Journal of Applied Water Engineering and Research, 2017
https://doi.org/10.1080/23249676.2017.1355759

Case Report

Application of HEC-ResSim® in the study of new water sources in the Panama Canal

Lucas E. Calvo Gobbetti*

Centro de Investigaciones Hidráulicas e Hidrotécnicas, Universidad Tecnológica de Panamá, Panamá, República de Panamá

(*Received 10 July 2016; accepted 29 May 2017*)

This paper presents an evaluation of different projects for new water sources in the Panama Canal using the HEC-ResSim® program for simulating the reservoir systems. The HEC-ResSim® models of the reservoir systems were used to evaluate the discharges in spillways during the rainy months, hydroelectric generation at Gatun and Alhajuela Lakes, volumes available for navigation, municipal and industrial consumption at Gatun Lake and volumes supplied at Alhajuela Lake for municipal and industrial use. For each project analyzed, additional equivalent lockages were determined that could deliver 99.6% water reliability or 97.5% draft reliability. The results were validated using the storage–yield relationships of the reservoir systems. The storage–yield curves of the analyzed systems are highly similar to the storage–yield curve of White River [Vogel RM, Lane M, Ravindiran RS, Kirshen P. (1999). Storage reservoir behaviour in the United States. J Water Resour Plann Manag. 125:245–254], which was obtained to deliver a specific yield without failures (100% water reliability). Storage–yield curves based on the independent operation of individual reservoirs can be compared with the storage–yield curves of multiple reservoir systems operating in tandem if the storage ratio and yield ratio of the reservoir systems are calculated with consideration of the sum of their individual storages and inflows. The results indicate the generality of storage–yield curves, such as those developed by Vogel et al. (1999), and also indicate that storage–yield curves can be used as guides for the development of new water source projects.

Keywords: Panama Canal; reservoir system simulations; HEC-ResSim®; water and draft reliabilities; storage–yield curves

Introduction

Due to the Panama Canal expansion, an increase in the number of lockages is expected in the medium term. Natural increases in municipal and industrial water consumption in the cities of Panama and Colon are also expected. Consequently, it is necessary to consider the use of additional water sources for the canal operation and other purposes. The new water sources should supply the Panama Canal with the ability to avoid draft restrictions due to El Niño Southern Oscillation (ENSO) induced droughts, which cause unusually low levels in the lakes. The strongest ENSO recorded to date occurred in 1997–1998 when the Panama Canal operated with draft restriction (less than 12 m of normal draft) for more than two months, causing considerable losses. More recently, during the 2015–2016 ENSO, draft restrictions were contemplated but were finally not implemented.

The aim of this paper is to evaluate potential new water sources for the Panama Canal and the cities of Panama and Colon using the HEC-ResSim® tool and validate the simulations using previously known storage–yield relationships. Figure 1 shows data regarding the reservoirs used in the Panama Canal, Gatun Lake and Alhajuela Lake. Gatun Lake was created in 1910 to minimize excavation needs and protect against the flooding of the many rivers that flowed into the navigation channel. Alhajuela Lake was created in 1935 to support Gatun Lake and generate hydroelectricity.

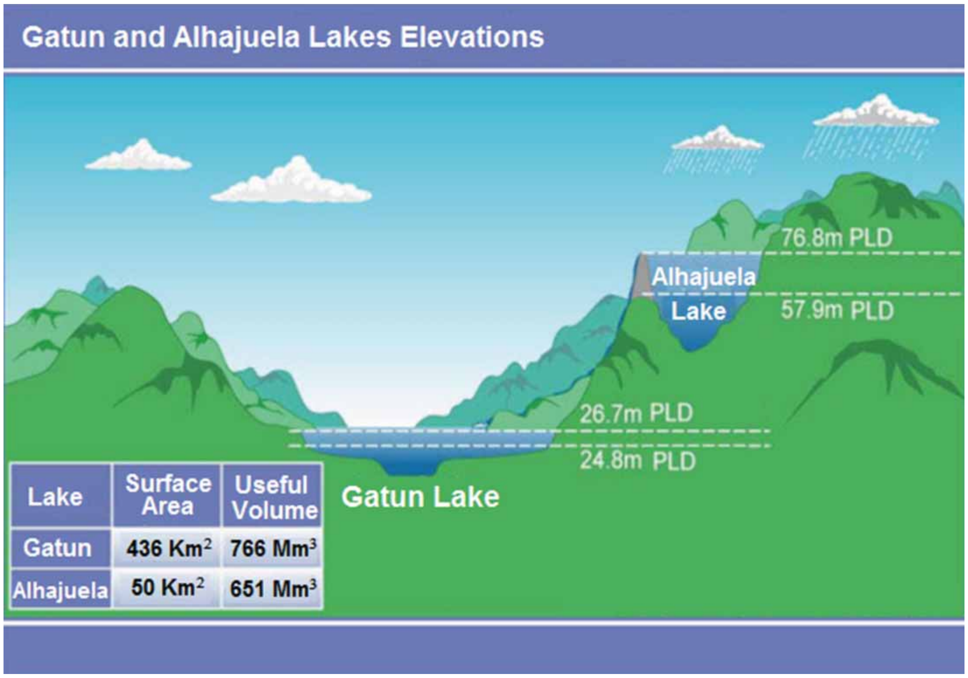
Projects analyzed

The projects analyzed in this study were the Alto Chagres project, the Rio Indio project, the Trinidad/Caño Quebrado project, the Deepening of Navigation Channels to 7.6 m PLD (Precise Level Datum, vertical reference datum in the Panama Canal, located 0.3 m below the average level of the Pacific Ocean) project and several possible combinations of these projects.

Alto Chagres project

The Alto Chagres project includes the construction of a reservoir immediately upstream of Alhajuela Lake as shown in Figure 2. The useful volume between elevation 155 m (normal minimum level) and elevation 210 m (normal maximum level) would be 450 Mm^3. This project stands out due to its high hydroelectric potential. The cost of the project was estimated in US$ 330 million (ACP 2006). The environmental impact of the project is considered high because it is located in a forest reserve

*Email: lucas.calvo@utp.ac.pa



Lake	Surface Area	Useful Volume
Gatun	436 Km²	766 Mm³
Alhajuela	50 Km²	651 Mm³

Figure 1. Gatun and Alhajuela Lakes (From: ACP 2006).

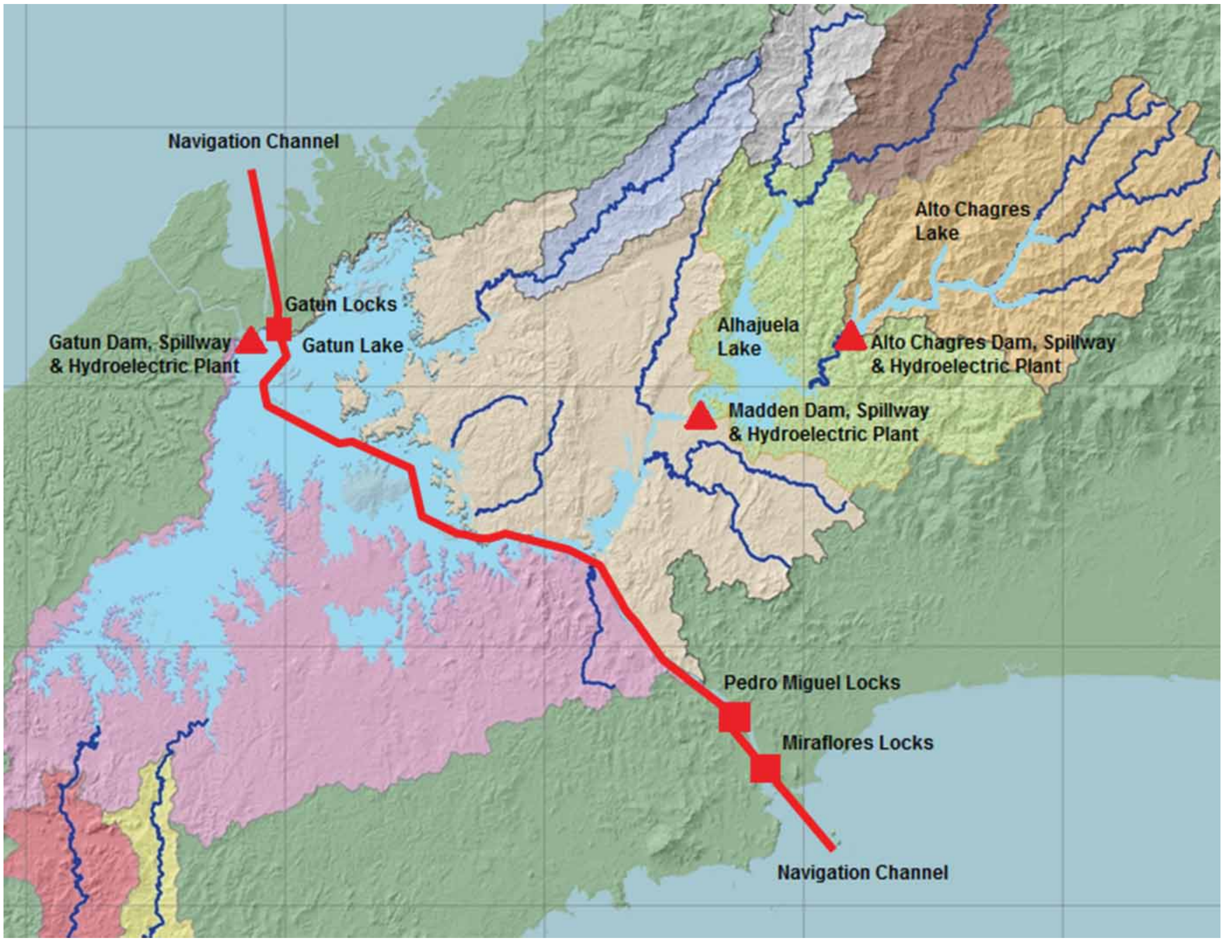


Figure 2. Current system with Alto Chagres Project.

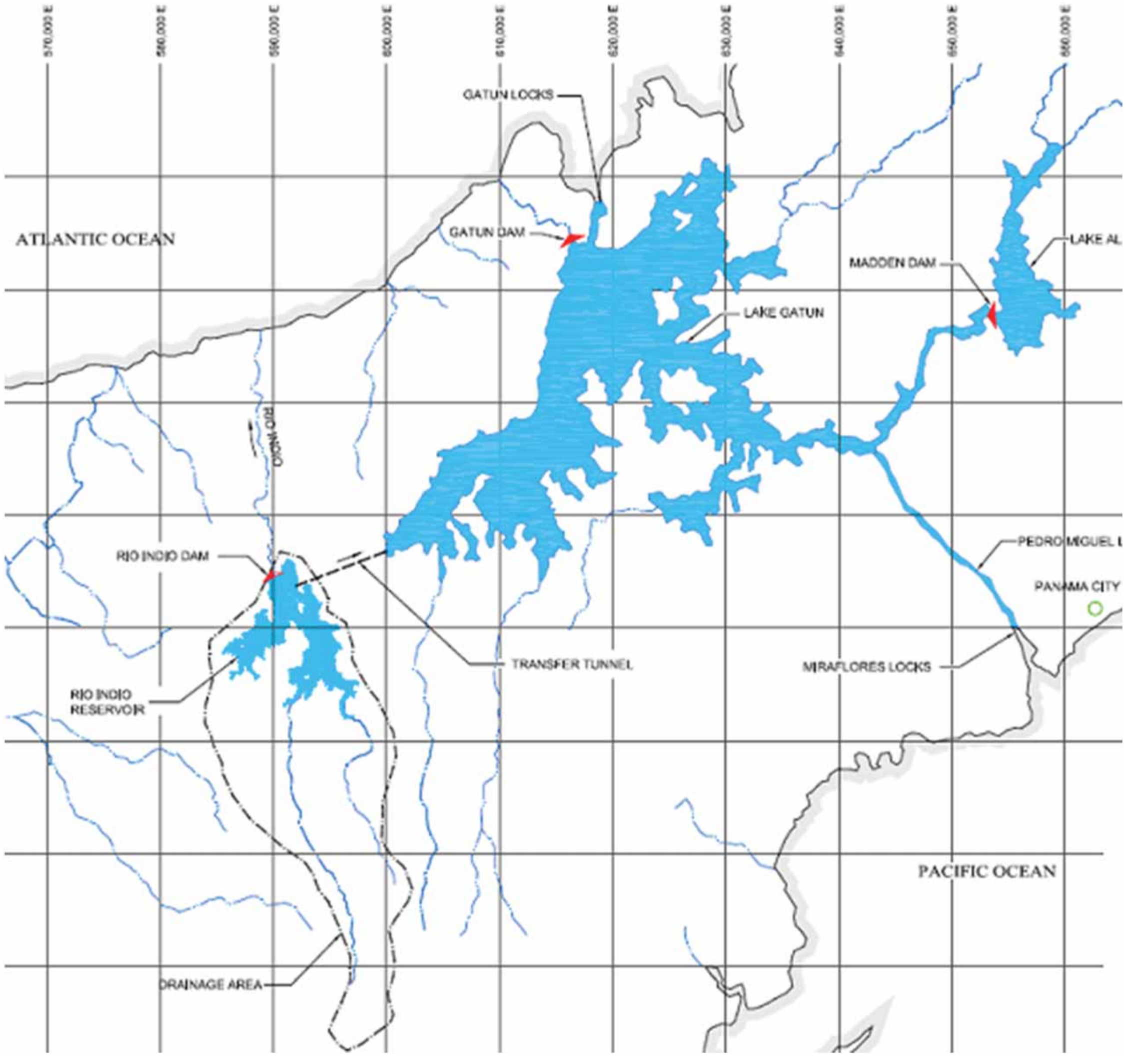


Figure 3. Rio Indio Project (From: Montgomery Watson Harza 2003).

with the largest extension of primary tropical forest in the Panama Canal Basin.

Rio Indio project

The Rio Indio project includes a dam and a transfer tunnel that would bring water directly from Indio River to Gatun Lake (Figure 3). The useful volume between elevation 40 m (normal minimum level) and elevation 80 m (normal maximum level) would be 1294 Mm^3. The cost of the project was estimated to amount US$ 290 million (ACP 2006). The environmental impact of the project is considered low because it is located on deforested land devoted primarily to subsistence agriculture.

Trinidad project

The Trinidad project consists of an underwater filling dam that would separate the Trinidad arm, a portion of Gatun Lake, from the main body of the lake (Figure 4). This dam would bring the water level in the arm up to approximately 30.5 PLD, and its lowest level would drop to 22.9 m PLD, reaching an additional useful volume of 891 Mm^3.

Figures 5 and 6 illustrate the concept of a pump reservoir in Trinidad. In rainy periods, excess water in Gatun Lake could be pumped into the Trinidad arm to take advantage of its additional storage capacity (Figure 5). In dry periods, Trinidad Lake can supply Gatun Lake via gravity and can also be reduced to its lowest level of 22.9 m PLD (Figure 6). Trinidad Lake can be increased by incorporating the Caño Quebrado arm, another portion of Gatun Lake, which would be joined with Trinidad Lake through a diversion channel. The Trinidad project was analyzed for maximum elevations of the Trinidad reservoir of 30.5, 32 and 33.5 m PLD with and without the auxiliary Caño Quebrado reservoir. The cost of the project was estimated in US$ 700 million (ACP 2006). The environmental impact of the project is considered low because it is located on

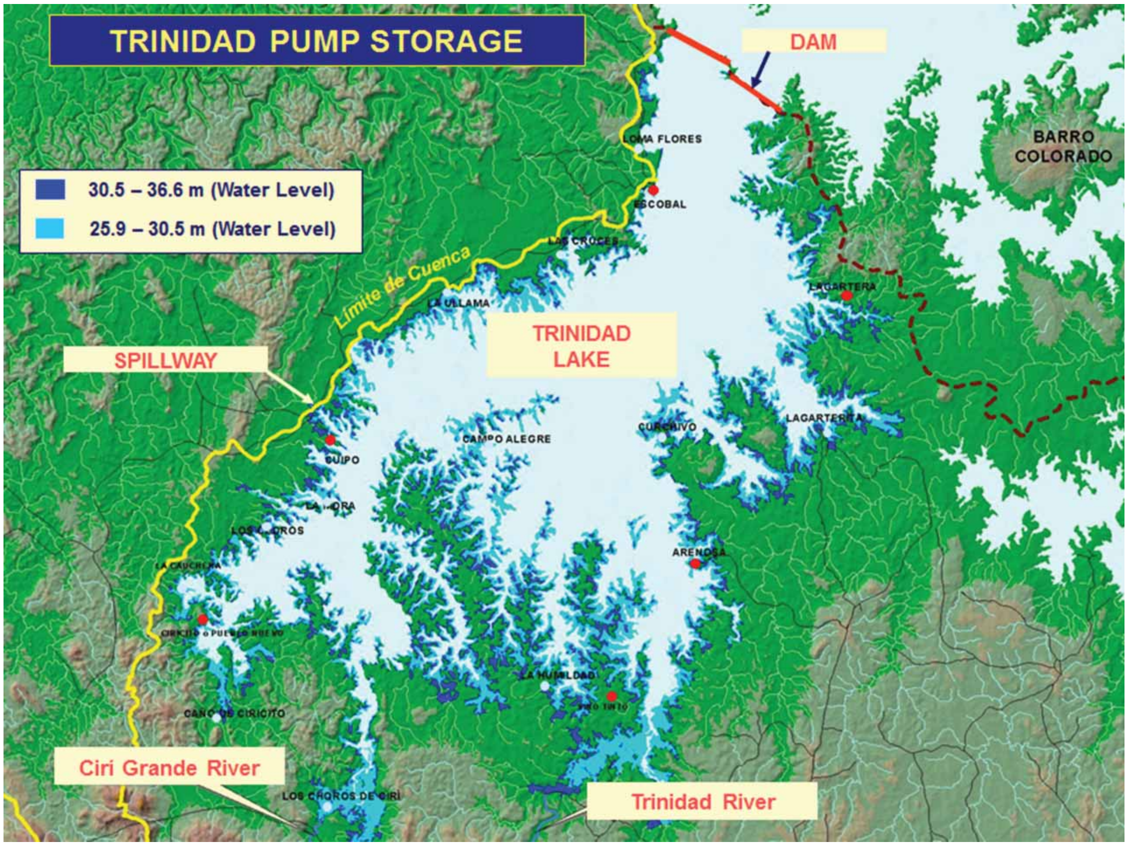


Figure 4. Trinidad Project (From: ACP 2001).

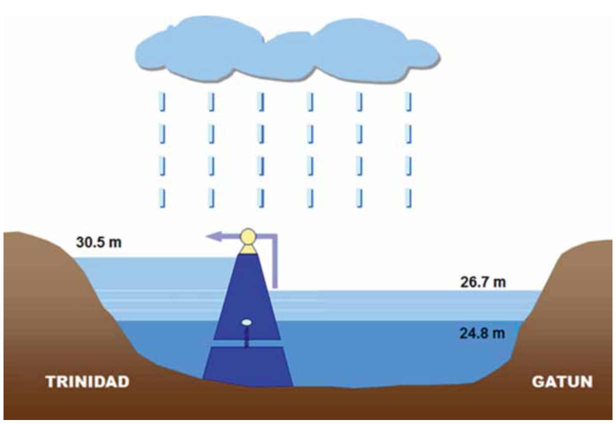


Figure 5. Pumping from Gatun Lake to Trinidad Lake (Rainy Season) (From: ACP 2001).

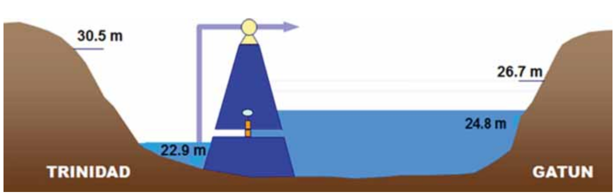


Figure 6. Pumping from Trinidad Lake to Gatun Lake (Dry Season) (From: ACP 2001).

land belonging to the Panama Canal Authority (Autoridad del Canal de Panamá, ACP) immediately adjacent to Gatun Lake.

Deepening of the navigation channel to 7.6 m PLD project

The bottom elevation of the navigation channel has changed from 11.3 to 9.14 m PLD in recent years due to improvement projects and the Panama Canal expansion. The project calls for a further deepening of the existing navigation channel to reduce the bottom to 7.6 m PLD. Additional deepening of the navigation channel would allow the passage of ships with drafts of 15.24 m with 1.5 m UKC (Under Keel Clearance), bringing the normal minimum level of Gatun Lake to 24.4 m PLD. The cost of the project was estimated to amount US$ 150 million (ACP 2006). The deepening of the navigation channels would have notably few direct effects, and thus its environmental impact would be low.

CURRENT system: HEC-ResSim® reservoir simulation model

HEC-ResSim®, developed by the Hydrologic Engineering Center of the United States Army Corps of Engineers

(USACE), was used in the simulation of the reservoir systems. This model has the ability to model the operation of multiple reservoirs, pumps and hydroelectric generation stations, among many other simulation options.

A simulation model of the current system was built, including Alhajuela and Gatun Lakes. As input data, the model uses the average monthly flows with a daily calculation time interval. The incoming flows of each day of the month were taken as equal to the monthly average. The monthly inflow volumes into the reservoirs used in all simulations are the net volumes obtained indirectly from water balances. In each reservoir, the volumes at the beginning and end of month, spilled at spillways, used in hydroelectric generation, in municipal and industrial consumption and in lockages are known (observed), so the only unknowns in the water balance equations are the net monthly inflow volumes. These net monthly inflow volumes include the infiltration and evaporation losses at the reservoirs. For Alhajuela Lake, these values were obtained by:

$$\mathrm{NIA}_i = \mathrm{IA}_i - \mathrm{EA}_i - \mathrm{Inf\,A}_i = \mathrm{VA}_{i+1} - \mathrm{VA}_i + (\mathrm{SA}_i + \mathrm{GA}_i + \mathrm{MIA}_i) \quad i = 1, 2, 3, \ldots n, \tag{1}$$

NIA_i = net monthly inflow volume at Alhajuela Lake during month i, IA_i = monthly inflow volume at Alhajuela Lake during month i, EA_i = monthly volume of evaporation at Alhajuela Lake during month i, $\mathrm{Inf\,A}_i$ = monthly volume of infiltration at Alhajuela Lake during month i, VA_{i+1} = volume of Alhajuela Lake at the beginning of month $i+1$ (observed), VA_i = volume of Alhajuela Lake at the beginning of month i (observed), SA_i = volume spilled from Alhajuela Lake during month i (observed), GA_i = volume used in hydroelectric generation in Alhajuela Lake during month i (observed), MIA_i = volume used in municipal and industrial water supply at Alhajuela Lake during month i (observed), n = number of months in the horizon simulation, For Gatun Lake these values were obtained by:

$$\mathrm{NIG}_i = \mathrm{IG}_i - \mathrm{EG}_i - \mathrm{Inf}\,G_i = \mathrm{VG}_{i+1} - \mathrm{VG}_i + (\mathrm{SG}_i + \mathrm{GG}_i + \mathrm{MIG}_i + \mathrm{LG}_i) - (\mathrm{SA}_i + \mathrm{GA}_i) \quad i = 1, 2, 3, \ldots n, \tag{2}$$

where NIG_i = net monthly inflow volume at Gatun Lake (downstream of Madden Dam discharge) during month i, IG_i = monthly inflow volume at Gatun Lake during month i, EG_i = monthly volume of evaporation at Gatun Lake during month i, $\mathrm{Inf}\,G_i$ = monthly volume of infiltration at Gatun Lake during month i, VG_{i+1} = volume of Gatun Lake at the beginning of month $i+1$ (observed), VG_i = volume of Gatun Lake at the beginning of

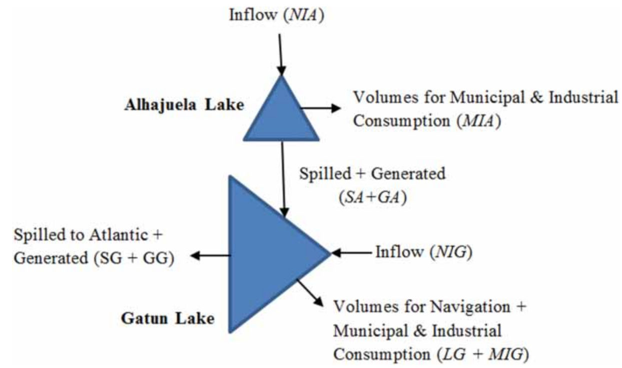


Figure 7. HEC-ResSim® model scheme of the current system.

month i (observed), SG_i = volume spilled from Gatun Lake during month i (observed), GG_i = volume used in hydroelectric generation in Gatun lake during month i (observed), MIG_i = volume used in municipal and industrial water supply at Gatun Lake during month i (observed), LG_i = volume used in lockages at Gatun Lake during month i (observed).

The model replicates the discharges in spillways, the hydroelectric generation at Gatun and Alhajuela, the volumes supplied in Gatun for navigation and municipal and industrial consumption and the volumes supplied in Alhajuela for municipal and industrial consumption. A scheme of the HEC-ResSim® model of the current system is shown in Figure 7.

In the HEC-ResSim® model, the operation of each reservoir is determined by the zone in which the reservoir level is located. By definition, three zones exist as follows: flood control, conservation and inactive. The reservoir guide curve is located at the upper boundary of the Conservation zone. Each particular zone contains operating rules that must be followed by the reservoir when the levels are in that zone. The model always attempts to bring the level of the reservoir as close as possible to the guide curve by obeying the operation rules. The current guide curve of Gatun Lake, which similar to Alhajuela's, is shown in Figure 8. The guide curve is typical of tropical seasonal systems, with rainy and dry seasons and with the ability to fill at the end of each year.

The current system model begins with Alhajuela Lake receiving the net flows of its basin. The following rules apply for Alhajuela Lake in flood control and conservation zones:

- Generate and/or spill through the Madden hydroelectric and/or Madden spillway to Gatun Lake synchronously with the Gatun Lake levels (tandem rule). Alhajuela Lake is forced to team up with Gatun Lake, with both lake levels increasing or decreasing simultaneously, as in practice.
- Deliver volumes for municipal and industrial supply (Alhajuela Water Treatment Plant).

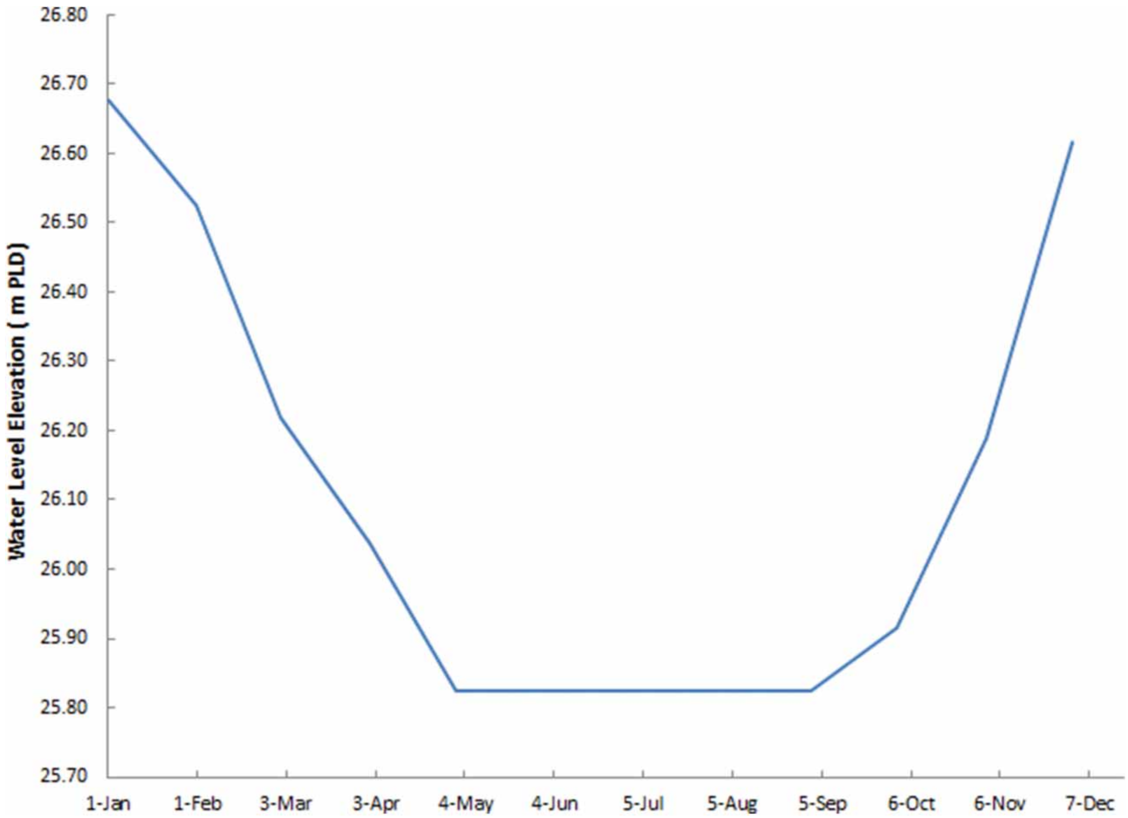


Figure 8. Current guide curve of Gatun Lake.

Alhajuela Lake has an additional minimum level zone in which the following rule is enforced:

- When decreasing the reservoir level below the minimum level of 57.9 m PLD, volumes for municipal and industrial water supplies are delivered, but neither generation nor spilling into Gatun Lake occur.

Gatun Lake receives the volumes generated and/or spilled from Alhajuela Lake and the net flows in the portion of the basin that is not controlled by Madden Dam in Alhajuela. The following rules are imposed in the flood control and conservation zones for Gatun Lake:

- Deliver volumes for municipal and industrial water supply (Miraflores, Mount Hope and Mendoza Water Treatment Plants) and navigation (Pedro Miguel and Gatun Locks).

Volumes delivered for navigation in the normal operating range (above the minimum level) are average monthly volumes that depend on the guide curve of Gatun Lake. Gatun Lake has an additional minimum level zone in which the following rule is enforced:

- When decreasing the reservoir level below the minimum level of 24.8 m PLD, the volume for navigation is supplied depending on the reservoir level.

Current system model (1985–1995)

The current system model with the zones and rules described above was used to reproduce the current system operation for the years 1985–1995. The model was fed with monthly net input flows to Alhajuela Lake and monthly net input flows to Gatun Lake that do not originate from the Alhajuela sub-basin for the years 1985–1995. The calculation time interval was daily. The incoming flows for each day of a month were taken as equal to the monthly average. The municipal and industrial supply demands in Alhajuela and Gatun Lakes and the navigation demands in Gatun Lake were taken as the monthly average demands of the years 1985–1995.

As the model was fed with net monthly flows, the level comparisons were conducted at the beginning of each month. Figure 9 presents comparisons between the simulated and observed daily levels at the beginning of each month for Gatun and Alhajuela Lakes from 1985 to 1995.

The coefficients of determination (R^2), the Nash–Sutcliffe efficiency coefficient (NSCE) and the root-mean square error (RMSE) were used to quantify the similarity

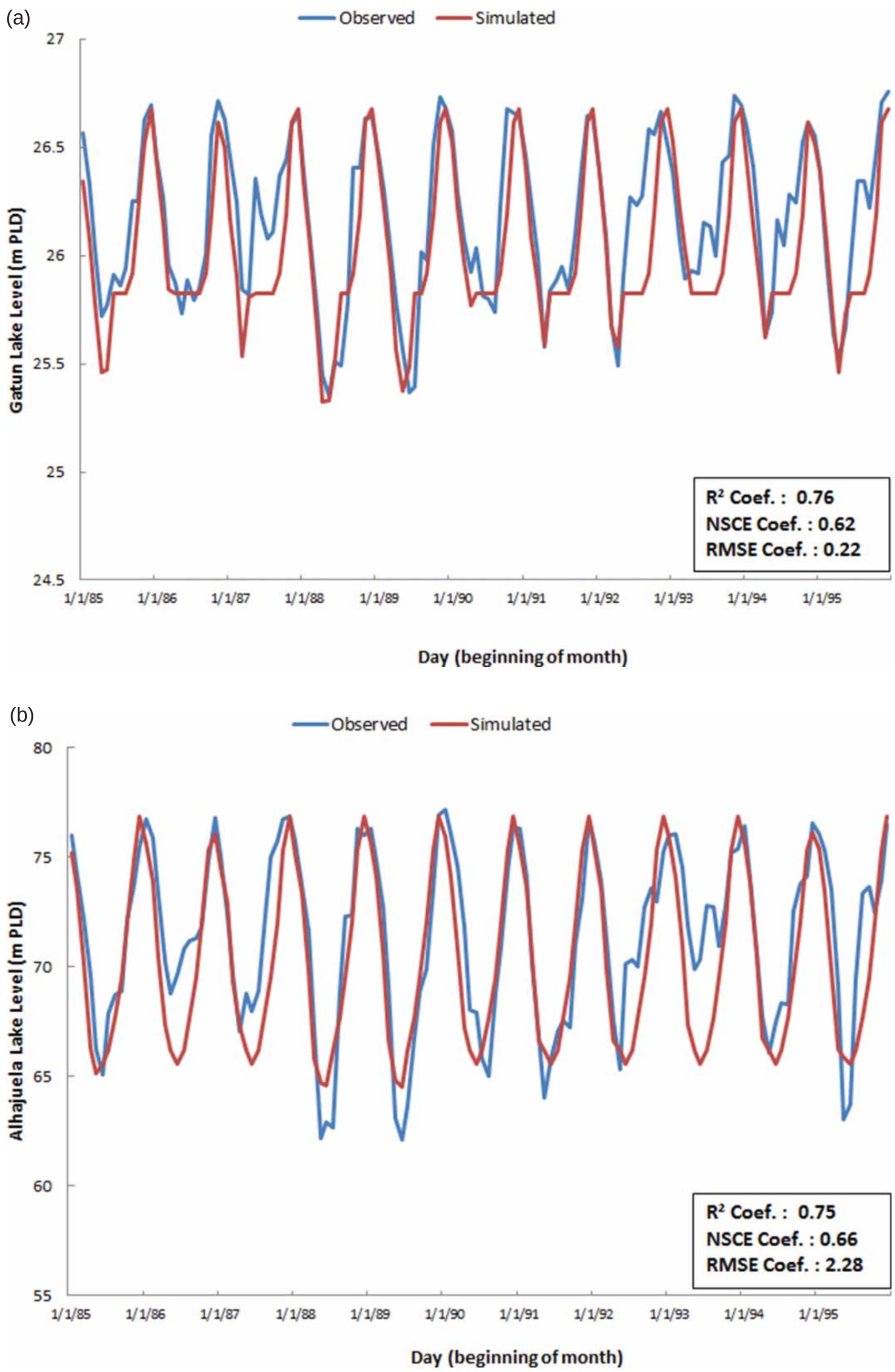


Figure 9. Simulated vs. observed levels at the beginning of each month (1985–1995), (a) Gatun, (b) Alhajuela.

between the simulated and observed levels. The R^2 coefficient measures the degree of collinearity between the simulated and observed levels. The NSCE coefficient is a measure of the predictive power of a hydrological model. The RMSE coefficient measures the residual value between the observed and simulated levels in actual units of measure of the levels. The R^2 and NSCE values of 1 and RMSE of 0 are optimal values (Li et al. 2016). The formulas for R^2, NSCE and RMSE are given by the following:

$$R^2 = \frac{\sum_{i=1}^{n}\left[(y_i - \bar{y}_i)(\tilde{y}_i - \bar{\tilde{y}}_i)\right]^2}{\left[\sum_{i=1}^{n}(y_i - \bar{y}_i)^2 \sum_{i=1}^{n}(\tilde{y}_i - \bar{\tilde{y}}_i)^2\right]}, \tag{3}$$

$$\mathrm{NSCE} = 1 - \sum_{i=1}^{n}(y_i - \tilde{y}_i)^2 \Big/ \sum_{i=1}^{n}(y_i - \bar{y}_i)^2, \tag{4}$$

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n} (y_i - \tilde{y}_i)^2 / n}, \qquad (5)$$

where y_i are the daily levels observed at the beginning of month i, $\tilde{y}_i$ are the daily levels simulated at the beginning of month i, $\bar{y}_i$ is the average of the daily levels observed, $\bar{\tilde{y}}_i$ is the average of the daily levels simulated and n is the number of months in the simulations. For Gatun Lake, the following values were obtained:

- R^2 coefficient: 0.76
- NSCE coefficient: 0.62
- RMSE coefficient: 0.22 m

For Alhajuela Lake, the following values were obtained:

- R^2 coefficient: 0.75
- *NSCE* coefficient: 0.66
- *RMSE* coefficient: 2.28 m

The differences between the daily values of the calculated and observed levels at the beginning of each month are considered acceptable. Selected considerations of these differences are described as follows:

- The resulting daily levels are a product of the monthly net flows that were fed into the model.
- The municipal, industrial and navigation demands were approximated by the average monthly demands during the years 1985–1995.
- The volumes actually generated or spilled through the Madden Hydroelectric Plant or Madden Dam Spillway are determined based on the experience of the operator. The model tandem rule is an automation of this process.
- The small residual value between the observed and simulated levels (RMSE = 0.22 m) is especially important in Gatun Lake due to the use of the lake in navigation. The bigger residual value for Alhajuela Lake can be explained by the use of the tandem rule.
- The R^2 and NSCE values show an acceptable correlation and prediction between the calculated and observed levels.

Verification of the current system model (1995–2005)

The model of the current system and its zones and operating rules were verified to reproduce the operation of the current system for the years 1995–2005. This period includes the strongest ENSO phenomenon registered until now (1997–1998), during which the Panama Canal operated with draft restrictions for more than two months. The model was fed with the monthly net inflows to Gatun and Alhajuela Lakes for the years 1995–2005. The calculation time interval was daily. The incoming flows of each day of the month were taken as equal to the monthly average. The municipal, industrial and navigation demands were taken as the average monthly demands of 1995–2005. Figure 10 shows the comparisons between the simulated and observed daily levels at the beginning of each month for Gatun and Alhajuela Lakes from 1995 to 2005.

For Gatun Lake, the following values were obtained:

- R^2 coefficient: 0.8
- NSCE coefficient: 0.71
- RMSE coefficient: 0.29 m

For Alhajuela Lake, the following values were obtained:

- R^2 coefficient: 0.69
- NSCE coefficient: 0.57
- RMSE coefficient: 2.76 m

Figure 10 shows that the model was able to reproduce the behavior of the lakes during the extreme ENSO of 1997–1998.

Water and draft system reliability

Once built and verified, the model allowed evaluation of the water and draft system reliabilities. Water reliability is defined as the sum of water volumes supplied by the system divided by the sum of water volumes demanded by the system in a given period:

$$\text{Water reliability} = \frac{\sum \text{supplied volume}}{\sum \text{demanded volume}} \times 100\%. \qquad (6)$$

The use of draft reliabilities is more common in navigation systems. Draft reliability is the frequency guaranteed for a given draft or the frequency with which the lake level is above a given minimum level. The draft reliability in a given period is:

$$\text{Draft reliability} = \frac{\sum \text{days above minimum level}}{\sum \text{days of the period}} \times 100\%. \qquad (7)$$

The draft and water reliabilities depend on the demands and the study horizon and are approximately linearly related because lockage demands are much larger than municipal demands, and the water volume used in each lockage is a linear function of the lake depth. Figure 11 shows a comparison between water and draft reliabilities of the current system obtained varying artificially the demands.

In the 51-year period from 1948 to 1998 (study period used in USACE 1999), with the average demands of the years 1993 to 1997, the water reliability was 99.6%, and the draft reliability was 97.5%. It was decided that the projects analyzed should ensure these water and draft reliabilities.

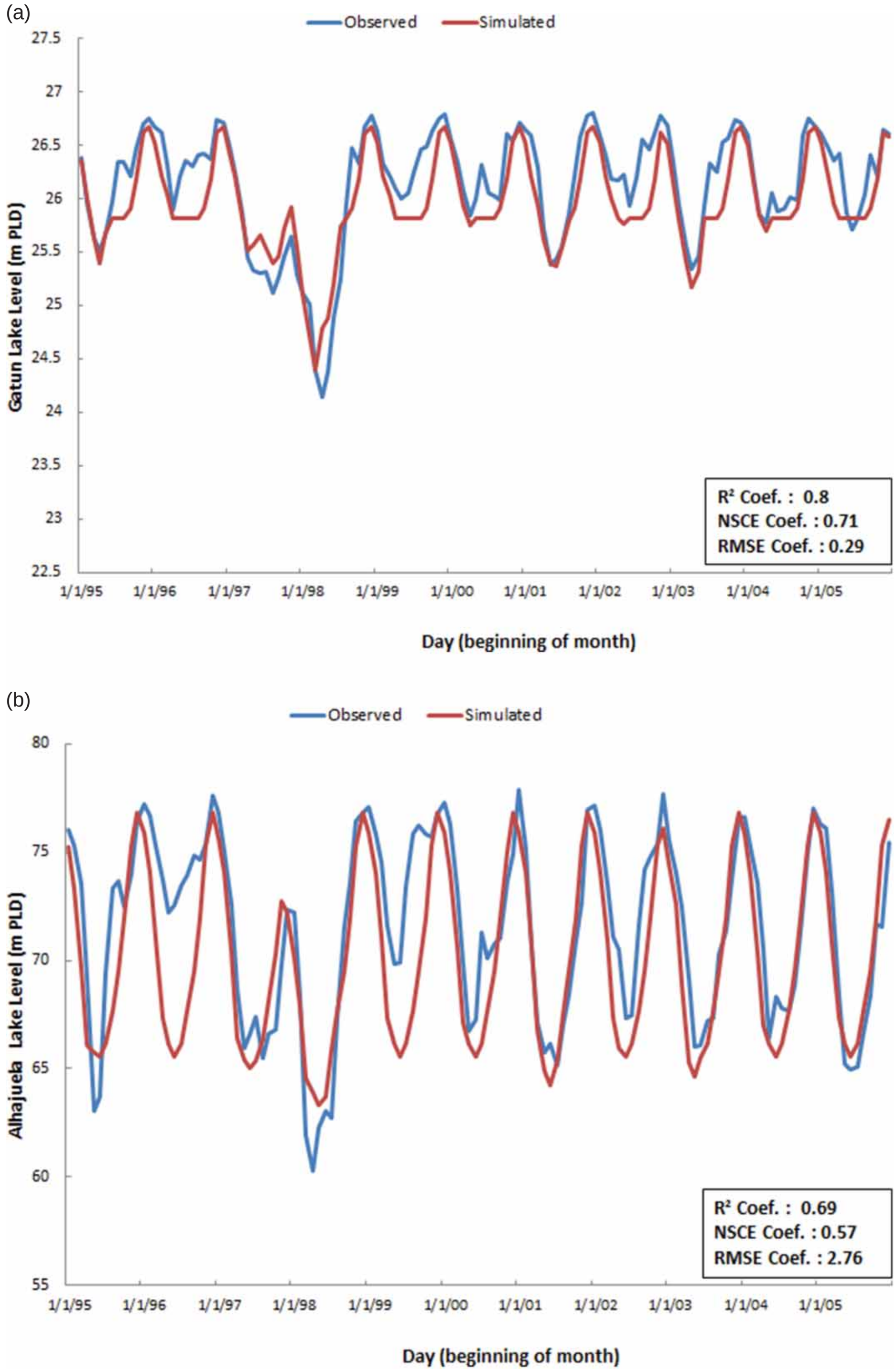


Figure 10. Simulated vs. observed levels at the beginning of each month (1995–2005), (a) Gatun, (b) Alhajuela.

Simulation models of the projects

In the simulation of the projects, the models were fed with monthly net flows corresponding to 51 years (from the beginning of January 1960 to the end of December 2010). This period includes various extreme hydrological phenomena, from the drought caused by the 1997–1998 ENSO to the rainy event of 8 December 2010 known as 'La Purisima'. All models of the projects were initially subjected to the total demands of 2015, which were 38.9 equivalent daily lockages (one lockage in the old locks is equivalent on average to 0.21 Mm^3), of which 32 lockages are used in navigation and 6.9 equivalent lockages are used in municipal and industrial consumption. These demands were designed to increase in the models to attain water and

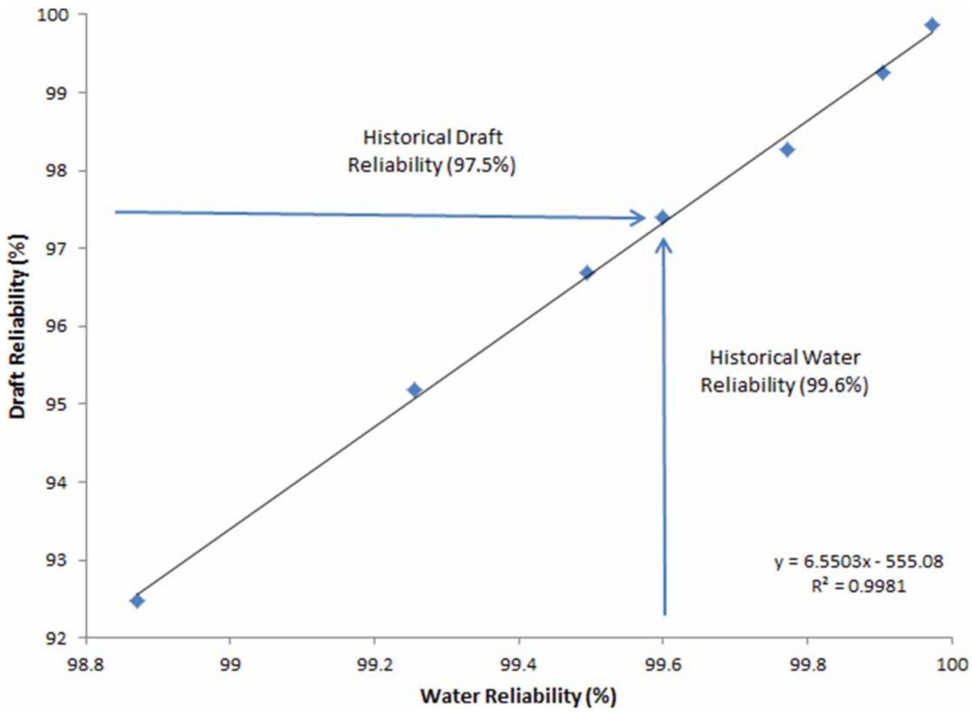


Figure 11. Comparison of water and draft reliabilities of the current system under different demands.

draft reliabilities of 99.6% and 97.5%, respectively. The lockages attained beyond the initial 38.9 daily lockages are the additional equivalent daily lockages created for each project. The results were analyzed for the case of Gatun Lake with its current variation, between 24.8 and 26.7 m PLD, and when the Panama Canal expansion is in full operation, between 25.9 and 27.1 m PLD. To allow the transit of Post-Panamax vessels with up to 15.24 m of the draft, the minimum operational level of Gatun Lake must increase to 25.9 m PLD.

Alto Chagres project model

The HEC-ResSim® model of the current system was modified to include the Alto Chagres reservoir. This reservoir discharges directly into Alajuela Lake using a tandem operation rule.

Rio Indio project model

The HEC-ResSim® model of the current system was modified to include the Rio Indio reservoir (Figure 12). The Rio Indio reservoir discharges into Gatun Lake through a transfer tunnel. The water stored in Indio Lake is delivered to Gatun Lake through a tandem operation rule with this lake. The ecological flow is maintained downstream of the dam on the Indio River.

Trinidad project model

The HEC-ResSim® model of the current system was modified to include the Trinidad reservoir. The Trinidad reservoir discharges into Gatun Lake through a gated spillway. Two-way pumping is permitted between Trinidad and Gatun Lakes. The guide curve used in Trinidad reservoir was inspired by the Alhajuela guide curve and optimized to guarantee the maximum yield.

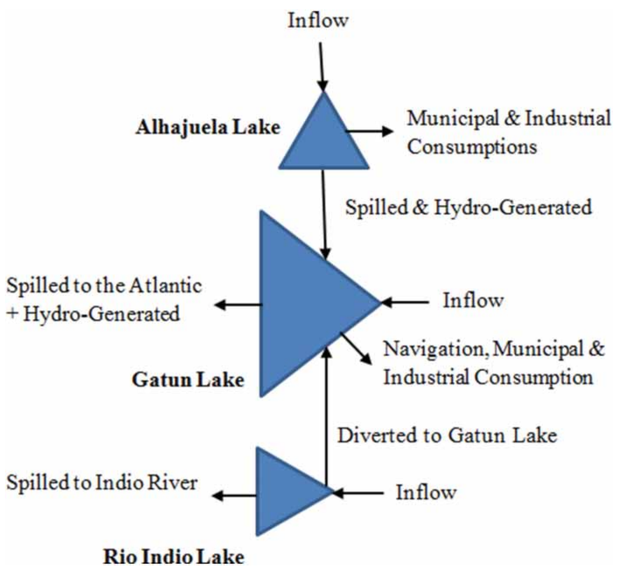


Figure 12. HEC-ResSim® model scheme of the current system with the Rio Indio Project.

Deepening of the navigation channel project model

By decreasing the level of the navigation channel to 7.6 m PLD, Post-Panamax vessels with 15.24 m draft could transit Gatun Lake operating at the minimum level of 24.4 m PLD. The HEC-ResSim® model of the current system was modified to allow the level of Gatun Lake to drop to a minimum of 24.4 m PLD.

Project combinations

In addition to the individual projects of Alto Chagres, Rio Indio, Trinidad and the deepening of the navigation channel, possible combinations of these projects that could increase the overall water efficiency were also studied.

For the project combinations, two different sites for the dam on Indio River were considered. The study site of Montgomery Watson Harza (2003) considered a dam with water levels ranging from 40 to 80 m and a smaller dam with varying levels between 40 and 45 m. The other site in the Indio River is located a few kilometers upstream, and a diversion dam with levels ranging from 45.5 to 50 m was planned.

The current system HEC-ResSim® model was modified to include combinations of reservoirs. Table 1 shows the additional equivalent daily lockages of all projects and their combinations.

The Rio Indio project (40–80 m) stands out among all individual projects as the alternative with the greatest water yield, and its environmental impact is low. The Rio Indio project is followed in water yield by the Trinidad project operating at the normal maximum level of 30.5 m PLD, which also has a low environmental impact. The Alto Chagres Project has a high environmental impact because it is located in a forest reserve. The project that would deepen navigation channels has the lowest environmental impact of all individual projects and is a project that would serve as a complement to other projects because it creates the ability to transit ships with a draft of 15.24 m.

The combination of projects greatly increases the water yield. Combined projects such as Trinidad to 30.5 m PLD + Rio Indio (40–80 m) supplies 20 additional daily lockages (Table 1: Gatun after expansion). These projects could offer a greater margin of security of attendance to future water demands, especially in the face of foreseeable increases in municipal, industrial, and navigation demands and the flow reduction of the rivers adjacent to Gatun Lake due to climate change.

Storage–yield relationships of reservoir systems

The results of Table 1 can be validated using the storage–yield relationships. The behavior of a reservoir depends primarily on the storage ratio S/μ, yield ratio Y/μ and the

Table 1. Additional storages and equivalent daily lockages.

Project	Gatun before expansion: (24.8/24.4[a]–26.7 m PLD) useful volume: 1417 Mm^3		Gatun after expansion: (25.9/24.4[a]–27.1 m PLD) useful volume: 1050 Mm^3	
	Additional storage volume (Mm^3)	Additional daily lockages	Additional storage volume (Mm^3)	Additional daily lockages
Ind (40–80 m)	1294	15.4	1294	11.2
Alto Chagres	446	5.25	446	1.76
Deepening	184	3.86	730	4
Chagres + deepening	630	6.85	1176	7
Ind (40–80 m) + deepening	1478	17	2024	17
Ind (45.5–50 m) + deepening	184	6.02	730	6.15
Ind (40–45 m) + deepening	293.5	7.43	840	7.6
Tri 30.5 m	891	10.68	1066	9.51
Tri 32.0 m	1210	12.41	1385	10.5
Tri 33.5 m	1529	13.35	1704	10.48
Tri + Ca 30.5 m	1016	11.97	1191	10.56
Tri + Ca 32.0 m	1380	15.27	1555	12.79
Tri + Ca 33.5 m	1743	16.3	1918	12.86
Tri + Ca 30.5 m + Ind (45.5–50 m)	1051	15.96	1226	13.02
Tri + Ca 32.0 m + Ind (45.5–50 m)	1415	18.84	1590	16.11
Tri + Ca 33.5 m + Ind (45.5–50 m)	1779	21.99	1954	18
Tri 30.5 m + Ind (40–80 m)	2185	25.79	2360	20.59
Tri 32.0 m + Ind (40–80 m)	2504	27.03	2679	21.84
Tri 33.5 m + Ind (40–80 m)	2823	28.23	2998	22.07
Tri 30.5 m + Ind (45.5–50 m)	891	15	1066	12.37
Tri 32.0 m + Ind (45.5–50 m)	1246	17.96	1421	15.21
Tri 33.5 m + Ind (45.5–50 m)	1529	21.06	1704	16.73
Tri + Ca 30.5 m + Ind (40–80 m)	2310	26.04	2485	21.07
Tri + Ca 32.0 m + Ind (40–80 m)	2673	27.93	2848	22.18
Tri + Ca 33.5 m + Ind (40–80 m)	3037	28.65	3212	23.3

[a]Projects with deepening allow 24.4 m PLD of minimum level.

standardized net inflow m to the reservoir, where S, Y and μ are the storage capacity, annual yield and mean annual inflow to the reservoir, respectively (Vogel et al. 2007).

The standardized net inflow m, introduced by Hazen (1914), is defined as follows:

$$m = \frac{\mu - Y}{\sigma} = \frac{(1-\alpha)}{C_v}, \tag{8}$$

where σ is the standard deviation of the annual inflows, $\alpha = Y/\mu$ is the yield ratio and C_v is the coefficient of variation of the annual inflows ($C_v = \sigma/\mu$).The standardized net inflow, in addition to C_v, offers a measure of the degree to which the design capacity of a reservoir system depends on within-year (seasonal) versus over-year (carryover) storage requirements (guide curves).

Vogel et al. (1999) computed the storage–yield curves of individual reservoirs using historic annual and monthly data of 10 fluviometric stations. These stations were selected to reflect the range of inter-annual variability of streamflows across the entire United States with values of C_v that range from 0.23 to 0.85. In general, for a given storage ratio, the yields are higher in temperate regions where C_v is small than in arid regions where variability is greater. The storage–yield curves were calculated using an algorithm equivalent to the use of a storage–mass curve. The algorithm estimated the minimum reservoir capacity required to supply a specific yield without failures over a given planning horizon.

To calculate the storage ratio, yield ratio and standardized net inflow, the useful volume of the current system (1417 Mm^3) and the average annual inflow to Gatun and Alhajuela Lakes (5263 Mm^3/year) were used in all projects (ACP 2006). The mean coefficient of variation C_v of the average annual streamflows of six stations in the Panama Canal Basin is 0.23 (ACP 2009).

The storage–yield curves computed in Vogel et al. (1999) and in Vogel et al. (2007) are based on the operation of individual reservoirs working independently. Because the analyzed systems operate together to maximize the total yield (tandem rules) their storage–yield curves can be calculated by considering the sum of their individual storages and inflows. In the case of the Rio Indio project, the additional storage is 1294 Mm^3. The average annual inflow to Indio Lake (outside the Panama Canal watershed) is 798 Mm^3/year. The storage ratio S/μ is calculated as follows:

$$\frac{S}{\mu} = \frac{(1417 + 1294)}{(5263 + 798)} = 0.45.$$

The Rio Indio Project would provide 15.4 equivalent daily lockages in addition to the current 38.9 daily lockages (Table 1, Ind (40–80 m) – Gatun before expansion), and thus its yield ratio Y/μ would be:

$$\frac{Y}{\mu} = \frac{(15.4 + 38.9) \times 365 \times 0.2082}{(5263 + 798)} = 0.68.$$

Table 2. Storage ratio, yield ratio and standardized net inflow of projects without Trinidad.

	Storage ratio (S/μ)		Yield ratio (Y/μ)		Standardized net inflow m	
Project	(a)	(b)	(a)	(b)	(a)	(b)
Indio	0.45	0.39	0.68	0.63	1.39	1.62
Alto Chagres	0.35	0.29	0.64	0.59	1.58	1.79
Deepening	0.30	0.34	0.62	0.62	1.66	1.65
Chagres + Prof.	0.39	0.42	0.66	0.66	1.48	1.47
Indio (40–80 m) + deep.	0.48	0.51	0.70	0.70	1.30	1.3
Indio (45.5–50 m) + deep.	0.26	0.29	0.56	0.56	1.90	1.89
Indio (40–45 m) + deep.	0.28	0.31	0.58	0.58	1.82	1.81
Current system	0.27		0.56		1.91	
Current system 2	1.00		0.84		0.70	
Current system 3	1.50		0.87		0.57	
Current system 4	2.00		0.88		0.52	
Current system 5	0.20		0.47		2.30	
Current system 6	0.75		0.80		0.87	
Current system 7	0.60		0.76		1.04	
Current system 8	0.50		0.73		1.20	
Current system 9	1.25		0.86		0.61	

(a) Gatun before expansion: 24.8/24.4[a]–26.7 m PLD
(b) Gatun after expansion: 25.9/24.4[a]–27.1 m PLD

Average annual inflow to the current system: 5263 Mm^3/year
Average annual inflow to Indio Lake (outside the canal basin): 798 Mm^3/year

Coefficient of variation of the average annual streamflows C_v: 0.23
Current daily equivalent lockages: 38.9

[a]Projects with deepening allow 24.4 m PLD of minimum level.

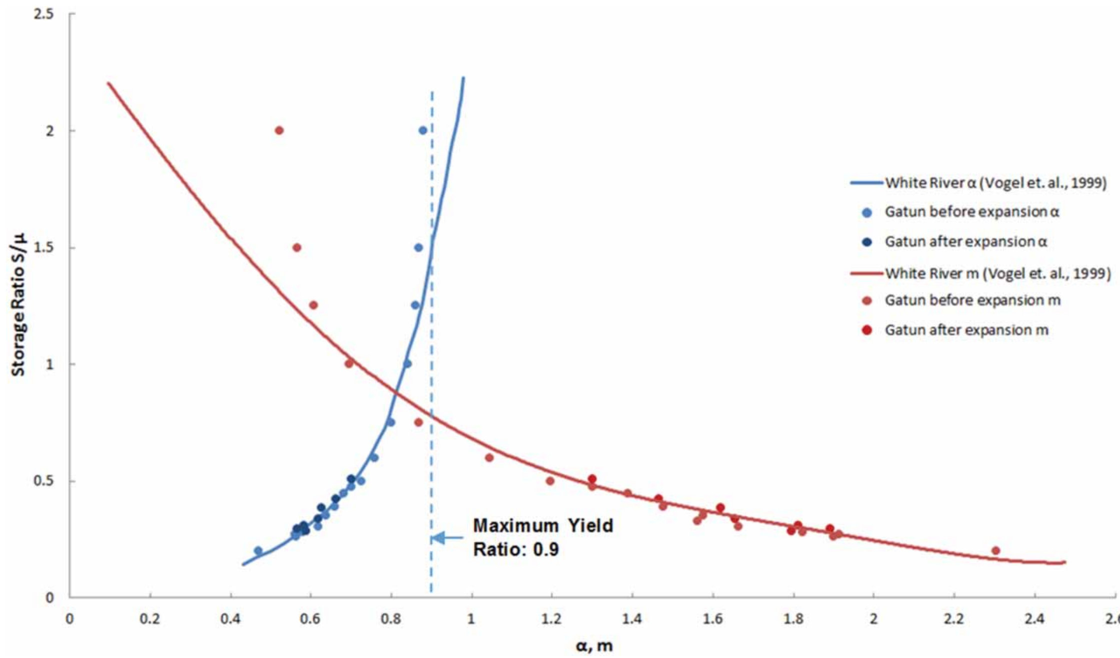


Figure 13. Storage–yield curves of White River and projects without Trinidad.

Table 3. Storage ratio, yield ratio and standardized net inflow of projects with Trinidad.

	Storage ratio (S/μ)		Yield ratio (Y/μ)		Standardized net inflow m	
Project	(a)	(b)	(a)	(b)	(a)	(b)
Tri 30.5 m	0.44	0.4	0.72	0.7	1.24	1.31
Tri 32.0 m	0.50	0.46	0.74	0.71	1.13	1.24
Tri 33.5 m	0.56	0.52	0.75	0.71	1.07	1.25
Tri + Ca 30.5 m	0.46	0.43	0.73	0.71	1.15	1.24
Tri + Ca 32.0 m	0.53	0.49	0.78	0.75	0.95	1.10
Tri + Ca 33.5 m	0.60	0.56	0.80	0.75	0.88	1.09
Tri + Ca 30.5 m + Ind (45.5–50 m)	0.41	0.38	0.69	0.65	1.36	1.52
Tri + Ca 32.0 m + Ind (45.5–50 m)	0.47	0.44	0.72	0.69	1.20	1.35
Tri + Ca 33.5 m + Ind (45.5–50 m)	0.53	0.5	0.76	0.71	1.03	1.25
Tri 30.5 m + Ind (40–80 m)	0.59	0.56	0.81	0.75	0.82	1.10
Tri 32.0 m + Ind (40–80 m)	0.65	0.62	0.83	0.76	0.75	1.04
Tri 33.5 m + Ind (40–80 m)	0.70	0.67	0.84	0.76	0.69	1.02
Tri 30.5 m + Ind (45.5–50 m)	0.38	0.35	0.68	0.64	1.41	1.55
Tri 32.0 m + Ind (45.5–50 m)	0.44	0.41	0.71	0.68	1.25	1.40
Tri 33.5 m + Ind (45.5–50 m)	0.49	0.45	0.75	0.70	1.08	1.31
Tri + Ca 30.5 m + Ind (40–80 m)	0.61	0.58	0.81	0.75	0.81	1.08
Tri + Ca 32.0 m + Ind (40–80 m)	0.67	0.64	0.84	0.77	0.70	1.02
Tri + Ca 33.5 m + Ind (40–80 m)	0.73	0.70	0.85	0.78	0.67	0.96

(a) Gatun before expansion: 24.8–26.7 m PLD
(b) Gatun after expansion: 25.9–27.1 m PLD

Average annual inflow to the current system: 5263 Mm^3/year
Average annual inflow to Indio Lake (outside the canal basin): 798 Mm^3/year

Coefficient of variation of the average annual streamflows C_v: 0.23
Current daily equivalent lockages: 38.9

The standardized net inflow calculated by formula (8) is $m = (1 - 0.68)/0.23 = 1.39$.

The projects in Table 1 have been divided between those that include the Trinidad project and those that do not. The Trinidad project considers upstream pumping from Gatun Lake toward Trinidad Lake. This water would normally be discharged into the ocean during the rainy season by the Gatun spillway. The additional yield achieved by this pumping is not linked either to a storage increase or an inflow increase into the lakes (diversion), and thus

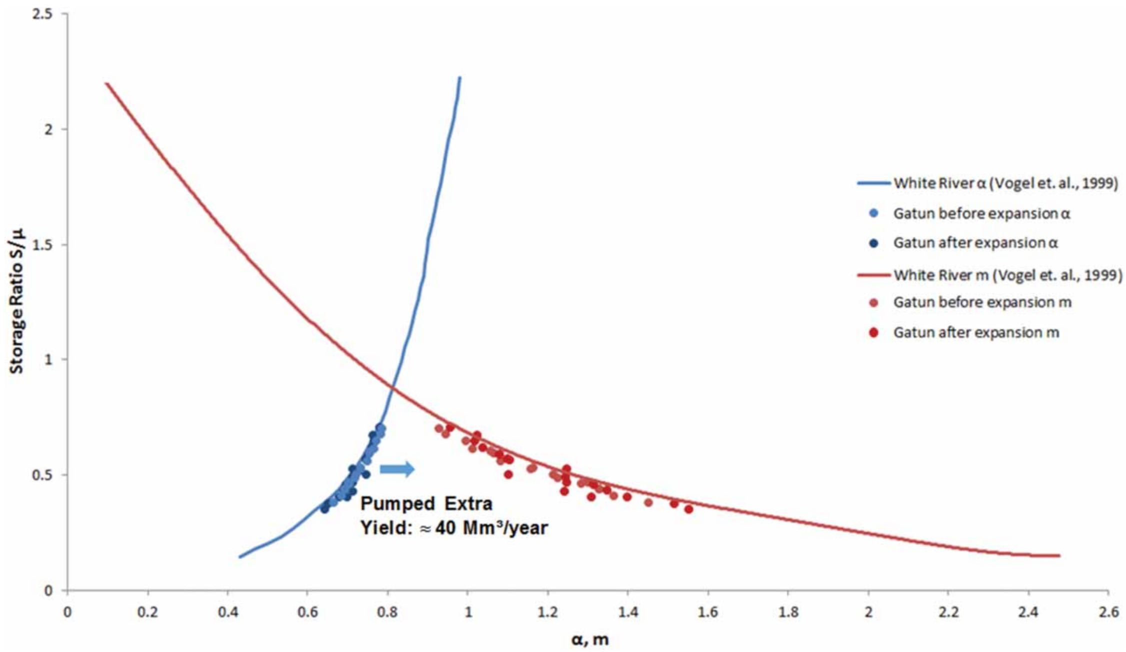


Figure 14. Storage–yield curves of White River and projects with Trinidad.

it must be treated as a case different from the normal operation of reservoirs.

Table 2 shows the storage ratio, yield ratio and standardized net inflow of all analyzed projects that do not include the Trinidad project. In Table 2, the current system was modified (current system 2–9) by proportionally increasing or decreasing the useful volumes of Gatun and Alhajuela Lakes to encompass the storage ratio range of the curves of Vogel et al. (1999).

The values of the standardized net inflow m in Table 2 correspond to seasonal systems which, according to the classification proposed by Vogel et al. (1999), are systems with $C_v < 1$ and standardized inflow in the range $C_v \le m \le 1/C_v$. For the coefficient of variation of annual streamflows in the Panama Canal Basin of $C_v = 0.23$, $0.23 \le m \le 4.3$. Seasonal systems are systems that have the capacity to fill each year because C_v is small (little annual variation of the inflows) and m is relatively high (water in excess of demands). According to Vogel et al. (1999), systems that operate multi-annually would be systems with $C_v > 1$ (high annual variation of inflows) or systems with $C_v < 1$ and standardized inflows in the range $0 \le m \le C_v$ (little water in excess of demands).

The storage–yield curves developed by Vogel et al. (1999) can be used as a guide in the validation of the results. Figure 13 shows a comparison between the values in Table 2 and the storage–yield curves based on monthly series of flows for the White River. On the abscissa of the figure is plotted both the yield ratio α and the standardized net inflow m. Both α and m are surrogates for system yield because as annual yield Y increases, α increases and m decreases.

White River, Vermont, in the United States, has the same coefficient of variation of the annual streamflows as the rivers in the Panama Canal Basin as follows: $C_v = 0.23$. The values in Table 2 correspond well with the White River curve until approximately the value of $S/\mu = 1$. The differences from this value, which indicate lower yield for the same White River storage, could be explained by the inclusion of lake surface evaporation and infiltration in the water balances used to determine the net inflows to the lakes (Equations (1) and (2)). Approximately 9% of the water that reaches the Panama Canal lakes annually evaporates from its surface, and only 91% is actually available to supply the consumption of the population and to ensure the functioning of the Panama Canal (ACP 2006). Consequently, the maximum value of the Panama Canal yield ratio tends to be approximately $\alpha = Y/\mu = 0.9$ (Figure 13). Lake surface evaporation and infiltration were not contemplated in the construction of the curves of Vogel et al. (1999).

Table 3 shows the storage ratio, yield ratio and standardized net inflow of all analyzed projects that include the Trinidad project. The effect of pumping on the Trinidad project is presented in Figure 14, which shows a comparison between the values in Table 3 and the storage–yield curves developed by Vogel et al. (1999) for White River.

In the Trinidad project, the average annual pumped volume (with a pumping capacity of 140 m^3/seg) from Gatun Lake to Trinidad Lake is 40 Mm^3. The slight deviation to the right in relation to the White River storage–yield curve (S/μ vs. α) consequently corresponds to an approximate increase of 40 Mm^3 in the annual yield. This additional yield of approximately 0.5 lockages per day is not linked to an increase of either storage or inflows to the lakes because it is water that would normally be discharged at Gatun spillway without pumping.

Conclusions

The HEC-ResSim® software proved to be an effective tool for evaluating projects of new water sources for the Panama Canal and the cities of Panama and Colon. The successful use of this tool depends on the correct identification of the zones and rules of operation of each reservoir. Even when using monthly data, the program managed to reproduce the daily behavior of the reservoirs. The models replicated discharges in spillways during the rainy months, hydroelectric generation at Gatun and Alhajuela Lakes, volumes supplied in Gatun Lake for navigation, municipal and industrial consumption, and volumes supplied in Alhajuela Lake for municipal and industrial consumption.

For each project analyzed, additional equivalent lockages were determined that could deliver 99.6% water reliability or 97.5% draft reliability. The results were validated using the storage–yield curve of White River, as developed by Vogel et al. (1999), which has the same coefficient of variation of the annual streamflows as the rivers in the Panama Canal Basin as follows: $C_v = 0.23$. The storage–yield curves of the analyzed systems are highly similar to the storage–yield curve of White River obtained to supply a specific yield without failures (100% water reliability). The differences for the values of $S/\mu > 1$ can be explained by the inclusion of lake surface evaporation and lake infiltration in the water balances of analyzed systems.

The values of the standardized net inflow m of the analyzed systems correspond to seasonal systems (with the capacity to fill each year), which are systems with $C_v < 1$ and standardized inflow in the range $C_v \leq m \leq 1/C_v$ (Vogel et al. 1999). For the coefficient of variation of annual streamflows in the Panama Canal Basin $C_v = 0.23$, the values of m are in the range $0.23 \leq m \leq 4.3$.

Storage–yield curves based on the operation of individual reservoirs operating independently can be compared with storage–yield curves of multiple reservoir systems operating in tandem if the storage ratio and yield ratio of the reservoir systems are calculated by considering the sum of their individual storages and inflows.

The results point to the generality of storage–yield curves such as those developed by Vogel et al. (1999) and indicate that storage–yield curves can be used as guides in the development of new water source projects.

Acknowledgements

The author wishes to thank the Engineering Division of the Panama Canal Authority and the Center for Hydraulic Research of the Technological University of Panama for their support of this work.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributor

Lucas E. Calvo Gobbetti holds an MSc. and a PhD in Hydraulic Engineering from the Escola Politécnica da Universidade de São Paulo, Brazil. Dr Calvo has worked as a Hydraulic Engineer in the Engineering Division of the Panama Canal Authority and is currently a researcher at the Center for Hydraulic Research of the Technological University of Panama (CIHH).

References

ACP. 2001. *Trinidad project development plan*. Panamá: República de Panamá.

ACP. 2006. *Plan Maestro del Canal de Panamá*. Panamá: República de Panamá.

ACP. 2009. *Agua y Bosques en la Cuenca del Canal: Tendencias de Largo Plazo*. Panamá: República de Panamá.

Hazen A. 1914. Storage to be provided in impounded reservoirs for municipal water supply. Trans ASCE. 77:1539–1640.

Li B, Yang G, Wan R, Dai X, Zhang Y. 2016. Comparison of random forests and other statistical methods for the prediction of lake water level: a case study of the Poyang lake in China. Hydrol Res. 47(S1): 69–83.

Montgomery Watson Harza. 2003. Río Indio water supply project, feasibility design of the Río Indio water supply project.

USACE. 1999. *Panama Canal reconnaissance study*, Vol. I & II. US Army Corps of Engineers, Mobile District.

Vogel RM, Lane M, Ravindiran RS, Kirshen P. 1999. Storage reservoir behaviour in the United States. J Water Resour Plann Manag. 125:245–254.

Vogel RM, Sieber J, Archfield SA, Smith MP, Apse CD, Huber-Lee A. 2007. Relations among storage, yield and instream flow. Water Resour Res. 43, W05403, doi:10.1029/2006WR005226