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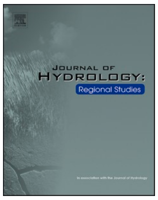

Spatiotemporal distribution of salinity in Gatun Lake and the Panama Canal pre- and post-expansion

María G. Castrellón [a,b,*], Carlos Lu [c], Iván Domínguez [c], Raúl Matos [c], Karen Anguizola [c], Ioana Popescu [a,b,d]

[a] IHE Delft Institute for Water Education, Westvest 7, Delft 2611 AX, the Netherlands
[b] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Building 23, Stevinweg 1, Delft 2628 CN, the Netherlands
[c] Autoridad del Canal de Panamá (ACP), Edificio de la Administración, Balboa, Ancón, Panama
[d] Faculty of Civil Engineering, Politehnica University Timisoara, Romania

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ABSTRACT

Study region: Gatun Lake, Panama Canal, Republic of Panama.

Study focus: The Panama Canal expansion, which was completed in June 2016, included the construction of new locks, known as Neo-Panamax, which are 3.3 times larger in volume than the old locks, known as Panamax. Water quality measurements of Gatun Lake, the main lake of the Panama Canal, are available, at different temporal scales, for the periods before and after the expansion. However, a statistical analysis of the salinity data has not been made available to the scientific community. This study quantifies spatiotemporal variations in salinity concentrations of Gatun Lake before and after the expansion of the Panama Canal, and examines their interaction with lake water levels and El Niño Southern Oscillation (ENSO) cycles. To achieve this, summary statistics, trend analyses and interpolation methods were applied to the available salinity and water level data for Gatun Lake.

New hydrological insights for the region: Before the expansion of the Panama Canal, average salinity in Gatun Lake was < 0.05 Practical Salinity Units (PSU). After the expansion, average salinity is 0.21 PSU, which represents an increase of over four times. In Gatun Lake salinity has been observed to be the highest near the Neo-Panamax locks, averaging 0.6 and 0.5 PSU after the expansion near Agua Clara locks in the Atlantic and Cocolí locks in the Pacific, respectively. After the expansion, salinity in Culebra Cut, the narrowest part of the Panama Canal, is about 0.1 PSU. This study concludes that average salinity in Gatun Lake is weakly anti-correlated to its water level and it responds to changes in water level with a delay of one to two months. In June 2020, at the end of a strong El Niño period, average salinity in Gatun Lake reached its peak of 0.39 ± 0.19 PSU, only one month after the lake's water level reached its second lowest level in the past decade (24.5 m). During El Niño events, salinity showcases a statistically significant increasing trend whereas during La Niña events no significant trend could be identified.

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[*] Corresponding author at: Faculty of Civil Engineering and Geosciences, Delft University of Technology, Building 23, Stevinweg 1, Delft 2628 CN, the Netherlands.

E-mail address: m.g.castrellonromero@tudelft.nl (M.G. Castrellón).

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1. Introduction

The Central American country of Panama has an extraordinary amount of water resources. The country receives an average precipitation of 2924 mm/year, which results in approximately 29,000 cubic meters of fresh water per capita (Comité de Alto Nivel de Seguridad Hídrica, 2016). Naturally, fresh water forms the cornerstone of Panama's economy. Within the last decade, water intensive activities such as agriculture, food industry, hydroelectric power generation, tourism and transportation generated between 18 % and 22.5 % of the country's GDP, out of which ~5 % were direct contributions from the Panama Canal (Garcimartín et al., 2020).

Built between 1881 and 1914, the Panama Canal is an 80 km waterway that connects the Atlantic and Pacific Oceans through the isthmus of Panama. Its transit route crosses Culebra Cut, an excavated canal through the continental divide, and Gatun Lake, a reservoir with a surface area of 436 km^2 (Wijsman, 2013). In addition to being the primary water source for the operations of the Panama Canal, Gatun Lake currently supplies freshwater to four drinking water treatment plants with another three under construction (IDAAN, 2022). Gatun Lake's water level is about 26 m higher than the level of the ocean and thus locks are required to elevate and lower the vessels. The original locks (Gatun in the Atlantic and Pedro Miguel and Miraflores in the Pacific) consist of two lanes. Due to an increasing demand of shipping traffic and in order to accommodate larger vessels, the Panama Canal was expanded and this included the construction of a new set of locks (Agua Clara in the Atlantic and Cocolí in the Pacific) with bigger lock chambers. The old and new set of locks are known as Panamax and Neo-Panamax, respectively. The expansion project started on September 3rd 2007 and culminated with the inauguration of the Neo-Panamax locks on June 26th 2016.

Since its creation at the beginning of the 20th century, Gatun Lake has slowly been transitioning from a swamp environment to a more saline-governed ecosystem due to the operation of the canal's locks and other anthropogenic activities taking place in the surrounding catchment (Salgado et al., 2020). However, since the conception of the Panama Canal expansion project there were concerns about its environmental impact on Gatun Lake, especially regarding its salinity. As a consequence, saltwater intrusion into Gatun Lake due to the operation of the Neo-Panamax Locks was researched and modelled. Saltwater intrusion was expected to increase overall in the canal-locks-lake system after the expansion, however the results from different modelling efforts showed this would only impact Gatun Lake's salinity during the dry season and during dry years caused by El Niño but mainly in regions near the locks (Wijsman, 2013). ACP internal reports also concluded that, after the expansion, Gatun Lake would maintain an overall water quality able to sustain a stable freshwater aquatic ecosystem (Akhmetova, 2012; Wijsman, 2013). Nevertheless, after the completion of the Panama Canal expansion project in 2016, the number of non-native large marine fish species observed within Gatun Lake has drastically increased (Castellanos-Galindo et al., 2020; Schreiber et al., 2023), and the hypothesis is that this is likely due to a much higher salinity concentration than anticipated as a result of the operation of the Neo-Panamax locks and an increase in vessel transits. Given that Gatun Lake acts as a physical barrier, preventing the migration of marine species between Panama's Caribbean and Pacific coasts (Ros et al., 2014), the salinity increase of this water body is not only a concern from the perspective of drinking water supply and human health, but for biodiversity as well.

Salinization of freshwater resources, defined as the increase and shift of ion concentration ratios in freshwater (Cañedo-Argüelles, 2020), is an increasing global concern. This involves an increase of both salinity and alkalinity levels in freshwater caused directly by anthropogenic activities such as agricultural and urban runoff and indirectly by the acceleration of natural weathering processes (Kaushal et al., 2018). Dugan et al. (2017) examined the long-term chloride concentration trends of several North American lakes and found evidence of salinization for lakes surrounded by > 1 % of impervious land cover. Similarly, Tang et al. (2022) studied the historical water level and salinity dynamics of Lake Bosten in China and found that climate change was the main factor in reducing its water levels and causing its salinization in recent decades. High salinity in lakes not only increases stratification which could delay or prevent mixing (Ladwig et al., 2021; Sibert et al., 2015), but it also can destabilize aquatic ecosystems through trophic cascades (Hintz et al., 2017). However, lack of data from the Neotropics has prevented gaining an in-depth understanding of the effects of freshwater salinization in this region (Castillo et al., 2018). Gatun Lake in Panama thus serves as a significant example to study the mechanisms causing freshwater salinization and to understand its effect on aquatic ecosystems.

The Panama Canal Authority (ACP) has been monitoring salinity and other water quality parameters of Gatun Lake since 2003 but only at a handful of locations and with once a month time frequency. In 2011 ACP started performing vertical salinity profile measurements at several locations within Gatun Lake and in 2015, shortly before the completion of the expansion project, telemetry buoys were installed for continuous salinity monitoring. These data are used internally by ACP to inform their decisions regarding the management and implementation of saltwater intrusion mitigation strategies. ACP shared monitored data for this study, making it the first attempt to characterize the spatiotemporal distribution of salinity within Gatun Lake after the expansion and compare it with pre-expansion conditions. In addition, the variation of Gatun Lake's salinity in different phases of the ENSO cycle was explored. To achieve this, a thorough statistical analysis, including the use of Mann-Kendall, Theil-Sen and Wilcoxon rank sum tests, as well as interpolation of the available salinity datasets and Gatun Lake's water level were conducted.

Results of these analyses are presented in this paper. The structure of this paper is as follows: after this introduction, section two contains a description of the study area as well as an explanation of the data sources and the data analysis methods used; section three describes the results obtained, section four presents the discussion and section five offers conclusions based on the obtained results.

2. Materials and methods

2.1. Study area

2.1.1. The Panama Canal System

The construction of the Panama Canal from 1881 to 1914 involved the damming of the Chagres River, which flooded thousands of hectares of land in the central part of the isthmus of Panama and created the Gatun Lake (Fig. 1a). With a surface area of 436 km^2 and the ability to store about 5200 hm^3 of water, Gatun Lake was the largest reservoir in the world by the time of its completion in 1913 (Salgado et al., 2020; Wijsman, 2013).

The elevation of Gatun Lake is measured relative to the Precise Level Datum (PLD), a reference point situated 0.3 m below the mean sea level at the Pacific entrance and 0.06 m below the mean sea level at the Atlantic entrance (ACP, 2001). Gatun Lake's mean water level is 26 m above PLD and it ranges from 24.84 to 26.67 m above PLD (Wijsman, 2013). The lake has a complex bathymetry with a deep region ($<$20 m) near Gatun Dam in the north, as well as shallow basins ($<$10 m) near its southwestern and northeastern borders (Bunch et al., 2003; Salgado et al., 2020). The mean depth along the route for vessel transit within Gatun Lake (Fig. 1a), known as the Panama Canal navigation channel (PCNC), varies from 16.77 to 17.98 m, depending on Gatun Lake's water level (ACP, 2020).

A series of locks are in place to raise and lower the vessels to and from Gatun Lake while transiting the Panama Canal. The original system of locks, known as the Panamax Locks, completed in 1914 consists of Gatun Locks on the Atlantic side and Miraflores and Pedro Miguel Locks on the Pacific side. At the Atlantic side of the Canal, Gatun Locks have three steps or chambers that elevate the vessels directly to the level of Gatun Lake (Fig. 1a,b). At the Pacific side of the Canal, Pedro Miguel Locks with one chamber lower the vessels 10 m from Gatun Lake to the level of Miraflores Lake and then Miraflores Locks, consisting of two chambers, lower the vessels to sea level (Fig. 1a,c). These locks all have two lanes and their chambers are 304.8 m long, 33.53 m wide and 12.5 m deep, allowing for vessels with maximum dimensions of 32.3 m in beam, 294.1 m in length and 12 m of draft to transit through them (Wijsman, 2013). There are no pumps involved in the operation of the locks since water transfers between chambers are accomplished by gravity.

The Panama Canal expansion project included the construction of new locks to accommodate larger vessels. These new locks, known as the Neo-Panamax Locks, consist of the Cocolí Locks on the Pacific side and the Agua Clara Locks on the Atlantic side (Fig. 1a-d). As the original set of locks, the Neo-Panamax Locks are operated by gravity. Each lock has three chambers and one lane. The chambers are 55 m wide, 427 m long and 18.3 m deep, which makes them about 3.3 times larges in volume than the original lock chambers (Wijsman, 2013). Their larger volume implies that a higher amount of freshwater is lost to the ocean during their operation. A lockage in the Panamax locks requires 55 million gallons (0.21 hm^3) of water whereas in the Neo-Panamax locks it requires 120 million gallons (0.45 hm^3) of water, 2.4 times more than the Panamax locks. In order to reduce the loss of freshwater, a system of water saving basins (WSBs) was designed for the Neo-Panamax Locks. However, the concentration of salt in these WSBs is higher than in the adjacent lock chamber. Therefore, when brackish water is drawn from the WSB, it mixes with the water in its adjacent lock chamber and due to density flows and water exchange when a ship moves from one lock chamber to the next, saltwater eventually reaches Gatun

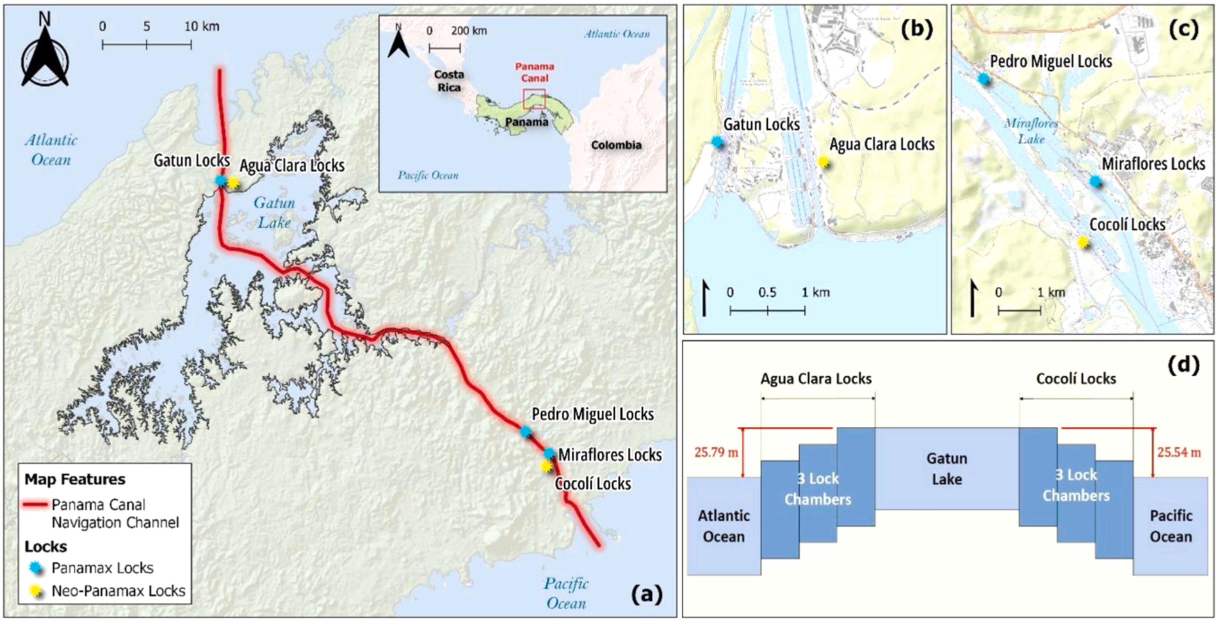

Fig. 1. (a) Location of Gatun Lake and the Panama Canal within Panama. The red line indicates the route for vessel transit, known as the Panama Canal navigation channel (PCNC); (b) Atlantic locks; (c) Pacific locks; (d) Schematic profile of the Panama Canal showing the height difference between Gatun Lake and the ocean (mean sea level).

Lake (Wijsman, 2013).

2.1.2. Historical salinity in the Panama Canal

Throughout the 20th century different studies reported that, except for the lower lock chambers, water in the Panama Canal can be considered fresh with very low to negligible salinity concentration. Hildebrand (1939) measured surface salinity under 3.0 PSU and 0.020 PSU in Miraflores and Gatun Lakes respectively, whereas Menzies (1968) reported salinity below 1 PSU in Miraflores Lake and close to 0 PSU in Gatun Lake (Table 1). For both studies it is unclear in which season these measurements were taken and in the case of the latter it is also unclear at which depth the measurements were taken.

To the authors' knowledge, the first salinity and temperature vertical profiles in the Panama Canal were measured during a monitoring campaign that took place in April and November 1972 (Jones and Dawson, 1973). They found that although the salinity is slightly higher at the end of the dry season (April) than at the end of the wet season (November), salinity concentration remained below 1 PSU in both Gatun and Miraflores Lakes (Table 1). More recently, Schreiber et al. (2023) measured salinities that ranged from 0.08 PSU to 0.48 PSU in Gatun Lake with higher values detected near the locks and the PCNC and lower values near Gamboa where the Chagres River inflows meet the PCNC. These measurements were taken between November 2019 and February 2020 and correspond to surface measurements.

2.1.3. Hydrometeorology of the Panama Canal Watershed

Gatun Lake is located within the Panama Canal Watershed (PCW) which has an area of 3380 km^2 and an average precipitation of 2700 mm per year. According to over 40 years of records (1980–2023), average monthly precipitation in the PCW during the driest month (February) and the wettest month (November) corresponds to 28.5 and 303.7 mm, respectively. As a consequence, nearly 60 % of the inflows to the PCW reservoirs, including Gatun Lake, occur at the end of the rainy season, from September to December. Median minimum and maximum inflows to Gatun Lake occur in March and November and correspond to 82 and 860 hm^3, respectively (Graham et al., 2005).

Precipitation and streamflow in the PCW are also strongly affected by the El Niño Southern Oscillation (ENSO) cycle. An increase in sea surface temperature (SST) in the Pacific Ocean causes an El Niño episode whereas a decrease in SST causes a La Niña episode. In Panama, El Niño causes droughts and La Niña causes abundant rainfall. During the El Niño episodes of 1976–77, 1982 and 1997, precipitation in the PCW was 25–35 % lower than average and streamflow was 20–30 % lower than average (MWH, 2001).

2.2. Data sources

2.2.1. Salinity measurements

ACP carries out a water quality monitoring and surveillance program since 2003 in which several water quality parameters are measured monthly at different locations within the PCW. In Gatun Lake there are 15 monitoring locations (see Fig. 2a). Water quality parameters measured include chloride concentration, chlorophyll-a, nutrients (nitrate and phosphate), turbidity, salinity and water temperature, among others. Most of these parameters are measured at two depths which are labelled as shallow (near the surface) and deep (near the bottom). Results from these measurements are included in ACP's yearly water quality reports, which are published through their website in pdf format. In addition, the Smithsonian Tropical Research Institute (STRI) recently published these data in tabular format through their online data repository (Paton and Equipo de Análisis de Calidad de Agua, 2022). An overview of the availability of these data for the locations within Gatun Lake is presented in detail in Tables 2 and 3. These tables include data for times before and after the expansion of the Panama Canal, including details on % of missing data in the time interval of the data.

In addition to monthly water quality monitoring campaigns, salinity vertical profiles measurement campaigns are carried out. These measurements are performed using an SBE 19 + V2 SeaCAT CTD Profiler from Sea-Bird Electronics and the results are provided in PSU. Salinity vertical profiles have been measured at nearly 200 locations within Gatun Lake. However, consistent measurements are carried out in less than half of these locations. From 2011 to early 2016 (right before the expansion), salinity profiles were measured seldomly (only a few times per year) at 22 locations and in mid-2016, after the expansion, salinity profiles have been measured monthly in 69–76 locations within Gatun Lake. An overview of the data made available for this study, based on their types, the number of locations and the period of records are presented in Tables 2–4.

In the last years ACP has also been continuously measuring salinity and temperature in the PCNC by using telemetry buoys. The equipment deployed consists of SBE 37 MicroCAT high-accuracy automatic recorders from Sea-Bird Electronics which provide salinity measurements in PSU. These buoys were progressively being installed since early 2015 with the last buoys installed in 2019. By November 2023, there were a total 13 telemetry buoys installed (Fig. 2c). The frequency of measurements is every 15 minutes, except for BR-1 located in the Atlantic entrance of the Canal near Agua Clara locks, which records values every 5 minutes (see Fig. 2d). In most

Table 1
Historical salinity concentration in Gatun and Miraflores Lakes as reported by different authors.

Reference	Gatun Lake	Miraflores Lake
(Hildebrand, 1939)	0.005 – 0.020 PSU	0.1 – 3.0 PSU
(Menzies, 1968)	~ 0 PSU	~ 1 PSU
(Jones and Dawson, 1973)	< 1.0 PSU	< 1.0 PSU
(Schreiber et al., 2023)	0.08 – 0.48 PSU	0.47 – 1.18 PSU

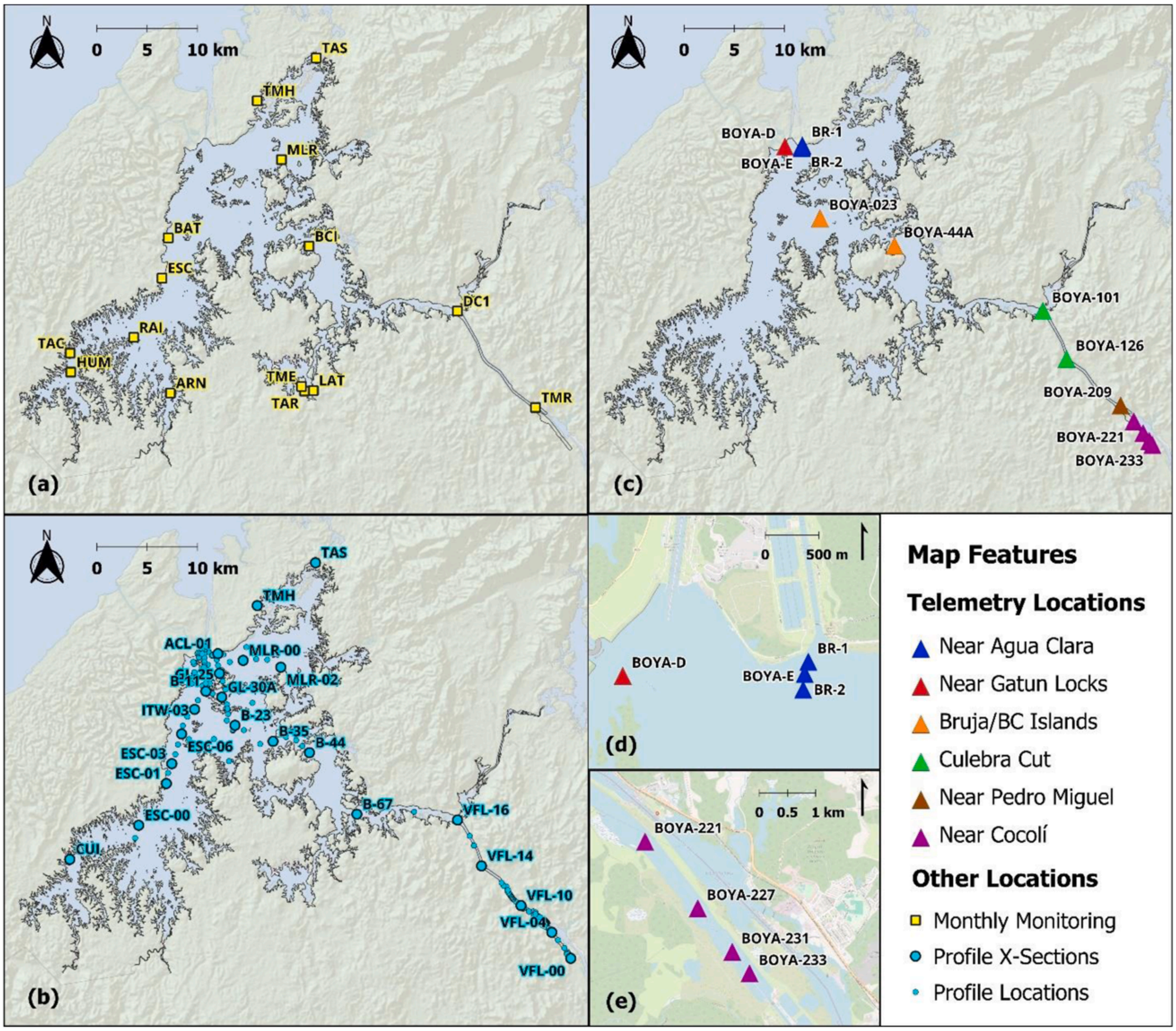

Fig. 2. Salinity monitoring locations in the Panama Canal waterways. (a) Monthly measurement locations; (b) vertical profile measurement locations and (c) location of telemetry buoys. A close-up to telemetry buoys near the Atlantic (d) and Pacific (e) locks is also provided.

Table 2
Data availability for salinity from the monthly water quality monitoring campaigns.

Station ID	Pre-Expansion			Post-Expansion		
	Start of Record	End of Record	% Missing	Start of Record	End of Record	% Missing
ARN	2003–01–22	2010–12–14	30 %	2017–04–18	2020–12–09	14 %
BAT	2003–04–29	2010–12–15	28 %	2016–08–17	2020–12–09	4 %
BCI	2003–04–29	2010–12–15	27 %	2016–11–15	2020–12–15	5 %
DC1	2003–03–27	2010–12–15	16 %	2019–05–22	2020–12–15	80 %
ESC	2003–01–22	2010–12–14	28 %	2016–08–17	2020–12–09	2 %
HUM	2003–01–22	2010–12–14	30 %	2019–05–21	2020–12–09	78 %
LAT	2003–01–24	2010–12–10	30 %	N/A	N/A	N/A
MLR	2003–04–29	2010–12–15	17 %	2016–08–17	2020–12–09	13 %
RAI	2003–01–22	2010–12–14	30 %	2017–02–14	2020–12–09	2 %
TAC	N/A	N/A	N/A	2019–12–30	2020–12–09	46 %
TAR	2003–08–28	2010–12–10	34 %	N/A	N/A	N/A
TAS	N/A	N/A	N/A	2017–04–20	2020–12–22	0 %
TME	2010–01–20	2010–12–10	0 %	N/A	N/A	N/A
TMH	N/A	N/A	N/A	2017–03–15	2020–12–22	0 %
TMR	2003–01–24	2010–12–15	6 %	2016–07–13	2020–12–15	19 %

Table 3
Data availability for chloride concentration from the monthly water quality monitoring campaigns.

Station ID	Pre-Expansion			Post-Expansion		
	Start of Record	End of Record	% Missing	Start of Record	End of Record	% Missing
ARN	2008–01–23	2016–05–23	0 %	2016–08–17	2020–12–09	0 %
BAT	2008–01–23	2016–05–23	0 %	2016–08–17	2020–12–09	1 %
BCI	2008–01–22	2016–05–25	0 %	2016–07–13	2020–12–15	0 %
DC1	2008–01–22	2016–05–25	0 %	2016–07–13	2020–12–15	5 %
ESC	2008–01–23	2016–05–23	0 %	2016–08–17	2020–12–09	0 %
HUM	2008–01–23	2016–05–23	0 %	2016–08–17	2020–12–09	0 %
LAT	2008–01–22	2016–05–25	0 %	2016–07–13	2020–12–15	0 %
MLR	2008–01–22	2016–05–23	0 %	2016–08–17	2020–12–09	0 %
RAI	2008–01–23	2016–05–23	0 %	2016–08–17	2020–12–09	0 %
TAC	N/A	N/A	N/A	2017–01–17	2020–12–09	0 %
TAR	2008–01–22	2012–12–19	1 %	N/A	N/A	N/A
TAS	N/A	N/A	N/A	2017–01–19	2020–12–22	0 %
TME	2010–01–20	2016–05–25	0 %	2016–07–13	2020–12–15	0 %
TMH	2013–02–26	2016–05–17	0 %	2016–07–14	2020–12–22	0 %
TMR	2008–01–22	2016–05–25	0 %	2016–07–13	2020–12–15	0 %

Table 4
Summary of salinity data types, available record length and measurement frequency. For all data types salinity values were retrieved in Practical Salinity Units (PSU).

Data Type	No. Locations	Data Availability		Measurement Frequency
		Start of Record	End of Record	
Telemetry	13	February 2015	July 2023	15 minutes
Profiles	22	April 2011	May 2016	Quarterly
	69	July 2016	December 2023	Monthly
Water Quality	15	January 2003	December 2020	Monthly

buoys, measurements are taken at different depths near the surface and the bottom of the lake/channel, but the exact depth has been modified a few times since the buoys were installed due to malfunction of the sensors, equipment replacement or other operational reasons.

2.2.2. Hydrometeorological variables

The Water Resources Division of the ACP routinely collects meteorological and hydrological data at several locations within the PCW. Gatun Lake's water level is measured with telemetry buoys every 15 minutes at four locations within the lake. These data are publicly available and were obtained from ACP's AQUARIUS web portal (ACP, 2023). In addition, a dataset of Multivariate ENSO Index Version 2 (MEI.v2) was downloaded from NOAA's Physical Science Laboratory website (NOAA, 2023). This dataset contains values for every pair of months since 1979 indicating the strength of the different phases of the ENSO cycle where positive and negative values correspond to El Niño and La Niña phases of the cycle, respectively.

2.3. Data analysis

2.3.1. Summary statistics

Summary statistics of salinity concentration for pre- and post-expansion conditions were calculated based on the data from the monthly water quality surveys, from the locations represented in Fig. 2a. Similarly, data from the telemetry buoys was analysed using summary statistics and visualizations such as boxplots and time series graphs. For these analyses, data were grouped based on the location of the telemetry buoys (Fig. 2c). Additionally, two different average salinity concentrations were calculated, a monthly average for Gatun Lake as a whole and a daily average for the PCNC only. Mean monthly salinity concentration of Gatun Lake was calculated as weighted average using data from 50 vertical profile locations and 7 monthly water quality locations (Fig. 2b). The weights for each location were calculated using Thiessen Polygons. Mean daily salinity for the PCNC was calculated as an arithmetic mean using bottom salinity data from six telemetry buoys, namely BOYA-D, BOYA-023, BOYA-44A, BOYA-101, BOYA-126 and BOYA-209 (Fig. 2c).

2.3.2. Trend analyses

The Mann-Kendall test (Kendall, 1955; Mann, 1945) was used to determine if the variable of interest, in this case salinity, showcases a monotonic trend over time. The null hypothesis declares that there is no monotonic trend whereas the alternative hypothesis states that a monotonic trend is present in the data. If a trend is present, this can be upwards or downwards for a variable that is increasing or decreasing over time, respectively. Additionally, the Theil-Sen slope estimator (Sen, 1968; Theil, 1950) was used to assess the magnitude of the monotonic trend (if present) on the salinity data over time. Both the Mann-Kendall and Theil-Sen are non-parametric tests, which means that no prior assumption of a normal distribution of the data is necessary.

The Wilcoxon rank sum test (Wilcoxon, 1945) was applied to the salinity datasets to determine if salinity after the expansion is greater than before the expansion and if salinity during El Niño is greater than during La Niña. The Wilcoxon rank sums is a non-parametric test, analogous to the two-sample *t*-test for a normal distribution, used to determine whether the central tendency of two distributions (X and Y) is equal or not. The null hypothesis considers that there is no difference between the two distributions ($X = Y$) whereas the alternative hypothesis can evaluate if the distributions are different ($X \neq Y$) or whether one distribution is stochastically greater than the other ($X > Y$ or $Y > X$).

2.3.3. Spatial analyses

Data from salinity vertical profiles was interpolated used to generate cross-sections along and across the PCNC. This data was also used to create hexagon mosaic maps (Carr et al., 1992) depicting the frequency with which salinity measurements exceeded the chronic toxicity threshold for freshwater ecosystems of 230 mg/l of chloride concentration (~0.42 PSU) recommended by the Environmental Protection Agency of the United States (US EPA, 1988). Panama does not have any regulation regarding water quality standards, and therefore the threshold recommended by the US EPA is used here as a reference to characterize the health of Gatun Lake's aquatic ecosystem before and after the expansion. Additionally, spline interpolation, based on the method proposed by Donato and Belongie (2003), was used to create maps of average salinity before and after the expansion using monthly measurements from the water quality surveys and salinity profile data.

3. Results

3.1. Monthly salinity

Before the expansion of the Panama Canal, during the 2000s and early 2010s, salinity and chloride concentration in Gatun Lake remained below 0.1 PSU and 50 mg/l, respectively (Fig. 3). Average salinity and chloride concentration for the period pre-expansion (2003 to mid-2016) corresponded to 0.033 PSU and 8.26 mg/l, respectively. After the inauguration of the expanded canal in June 2016, salinity sharply increased reaching up to almost 0.4 PSU at some locations, and although it slightly decreased in the following years, it rose again in 2020 reaching nearly 0.5 PSU at some locations. Average salinity and chloride concentration in the period post-expansion (mid-2016 to late 2020 in this dataset) were 0.22 PSU and 71.6 mg/l, respectively.

Summary statistics and results of Wilcoxon rank sum tests of salinity pre- and post-expansion at all locations within Gatun Lake are presented in Tables 5 and 6, respectively. The results from the Wilcoxon rank sum tests suggest, with statistical significance ($p < 0.05$), that salinity after the expansion is stochastically greater than before the expansion at all locations where data for both periods are available. Mean salinity concentration increased the most after the expansion at BAT, ESC and MLR, situated closest to the Agua Clara Locks and it increased the least at DC1, located near Gamboa.

3.2. Spatial salinity distribution

3.2.1. Cross-sections

Data from salinity vertical profiles were linearly interpolated to generate salinity cross-sections parallel and perpendicular to the PCNC, respectively. Fig. 4 shows cross-sections of monthly average salinity along the PCNC from Agua Clara locks to Cocolí locks which is roughly in the N to S direction. In May 2016, before the expansion, salinity in the Atlantic entrance of the Canal, at 1.5 km southeast of Gatun locks, was about 0.13 PSU. However, along the PCNC salinity was for the most part below 0.1 PSU (Fig. 4a). In

Fig. 3. Monthly depth-averaged salinity and chloride concentration measured at 15 locations within Gatun Lake. The vertical dotted line indicates the inauguration date of the Neo-Panamax Locks (26 June 2016).

Table 5
Summary statistics of monthly salinity measurements at 15 locations within Gatun Lake. Pre-expansion and post-expansion statistics correspond to the periods from January 2003 to May 2016 and from July 206 to December 2020, respectively.

Station ID	Salinity Pre-Expansion (PSU)					Salinity Post-Expansion (PSU)				
	Mean	SD	CV	Min	Max	Mean	SD	CV	Min	Max
ARN	0.025	0.009	0.372	0.000	0.040	0.157	0.051	0.325	0.100	0.320
BAT	0.036	0.011	0.292	0.000	0.060	0.292	0.106	0.363	0.130	0.540
BCI	0.040	0.010	0.259	0.000	0.060	0.214	0.076	0.354	0.100	0.410
DC1*	0.048	0.016	0.334	0.000	0.070	0.118	0.009	0.075	0.100	0.130
ESC	0.035	0.011	0.320	0.000	0.060	0.270	0.104	0.384	0.110	0.500
HUM*	0.015	0.006	0.439	0.000	0.030	0.102	0.004	0.043	0.100	0.110
LAT	0.010	0.008	0.825	0.000	0.060	N/A	N/A	N/A	N/A	N/A
MLR	0.045	0.012	0.259	0.000	0.060	0.233	0.116	0.499	0.100	0.570
RAI	0.026	0.010	0.370	0.000	0.040	0.195	0.071	0.363	0.100	0.400
TAC	N/A	N/A	N/A	N/A	N/A	0.147	0.032	0.216	0.100	0.190
TAR**	0.009	0.005	0.507	0.000	0.030	N/A	N/A	N/A	N/A	N/A
TAS	N/A	N/A	N/A	N/A	N/A	0.170	0.058	0.341	0.100	0.320
TME	0.008	0.004	0.467	0.000	0.010	N/A	N/A	N/A	N/A	N/A
TMH	N/A	N/A	N/A	N/A	N/A	0.180	0.064	0.356	0.100	0.350
TMR	0.058	0.015	0.268	0.000	0.080	0.267	0.099	0.373	0.130	0.570

* At these stations > 75 % of the data for the period post-expansion is missing.
** This measurement location was discontinued in 2012.

Table 6
Statistical results of Wilcoxon rank sum tests on monthly salinity concentrations pre- and post-expansion at different locations within Gatun Lake.

Station ID	**Wilcoxon's p-value**	**Median Diff.**	**Mean Diff.**
ARN	2.87E−31	0.110	0.134
BAT	1.68E−37	0.220	0.255
BCI	4.36E−36	0.170	0.175
DC1*	1.04E−06	0.070	0.069
ESC	4.70E−37	0.200	0.235
HUM*	3.14E−07	0.085	0.088
MLR	1.73E−31	0.150	0.190
RAI	3.17E−35	0.140	0.169
TMR	2.14E−38	0.190	0.210

* At these stations > 75 % of the data for the period post-expansion is missing.

August 2016, two months after the inauguration of the Neo-Panamax locks, salinity near Agua Clara locks was about 0.25 PSU and near Cocolí locks it was about 0.5 PSU but it surpassed 1.5 PSU at the bottom of the water column (Fig. 4b). This clearly evidences the presence of saltwater intrusion through the Neo-Panamax locks. Nevertheless, in the rest of the PCNC salinity was still below 0.1 PSU. In March 2020 salinity near Agua Clara and Cocolí locks was 0.52 and 0.75 PSU, respectively, but it reached up to 3.6 PSU at 19 m of depth near Agua Clara (Fig. 4d). In November 2023, salinity near Agua Clara and Cocolí was about 0.5 and 0.9 PSU, respectively, but it reached up to 2.7 PSU at a depth of 19 m near Agua Clara. Despites the increase in saltwater intrusion through the Neo-Panamax locks salinity in Culebra Cut (buoys VFL-16 and VFL-14) remained low (~0.1 PSU) in the period post-expansion and near Barro Colorado Island (buoy B-35) it hovered around 0.3 PSU.

Fig. 5 shows average monthly salinity cross-sections perpendicular to the PCNC, along the north shore of Gatun Lake, roughly in the SW to NE direction. In these cross-sections, B-11, GL-25 and MLR-00 are located 4.4 km SW, 2.5 km S and 2.7 km SE from Agua Clara locks, respectively. In March 2017 average salinity in this section of Gatun Lake ranged from 0.1 to 0.6 PSU with salinity being higher at the bottom of Gatun Lake in an area very near to the Agua Clara locks (buoys B-11 and GL-25) and decreasing further away from the locks (Fig. 5a). In March 2020 salinity ranged from 0.3 PSU near Escobal to 0.5 PSU near Monte Lirio and a region with salinity above 0.4 PSU extends nearly 9 km to the west and 6 km to the east of Agua Clara locks, from buoy ESC-06 to buoy MLR-02 (Fig. 5b). In March 2022 salinity was slightly lower (<0.30 PSU) and very uniform in this cross-section (Fig. 5c). In November 2023 salinity was 0.3 and 0.5 PSU, near Escobal and Monte Lirio, respectively and it surpassed 0.6 PSU at the bottom of the water column in the areas very close to the Agua Clara locks, from ITW-03 to GL-25 (Fig. 5d).

3.2.2. Salinity maps

The spatial distribution of average salinity in Gatun Lake before and after the expansion of the Panama Canal is shown in Fig. 6a and b, respectively. The US EPA recommends a chloride concentration of 230 mg/l as the chronic toxicity threshold for freshwater (US EPA, 1988). This value corresponds to a salinity concentration of approximately 0.42 PSU. Hexagon mosaic maps depicting the frequency with which depth-averaged salinity in Gatun Lake exceeded this threshold before and after the expansion are shown in Fig. 6c

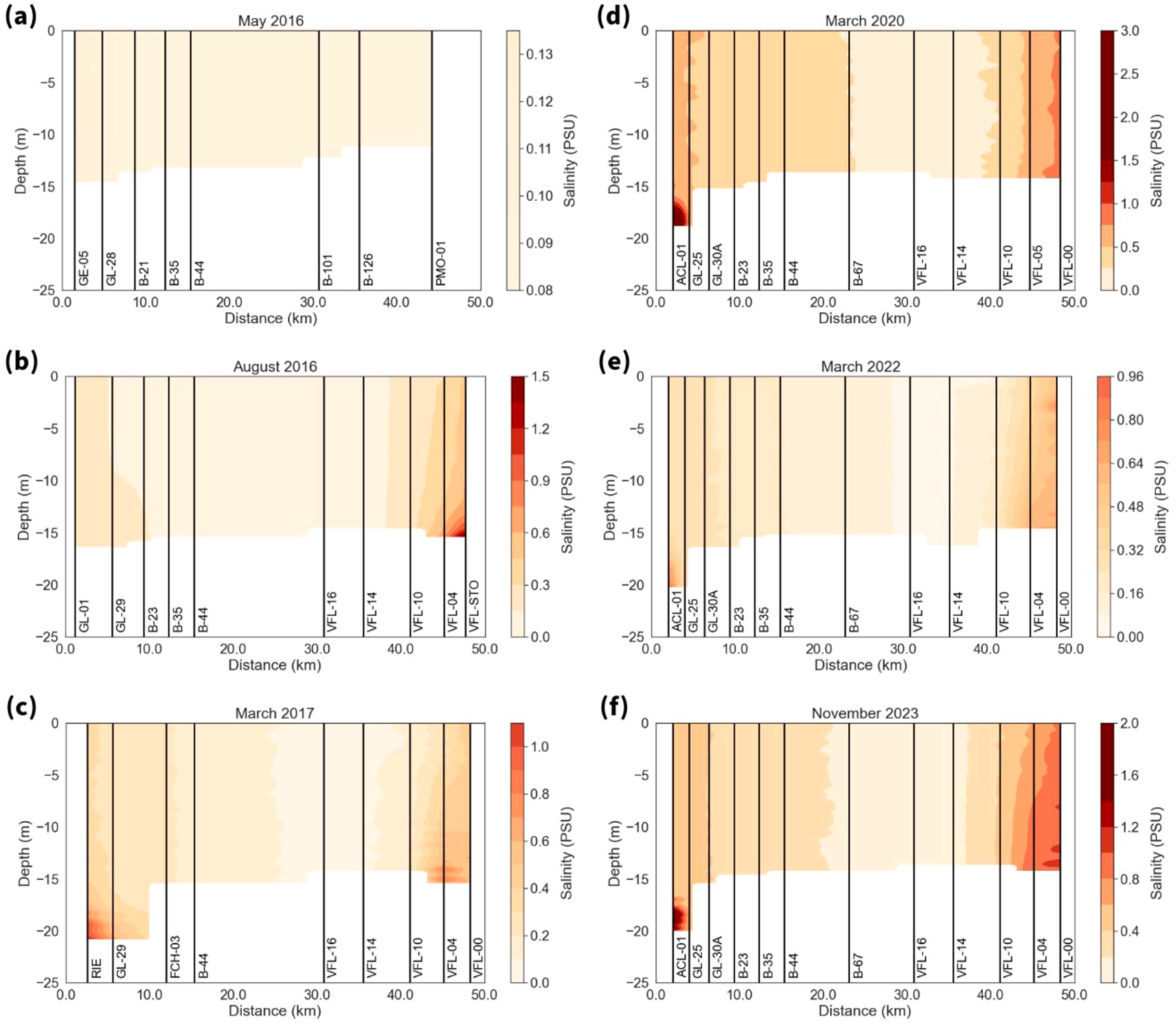

Fig. 4. Average monthly salinity cross-sections along the PCNC (from Agua Clara to Cocolí) for (a) May 2016, (b) August 2016, (c) March 2017, (d) March 2020, (e) March 2022, and (f) November 2023. This were generated by linearly interpolating the data from the vertical profiles. The vertical axis corresponds to the depth below the surface and the horizontal axis corresponds to the distance from the Gatun locks in the Atlantic entrance of the Panama Canal. The scale of the colour palette is the same for all cross-sections.

and d, respectively. Before the expansion average salinity was very low (<0.18 PSU) all throughout Gatun Lake, but right next to Gatun locks salinity exceeded 0.42 PSU during 17 % of the observation period. After the expansion average salinity in Gatun Lake was 0.56 and 0.63 PSU in the immediate vicinity of Agua Clara and Cocolí locks, respectively. Outside of Agua Clara locks salinity surpassed the 0.42 PSU threshold 38 % of the time. Moving away from the Atlantic locks, the exceedance frequency reduces to 12 % and 8 % at 3 and 6 km south of the Agua Clara locks, respectively. Next to Barro Colorado Island, located about 12 km from Agua Clara locks, the exceedance frequency oscillates between 2 % and 0.7 % of the time and throughout Culebra Cut salinity remained below the threshold. Right next to Cocolí locks in the Pacific, salinity exceeded the threshold from 75 % to 85 % of the time, but 3 km north of the locks the frequency gets reduced to 35 % and it drops to 7 % near Paraíso, located 6 km north of Cocolí locks.

3.3. Salinity in the Panama Canal Navigation Channel

Continuous salinity measurements from the 13 telemetry buoys located along the PCNC were organized into six groups according to the geographical location of the buoys (Fig. 2c). The first group was comprised of buoys located near the Agua Clara locks in the Atlantic, namely BR-1, BR-2, and BOYA-E (Fig. 2d). The second group contains BOYA-D located near Gatun locks also in the Atlantic. The third group corresponds to BOYA-023 and BOYA-44A located in between Bruja and Barro Colorado (BC) Islands in the middle of Gatun Lake. The fourth group and fifth groups are comprised by buoys located in Culebra Cut (BOYA-101 and BOYA-126) and near Pedro Miguel (BOYA-209), respectively. The sixth group corresponds to buoys located near the Cocolí locks in the Pacific, namely

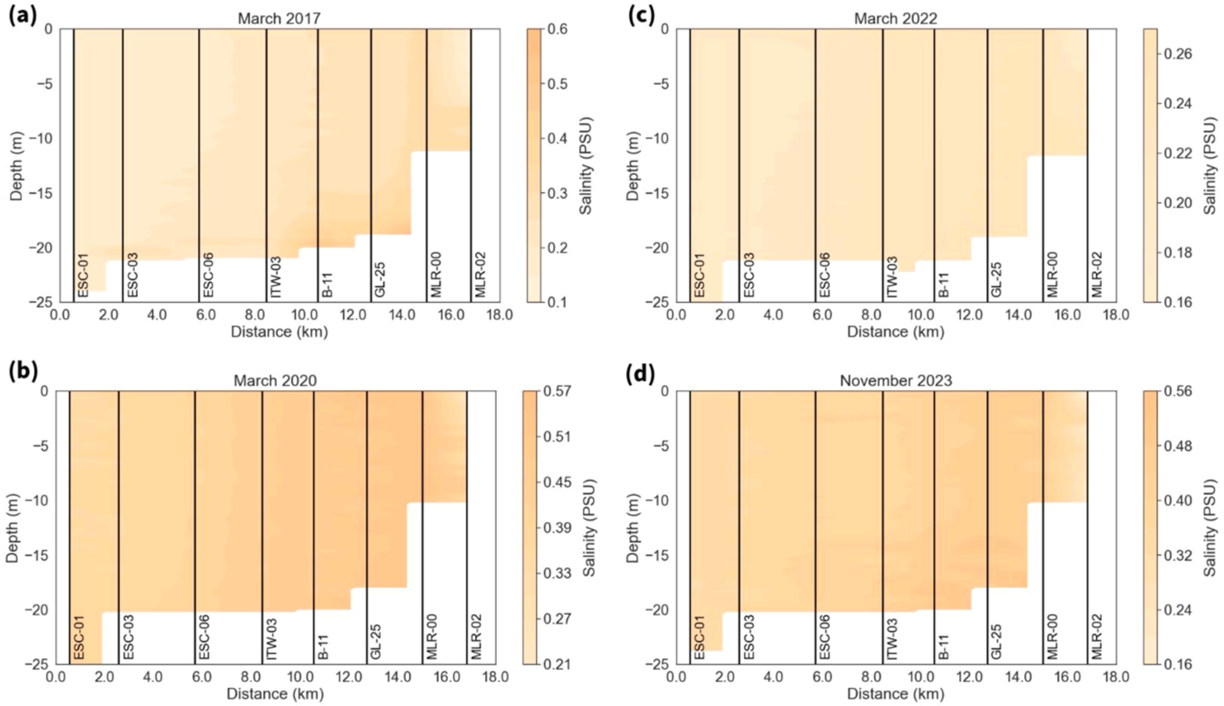

Fig. 5. Average monthly salinity cross-sections across the PCNC (from Escobal to Monte Lirio) for (a) March 2017, (b) March 2020, (c) March 2022, and (d) November 2023. This were generated by linearly interpolating the data from the vertical profiles. The vertical axis corresponds to the depth below the surface and the horizontal axis corresponds to the distance from the town of Escobal in the north shore of Gatun Lake. The scale of the colour palette is the same for all cross-sections.

BOYA-221, BOYA-227, BOYA-231 and BOYA-233 (Fig. 2e).

Summary statistics of salinity for these different groups before and after the expansion are presented in Tables 7 and 8, respectively. Near Agua Clara in the Atlantic and Cocolí in the Pacific, average salinity is 7.1 and 6.4 times greater than in Culebra Cut, respectively. Results of Wilcoxon rank sum tests on salinity data at different locations within the PCNC are presented in Table 9. At all buoy groups in the PCNC, except for the ones located near Agua Clara, there is a statistically significant ($p < 0.05$) increase in salinity concentration after the expansion. The largest difference between mean salinity before and after the expansion occurred near Cocolí and near Gatun locks where average salinity increased by 0.43 and 0.31 PSU, respectively.

The distribution of salinity measurements (surface and bottom combined) for each telemetry buoy is presented in Fig. 7. The color convention for the buoy groups in Fig. 7 corresponds to the location of the buoys as presented in Fig. 2c. These results show that after the expansion, the distribution of salinity measurements is much wider for the buoys located near the Agua Clara, Gatun and Cocolí locks and their average is relatively high (>0.5 PSU) whereas for the buoys located in Culebra Cut the distribution is narrower and the average is low (~0.1 PSU). This indicates that not only is salinity on average much higher near the locks than in Culebra Cut, but it also has a greater variability.

Salinity in the PCNC follows a distinct temporal pattern both inter-annually (Fig. 8) and intra-annually (Fig. 9). At the inter-annual scale, salinity peaked right after the expansion, in early to mid-2019, in early 2020 and in early 2023. This pattern is noticeable at all locations in the PCNC except for Culebra Cut. Right after the opening of the Neo-Panamax locks, salinity increased sharply near the Gatun, Agua Clara, Cocolí and Pedro Miguel locks, reaching 0.89, 0.85, 0.77 and 0.46 PSU, respectively. At the end of the wet season, in December 2016, salinity at these locations had decreased to less than 0.4 PSU. In March 2017 salinity near Agua Clara rose to 0.95 PSU, near Gatun locks it peaked at 0.92 PSU and near Cocolí it reached 0.66 PSU. In late April 2020, salinity near the locks peaked and reached 1.45, 0.87 and 1.0 PSU near Agua Clara, Gatun and Cocolí locks, respectively. In late June and early July 2023, salinity near Agua Clara peaked, reaching up to 2.0 PSU. Near Pedro Miguel after the initial peak of 0.48 PSU in October 2016, salinity decreased and remained below 0.42 PSU, except for March and April 2020 when it reached 0.52 PSU and July 2023 when it reached 0.74 PSU. The high short-term variability of salinity at this location suggests that the operations of the Cocolí locks have a high impact on salinity at this location. In the reach in between Bruja and Barro Colorado Islands in Gatun Lake salinity increased slightly after the expansion, but for the most part it remained well below 0.42 PSU, expect for May 2020 when it rose to 0.49 PSU. Also, short-term variability of salinity at this location is less pronounced than near the locks or at Pedro Miguel, which suggests a lesser effect from lock operations. Lastly salinity in Culebra Cut has remained for the most part at or below 0.1 PSU, except for December 2019 and May 2023 when it reached 0.15 and 0.14 PSU, respectively.

At the intra-annual scale, there is a distinct pattern in which salinity concentration rises during the first half of the year and

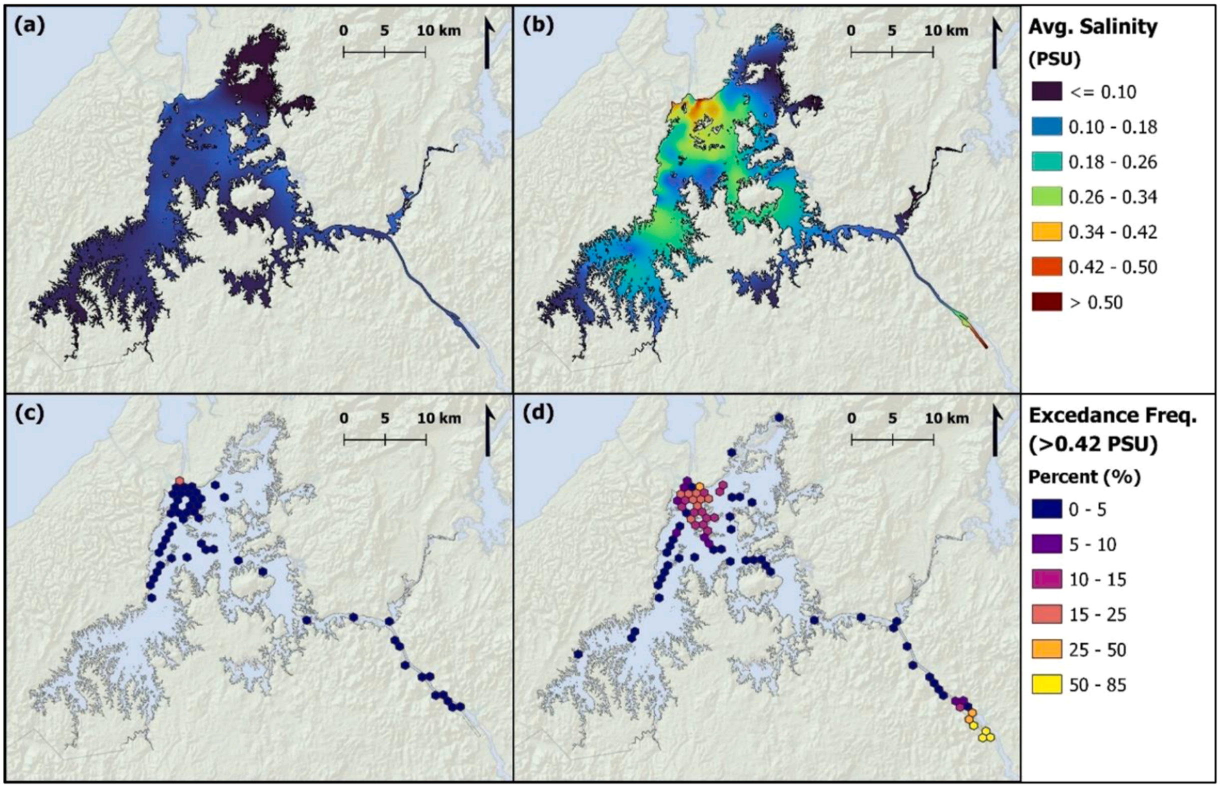

Fig. 6. Average salinity in Gatun Lake and frequency with which depth-averaged salinity exceeded the US EPA recommended salinity threshold for freshwater ecosystems (230 mg/l of chloride or 0.42 PSU) before (a, c) and after (b, d) the expansion of the Panama Canal.

Table 7
Summary statistics of salinity measurements pre-expansion by telemetry buoys at different location within the PCNC. Mean, standard deviation (SD), coefficient of variation (CV), 25 % percentile (Q1), median (Q2) and 75 % percentile (Q3) are presented.

Location	Mean	SD	CV	Q1	Q2	Q3
Near Agua Clara	N/A	N/A	N/A	N/A	N/A	N/A
Near Gatun Locks	0.136	0.040	0.296	0.110	0.128	0.152
Bruja/BC Islands	0.105	0.024	0.226	0.084	0.106	0.113
Culebra Cut	0.076	0.006	0.084	0.071	0.077	0.081
Near Pedro Miguel	0.086	0.010	0.122	0.075	0.088	0.094
Near Cocolí	0.122	0.010	0.086	0.116	0.120	0.129

Table 8
Summary statistics of salinity measurements post-expansion by telemetry buoys at different location within the PCNC. Mean, standard deviation (SD), coefficient of variation (CV), 25 % percentile (Q1), median (Q2) and 75 % percentile (Q3) are presented.

Location	Mean	SD	CV	Q1	Q2	Q3
Near Agua Clara	0.604	0.396	0.655	0.390	0.511	0.654
Near Gatun Locks	0.444	0.184	0.414	0.315	0.417	0.521
Bruja/BC Islands	0.234	0.095	0.407	0.163	0.222	0.279
Culebra Cut	0.085	0.019	0.219	0.072	0.079	0.091
Near Pedro Miguel	0.239	0.123	0.514	0.130	0.231	0.309
Near Cocolí	0.547	0.253	0.462	0.378	0.521	0.690

decreases during the second half of the year (Fig. 9). This roughly corresponds to the dry (Jan – Apr) and wet (May – Dec) seasons in Panama, respectively. Near the Agua Clara and Cocolí locks, the highest salinity occurs in April, at the end of the dry season, and corresponds to 0.82 and 0.72 PSU, respectively (Fig. 9a). Near Agua Clara the lowest average salinity (0.48 PSU) occurs in January, at the end of the wet season, whereas Near Cocolí, the lowest average salinity (0.41 PSU) occurs in October, in the middle of the wet season. This is likely due to the fact that the diffusion of the salinity in water volume near Agua Clara and Cocolí are different, given

Table 9
Statistical results of Wilcoxon rank sum tests on salinity data from telemetry buoys pre- and post-expansion at different locations within the PCNC. N_1 and N_2 correspond to the number of measurements before and after the expansion, respectively.

Location	Wilcoxon's p-value	N_1	N_2	Mean Diff.
Near Agua Clara	N/A	0.00E+ 00	1.02E+ 06	N/A
Near Gatun Locks	0.00	2.13E+ 04	5.41E+ 05	0.308
Bruja/BC Islands	0.00	1.46E+ 04	6.08E+ 05	0.129
Culebra Cut	0.00	1.49E+ 04	3.84E+ 05	0.009
Near Pedro Miguel	0.00	1.34E+ 04	2.96E+ 05	0.154
Near Cocolí	0.00	3.90E+ 03	9.57E+ 05	0.426

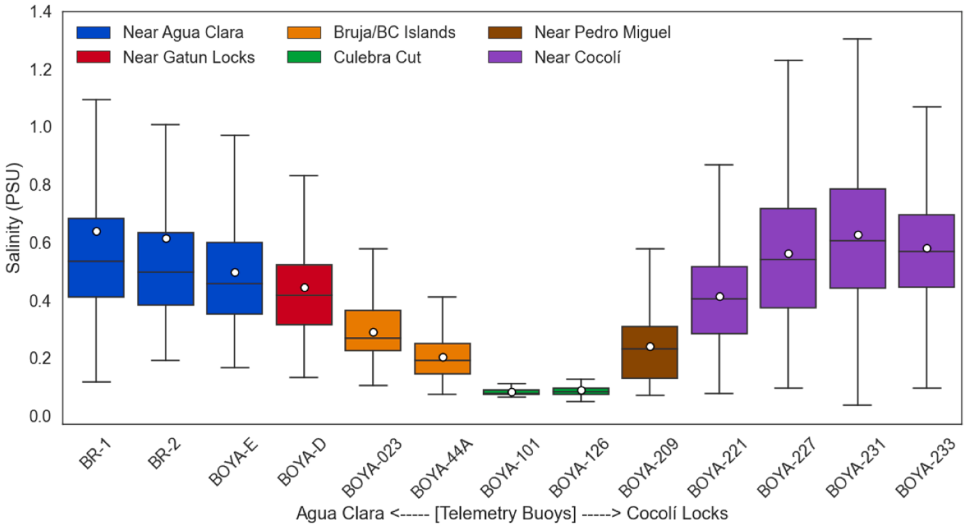

Fig. 7. Distribution of salinity concentration after the expansion measured using telemetry buoys deployed at different locations along the PCNC. Location of buoys is shown in Fig. 2c.

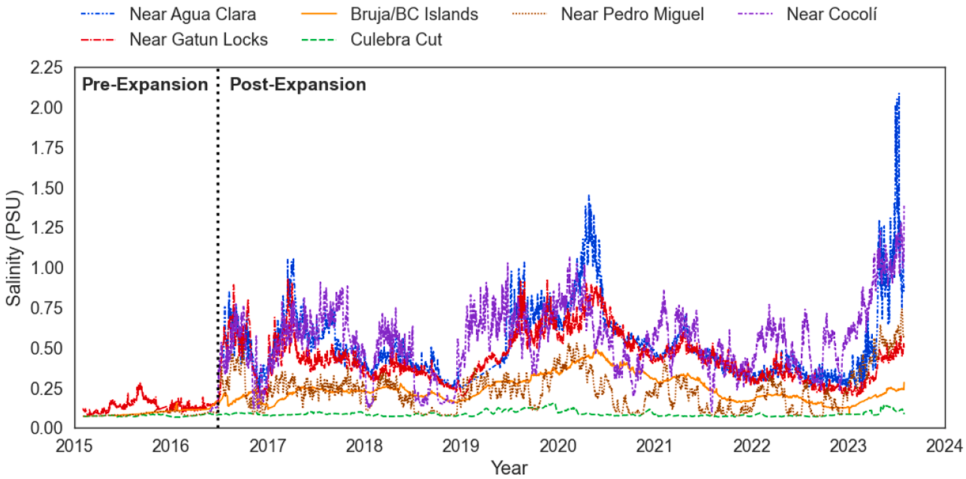

Fig. 8. Average daily salinity at different locations within the PCNC, calculated based on the continuous monitoring carried out using the telemetry buoys. The vertical dotted line indicates the inauguration date of the Neo-Panamax Locks (26 June 2016).

that in Agua Clara the locks open directly to Gatun Lake (large volume of water) and in Cocolí the locks open to a channel (small volume of water) that leads to the narrow Culebra Cut. In Pedro Miguel average salinity is at its highest (0.32 PSU) from February to April and it is at its lowest (0.15 PSU) in October (Fig. 9b). In Bruja/BC Islands, average salinity concentration peaks in May with a mean of 0.27 PSU and it is at its lowest in December with a value of 0.21 PSU. The aforementioned patterns suggest that although

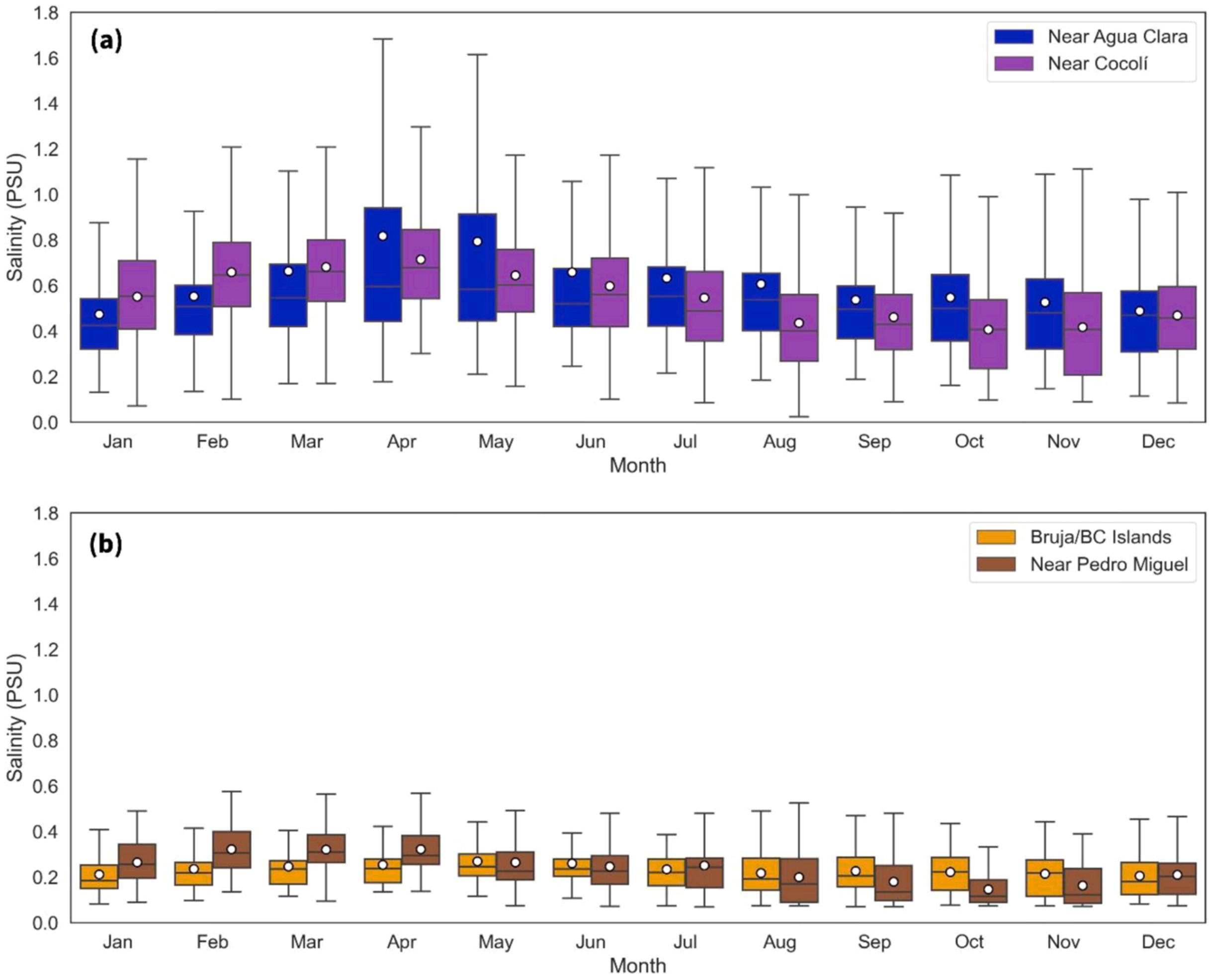

Fig. 9. Monthly distribution of salinity concentration at different locations within the PCNC, calculated based on the continuous monitoring carried out using the telemetry buoys.

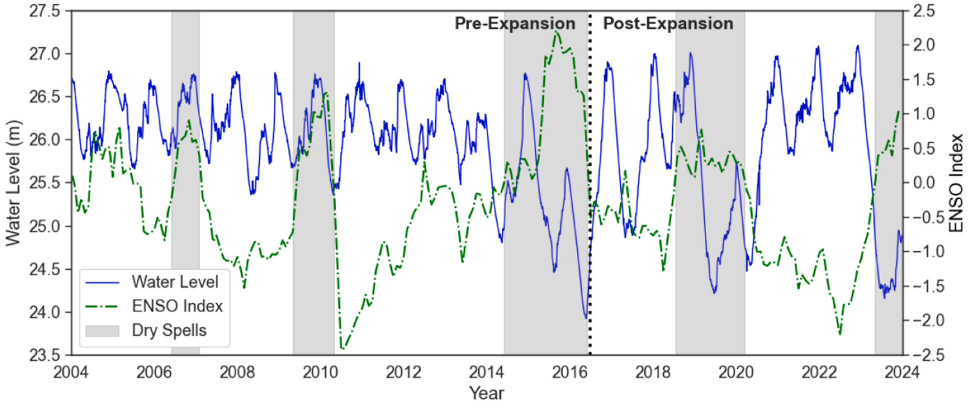

Fig. 10. Multivariate ENSO Index Version 2 (MEI.v2) and average daily water level in Gatun Lake. Positive and negative ENSO Index values indicate El Niño and La Niña episodes, respectively. The shaded grey areas indicate the most important dry (El Niño) spells in the past 20 years. The vertical dotted line indicates the inauguration date of the Neo-Panamax Locks (26 June 2016).

seasonality (wet months vs dry months) does impact salinity concentration in the PCNC, its effect is not uniform across this body of water. This might be due to the fact that the areas near the locks are directly subjected to saltwater intrusion through the locks regardless of the season whereas locations in the middle of the lake respond more gradually to salt inputs and are more dependent on the lake's water level.

3.4. Salinity, water level and ENSO phases

In the past 20 years, several El Niño episodes occurred in Panama, causing major droughts across the country. These dry spells are depicted as grey shaded areas in Fig. 10. According to the Multivariate ENSO Index Version 2 (MEI.v2), from mid-2014 to early 2015 a weak El Niño episode occurred (index value of 0.4) and from mid-2015–2016 a strong to very strong El Niño episode took place (index value of 2.2). During this period, water level in Gatun Lake decreased significantly reaching 24.5 and 23.9 m above PLD in August 2015 and May 2016, respectively. The latter was the lowest water level recorded since Canal operations began in 1914 and it occurred just before the inauguration of the Neo-Panamax locks. In 2022, a very strong La Niña year (index value of −2.2), Gatun Lake registered its highest water level on record, 27.1 m in December, right at the end of the wet season. The Pearson correlation coefficient between Gatun Lake's water level and ENSO Index was −0.36 before the expansion of the Panama Canal, and after the expansion it is −0.64. This evidences the existence of an anti-correlation between water level in Gatun Lake and ENSO Index which became more pronounced after the expansion of the Panama Canal.

Fig. 11 shows a time series of Gatun Lake's weighted average salinity and water levels in the past 20 years. The Pearson correlation coefficient between Gatun Lake's monthly average salinity and water level corresponded to −0.24 and −0.34 before and after the expansion, respectively. This implies the existence of a weak anti-correlation between these two quantities, even after the expansion. Average salinity in Gatun Lake was 0.02 and 0.21 PSU before and after the expansion, respectively. Before the expansion average salinity does not show a significant ($p > 0.05$) trend, whereas after the expansion there is a statistically significant ($p < 0.05$) trend with a slope of 1.19E-03 PSU per month (Table 10). Gatun Lake's average salinity is also affected by the hydro-meteorological conditions brought by the different phases of the ENSO cycle, but its impact changed after the expansion of the Panama Canal. Before the expansion salinity during El Niño years did not show a statistically significant trend ($p > 0.05$), but during La Niña years salinity had a significant decreasing trend of −1.04E-04 PSU per month. After the expansion, Gatun Lake's average salinity has a statistically significant ($p < 0.05$) increasing trend of 6.02E-03 PSU per month, but during La Niña years, even though salinity can be seen decreasing as water level increases (Fig. 11), no statistically significant trend could be identified (Table 10). The highest average salinity in Gatun Lake was observed in June 2020 and it corresponded to 0.39 ± 0.19 PSU. This occurred one month after the lake reached its lowest level for that year (24.5 m) and right after the 2018–2020 El Niño episode (index value of 0.8). Given the increasing trend of salinity after the expansion during El Niño events and the lack of a significant trend during La Niña events, it could be interpreted that El Niño episodes affect salinity more than La Niña episodes. However, the results from a Wilcoxon rank sums test (Table 11) reveal that salinity during El Niño is not stochastically greater ($p > 0.05$) than during La Niña. This might be due to the fact that salinity peaks right after El Niño events have culminated, just as conditions are getting progressively wetter, hence higher salinity concentration actually occur at the onset of La Niña events.

Average daily salinity in the PCNC follows a similar pattern to the monthly average salinity of Gatun Lake (Fig. 12). Salinity in the PCNC peaked in October 2016, four months after the inauguration of the Neo-Panamax locks, reaching 1.29 PSU, but by January 2018 it had dropped to 0.15 PSU, reaching a value very similar to that of Gatun Lake. During the 2018–2020 El Niño, average salinity in the PCNC peaked at 0.48 PSU, one month before the lake reached its maximum water level for the season (25.7 m) in January 2020. In May 2020 when Gatun Lake reached its minimum water level for that year (24.5 m), average salinity of the PCNC rose to 0.43 PSU. Not only is this value higher than the peak average salinity of Gatun Lake (0.39 PSU), but also occurred one month sooner. During el Niño years salinity in the PCNC has a statistically significant increasing trend whereas during La Niña there is a statistically significant decreasing trend (Table 12). The data shows that PCNC's salinity is more susceptible to changes in water level than the salinity of Gatun Lake as a whole, but this might not be the case since the variable observed could be due to the fact that there is considerable more data available for the PCNC than for the Gatun Lake average salinity calculation.

4. Discussion

Before the expansion of the Panama Canal, average salinity in Gatun Lake was less than 0.05 PSU. However, this was not uniform throughout the lake. Average salinity at locations in the southwestern shore of Gatun Lake (ARN, HUM, RAI) was well below 0.05 PSU (see Table 5). In contrast, in the PCNC (which traverses Gatun Lake) salinity concentration before the expansion was 0.11, 0.08 and 0.09 PSU close to Bruja/BC Islands, in Culebra Cut, and near Pedro Miguel locks, respectively (see Table 7). Also, salinity in Gatun Lake before the expansion was the highest near Gatun locks in the Atlantic, averaging 0.14 PSU but occasionally surpassing the 0.42 PSU threshold (see Fig. 6c). However, telemetry buoys in the PCNC, including BOYA-D located near Gatun locks, were installed during 2015 (a very dry El Niño year) and thus the average pre-expansion salinity calculated for these locations is likely to be overestimating the actual pre-expansion conditions. For instance the monthly data shows that at locations TMR near Pedro Miguel locks and DC1 in Culebra Cut, salinity pre-expansion was on average 0.06 and 0.05 PSU, respectively (see Table 5).

After the expansion, average salinity of Gatun Lake rose to 0.21 PSU which represented an increase of over four times when compared to pre-expansion conditions. Nevertheless, this increase was not uniformly distributed across the lake. Near Gatun locks in the Atlantic, salinity tripled and reached 0.44 PSU after the expansion (see Table 8). Similarly, average salinity at TMR, located near the Pedro Miguel locks in the Pacific, increased 3.5 times reaching 0.27 PSU after the expansion (see Table 5). Average salinity at BCI,

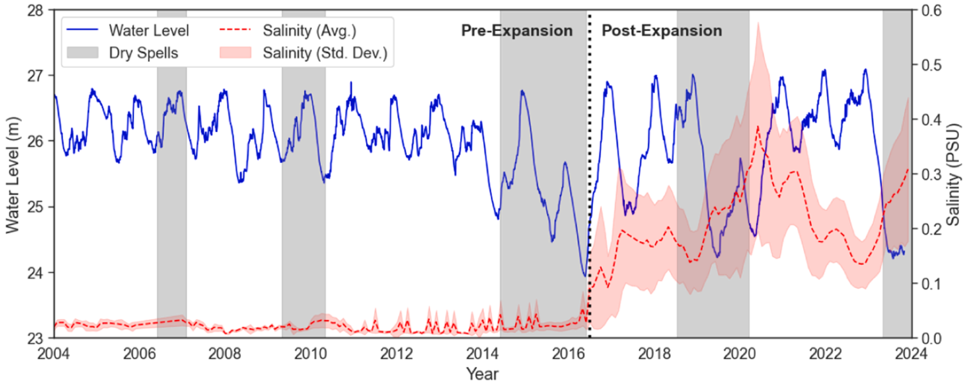

Fig. 11. Average daily water level and monthly weighted average salinity of Gatun Lake. The time spans shaded in grey correspond to the most important dry spells that have occurred in the past 10 years. The vertical dotted line indicates the inauguration date of the Neo-Panamax Locks (26 June 2016).

Table 10
Mann-Kendall trends and score for Gatun Lake's weighted average salinity during different phases of the ENSO cycle before and after the expansion of the Panama Canal.

Period	ENSO Phase	Trend	p-value	Z-value	Mann-Kendall Score	Theil-Sen Slope
Pre-Expansion	All	No trend	6.23E−02	−1.86E+ 00	−1.07E+ 03	−3.50E−05
	El Niño	No trend	7.15E−01	3.66E−01	5.00E+ 01	1.80E−05
	La Niña	Decreasing	3.96E−03	−2.88E+ 00	−8.14E+ 02	−1.04E−04
Post-Expansion	All	Increasing	7.00E−05	3.98E+ 00	1.16E+ 03	1.19E−03
	El Niño	Increasing	0.00E+ 00	5.80E+ 00	3.10E+ 02	6.02E−03
	La Niña	No trend	3.13E−01	1.01E+ 00	1.67E+ 02	4.01E−04

Table 11
Statistical results of Wilcoxon rank sum tests on Gatun Lake's average salinity during El Niño and La Niña pre- and post-expansion.

Period	Wilcoxon's p-value	Mean Salinity		
		El Niño	La Niña	Difference
Pre-Expansion	6.20E−05	0.024	0.018	0.005
Post-Expansion	7.38E−02*	0.217	0.202	0.015

* $p > 0.05$

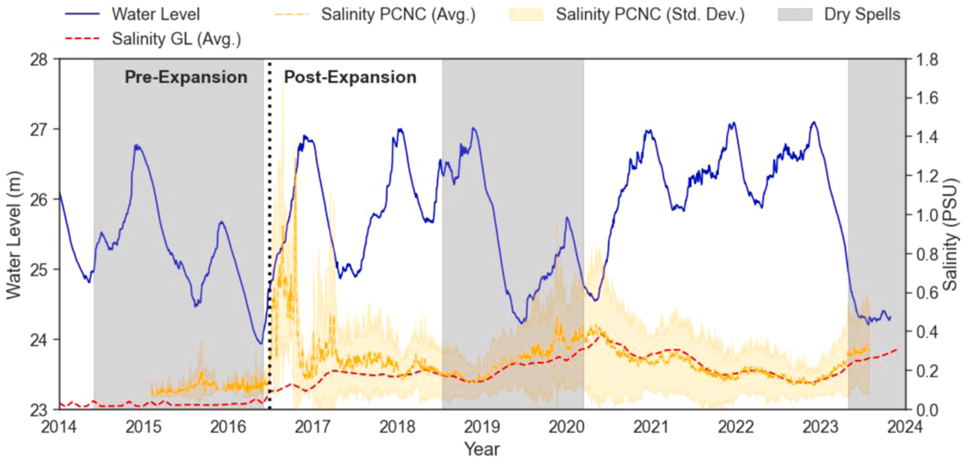

Fig. 12. Average daily salinity of the PCNC and average daily water level and monthly weighted average salinity of Gatun Lake (GL). The time spans shaded in grey correspond to the most important dry spells that have occurred in the past 10 years. The vertical dotted line indicates the inauguration date of the Neo-Panamax Locks (26 June 2016).

Table 12
Mann-Kendall trends and score for daily average salinity in the PCNC salinity after the expansion during different phases of the ENSO cycle.

ENSO Phase	Trend	p-value	Z-value	Mann-Kendall Score	Theil-Sen Slope
All	Decreasing	0.00E+ 00	−1.60E+ 01	−7.04E+ 05	−3.30E−05
El Niño	Increasing	0.00E+ 00	2.62E+ 01	1.64E+ 05	3.31E−04
La Niña	Decreasing	0.00E+ 00	−2.76E+ 01	−7.54E+ 05	−7.90E−05

located in the PCNC, went from 0.04 to 0.21 PSU before and after the expansion, respectively, which is an increment of a little over five times (see Table 5). Interestingly, salinity at BAT, located at near the shore of Gatun Lake 11 km southwest from Agua Clara locks, increased 7 times after the expansion going from 0.04 to 0.29 PSU before and after the expansion, respectively. In contrast, salinity in Culebra Cut only increased by roughly 77 % after the expansion reaching 0.09 PSU (see Table 8). The uneven increase of salinity at different locations within Gatun Lake is likely due to an irregular dispersion of the salt mass than enters through the Neo-Panamax locks, especially in the Atlantic side of the Canal where the locks open directly to the main body of the lake. Nevertheless, discovering and understanding the driving forces behind the spatial distribution of salinity in Gatun Lake after the expansion would require the development of a hydrodynamic model.

After the expansion, salinity in Gatun Lake showed a statistically significant increasing trend (see Table 10). However, this increase in salinity after the expansion did not occur gradually or at a constant rate. Right after the expansion there was a sharp increase in salinity concentration in the Gatun Lake and the PCNC, but it then decreased at the end of 2016 and beginning of 2017, before starting to rise again in 2019 (see Figs. 8, 11 and 12). The rapidly changing hydrometeorological conditions, from a strong El Niño in 2016 (index value of 1.2) to a moderate La Niña (index value of −0.5) could have played a major role on the initial spike in salinity right after the expansion and its subsequent decrease a couple of months later. However, salinity after the expansion during El Niño events is not stochastically greater ($p > 0.05$) than during La Niña events (see Table 11). In addition, during successive dry periods brought by the El Niño events of 2018–2020 and 2023, salinity in Gatun Lake showed a statistically significant increasing trend, but no trend could be identified for the 2017 and 2021–2022 La Niña events (see Table 10). This implies that salinity is mostly affected during the El Niño phase of the ENSO cycle where it increases and during La Niña salinity is overall maintained.

The Panama Canal is a heavily controlled system from the hydrological point of view, and thus Gatun Lake’s water level, and consequently its salinity, not only depend on climatic or hydrometeorological conditions but they are also subjected to the operation of the different hydraulic structures present in the system, most notably the locks. The inauguration of the expanded canal coincided with the end of a strong El Niño event and since then there have been two additional El Niño events. However, this study does not consider the changes in water demand that occurred due to the operation of the new locks and an increase of vessel transit through the Panama Canal after the expansion. Therefore, based on available data for current analysis it is not possible to isolate the effect of the ENSO cycle on Gatun Lake’s water level and its average salinity. Further analysis on correlations with climatological covariates was not explored, because of the highly controlled nature of the system. In order to fully comprehend the causes of the observed salinity patterns it is imperative to explore the combined and individual impact of climate, vessel transit, and lock operations either through data-driven or physically-based modelling approaches.

According to Panamanian regulations, the permitted limit for drinking water purposes in terms of salinity is 250 mg/l of chloride concentration (MICI, 2019), which corresponds to approximately 0.45 PSU. Most intakes for drinking water treatment plants are located at the edges of Gatun Lake (TAC, TAS, TME, TMH) or at Gamboa (DC1) where average salinity has remained relatively low (<0.2 PSU) even after the expansion. Maximum salinity at these locations has also remained below the permitted limit for drinking water (see Table 5), which suggest that thus far these locations have been relatively shielded from saltwater intrusion. Nevertheless, it is unclear how these locations are going to be impacted in the future and thus rigorous monitoring needs to be continued. In contrast, the water intake at Paraíso near Pedro Miguel, which is monitored monthly at TMR (see Fig. 2a) and continuously with BOYA-209 (see Fig. 2c), has experienced salinity concentrations that have occasionally surpassed the permitted limit. For instance, at BOYA-209 located near Pedro Miguel, salinity reached 0.48, 0.52 and 0.64 PSU in October 2016, April 2020 and May 2023, respectively (see Fig. 8). Even though raw water from the Paraíso water intake gets mixed with raw water from the Gamboa water intake before entering the Miraflores drinking water treatment plant, ACP is in the process of relocating the Paraíso water intake in order to reduce the salinity of the raw water entering the plant (ACP, 2024). This is a clear indication that saltwater intrusion through Neo-Panamax locks is already affecting water supply to Panama City.

Apart from the direct impact to drinking water supply at locations near the Neo-Panamax locks, the rapid salinization of Gatun Lake could also be affecting its ecosystem and biodiversity. After the expansion, salinity 5–8 km away from the Neo-Panamax locks has been above the US EPA’s recommended chronic salinity threshold for freshwater ecosystems (0.42 PSU) 15–60 % of the time near Agua Clara and 13–80 % of the time near Cocolí (see Fig. 6). In addition, an ever-decreasing proportion of freshwater species has been observed inhabiting Gatun Lake since the inauguration of the Neo-Panamax locks in June 2016 (Schreiber et al., 2023). This suggests that Gatun Lake’s aquatic ecosystem and biodiversity might be at risk of experiencing chronic damages. Nevertheless, it is unclear whether the EPA’s threshold applies to a tropical aquatic ecosystem such as Gatun Lake or if the observed trend in population decrease of freshwater species is evidence of a long-term impairment of ecosystem functioning given that it has been less than 10 years since the inauguration of the Neo-Panamax locks. Therefore, in order to assess the environmental impact of saltwater intrusion into Gatun Lake, it would be necessary to carry out a detailed study that considers the specific conditions of the lake and its ecosystem.

According to Wijsman (2013) the salt mass load to Gatun Lake due to the operation of the Neo-Panamax locks was estimated to be between 500 and 1500 tons per day, depending on the use of the WSBs. The use of the WSBs was a known issue even before the expansion. Salinity in the water saving basins tends to be higher than in their adjacent lock chamber, and thus when used, salt water intrusion to Gatun Lake increases (Wijsman, 2013). Since their inauguration, the operation of the Neo-Panamax locks has been continuously evaluated and improved in order to mitigate saltwater intrusion. Apart from reducing the use of the WSBs, operational measures such as flushing of the lock chambers to reduce their salinity and decreasing the time that the locks gates remain open during a lockage have been implemented. According to ACP specialists, these operational measures have been effective in reducing saltwater intrusion through the locks and maintaining Gatun Lake's salinity below the required thresholds as much as possible.

5. Conclusion

This study characterizes the spatiotemporal distribution of salinity in Gatun Lake and the PCNC in the last 20 years and it also attempts to describe Gatun Lake's salinity variations in relation to the different phases of the ENSO cycle. The results from this study reveal that the spatiotemporal distribution of salinity within Gatun Lake has significantly changed after the expansion of the Panama Canal. Before the expansion, salinity throughout Gatun Lake was on average < 0.05 PSU with salinity in the PCNC being ~ 0.1 PSU and near Gatun locks being 0.14 PSU. After the expansion, average salinity in Gatun Lake is 0.21 PSU, which represents an increase of over four times with respect to pre-expansion conditions. The highest salinity after the expansion has been observed in the proximity of the Neo-Panamax locks averaging 0.6 and 0.5 PSU near Agua Clara and Cocolí, respectively, whereas in the Culebra Cut it has been observed to be lowest at about 0.1 PSU. Despites Gatun Lake's salinity showcasing a statistically significant increasing trend after the expansion, its behaviour in time has not been constant but rather it has been observed to vary with the lake's water level with a weak anti-correlation. Gatun Lake's average salinity reached its maximum value of 0.39 ± 0.19 PSU in June 2020, one month after its lowest water level of the season (24.5 m) right at the end of the 2018–2020 El Niño episode. Average salinity in Gatun Lake presents an increasing trend during El Niño episodes, but no significant trend for salinity could be identified during La Niña years.

The strength of the data analysis presented in this paper is limited to the quantity and quality of the available data. For most of the pre-expansion period, salinity measurements were only available on a monthly timescale at a handful of locations within Gatun Lake and no measurements were carried out in the vicinity of Gatun Locks in the Atlantic. Despites sensors were deployed and more salinity measurements were carried out in the years leading to the expansion, measurements with high spatial resolution (salinity profiles) have a low temporal resolution and data with high temporal resolution (telemetry buoys) are only available at a handful of locations within the PCNC. Therefore, a statistical analysis of the scarce salinity data available will not capture the complexity of the salinity distribution in Gatun Lake, before the expansion, nor does it offer a concrete explanation or mechanistic understanding of the underlying processes that generated the observed data. Most notably, no external factors other than the ENSO Index were evaluated when trying to explain variations in Gatun Lake's water level and consequently its salinity. The Panama Canal is a highly controlled system and thus Gatun Lake's water level and average salinity do not only depend on the lake's hydrodynamics and hydrometeorological conditions but they are also heavily dependent on the operation of the locks. Therefore, future research should focus on simulating climate change induced hydrometeorological conditions and different lock operation strategies in order to understand the individual response of salinity to these factors as well as their interdependence. Further studies should also focus on assessing how the use of the WSBs impacts the magnitude of salt mass load entering Gatun Lake due to the operation of the Neo-Panamax locks.

The increase in Gatun Lake's salinity after the expansion of the Panama Canal has put into question the long-term sustainability of its freshwater ecosystem and its reliability as a source of potable water for many Panamanians. Even though mitigation strategies, such as the relocation of water intakes for drinking water treatment plants and the modification of lock operations, have been implemented, the long-term impact of these solutions is uncertain. Additionally, climate variable will hinder the efficient operation of the Panama Canal in terms of maximizing revenue and minimizing environmental and human impacts.

In view of all of the above, it is important to involve all stakeholders of the ACP, as well as of the general public in collaborating and participating in the design and decision-making about the way to operate the Panama Canal such that there will be expected economic benefits for the country, while mitigating the risks and undesired consequences, especially in the face of an uncertain future.

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CRediT authorship contribution statement

Anguizola Karen: Writing – review & editing, Validation, Resources. **Matos Raúl:** Validation, Resources. **Domínguez Iván:** Writing – review & editing, Validation, Methodology, Investigation, Data curation. **Lu Carlos:** Writing – review & editing, Validation, Resources, Investigation, Data curation, Formal analysis. **Popescu Ioana:** Writing – review & editing, Supervision. **Castrellón María Gabriela:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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