maximum allowable limits for water used for consumption and households uses, that only requires conventional treatment	WHO: Guidelines for Drinking-water quality
Ammonia (mg N L^{-1})	1	1	35*[&]
Biochemical Oxygen Demand (BOD_5) (mg L^{-1})	2	2	-
Chemical Oxygen Demand (COD) (mg L^{-1})	-	-	-
Chloride (mg L^{-1})	250	250	250*
Conductivity	-	-	-
Dissolved Oxygen (DO)	No less than 80% saturation and 6 mg L^{-1}	No less than 80% saturation and 6 mg L^{-1}	-
Nitrate (mg N L^{-1})	10	10	50
pH	6.0 - 9.0	6.0 - 9.0	6.5 - 8.5
Sulfate (mg L^{-1})	250	400	250*
Temperature	Natural Condition +/- 3 degrees	Natural condition +/- 3 degrees	-
Total Dissolved Solids (TDS) (mg L^{-1})	500	1000	600
Turbidity (NTU)	10	100	5 - 10
Total Coliforms (MPN/100 mL)	50	3000	0
Fecal Coliforms (MPN/100 mL)	-	600	0

* Taste threshold
[&] For ammonium

Table 2 presents a summary of the data for the physical-chemical and microbiological measurements, averaged across each drinking water source site: Cerro Gato, La Toma and El Progreso. The characterization of the ready to be consumed drinking water sample is also shown in Table 2. In water samples from the sources, dissolved oxygen (DO) and pH were the only physical-chemical parameters that fell outside Ecuadorian and WHO regulations (MAE, 2003) (WHO, 2011). The DO concentration of samples at Cerro Gato and El Progreso were 7.51 $\pm$ 0.53 and 9.42 $\pm$ 1.49 mgL^{-1}, respectively, while the value registered at La Toma was significantly lower (3.24 $\pm$ 0.41 mg L^{-1}) than the maximum allowable limit established by TULAS for both cases water that only requires disinfection and water that requires conventional treatment (MAE, 2003). These results are in agreement with those reported by López and Rueda in the monitoring of water quality of 8 sample sites in 3 of the most populated islands in Galápagos (López & Rueda, 2010). The DO values ranged between 4.4 and 10.1 mg L^{-1} similar to the range reported in this research, 3.24 to 9.42 mg L^{-1}. In the case of pH, the samples at La Toma and El Progreso reported values lower than the TULAS and WHO allowable ranges, registering values of 5.58

and 5.82, respectively. pH values lower than 6 suggest that precipitation had a significant effect since water sources are located in the highlands completely open and allow rain water to also be collected (López & Rueda, 2010).

The values for BOD_5 and sulfide were under the detection limits for all water samples analyzed. TDS values were very similar for samples from La Toma and Cerro Gato, around 20.2 $\pm$ 1.7 mg L^{-1}, while samples from Cerro Gato registered a high value of 71.33 $\pm$ 1.60 mg L^{-1} which is still within regulations. The same trend was observed for conductivity with the latter sample registering a value of 105.10 $\pm$ 0.16 µS cm^{-1}. For all water sources, ammonium, chloride, temperature and turbidity values met regulations and these measurements were relatively similar for the three water sources. The results of this study are in agreement with those published in the literature. López and Rueda reported the results of water quality monitoring systems in samples coming from Santa Cruz, San Cristóbal and Isabela (López & Rueda, 2010). Temperature values of 23 – 25^{o}C are similar to the ones measured in this study 24 – 25 ^{o}C (López & Rueda, 2010). Turbidity values reported for the three water source sites are in the same order of magnitude as the measurements found at the two sites in San Cristóbal, Municipal Plant and House, 2.7 and 3.7 NTU, respectively (López & Rueda, 2010). In terms of nitrate concentration, the value reported in this study is higher than those measured by López and Rueda (López & Rueda, 2010). This difference could be explained but the fact that the samples analyzed in this research were taken from water sources that are outdoors and can have a higher influence of human activities such as agriculture, among others.

Regarding fecal and total coliforms both of these values were far above the recommendations made by the WHO, as well as by TULAS for drinking water requiring only disinfection for all tree water sources (WHO, 2011) (MAE, 2003). The total coliforms and fecal coliforms concentrations for El Cerro Gato, La Toma y El Progreso were 1150, 1617 and 813 MPN/100 mL; and 267, 100 and 44 MPN/100 mL, respectively. In the study conducted by López and Rueda, fecal coliforms concentrations in 2008 varied among sites with Colegio San Francisco Crevice in Santa Cruz having the highest concentration of 1236 MPN/100 mL, followed by Manzanillo in Isabela with 756 MPN/100 mL and Ninfas Lagoon in Santa Cruz with 481 MPN/100 mL (López & Rueda, 2010). Although, the fecal colonies measured at Cerro Gato are 2 to 5 times lower than those reported by Lopez and Rueda, the presence of fecal coliforms in all water samples in San Cristóbal in 2012 indicates that water is unsuitable for human consumption. Based on these results it can be concluded that there is an urgent need to develop an integrated water management plan to protect water resources in Galápagos and to build drinking water facilities within the islands. Fortunately, the latter issue has been addressed, after completion of this study a drinking water treatment plant is known to be currently under construction in San Cristóbal.

Table 2. Physical-chemical and microbiological characterization of water samples from Cerro Gato, La Toma and El Progreso and a ready to be consumed drinking water sample.

Site	Ammonium $[NH_4^+]$ ($mg\ L^{-1}$)			BOD_5 ($mg\ L^{-1}$)			Chloride $[Cl^-]$ ($mg\ L^{-1}$)			Conductivity ($\mu S\ cm^{-1}$)			DO ($mg\ L^{-1}$)			Nitrate $[NO_3^-]$ ($mg\ L^{-1}$)			pH (pH Units)		
Cerro Gato	0.48	±	0.12	N/D	±	N/D	8.17	±	0.28	105.10	±	0.16	7.51	±	0.53	2.65	±	0.38	7.95	±	0.10
La Toma	0.28	±	0.01	N/A	±	N/A	6.30	±	0.09	24.42	±	1.03	3.24	±	0.41	0.00	±	0.00	5.58	±	0.33
El Progreso	0.41	±	0.20	N/D	±	N/D	7.13	±	0.50	28.63	±	3.56	9.42	±	1.49	0.00	±	0.00	5.82	±	0.33
Drinking water	0.42	±	0.00	N/D	±	N/D	8.52	±	0.00	227.73	±	0.00	N/A	±	N/A	0.00	±	0.00	7.03	±	0.10

N/D: Not detectable
N/A: Not available

Table 2 *(continued)*. Physical-chemical and microbiological characterization of water samples from Cerro Gato, La Toma and El Progreso and a ready to be consumed drinking water sample.

Site	Temperature (K)			Total Solids ($mg\ L^{-1}$)			TDS ($mg\ L^{-1}$)			Turbidity (NTU)			Total Coliforms (MPN/100 mL)			Fecal Coliforms (MNP/100 mL)		
Cerro Gato	24.16	±	0.11	80.00	±	1.45	71.33	±	1.60	6.30	±	0.87	1150	±	20	267	±	8
La Toma	24.05	±	0.12	21.67	±	2.36	19.00	±	0.30	5.15	±	0.23	1617	±	10	100	±	9
El Progreso	25.00	±	0.00	23.33	±	1.50	21.33	±	0.15	5.42	±	0.89	813	±	4	44	±	7
Drinking water	25.00	±	0.00	N/A	±	N/A	N/A	±	N/A	3.79	±	0.21	0	±	0	0	±	0

N/D: Not detectable
N/A: Not available

Drinking water sample fell within Ecuadorian and WHO maximum allowable limits for all parameters and is acceptable for human consumption. It is important to mention that no fecal and total coliforms were detected. These results are interesting taking into consideration that in 2008, López and Rueda, reported fecal coliforms concentrations in drinking water samples from a house in San Cristóbal and one in Isabella in the order of 433 and 1011 MPN/100 mL, respectively (López & Rueda, 2010). This complete elimination in fecal coliforms could be attributed to the impact of the study published by López and Rueda in 2008 (López & Rueda, 2010), where according to the authors the decrease in fecal coliform could be the result of mitigation activities after the study was presented to authorities and general public, in fact, the authors observed a similar effect in fecal coliforms concentration in Santa Cruz sites (López & Rueda, 2010).

It is well-known that wastewater (WW) could have serious negative impacts on the environment and public health; therefore, samples of raw sewage were also tested. Table 3 shows the physical-chemical and microbial parameters measured for the WW sample collected. The maximum allowable limits established by TULAS for discharges into body of freshwater and into ocean are also included in Table 3 (MAE, 2003).

Table 3. Physical-chemical and microbiological characterization of raw wastewater samples

Parameter	**Value**			**TULAS: Book VI, Annex 1, Table 12: Maximum allowable limits for water discharged into a body of freshwater**	**TULAS: Book VI, Annex 1, Table 13: Maximum allowable limits for water discharged into the ocean**
Ammonium (mg L^{-1})	54.52	±	4.91	--	--
BOD_5 (mg L^{-1})	N/A	±	N/A	100	100
Chemical Oxygen Demand (COD) (mg L^{-1})	492.16	±	52.95	250	250
Chloride (mg L^{-1})	383.08	±	21.69	1000	--
Conductivity (µS cm^{-1})	1461.00	±	4.24	--	--
Nitrate (mg-N L^{-1})	2.96	±	0.73	10	--
Nitrogen total (mg-N L^{-1})	57.48	±	3.56	15	40
pH	7.46	±	0.07	5.0 - 9.0	6.0 - 9.0
Sulfate (mg L^{-1})	70.77	±	5.84	1000	--
Sulfide (mg L^{-1})	N/D	±		0.5	0.5
Total Solids (TS) (mg L^{-1})	780.00	±	5.60	1600	--
Total Suspended Solids (TSS) (mg L^{-1})	24.00	±	1.90	100	100
Fecal Coliforms (MPN/100 mL)	4600	±	35.00	Less than 3,000 need no treatment, otherwise must have greater than 99.9% reduction	Less than 3,000 need no treatment, otherwise must have greater than 99.9% reduction

N/D: Not detectable
N/A: Not available

During this study, the WWP in San Cristóbal was being rehabilitated; therefore, the raw WW was pumped in to the ocean, off the coast of Playa Corolla (Flores, 2012). In the case of chloride, nitrate, pH, sulfate, TS and TSS measurements, these values met both sets of regulations. Sulfide values were lower than the detection limits. COD and total nitrogen measurements did not meet the criteria for discharges into the ocean. The total COD value measured in the raw WW sample was 492.16 $\pm$ 52.95 which was about 2 times higher than the maximum allowable limit set by TULAS. The total nitrogen concentration present in raw WW was calculated by adding the ammonium and nitrate concentrations expressed as mg N L^{-1}, and it was found to be 57.48 $\pm$ 3.56 mg N L^{-1}. This concentration was 1.4 times higher than the regulation established in TULAS (MAE, 2003). Discharges with increased concentration of organic matter and nutrients affect the marine ecosystems by an alteration of the communities and diversity, changes in the food chain, eutrophication, among others (Islam & Tanaka, 2004) (Howarth, et al., 2000). In terms of fecal coliforms, according to the Ecuadorian legislation WW samples should be treated before discharges because they have a fecal coliform count of 4,600 MPN/100mL (MAE, 2003). Unfortunately, WW is dumped without treatment at Playa Corolla which is a recreational site and these discharges could threaten the health of the residents.

In terms of wastewater treatment (WWT), the majority of physical-chemical and microbial parameters measured in the raw WW sample analyzed in this study are within the typical values found in domestic effluents (Metacalf & Eddy, 2003). However, the chloride concentration is quite high, 383.08 $\pm$ 21.69 mg L^{-1} which suggests infiltration of seawater into the collection system. In coastal areas is not uncommon to find intrusion of salt water in WWTP. For instance, in 2011, King County Wastewater Treatment Division reported infiltration of seawater in West Point Treatment Plant in Seattle. In fact, about 3 to 6 million gallons of salt water were reported to enter the system daily with chloride concentrations in raw WW ranging from 285 to 1295 mg L^{-1} (Phillips, 2011). Once the WWTP in San Cristóbal is operating, it is strongly recommended to monitor chloride because high concentrations of Cl could cause severe corrosion of the equipment at WWTP, increasing the cost of maintenance and repair as well as increasing the flow to the plant and the sustainable usage of treatment capacity (Phillips, 2011).

CONCLUSIONS

A baseline analysis of the quality of water sources of San Cristóbal was successfully conducted. Fecal and total coliforms concentrations in samples from Cerro Gato, La Toma and El Progreso are the biggest risk for human health. However, the drinking water sample can be acceptable for human consumption and household uses. The discharge of untreated wastewater into the ocean poses a great concern for contamination of water resources and the health of residents of the island. Finally, the development of an integrated plan to protect water resources as well as improvements in water infrastructure is critical to preserve the flora and fauna of this fragile ecosystem and the wellbeing of the population

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