Study of variations and trends in the historical rainfall and runoff data in the Gatun Lake watershed

Estudio de las variaciones y tendencias en los datos históricos de precipitación y escorrentía en la cuenca del lago Gatún

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EXECUTIVE SUMMARY

STUDY OF VARIATIONS AND TRENDS IN THE HISTORICAL RAINFALL AND RUNOFF DATA IN THE GATUN LAKE WATERSHED

E.0 EXECUTIVE SUMMARY

This report on the Study of Variations and Trends in the Historical Rainfall and Runoff Data in the Gatun Watershed is organized into two volumes. Volume 1 is the main report. Volume 2 includes seven appendices. The main report includes a description of the methodology used together with a summary of results and supporting tables and exhibits. Definitions of terms and abbreviation used in the report are provided after the Table of Contents. Appendix A includes references cited in the text. Historic data, inventory of rainfall and stream gauging stations, filled-in data with time series and mass curve plots, fill-in computer program input-output files, input-output files and detailed results of stochastic model, and synthetic flow series with computer input-output files are provided in appendices B to G, respectively. A summary of the report is discussed below.

E.1 Hydrometeorological Data

Monthly hydrometeorological data (rainfall and streamflow) were provided by the Autoridad Del Canal De Panama (ACP, the Panama Canal Authority). The rainfall and stream gauging stations for which detailed statistical analyses were made are listed in Table E-1. Data for climatic indices for El Nino and annual number of sunspots were obtained through the Internet.

The study area was divided into three basins :

- Madden Lake: watershed area draining into Madden Lake
- Gatun Downstream: watershed area between Madden Dam and Gatun Dam draining into Gatun Lake
- Gatun Total: total watershed area upstream from Gatun Dam including the drainage area upstream from Madden Dam

Monthly basin average rainfall over each of the above basins and flow generated from each basin were estimated. Statistical analyses were also performed for each of the three rainfall and three streamflow time series.

E.2 Review of Rainfall and Streamflow Data

E.2.1 Rainfall Data

The rainfall data collection system and instrumentation are well maintained. A tipping bucket rain gauge along with a float-operated storage gauge is installed on each station. Simultaneous observations from the two gauges over the past years were nearly the same except in a few cases. Currently, the meteorologist of ACP uses observation from either of the gauges based on observations on nearby stations and his knowledge of the operation of the gauges. It is suggested that ACP may discontinue the use of the storage gauge. The observation from a tipping bucket gauge can be reviewed and checked by comparing observations at nearby stations.

Table E-1

RAINFALL AND STREAM GAUGING STATIONS

A.	**Rainfall Stations**		
1.	Agua Clara	15.	Gatun
2.	Alhajuela	16.	Guacha
3.	Balboa Heights	17.	Hodges Hill
4.	Borro Colorado	18.	Humedad
5.	Candelaria	19.	Limon Bay
6.	Cano	20.	Monte Lirio
7.	Chico	21.	Peluca
8.	Ciento	22.	Pedro Miguel
9.	Chorro	23.	Racies
10.	Cascadas	24.	Rio Piedras
11.	Canones	25.	Salamanca
12.	Empire Hills	26.	San Miguel
13.	Escandalosa	27.	Santa Rosa
14.	Gamboa		
B.	**Stream Gauging Stations**		
1.	Gatun River at Ciento		
2.	Boqueron River at Peluca		
3.	Pequeni River at Candelaria		
4.	Chagres River at Chico		
5.	Trinidad River at Chorro		
6.	Ciri Grande River at Canones		

It is a general worldwide practice that a non-recording rain gauge is installed with a recording gauge to provide a check on the total rainfall measured by the recording gauge. The non-recording gauge provides data in case of malfunctioning of the recording gauge. We recommend that this practice may be followed in the Gatun watershed. Because of the remoteness of gauge locations, the non-recording gauge should have sufficient capacity to collect rainfall for about two weeks. All stations will have to be visited twice a month.

E.2.2 Stream Gauging Stations

The stations are well maintained and are operating satisfactorily. However, discharge-measuring procedures require significant improvement. Currently, all measurements are made from an overhead cableway. It is highly desirable that low flow measurements should be made by the wading method where feasible. The hydrographer should make discharge measurements by wading, up to a maximum feasible river stage.

The practice of taking depth and velocity observations at about three verticals across the width of a river during low flows and about six or seven verticals during high flows should be discontinued. The depth and velocity observations should be made at a minimum of 20 to 25 verticals across the river. However, the distance between two adjacent verticals should not be less than one meter for measurement from a cableway and 0.5 meter for wading measurements.

A review of measurements from a cableway indicated that due to drag on the sounding weights, vertical angles were observed. Corrections to observed depths are required due to the drag and depend upon the vertical angles. There are two types of corrections – air line and wet line. The vertical angle should be avoided by using heavy sounding weights consistent with the flow condition in the river. If an appropriate weight is not available, air line correction should be avoided using the procedures of United States Geological Survey, Water Resources Division (USGS). Reference to these procedures is given in the main report.

It was noticed that during a year, daily discharges at a gauging station were computed using the rating curve (stage-discharge relationship) updated in the previous years. The current year measurements were not used in the computation of daily discharges. These measurements were used at the end of the year or later when a revision was made to the rating curve. At that time the previously compute discharges were, probably, revised. This practice is quite common when there is a stable hydraulic control. In that case, the revised values are not significantly different from the first estimates. However, in the case of shifting control stations, the difference could be quite significant. All gauging stations in Gatun watershed have shifting channel controls. Since ACP is computing daily flows on a continuous basis, it is recommended that "shift adjustment" procedure of the USGS should be used. The procedure is discussed in the reference given in the report.

An inventory of rainfall and stream gauging stations is provided as Appendix C. This includes description of location, instruments, period of record, etc., for each station. A photograph of a station layout with instruments is provided where available.

E3 Extension of Rainfall Series

Five rainfall stations (Alhajuela, Balboa Heights, Gatun, Pedro Miguel and Gamboa) had complete monthly data for the period from 1911 to 2000. This period of 90 years was selected as a common period for all stations. Monthly historic rainfall data at all other stations (given in Appendix B) were filled-in and extended for this period using a FILLIN computer program developed by Texas Water Resources Development Board. The original program could handle 25 stations and 50 years of monthly data. The program was revised for 30 stations and 100 years of monthly data.

The extended and filled-in series were checked using mass curves and chronological time series plots. The filled-in and extended data were consistent with the historic data. The filled-in data and the plots are given in Appendix D.

E.4 Extension of Streamflow Series

Based on the monthly streamflow data at the six stations, a common period of 1941 to 2000 (60 years) was selected. The data were filled-in and /or extended using the FILLIN computer program discussed above. The plots of mass curves and flow time series showed that the filled-in/extended data were consistent with the historical data. Appendix D shows the historic data, filled-in data and plots.

E.5 Basin Average Rainfall

Monthly basin average rainfall series were computed for the 90-year period for Madden Lake, Gatun Downstream and Gatun Total basins. The Thiessen method was used to derive the station weights of pertinent stations relative to each basin. The generated series were compared with the series provided by ACP. Long-term mean annual rainfall values estimated by MWH were about 2.3, 2.5 and 2.6 percent higher than that estimated by ACP for Madden Lake, Gatun Downstream and Gatun Total, respectively. Comparisons were also made using double mass curves and scattered diagrams. The two sets (by MWH and ACP) were not significantly different.

E.6 Basin Inflows

Monthly inflow series were generated for Madden Lake, Gatun Downstream and Gatun Total basins. Madden Lake basin was divided into five sub-basins. The inflow to Madden Lake was the sum of flows of Chagres, Pequeni, Boqueron, intervening area and runoff from rainfall falling directly over the lake area. The flows for the intervening area were computed by transposing the combined flows of Chagres, Pequeni and Boqueron multiplied by a combined drainage area-mean annual rainfall ratio.

For estimating the monthly flows from Gatun Downstream, the basin was divided into eight sub-basins, three gauged sub-basins, four intervening areas and the lake area. Flows for the intervening areas were estimated by transposing the gauged flows multiplied by combined drainage area-mean annual rainfall ratios. The inflow was the sum of flows from seven sub-basins plus the runoff from rainfall directly falling over the lake area. The generated series were compared with the series provided by ACP. Long-term mean annual runoff values estimated by MWH were nearly equal for Madden Lake, about 9 percent higher for Gatun Downstream and about 5 percent higher for Gatun Total. Comparisons were also made using double mass curves and scattered diagrams. The two sets (by MWH and ACP) were not significantly different.

The above analysis provides a procedure that can be used when the flows at the gauging stations become available. An alternate method was developed to compute the inflows from basin average rainfalls. Linear regression equations were developed for Madden Lake and Gatun Downstream. The equations are given below:

Madden Lake

Flow (t) = 13.3 + 0.18 Rainfall (t) + 0.08 Rainfall (t-1),

Correlation coefficient = 0.84

where flow is in m^3/s , rainfall is basin average rainfall in mm and "t" in the month.

Gatun Downstream

Flow (t) = -6.7 + 0.38 Rainfall (t) + 0.17 Rainfall (t-1),

Correlation coefficient = 0.91

E.7 Statistical Analysis of Time Series

Linear trend analysis was made for all 27 rainfall stations. Detailed statistical analysis were made to test the consistency and homogeneity of the annual series given in Table E-2.

Table E-2

ANNUAL SERIES TESTED FOR CONSISTENCY AND HOMOGENEITY

Rainfall Series	Runoff Series
Madden Lake	Inflow to Madden Lake
Gatun Downstream	Inflow from Gatun Downstream
Gatun Total	Inflow from Gatun Total
Agua Clara	Ciri Grande River
Alhajuela	Trinidad River
Balboa Heights	Chagres River
Borro Colorado	Pequeni River
Chico	Boqueran River
Chorro	Gatun River
Gamboa	
Gatun	
Monte Lirio	
Pedro Miguel	
Salamanca	
San Miguel	

The tests were performed for randomness (auto correlation and modified Pormanteau tests), trend (linear correlation and Mann-Kendall & Abelson-Tukey tests) and one-population test using means and standard deviations of two sub-sets of each series. Final conclusions after careful review of all data. Statistical test results and plots are summarized in Table E-3.

A series was judged to be consistent if no jump was identified and the series was from the same population. A series was judged to be homogeneous if the trend was insignificant.

This study did not find any consistent decrease in rainfall since 1971 that could be attributed to change in instrumentation or environment at a station, physical changes in watershed or climatic factors. Actually, in most cases a decreasing trend was observed from late 1960's, which after 1985 became an increasing trend. Two sub-sets of a few series indicated that the means or standard deviations were significantly different at 95 percent level of confidence and, therefore, the data after 1971 could be from a different population. However, this statistically based conclusion was not considered valid because three El Nino episodes of 1976-77, 1982 and 1997-98 were very severe and resulted in significantly low mean annual flows. This is a short-term effect and cannot form a basis to show that the decreasing trends observed on some rainfall and runoff stations would continue. However, similar episodes may affect the rainfall and flows again.

Table E-3

SUMMARY OF CONSISTENCY AND HOMOGENEITY TESTS

Rainfall Station	Random	Trend	Rate	Consistent	Homogeneous
Agua Clara	Yes	significant, increasing,	6mm/yr	Yes	No
Alhajuela	Yes	insignificant, decreasing	1mm/yr	Yes	Yes
Balboa Heights	Yes	significant, increasing	2mm/yr	Yes	No
Borro Colorado	Yes	insignificant, decreasing	2mm/yr	Yes	Yes
Chico	Yes	insignificant, decreasing	2mm/yr	Yes	Yes
Chorro	Yes	insignificant, decreasing	3mm/yr	Yes	Yes
Gamboa	Yes	insignificant, increasing	1mm/yr	Yes	Yes
Gatun	Yes	insignificant, decreasing	3mm/yr	Yes	Yes
Monte Lirio	Yes	significant, decreasing	4mm/yr	Yes	No
Pedro Miguel	Yes	insignificant, increasing	1mm/yr	Yes	Yes
Salamanca	Yes	insignificant, increasing	2mm/yr	Yes	Yes
San Miguel	No	insignificant, increasing	1mm/yr	Yes	Yes
Madden Lake	Yes	insignificant, increasing	1mm/yr	Yes	Yes
Gatun Downstream	Yes	insignificant, decreasing	3mm/yr	Yes	Yes
Gatun Total	Yes	insignificant, decreasing	2mm/yr	Yes	Yes
Streamflow Stations					
Gatun – Ciento	Yes	insignificant, decreasing	5 l/s/yr	Yes	Yes
Boqueron – Peluca	Yes	insignificant, decreasing	5 l/s/yr	Yes	Yes
Pequeni – Candelaria	Yes	insignificant, decreasing	13 l/s/yr	Yes	Yes
Charges – Chico	Yes	insignificant, decreasing	24 l/s/yr	Yes	Yes
Trinidad – Chorro	Yes	insignificant, decreasing	18 l/s/yr	Yes	Yes
Ciri Grande – Canones	Yes	insignificant, decreasing	26 l/s/yr	Yes	Yes
Madden Lake	Yes	insignificant, decreasing	1 l/s/yr	Yes	Yes
Gatun Downstream	Yes	insignificant, decreasing	152 l/s/yr	Yes	Yes
Gatun Total	Yes	insignificant, decreasing	153 l/s/yr	Yes	Yes

E.8 Stochastic Model

A number of available stochastic models were reviewed to select an appropriate model that would fit the hydrologic time series of Gatun watershed and, when fitted to the series, would provide monthly forecasts a few months ahead of their occurrence. Based on this review, the periodic autoregressive (PAR) model developed by K.W. Hipel and A.I. McLeod of Canada was considered to be most suitable. The model was fitted to six time series - monthly basin average rainfall for Madden Lake, Gatun Downstream and Gatun Total, and monthly inflows from these three basins.

Monthly data for the period 1911 to 1995 was used to develop model parameters for the rainfall series. The data for last 5 years, 1996 to 2000, was used for verification of the parameters. The results are given in Appendix F. In case of inflow series, the model parameters were developed using 1941 to 1997 data and last three years, 1998-2000 were used for model verification. The results are also given in Appendix F.

The modeling results were generally quite good except that some of the high monthly rainfall and monthly inflows were not properly reproduced. The low and medium flows showed good fit. Appendix F provides comparisons of historical and simulated rainfall and flows.

E.9 Synthetic Time Series

HEC-4 computer model developed by the United States Army, Corps of Engineers, Hydrologic Engineering Center, was used to generate synthetic time series. Ten series, of 100 years period each, were generated for three series of basin average rainfall and three inflow series. The program used the monthly rainfall series of 90 years, and monthly inflow series of 60 years as input to generate the synthetic sequences. In the generation process, the means and standard deviations of the input series are maintained. Results are presented in Appendix G.

E.10 Effect of El Nino

All available data/information on the indices qualifying El Nino southern oscillation (ENSO) were obtained. The indices included: sea surface temperatures (SST) and its anomalies, southern oscillation index (SOI, difference between sea level pressures observed at Tahiti and at Darwin) and outgoing long wave radiation (OLR). Major El Nino episodes since 1525 were identified qualitatively and since 1951 on a quantitative basis. The regions of measurements of these indices were identified.

From the locations of the regions relative to the location of Gatun watershed, it was determined that a correlation, if any, would be between the ENSO indices observed in El Nino 3 region, North Atlantic region and SOI. However, actual data showed that there was no correspondence between the low flows in Gatun (or high flows) and the SST of North Atlantic and SOI. The SST recorded in the region of El Nino 3 could have some relationship.

To assess the effect of El Nino on the rainfall/runoff in the Gatun watershed, the long-term mean annual rainfall and runoff were compared with the annual rainfall/runoff recorded during the El Nino years. In all cases the recorded rainfall or runoff were significantly low. For the major episodes the data is given in Table E-4.

Table E-4

PERCENT DECREASES IN ANNUAL RAINFALL AND RUNOFF

Rainfall station	1930 Episode	1957 Episode	1976 Episode	!977 Episode	1982 Episode	1997 Episode
Madden Lake	22.3	28.8	37.8	18.7	27.4	33.4
Gatun Downstream	20.5	14.6	27.6	15.0	24.3	38.2
Gatun Total	21.1	19.3	30.9	16.3	25.4	36.7
Runoff Station						
Madden Lake	------	33.8	30.9	20.6	18.1	36.8
Gatun Downstream	------	37.4	31.5	25.6	23.5	49.3
Gatun Total	------	35.9	31.2	23.6	21.3	44.3

Similar comparison was made on a monthly basis for 1976-77, 1982-83 and 1997-98, the most severe episodes since 1951 for which the monthly data for ENSO indices were available. Table E-5 shows the comparison. Most affected months were of dry and transitional seasons as shown in the table.

Table E-5

PERCENTAGE DECREASES IN MONTHLY RAINFALL AND RUNOFF

Months and Year	Madden Lake	Gatun Downstream	Gatun Total
Average Rainfall			
Nov 76	41	47	45
Dec	86	67	74
Jan 77	0	46	39
Feb	76	65	68
Mar	46	78	66
Apr	70	73	71
Nov 82	62	58	59
Dec	75	85	83
Jan 83	59	69	71
Feb	47	88	74
Mar	29	75	60
Jul 97	52	31	39
Aug	55	42	46
Sep	16	19	18
Oct	28	42	38
Nov	25	39	38
Dec	86	83	84
Jan 98	55	83	79
Feb	44	44	45
Mar	22	13	17
Basin Inflow	Madden Lake	Gatun Downstream	
Dec 76	67	61	
Jan 77	42	52	
Feb	32	45	
Mar	31	55	
Apr	55	71	
May	53	40	
Jun	48	47	
Jul	35	46	
Nov 82	35	42	
Dec	61	72	
Jan	41	59	
Feb	43	52	
Mar	42	54	
Apr	44	38	
Jul 97	49	54	
Aug	55	66	
Sep	41	51	
Oct	36	49	
Nov	56	46	
Dec	67	75	
Jan 98	61	71	
Feb	50	61	
Emar	61	58	

E.11 Effect of Sunspots

Variations in sunspot numbers offer only a general indicator of solar activity. However, there is a strong association between sunspots and Earth's weather and climate. Amount of annual rainfall at many places in the world, shows dependence on the 11-year sunspot cycle. There is a reasonable trend for greater than average rainfall during solar maximum years in the equatorial latitude region (between 20° north and 20° south). In contrast to this, there are studies that have shown that increase in sunspots may decrease air temperature and decrease rainfall. However, orographic effects and other climatic indices may override any solar cycle influence.

E.12 Analysis of Droughts

Monthly runoff series of Madden Lake (drainage area draining into the lake), Gatun Downstream (drainage area between Madden Dam and Gatun Dam) and Gatun Total (drainage area upstream of Gatun Dam including the drainage area upstream from Madden Dam) were used. The period of record was 60 years from 1941 to 2000. The magnitudes of volume corresponding to selected duration and return periods are given in Table E-6.

The table also includes the driest and wettest period of record.

E.13 Global Warming

An extensive literature search was made to determine the effect of global warming on the water supply. There is no clear trend of the effects of global warming at various locations in the world. Rising temperatures could produce more than normal rainfall at some places and less than normal rainfall at other places. In the Gatun watershed at Balboa Heights (Balboa FAA), an increasing trend in temperature showed increase in rainfall. Since long-term temperature data were not available at other stations this trend could not be confirmed. Additional studies are required.

E.14 Conclusions and Recommendations

The conclusions and recommendations given in Section 19.0 are provided below for reference.

1. Hydrometeorological data collection and transmission system of ACP are well maintained.

Table E-6

RUNOFF VOLUMES (MCM) FOR SELECTED DURATIONS AND RETURN PERIODS

Duration in Months

Return Period (yr)	3	6	12	18	24	30	36
Madden Lake							
Driest	100	430	1309	2054	3387	3952	8266
Wettest	1432	2281	3478	5015	5990	7438	5340
10	135	500	1630	2450	3730	4790	6400
25	114	445	1480	2160	3500	4300	5500
50	110	425	1350	2060	3400	4000	5300
75	100	410	1250	2000	3300	3800	5100
Gatun D/s							
Driest	73	429	1599	2347	4375	5412	7255
Wettest	2419	3916	5447	7865	8971	11797	12942
10	127	533	2616	3404	5655	6745	9182
25	100	477	2104	2917	4839	5800	8223
50	80	440	1800	2500	4400	5600	7600
75	73	410	1700	2300	4100	5300	7100
Gatun Total							
Driest	223	868	2908	4426	8476	9364	12708
Wettest	3399	5629	8582	12057	16071	18115	20225
10	249	1061	4020	5860	10250	11800	15350
25	234	970	3580	5070	8500	10250	14050
50	230	900	3100	4700	8200	9400	13000
75	225	860	2800	4300	7900	8900	12000

2. Use of storage rainfall gauges may be discontinued. Instead a non-recording rain gauge should be installed at each meteorological station to provide a check on the tipping bucket gauge.

3. Stream gauging procedures should be improved. Wading discharge measuring method should be introduced for low flow measurements where feasible. The number of observation points for depth and velocities should be increased. The observations should be made at 20 to 25 verticals across the river. However, the minimum distance between the verticals should be 0.5 meter for wading and 1.0 meter for measurements from an overhead cableway.

4. Air line corrections should be avoided as discussed in the report.

5. Time series analysis indicated that all rainfall and runoff series are consistent and homogeneous. The decreasing trends shown are insignificant at 95 percent confidence level.

6. Long-term rainfall and runoff data at various locations in the watershed can be used for further analysis of canal lockages. There is no need to treat the data to correct for decreasing trend.

7. El Nino has a negative effect on the rainfall and runoff series. Depending upon the severity of an episode, the rainfall or runoff could be as low as 10 to 20 percent of normal values on monthly basis. Worst affected months are November through February / march.

8. A decreasing trend since 1971 (indicated by mass curves at some stations) could be due to most severe El Nino episodes of 1976-77, 1982-83 and 1997-98. These episodes affected the mean and standard deviation of the annual series from 1971 to 2000.

9. There is no reason to believe that slightly decreasing trend from early 1970's was due to any change in instrumentation, environment or observation techniques.

10. An increasing trend in number of sunspots from mid 1960's and decreasing trend since mid 1980's, may also be responsible for a slight decreasing trend since early 1970's.

11. There is an increasing trend in temperatures at the four selected stations. This could produce an increasing trend in the rainfall. Rainfall data at Balboa Heights confirms that but it must be confirmed by analyzing other stations.

12. A more detailed study may be initiated to analyze El Nino effect on hydrologic series and relation between El Nino, intertropical convergence zone and sunspots.