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Characterization of Gatun Lake's hydrodynamic behaviour and water quality

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Abstract

Gatun Lake, located in the Panama Canal Watershed (PCW), is the main source of freshwater for the Canal's operations and it provides drinking water for nearly 600,000 people, which represents roughly 15% of the country's population. 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. However, since the completion of the Canal's expansion project and inauguration of the Neo-Panamax locks in 2016, salinity in the lake has been increasing at a faster pace. The progressive salinization of this water body is not only a concern from the perspective of drinking water supply and human health, but for the lake's biodiversity as well. In order to understand the magnitude of this issue, evaluate the impact of climate change and design effective mitigation and management strategies, robust modelling tools are required. Nevertheless, these tools often require high volumes of high-quality data that are not always readily available. This paper illustrates the characterization of Gatun Lake's hydrodynamic behaviour and water quality condition using a numerical model built with Delft3D and publicly available open data, which includes bathymetry from GEBCO and hydrodynamic data from ACP's AQUARIUS web portal. Although further refinement of the model is still required, overall, it was demonstrated that reasonably good results can be obtained through a model built using publicly available open data.

Keywords: Panama Canal; Gatun Lake; Saltwater Intrusion; Hydrodynamic Modelling; Delft3D.

1. INTRODUCTION

The construction of the Panama Canal from 1904 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. Geographical position of Gatun lake is represented in Figure 1a. Apart from being the main source of water for the operation of the Panama Canal, Gatun Lake is the source of freshwater for nearly 600,000 people which corresponds to roughly 15% of Panama's population. Since its creation, Gatun Lake has slowly been transitioning from a swamp environment to a more saline-governed ecosystem due to the operation of the Panama Canal and other anthropogenic activities in the Panama Canal Watershed (PCW) (Salgado et al., 2020). However, since the completion of the Canal's expansion project and inauguration of the Neo-Panamax locks in 2016, salinity in the lake rapidly increased from its historical average of ~0.1 ppt and surpassed the 0.45 ppt mark in 2020, which is the limit for fresh drinking water according to regulations in Panama. 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 gradual salinization of this water body is not only a concern from the perspective of drinking water supply and human health, but for fish biodiversity as well. The current salinity levels have already made it possible for some non-native marine species to inhabit the lake (Schreiber et al., 2021) and if salinity keeps increasing, a permanent migration passage between both oceans could be established for fish, macroinvertebrates, and other marine species (Salgado et al., 2020). In order to understand salinity intrusion patterns, assess its impacts on biodiversity, evaluate the effects of climate change, and design effective mitigation and management strategies, a decision support system based on a robust modelling framework is required (Kaushal et al., 2021; Szklarek et al., 2022). The development of such modelling tools requires high volumes of high-quality data which is often not readily available. In the case of Gatun Lake, the Panama Canal Authority (ACP) routinely collects data both on water quantity and quality but only some of it is publicly available. Other important information such as detailed topography and bathymetry maps are not publicly available as well.

Despites the lack of in-situ data, models for saltwater intrusion characterization in estuaries and coastal lagoons can be built and/or enhanced by using globally available data sets, especially for offshore boundary conditions. For instance, Pereira et al. (2022) incorporated bathymetry data from the General Bathymetric Chart of the Oceans (GEBCO), ocean parameters derived from the Atlantic-Iberian Biscay Irish-Ocean Physics Reanalysis product and meteorological variables from the ERA-Interim atmospheric reanalysis model in their Delft3D simulation of two estuaries in northwest Portugal. Bitencourt et al. (2020) used salinity and temperature data from the Hybrid Coordinate Ocean Model (HYCOM), offshore tides and velocity fields from the OSU Tidal Inversion System (OTIS) and wind data from the European Centre for Medium-Range Weather Forecast (ECMWF) as initial and boundary conditions of their TELEMAC-3D model of a costal lagoon in southern Brazil. Similarly, Eslami et al. (2019)used offshore wind data from the Climate Forecast System Reanalysis (CSFR) and offshore tidal information from the TOPEX/Poseidon global inverse tide model (TPXO 8.0) in their 1D-2DH coupled numerical model of the Mekong Delta in Vietnam.

This paper illustrates the characterization of Gatun Lake's hydrodynamic behaviour and water quality condition using a numerical model built with publicly available open data. Our goal is to demonstrate the usefulness of publicly available open datasets for building hydrodynamic models by comparing modelling results with available in-situ measurements. In the following sections a brief description of the study area is presented, then the data sources and the model development procedure are detailed, after that results from the model are presented and discussed and finally some conclusions are offered.

2. STUDY AREA

Gatun lake (Figure 1a), located within the Panama Canal Watershed (PCW), has an area of 425 km^2 and the ability to store 5.2 km^3 of water. It has a complex bathymetry with a mean depth along the navigation channel of the Panama Canal varying from 16.77 to 17.98 m, as well as deeper areas in the northwest, and shallow basins near its southwester borders. Given its length to depth ratio, it can be classified as a shallow water system. The average water elevation in Gatun Lake ranges from 24.01 to 26.82 metres above main see level, thus, a series of locks are in place to raise and lower the vessels to and from the lake while transiting the Panama Canal (Rabelo et al., 2012). The original system of locks completed in 1914 consists of Gatun Locks on the Caribbean/Atlantic side and Miraflores and Pedro Miguel Locks on the Pacific side (Figure 1b). The new set of locks, inaugurated in 2016, consist of the Agua Clara Locks in the Caribbean/Atlantic side and the Cocolí Locks in the Pacific side. These new locks, called Neo-Panamax, are nearly three times larger than the original ones, called Panamax, and operate using water saving basins (Figure 1c). There are no pumps involved in the operation of either the Panamax or the Neo-Panamax locks since water transfers between chambers are accomplished purely by gravity (Wijsman, 2013).

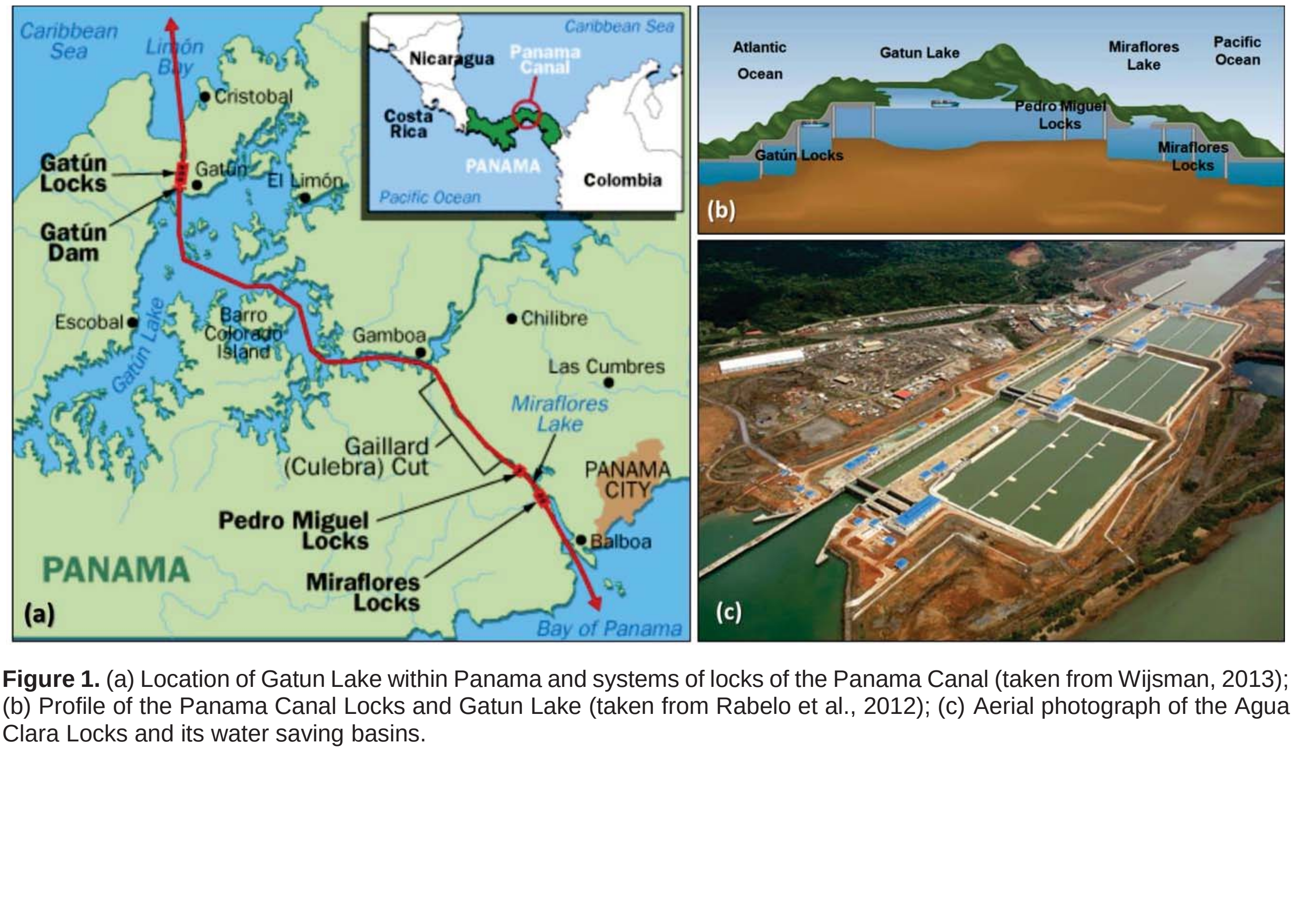

Figure 1. (a) Location of Gatun Lake within Panama and systems of locks of the Panama Canal (taken from Wijsman, 2013); (b) Profile of the Panama Canal Locks and Gatun Lake (taken from Rabelo et al., 2012); (c) Aerial photograph of the Agua Clara Locks and its water saving basins.

The research carried out to understand the hydrodynamic behaviour of Gatun Lake is limited. The main drivers for the lake's hydrodynamic movement are the water inflows and outflows at the locks in the Pacific side and the Atlantic side, followed by inputs from Alajuela Lake released through Madden Dam that reach Gatun Lake at Gamboa (Figure 1a). In addition, there are several other lateral inflows from rivers within the PCW which provide smaller discharges and have a lesser impact on the lake's hydrodynamic behaviour as compared to the aforementioned water inflows.

3. MATERIALS AND METHODS

3.1. Data Sources

Detailed bathymetry of Gatun Lake is not publicly available. Therefore, gridded bathymetry data from the GEBCO_2022 (GEBCO Compilation Group, 2022) was retrieved as it can be seen in Figure 2a. The General Bathymetric Chart of the Oceans (GEBCO) is a global terrain model for ocean and land which, in its most current version, GEBCO_2022, provides elevation data in meters in a grid with a resolution of 15 arc-seconds. For the study area, this roughly corresponds to a raster of cell size 458 by 458 meters.

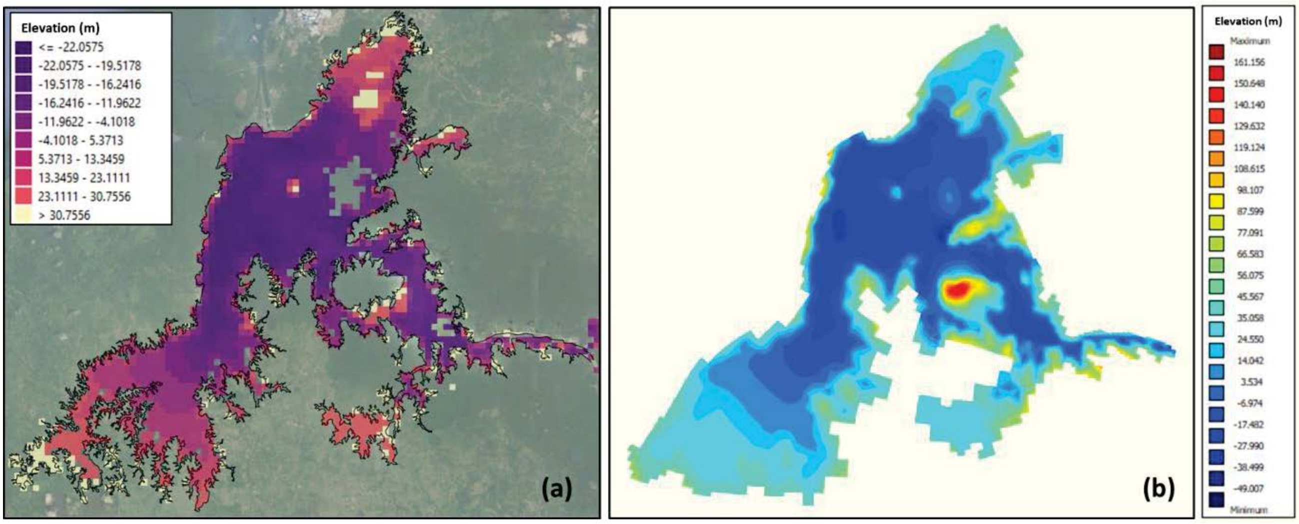

Figure 2. (a) Bathymetry of Gatun Lake retrieved from the GEBCO_2022 global dataset. (b) Interpolation of the GEBCO bathymetry using the QUICKIN tool from Delft3D.

The Water Resourses Division of the Panama Canal Authority (ACP) routinely collects meteorological and hydrological data at several locations within the Panama Canal Watershed (PCW). At some locations data has been collected since the beginning of the 20th century when the US Army Corps of Engineers started the preliminary studies for the construction of the Panama Canal. Until very recently, these data were not publicly available and could only be obtained after submitting a request to ACP. Nowadays, it is possible to visualize and download all ACP's meteorological and hydrological through their AQUARIUS web portal (Canal de Panamá, 2023). For the purposes of this modelling exercise, Gatun Lake's water level and discharge data were retrieved from ACP's AQUARIUS web portal. Water level of Gatun Lake is recorded every 15 minutes at four locations, and for the study period, it nearly does not vary from one location to the other (Figure 3a). The net water discharges through the Atlantic/Caribbean Locks (Agua Clara and Gatun) appears to be consistent over time, only increasing slightly for the Agua Clara Locks at the second half of 2020, however, releases through Madden Dam show great variability (Figure 3b).

ACP also regularly measures several water quality parameters at various locations within the PCW as part of their monthly water quality sampling and monitoring campaigns. These data are included in ACP's yearly water quality reports in pdf format. In addition, the Smithsonian Tropical Research Institute (STRI) recently published this data in tabular format through their website (Paton & Equipo de Análisis de Calidad de Agua, 2022). Salinity and temperature are measured at 14 locations within Gatun Lake (Figure 4). Both salinity and temperature follow a relatively stable seasonal pattern, but salinity in 2020 rose above 0.45 ppt which is the permitted limit for freshwater for drinking purposes as established by Panamanian regulations (Figure 4a).

STRI has also carried out continuous in-situ salinity and temperature measurements since 2019 at two locations within Gatun Lake: Barro Colorado Island (BCI) and Gamboa Dock (GBD), respectively (Figure 5). At both locations, readings are recorded every 15 minutes using HOBO Conductivity Loggers that were deployed at two depths, 1 m below the surface and approximately 1.5 m from the lake's bottom, respectively. In addition, daily measurements have been carried out manually to corroborate the sensor readings.

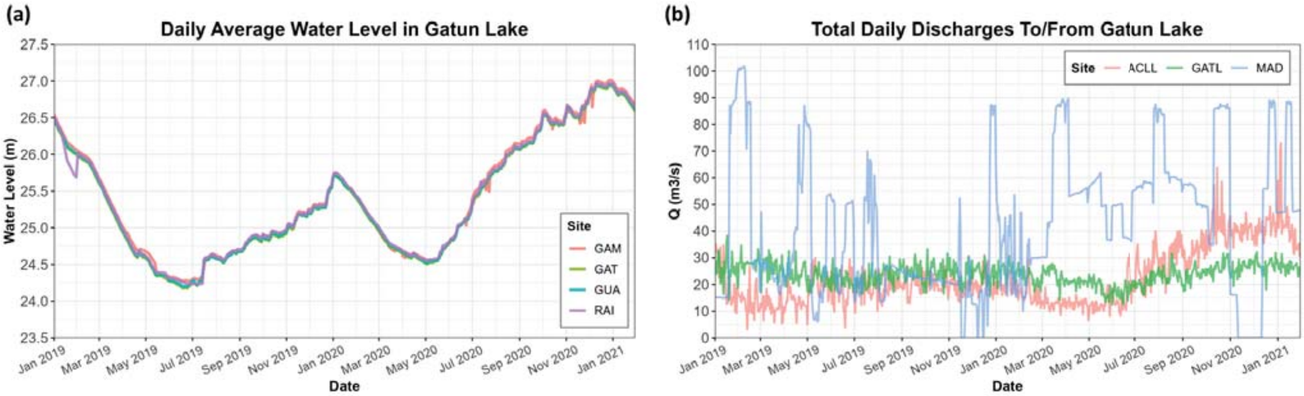

Figure 3. (a) Daily average water level of Gatun Lake measured at four locations: Gamboa (GAM), Gatun (GAT), Guacha (GUA) and Las Raíces (RAI). (b) Total daily water discharges from Gatun Lake through the Agua Clara (ACLL) and Gatun (GATL) locks and releases from the Madden Dam (DAM) which enter Gatun Lake through the Chagres River.

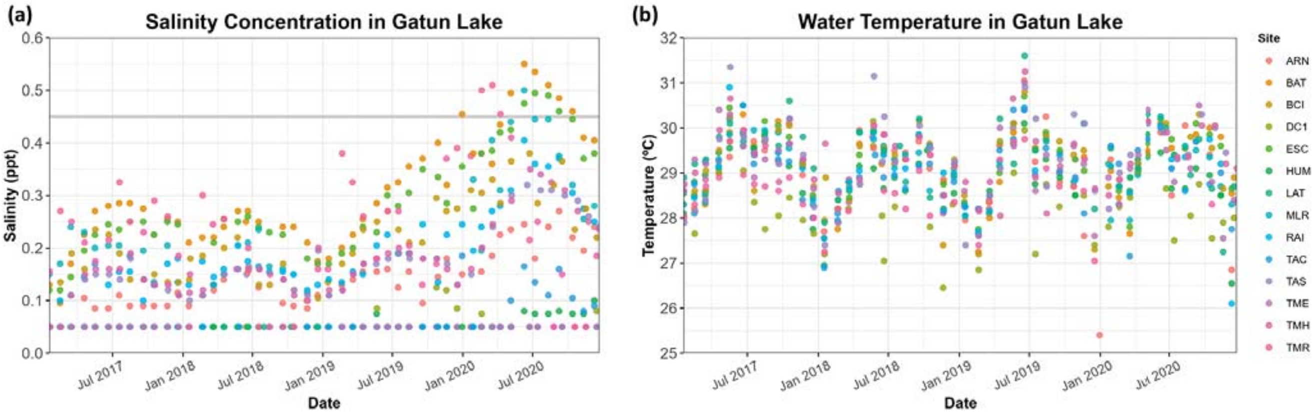

Figure 4. (a) Salinity concentration and (b) water temperature in Gatun Lake measured by ACP at 14 locations. The salinity limit for drinking water is 0.45 ppt, as established by Panamanian regulations.

3.2. Model Development

A 3D hydrodynamic model for Gatun Lake was built using the Delft3D-FLOW software by Deltares. The water quality constituents explored with this model are salinity and temperature. The computational domain spans the entirety of Gatun Lake from Gamboa at the end of the Gaillard/Culebra cut to the locks in the Atlantic/Caribbean entrance of the Panama Canal. The computational domain was discretized using a curvilinear grid built with the RGFGRID tool included in the Delft3D modelling suite. The horizontal grid has 2,676 cells that vary in size from ~100 to ~1000 m, with the smaller cells being located following the navigation channel of the Panama Canal (Figure 5a). The model has 5 layers, with layers being thinner near the surface and coarser near the bottom (Figure 5b). The simulation period spans from January 1st 2019 to December 31st 2020. Due to the relatively large cell size, in order to keep the Courant number low, a time step of 1 minute was chosen. The bathymetry for the hydrodynamic model was interpolated from the GEBCO_2022 raster and adjusted to the computational grid using the QUICKIN tool from Delft3D (Figure 2b).

The model was initialized by defining a constant water level, salinity and temperature corresponding to 26 m, 0.05 ppt and 28 degrees Celsius, respectively. Open boundary conditions were defined at Gatun Entrance (Figure 5c) and Culebra Cut (Figure 5d). The Gatun and Agua Clara locks are operated roughly every six hours when a batch of vessels is either going into the lake or going out to the ocean. Also, assuming that the salinity concentration difference between the lake and the third lock chamber is ~0.3 ppt, the velocity of the salt wedge intruding the lake is ~0.1 m/s. Therefore, the flow conditions at Gatun Entrance were approximated using a harmonic boundary condition with a frequency and amplitude of 15 deg/h and 0.1 m/s, respectively. The transport conditions at this boundary were specified based on assumed values varying linearly with depth and constant in time (Table 1). At the Culebra Cut open boundary, water level, salinity and temperature were specified using values measured at ACP's GAM/DC1 buoy located at the confluence of Gaillard/Culebra Cut and the Chagres River at Gamboa (Figure 5d). For water level, daily average values were used and for salinity and temperature, monthly values were used. In addition to open boundary conditions for flow (current) and water level, discharge locations were defined in the northern boundary of the computational domain to represent the total daily water lost through the operation of the Agua Clara (ACLL) and Gatun (GATL) locks, and near the southern boundary of the computational domain to represent inflows from the Chagres River. The inflows for Chagres River were calculated by performing river routing of water releases from Madden Dam (MAD) located 16 km upstream from Gamboa. These discharges were specified as being uniformly distributed across all model layers and their corresponding transport conditions were specified as constants values through time (Table 1).

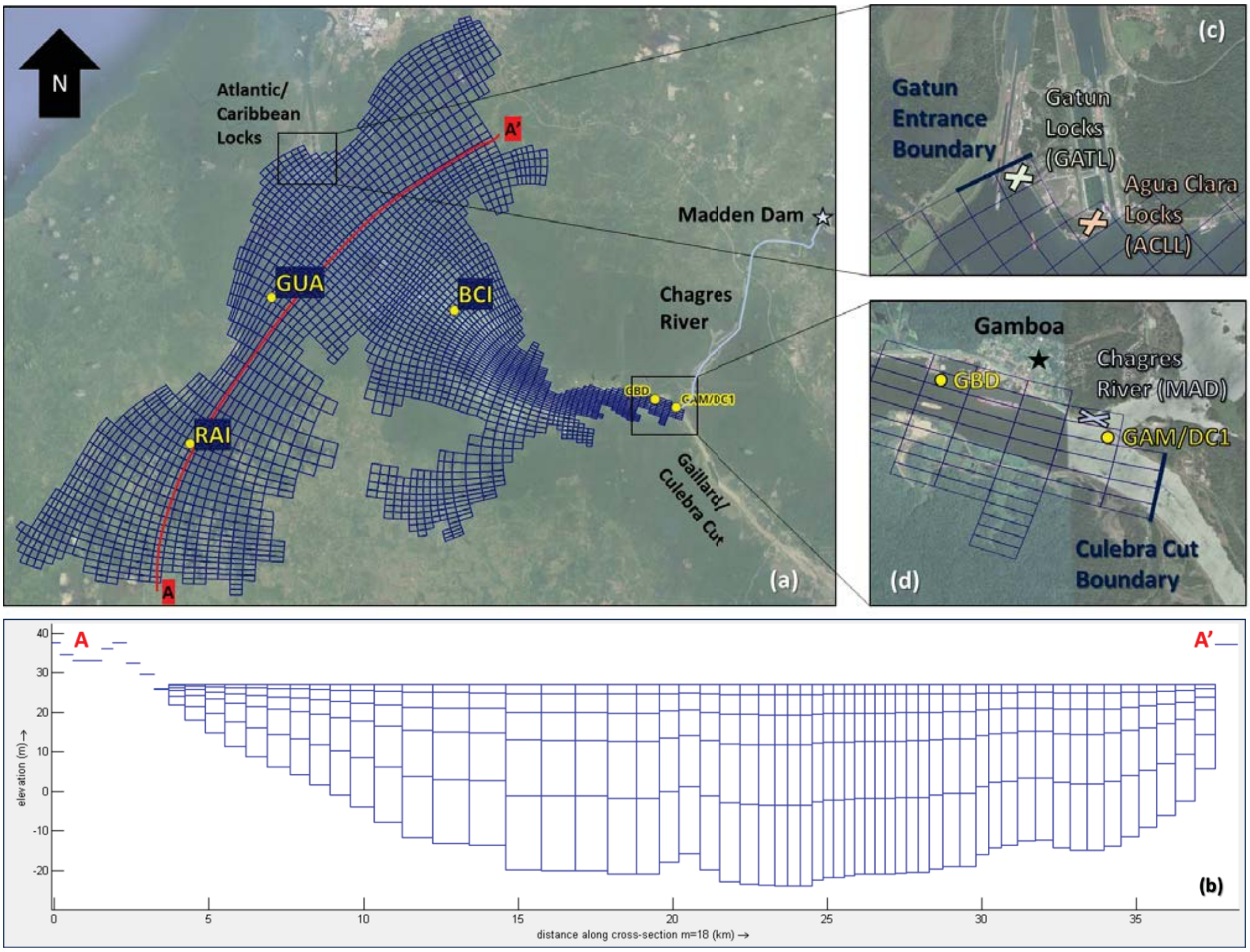

Figure 5. (a) Curvilinear grid for Gatun Lake's hydrodynamical model and monitoring locations. (b) Cross-section through the A-A' line displaying vertical grid distribution. (c) Location of the Gatun Entrance open boundary and water discharges from Gatun (GATL) and Agua Clara (ACLL) locks. (d) Location of the Culebra Cut open boundary condition and Chagres River inflows calculated by routing releases from Madden Dam (MAD) located 16 km upstream Gatun Lake.

Table 1. Salinity and temperature assigned to the Gatun Entrance open boundary condition and the discharges from the Gatun and Agua Clara locks and Chagres River.

	Gatun Entrance Surface	Gatun Entrance Bottom	Lock Discharges	Chagres River Discharge
Salinity (ppt)	0.10	0.30	0.05	0.00
Temperature (◦C)	28.0	26.0	28.0	28.0

To test the accuracy of the model, simulated water level, temperature and salinity were compared with in-situ measurements by ACP and STRI, respectively. Water levels were compared to measurements by ACP taken at Las Raices (RAI) and Guacha (GUA) whereas salinity and temperature were compared to automated measurements by STRI at Barro Colorado Island (BCI) and Gamboa Dock (GBD), respectively (Figure 5a). At each location and for each parameter, goodness of fit metrics such as mean absolute error (MAE), root-mean-squared error (RMSE), Kling-Gupta efficiency (KGE) and Nash-Sutcliffe efficiency (NSE) were calculated using the R package *hydroGOF* (Zambrano-Bigiarini, 2020).

4. RESULTS AND DISCUSSION

4.1. Hydrodynamics

The model simulates water level fluctuations in Gatun Lake extremely well. The RMSE for GUA and RAI locations are 0.04 and 0.06 metres respectively and NSE is 1 and 0.99 for both locations, respectively (Figure 6). This indicated that the boundary conditions chosen are able to represent the hydrodynamics of the study area. However, the excellent fit between observed and simulated water levels should not come as a surprise, since water levels across the lake are consistent then specifying water level as a boundary condition will result in accurate water levels simulated across the entire computational domain. With respect to water flow in Gatun Lake, the depth-averaged water velocity is slightly higher in the middle of the lake/reservoir (Figure 7). This indicates that inflows from Chagres River follow the course of its old riverbed which corresponds to the Panama Canal navigation channel.

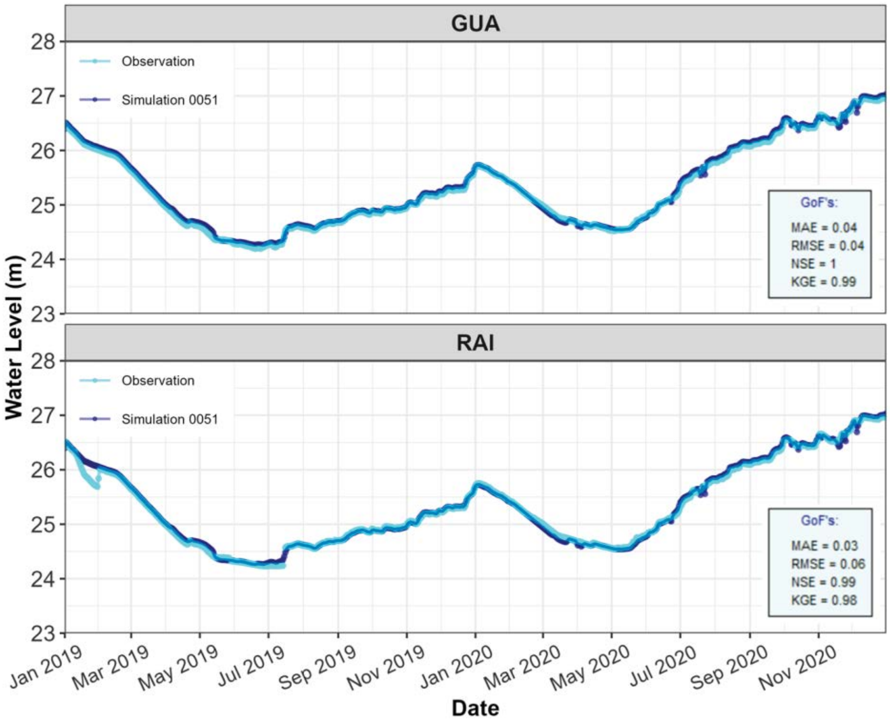

Figure 6. Simulated and observed water level in Gatun Lake at Guacha (GUA) and Las Raices (RAI).

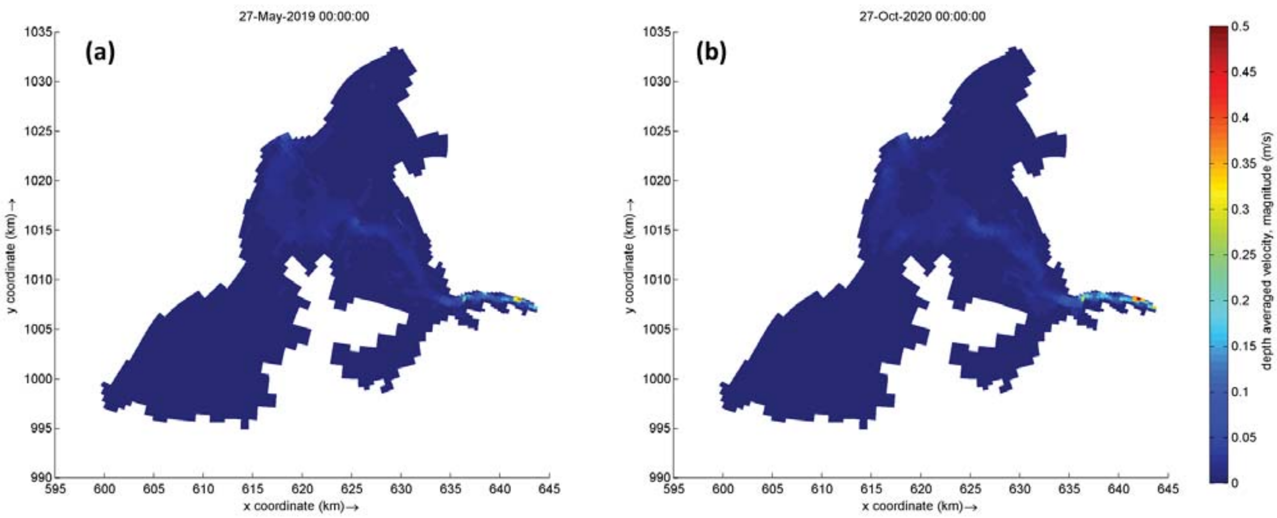

Figure 7. Simulated depth-averaged velocity in Gatun Lake for (a) May 27th, 2019 and (b) October 20th, 2020.

4.2. Water Quality

The model is able to reproduce salinity and temperature processes at Gamboa Dock (GBD) with more accuracy than at Barro Colorado Island (BCI). The RMSE for simulated temperature at BCI and GBD is 2.64 and 1.29 degrees Celsius, respectively (Figure 8a). Similarly, the RMSE for simulated salinity at BCI and GBD is 0.12 and 0.04 ppt, respectively (Figure 8b). Since, Gamboa Dock is located close to the Culebra Cut boundary condition, whereas Barro Colorado Island is located in the middle of the lake, it was expected to obtain more accurate results near the boundary condition than further in within the lake. This indicates that transport and mixing processes for salinity and temperature are not well represented by the model and other drivers or processes such as wind and evaporation need to be considered.

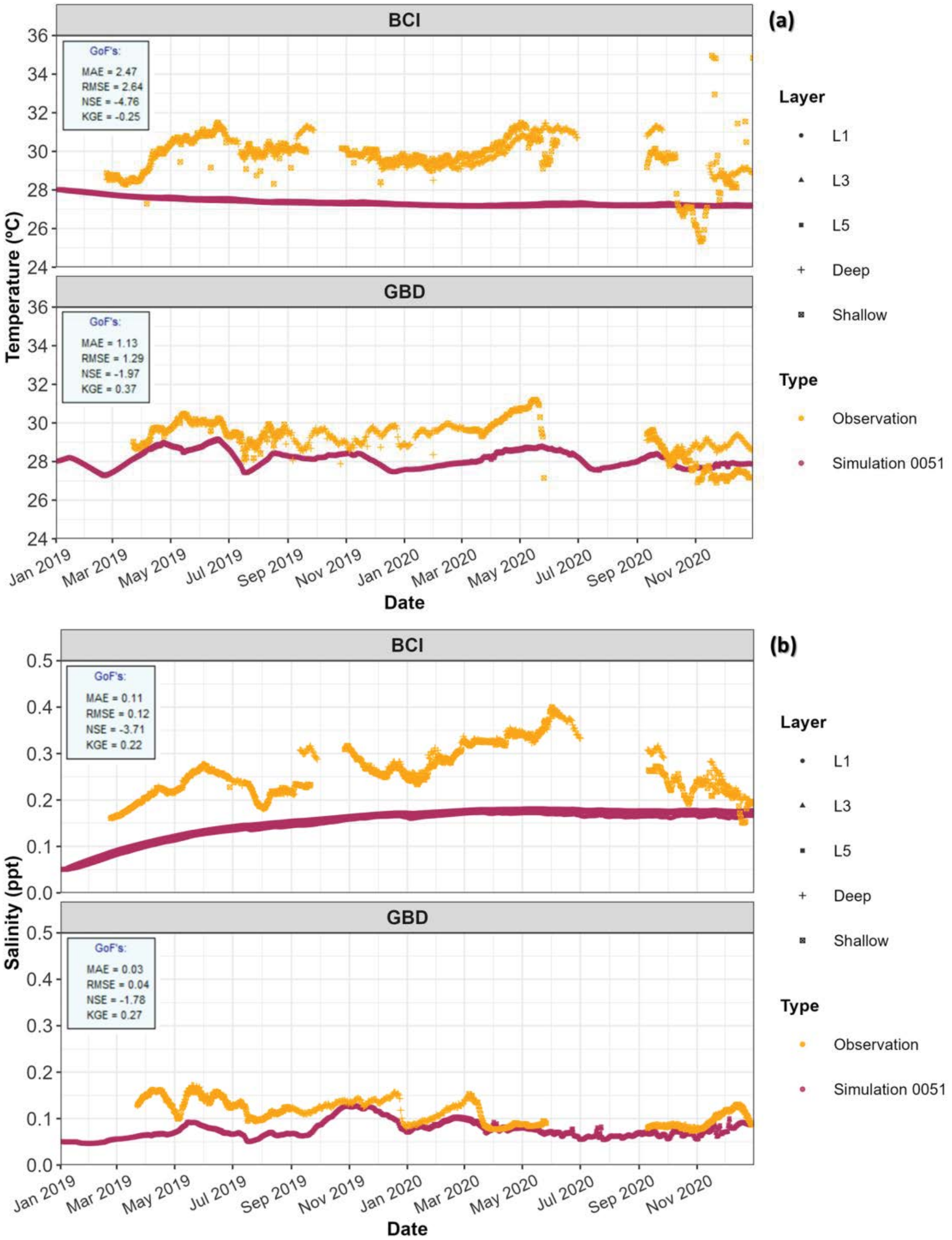

Figure 8. Simulated and observed (a) temperature and (b) salinity at Barro Colorado Island (BCI) and Gamboa Dock (GBD). For the simulated values, values from Layers 1, 3 and 5 of the model are shown whereas for observed values measurements at deep and shallow depths are shown. Goodness of fit metrics (GoFs) were calculated using depth-averaged values.

5. CONCLUSIONS

This paper describes the characterization of Gatun Lake's hydrodynamic behaviour and water quality condition using a numerical model built with open data. A Delth3D model was built using bathymetric data from GEBCO and water quality and hydrological data from ACP's AQUARIUS web portal as inputs. Simulated water levels were extremely accurate with RMSE < 0.1 m, but simulated water quality parameters (salinity and temperature) were notably less accurate due to the fact that important drivers for mixing and transport processes such as wind and evaporation were not included in the model. Overall, it was demonstrated that reasonably good results can be obtained from a model built using publicly available open data. Although further refinement is required in order to answer specific research questions, this model is useful to understand global hydrodynamic behaviour and discover potential data and information gaps. The development of this model will continue and future versions will include wind and other meteorological drivers, a more detailed representation of the saltwater intrusion through the Gatun and Agua Clara locks, and a more refined grid.

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7. REFERENCES

Bitencourt, L. P., Fernandes, E., Möller, O., & Ross, L. (2020). The contribution of ENSO cycles to the salinity spatio-temporal variability in a bar-built microtidal estuary. *Regional Studies in Marine Science*, *40*, 101496. https://doi.org/10.1016/j.rsma.2020.101496

Canal de Panamá. (2023). *Portal Web de la Sección de Meteorología e Hidrología del Canal de Panamá*. https://panama.aquaticinformatics.net/

Eslami, S., Hoekstra, P., Kernkamp, H., Nguyen Trung, N., Do Duc, D., Tran Quang, T., Februarianto, M., Van Dam, A., & van der Vegt, M. (2019). Flow Division Dynamics in the Mekong Delta: Application of a 1D-2D Coupled Model. *Water*, *11*(4), Article 4. https://doi.org/10.3390/w11040837

GEBCO Compilation Group. (2022). *GEBCO_2022 Grid*. https://doi.org/10.5285/e0f0bb80-ab44-2739-e053-6c86abc0289c

Kaushal, S. S., Likens, G. E., Pace, M. L., Reimer, J. E., Maas, C. M., Galella, J. G., Utz, R. M., Duan, S., Kryger, J. R., Yaculak, A. M., Boger, W. L., Bailey, N. W., Haq, S., Wood, K. L., Wessel, B. M., Park, C. E., Collison, D. C., Aisin, B. Y. 'aaqob I., Gedeon, T. M., … Woglo, S. A. (2021). Freshwater salinization syndrome: From emerging global problem to managing risks. *Biogeochemistry*, *154*(2), 255–292. https://doi.org/10.1007/s10533-021-00784-w

Paton, S., & Equipo de Análisis de Calidad de Agua, P. C. A. (2022). *Panama Canal Watershed water quality monitoring program*. Smithsonian Tropical Research Institute (STRI). https://doi.org/10.25573/data.19196240.v4

Pereira, H., Sousa, M. C., Vieira, L. R., Morgado, F., & Dias, J. M. (2022). Modelling Salt Intrusion and Estuarine Plumes under Climate Change Scenarios in Two Transitional Ecosystems from the NW Atlantic Coast. *Journal of Marine Science and Engineering*, *10*(2), Article 2. https://doi.org/10.3390/jmse10020262

Rabelo, L., Marin, M., Xanthopoulos, P., Arellano Lennox, C., Coiduras, P., Campos, B., Andrade, L., Collins, R., Atencio, E., & Pitty, D. (2012). Preliminary Hybrid Modeling of the Panama Canal: Operations and Salinity Diffusion. *Modelling and Simulation in Engineering*, *2012*, e806139. https://doi.org/10.1155/2012/806139

Ros, M., Ashton, G. V., Lacerda, M. B., Carlton, J. T., Vázquez-Luis, M., Guerra-García, J. M., & Ruiz, G. M. (2014). The Panama Canal and the transoceanic dispersal of marine invertebrates: Evaluation of the introduced amphipod Paracaprella pusilla Mayer, 1890 in the Pacific Ocean. *Marine Environmental Research*, *99*, 204–211. https://doi.org/10.1016/j.marenvres.2014.07.001

Salgado, J., Vélez, M. I., González-Arango, C., Rose, N. L., Yang, H., Huguet, C., Camacho, J. S., & O'Dea, A. (2020). A century of limnological evolution and interactive threats in the Panama Canal: Long-term assessments from a shallow basin. *Science of The Total Environment*, *729*, 138444. https://doi.org/10.1016/j.scitotenv.2020.138444

Schreiber, L., Castellanos-Galindo, G., Robertson, D. R., Torchin, M., Laakmann, S., & Saltonstall, K. (2021). *EDNA reveals widespread presence of marine fish in the Panama Canal*. 2.

Szklarek, S., Górecka, A., & Wojtal-Frankiewicz, A. (2022). The effects of road salt on freshwater ecosystems and solutions for mitigating chloride pollution—A review. *Science of The Total Environment*, *805*, 150289. https://doi.org/10.1016/j.scitotenv.2021.150289

Wijsman, J. (2013). *Panama Canal Extension: A review on salt intrusion into Gatun Lake* (C215/13). Institute for Marine Resources & Ecosystem Studies (IMARES).

Zambrano-Bigiarini, M. (2020). *HydroGOF: Goodness-of-fit functions for comparison of simulated and observed hydrological time series* (Version 0.4-0) [R package]. https://doi.org/10.5281/zenodo.839854