CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE
FACULTY OF ENVIRONMENTAL SCIENCES
DEPARTMENT OF LAND USE AND IMPROVEMENT (FES)
LAND AND WATER MANAGEMENT

MASTER OF SCIENCE (M.Sc.) THESIS

SOIL EROSION AND SEDIMENT YIELD IN THE PANAMA CANAL BASIN, PANAMA

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SUPERVISOR: **Ing. JANA KALIBOVÁ**

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CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Environmental Sciences

DIPLOMA THESIS ASSIGNMENT

Bc. Julián Eli Gutiérrez Hernández

Land and Water Management

Thesis title

Soil Erosion and Sediment Yield in the Panama Canal Basin, Panama.

Objectives of thesis

The main aim of my diploma thesis is to quantify the sediment yield from the two sub-basins supplying water for the Panama Canal, namely the Alhajuela Lake and the Gatun Lake sub-basins. The study will be based on the analysis of flow rate and sediment concentration data. The data will be obtained from the Panama Canal Authority for years 1998 – 2007 at several gauging stations situated on the main streams that feed the lakes.

Methodology

The Methodology consist of:

1. Collection of the suitable time series of precipitation, flow rate and sediment concentration at several gauging stations situated on the main streams that feed the lakes.

2. Estimation of sediment yield of the examined sub-basins, based on the data provided.

3. Comparison of the sediment yield of the examined sub-basins, using RStudio tools.

4. Discussion whether the sediment yield from the sub-basins poses a threat to the sustainability of the Panama Canal and whether any changes in the current basin management would be necessary.

The proposed extent of the thesis

40 – 60 pages

Keywords

Erosion, Sedimentation, Precipitation, Rainfall, Flow rate, Runoff, Lakes.

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Declaration

I hereby declare that I JULIÁN ELI GUTIÉRREZ HERNÁNDEZ. solely authored this master thesis as one of the prerequisite requirements for the M.Sc. degree at the Faculty of Environmental Sciences, Czech University of Life Sciences Prague.

I have carried out different studies connected to my thesis on my own work and quoted only according to the references listed within. However, contributions of others are involved, especially under the guidance of Ing. Jana Kalibová.

Prague, 14 th April 2016.

Julián Eli Gutiérrez Hernández

Julián Eli Gutiérrez Hernández.

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Abstract

Soil erosion is a major issue in Panama because the frequency of rainfall promotes transport of soil from disposal sites into the canal channel. Increased erosion means the canal channel needs to be dredged more frequently to keep the channel operational, even now with the expansion of the Panama Canal. The Alhajuela Lake and Gatun Lake sub-basin, provides up to 40% and 60 % of the water necessary to operate the Panama Canal (Larsen and Albertin, 1984). However, excessive loads of sediments in the Panama Canal Basin sediments largely impact in the Alhajuela Lake and Gatun Lake as they steadily reduce its water storage capacity. The main aim of my diploma thesis is to quantify the sediment yield from the two sub-basins supplying water for the Panama Canal, namely the Alhajuela Lake and the Gatun Lake basins. The study will be based on the analysis of flow rate and sediment concentration data. The data was obtained by the Panama Canal Authority in the years 1998 – 2007 at several gauging stations situated on the main streams that feed the lakes. The samples were taken measured in situ-produced sand-sized sediment samples (0.25 to 0.85 mm) to estimate the rate and distribution of sediment generation in the Panama Canal Basin in the years 1998 – 2007 at several gauging stations situated on the main streams that feed the lakes. Results indicate that the upper Alhajuela Lake sub-basin is generating sediment uniformly. This analysis showed that the sediment yield rates of 195 to 1109 [tons/km^2/year] for the Alhajuela Lake with the flow rates of 61.3 to 106 [m^3/s] and then to Gatun Lake, the sediment yield rates of 136 to 339 [tons/km^2/year] with the flow rates of 57.0 to 109 [m^3/s]. The sediment yield measured in the Panama Canal basin, for years 1998 to 2007 are: 5442[tons/km^2/year] for Alhajuela Lake and 2349.3 [tons/km^2/year] for Gatun Lake. Datasets for land cover, rainfall, slope, flow rate and sediment concentration at several gaunging stations situated on the main streams that feed the lakes; using the final units' tons per day [tons/day] (Julien 2010) were used in order to estimate the annual soil loss in each sub-basin. Thus, short-term sediment yields and long-term sediment generations are in balance, which implies steady landscape behavior over time. Such study highlights the importance of proper watershed management in order to reduce the sedimentation of Alhajuela Lake and Gatun Lake in the Panama Canal Basin.
 Keywords: Erosion, Sedimentation, Precipitation, Rainfall, Flow rate, Runoff, Lakes.

Abstrakt

Eroze půdy v Panamě představuje závažný problém, který podtrhují vysoká četnost a úhrny dešťových srážek. Erozní činnost dešťové vody vede k transportu sedimentu a zanášení průplavu. Pro zachování kapacity a provozuschopnosti průplavu je tak nutné průplav časteji vybagrovávat a sediment odstraňovat. Jezero Alhajuela a povodí jezera Gatun dodávají 40% až 60% objemu potřebné vody k fungování průplavu (Larsen and Albertin,1984). Avšak nadměrné množství sedimentů z povodí jezer Alhajuela a Gatun vyvolává snížení kapacity průplavu. Cílem mojí diplomové práce je kvantifikovat množství sedimentů z povodí jezer Alhajuela a Gatun, která jsou zodpovědná za konstantní dodávání vody k fungování panamského průplavu. Studie bude založena na analýze dat průtoku a koncentrací sedimentů v tocích povodí jezer. Data posyktne úřad panamského průplavu pro roky 1998 až 2007, a to pro několik měrných stanic situovaných na tocích napájejících zmíněná jezera. Vzorky byly odebrány a naměřeny in-situ. Vzorky sedimentu (0.25 až 0.85 mm) sloužily pro odhad rychlosti zanášení a distribuce sedimentů v povodí panamského průplavu od roku 1998 do roku 2007. Výsledky ukazují, že horní povodí jezera Alhajuela produkuje sedimenty rovnoměrně. Dle této analýzy byla pro jezero Alhajuela stanovena sedimentační rychlost 195 až1109 [tun/km^2]. rok a průtoku 61.3 až 106 [m^3/s]. Pro jezero Gatun byla sedimentační rychlost 136 až 339 [tun/km^2]. rok a průtoku 57.0 až 109 [m^3/s]. Produkce sedimentu naměřená v povodí panamského průplavu od roku 1998 do roku 2007 je pro jezero Alhajuela 5442 [tun/km^2]. rok a pro jezero Gatun je 2349.3 [tun/km^2]rok.Soubory dat pro land cover, dešťové srážky, sklon svahů, průtoky a koncentraci sedimentů v měrných profilech jsou vyjádřeny v tunách za den (Julien 2010) a slouží k odhadu roční ztráty půdy v každém povodí. Krátkodobá a dlouhodobá produkce sedimentu jsou v rovnováze, za předpokladu ustáleného chování podmínek krajiny po celou dobu měření. Tato studie upozorňuje na důležitost vhodného managementu povodí za účelem snížení produkce a transportu sedimentu v povodích jezer Alhajuela a Gatun zásobujících panamský průplav.

Klíčová slova: Erosion, Sedimentation, Precipitation, Rainfall, Flow rate, Runoff, Lakes.

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Symbols

Symbols and Units

Element	Symbol	Units	
		SI	English
Section area	A	m^2	1 foot $(ft)^2$
Basin area		km^2	acre
Flow rate	Q		mi^2
Sediment discharge	Q_s	m^3/s	$foot^3/s$
Suspended sediment discharge per unit are (annual production sediments)	q_s	t/year/ km^2 Q[m^3/s]	
Flow per unit area (Performance or specific flow)	q	l/s/ km^2	$ft^3/s/mi^2$
Sediment concentration	cs	mg/l	
Rainfall	R	mm	inch
Runoff	R_0	mm	inch
Volume	V	MMC,ml	Acre foot

MCF for 1000 cubic feet (M denotes mil, thousand)

MMC= million cubic metre

Conversion factor tons (short) to MCF (density 69.5 lbs/feet^3 [1.113 t/m^3]) =$3.07692x10^{-05}$

1 feet^3 = 0.02831685 m^3

Chapter 1

Introduction

1.1 General introduction

The Panama Canal (Spanish: Canal de Panamá) is a 48-mile (77 km) ship canal in Panama that connects the Atlantic Ocean (via the Caribbean Sea) to the Pacific Ocean located in Panama. Officially called the Republic of Panama, is a country in Central America situated between North and South America. The Panama Canal is a critical international trade route and pathway for global commerce.

The Alhajuela Lake and Gatun Lake sub-basin, provides up to 40% and 60 %, respectively, of the water necessary to operate the Panama Canal (Larsen and Albertin, 1984). Even though the storage capacity of the lakes is vital to the operation of the canal and thus, the global economy, little is known about the rate and processes of sediment production in tributary drainage basins. Transportation of this sediment into Alhajuela Lake and Gatun Lake are steadily reducing its water storage capacity. However, significant deforestation of the watershed has cleared away much of the vegetation, and reduced the area's water capacity. This has resulted in falling water levels in the lake during the dry season. Coupled with the massive increase in canal traffic since its opening, and the resultant increase in water usage, this is an ongoing problem for the canal, and actually problem with erosion and sediments yields (1998-2007).

The erosion and consequent runoff are the most common cause of high levels of turbidity and color in the water (Vasyukova et al., 2012). Turbidity has no health consequence, but it is targeted in water treatment because it is an indicator of the presence of disease-causing organisms and the production of disinfection by-products, which are carcinogens (EPA, 2013; Viessman et al., 2009). A study conducted in the Delaware River, USA found that increased concentrations of Giardia, Cryptosporidium and a variety of other microorganisms were associated with rainfall. This increase was partly attributed to erosion and consequent surface runoff of particulate matter, re-suspension of river bottom and storm drain sediments (Atherholt et al., 1998). Another concern is the transport of nutrients, pesticides and other damaging farm chemicals into water bodies, which also decrease water quality and can cause eutrophication (Kouli et al., 2009). However, in recent decades there has been concern that the water storage capacity of Alhajuela Lake is decreasing due to the accumulation of sediment in the lake, the source of which is the surrounding watersheds (Heimsath et al.,2002; Perg et al.,2003; Phillips et al., 1998). Others worry that future decreases in runoff (perhaps driven by human-induced climate change or by land use) might be more important than sedimentation (Condit et al., 2001). In any case, decreased water storage in Alhajuela Lake due to either sedimentation or decreased runoff from the watershed could hinder canal operation.

Soil erosion is a natural process that contributes to the formation of the earth surface over both short and long time scales (Rozos et al., 2013). Nonetheless, soil erosion is now greatly exacerbated by inappropriate agricultural practices, deforestation, overgrazing and construction activities (van der Knijff et al., 2000; Arekhi et al. 2012; Kouli et al., 2009). These and other anthropogenic activities have made erosion a very serious environmental problem in many areas (Rozos et al., 2013). At the same time, increasing global population and the impacts of climate change are putting stress on water resources (Anderson et al., 2011). In developing countries, where water agencies struggle to afford high-cost water treatment technologies to cope with water quality issues, it becomes imperative to promote integrated water resources management (IWRM) as the most feasible and sustainable solution (Kalbus et al., 2012). IWRM has been defined as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Kalbus et al., 2012).

This area of study is an approach to soil erosion risk assessment that relies on field observations. Factorial scoring is the assignation of scores based on established classes, the scores are multiplied, and the result is used to determine the level of vulnerability to erosion (van der Knijff et al., 2000). Montier et al. (1998) developed an erosion map for the whole of France using this method. "The choice for a particular study largely depends on the purpose for which it is intended and the available data, time and money" (van der Knijff et al., 2000).

Anderson et al. (2011) conducted a regional study in Latin America and the Caribbean where they examined the potential impacts of climate change on surface water runoff under a wide range of future precipitation scenarios. For this thesis I developed the analysis of the Sediment Yield, using the rainfall-runoff data base based on curve numbers and the result of different climate change.

The study concluded that the sub-basin with more input of Sediment Yield was the Alhajuela Lake; erosion in the Panama Canal is expected to increase because the Sediment Yield has a direct relationship with the Precipitation [mm] but in with drier conditions El Niño event can be fluctuating, broken up by intense storms, and a decrease in of rainfall. The Panamanian rainy season is fall and early winter, which brings the water needed to fill the lakes each year. Unfortunately, rainfall from the El Niño event was well below normal, as the summer and drought keep going and water levels can lower even more. The Panama Canal Authority expanded the canal, making it wider and deeper to accommodate the largest ships, called Panamax. Naturally, more water is needed to fill the deeper, wider channel. The concern is that, as the drought continues, lakes Gatun and Alajuela will not have enough water to allow the ships that ride lower in the water to make the trip through the canal, as a result, the canal will be forced to place a restriction on the types of ships that can pass through the canal, which will have a worldwide impact on the shipment of goods.

Should the drought continue and ships have to travel all the way around the tip of South America, it will add significantly to the cost of goods worldwide. In the end, the additional cost, including extra fuel, will hit consumers. The drought is a normal consequence of El Niño, the periodic warming of ocean temperatures between Peru and Indonesia. This trend combined with existing rates of soil loss and sediment caused by poor land management were considered as strong motivations to continue performing this type of study at lower geographical Scales in Panama Canal Basin. The present study will focus on using the instant solid flow in tons per day [tons/day] (Julien 2010) to assess the vulnerability to Soil Erosion and Sediment Yield of the Panama Canal Basin located in Panama.

Chapter 2

Objective of the Study

The main aim of my diploma thesis is to quantify the sediment yield from the two sub-basins supplying water for the Panama Canal, namely the Alhajuela Lake and the Gatun Lake sub-basins. The study will be based on the analysis of flow rate and sediment concentration data. The data will be obtained by the Panama Canal Authority for years 1998 – 2007 at several gauging stations situated on the main streams that feed the lakes.

2.1 Specific objectives are:

- Based on the historical data of sediment concentration and rates calculate the annual average soil loss rate; the sediment concentration brought into the Panama Canal.
- Analyze the development of erosion rate, related to flow rates, precipitation, slope gradient and land use.
- Identify which sub-basin has higher production rates sediment and compare the results using RStudio tools.
- Quantifying the effects of sediments yield concentration in order to understand the relationship between the high sediments yield and rainfall pattern.
- Predicting the effect of deforestation on sediment losses under different land cover scenarios at the Alhajuela Lake and Gatun Lake sub-basin located in the Panama Canal Basin.
- Recognition of critical areas for soil conservation planning.

Chapter 3

Material and Methods

For the development of this thesis, I tested the database from the Panama Canal Authority; the data were obtained by the Panama Canal Authority in years 1998 – 2007 at several gauging stations situated on the main streams that feed the lakes; Precipitation [mm], Flow rate Q[m^3/s], Sediment Yield [mg/l] – [tons/day]. Once I got it the database, the percent annual of all these: time series of Precipitation [mm], Flow rate Q[m^3/s] and Sediments Yield [ton/year]-[ton/km^2/year]; was calculated; then I used RStudio for all the graphics and get box-plot, and then analyze all my results.

3.1 Physical characteristics of the sub-basins

The research was situated in two lake basins supplying the Panama Canal, in Panama these were Gatun Lake and Alhajuela Lake (Figure 5-6, Appendix 1) and the Geographical coordinates **(Table 5)**.

Some of the physical characteristics that influence the production of sediments such as the drainage area, vegetation covers and the slope ranges were defined until the measurement sites located in the section of appraisal of the seven hydrometric stations analyzed outflows. **(Table 7 and Appendix 1,2)**.

The drainage area measures until the section of capacities of the sub-basins Alhajuela sub-basins: rivers Chagres, Pequení and Boquerón represent 66% (640 km^2) of the total area of inputs of sediments. The average gradient of these sub-basins with control hydrometric varies between 47% and 56% and in the relief they predominate the steep slopes to very pronounce that cover between 55 and 70% of its drainage areas. The forest cover is the type of dominant vegetation, as is the case of the sub-basins of the rivers Pequení Chagres and in where it occupies 98% of their areas drained. The average rainfall in the sub-watershed of the reservoir Alhajuela was estimated at 3183 mm for the period 1998-2007. **(Table 4, and Appendix 4)**.

For the Gatun Lake the drainage area measures until the section of appraisal of the sub-basins Cirí gauging rivers Grande, Trinidad, Gatun and Caño Quebrado represents 29% (544 km^2) of the total area of inputs of sediments. In these sub-basins the average gradient varies between 10% and 40% and presents a relief with gentle slopes to moderate covering between 46% and 97% of its drainage areas. In the western sector the main plant cover are the pastures and cover between 47% and 73% of the drainage area of the sub-basins of the rivers Ciri Grande, Trinidad and Caño. The average rainfall in the sub-watershed of the Gatun Dam was estimated at 2334 mm for the period 1998-2007. **(Table 5, and Appendix 4)**.

Although the forest coverage prevails in a high percentage in the sub-watershed of the reservoir Alhajuela, the characteristics of terrain slope and rainfall regime are most critical to the production of sediments that in the sub-watershed of the Gatun Dam.

3.2 Field Samples collection in the Alhajuela Lake and Gatun Lake

Suspended sediment samples were taken with equipment of updated technology for to get the most precise samples, which are hydrodynamic and standardized by agencies of the United States, that inserts a glass bottle with a capacity of 500 ml. These bottles are connected to a line that allows the air outlet as the water enters the bottle by means of a nozzle. The nozzle in turn controls the input speed of the water so that it is approximately equal to the rate of flow of the current. Local this feature is important so that the sample is representative of the volume of sediments transported by the current.

Since the beginning of the PMCSS in 1980, used the following models of samplers of suspended sediments: US DH-48, US DH-59 and US D-74.

The US DH-48 applied when the river has depths less than 1.0 m (3.0 ft) and the sampling is performed by video. The US DH-59 is used from the cable track when the depths in the river does not allow collecting samples by video and the US D-74 is used to take samples during floods. Each one of these samplers account with nozzles 1/8, 3/16, 1/4 inch, depending on the speed of the river.

The gauging was taken from the periods of January 1998 to December 2007; the samples were taken generally daily a sample and every hour during floods when was necessary. The samples were taken samples of suspended sediment normally: per day, after per week, after calculate monthly and then per year in the basis and during periods of gauging. Currently the number of samples for the samples were taken is per month and up to three samplings only during the periods of floods: of lifting, lowering and if possible at the time of maximum of the flood.

For taken the outflow, the sampling methodology of the engineer is based on the selection of vertical section of gauging section that represents equal increments of flow or discharge (EDI by its acronym in English). After all items listed above have been done, the measurement note sheets for recording observations are prepared. The following information will be recorded for each discharge measurement:

1. Name, date of stream and location to correctly identify the established gauging station.
2. Developing a Cross-Section of the Site and Establishing a Reference or Staff Gauge.
3. The capacity is performed to determine the four vertical (EDI) that correspond to increments equal to 25% of the total flow of the section, or used the graphs that relate the EDI with the lift of the river, depending on the speed with which change the flow rate.
4. Time measurement was started using military time (24-hr clock system).
5. Select the type of sediment sampler; you choose the size of the nozzle and determine the time of the descent and ascent of the sampler According to the graph of filling time of bottles.
6. In each sampling vertical focuses, the sampler with the nozzle facing the outlet and from the surface is lowered until the Fund and climbs at a steady pace.
7. So that each sample is representative and validated should have a volume between 300 ml and 400 ml.
8. Bank of stream that was the starting point.
9. Gauge heights and corresponding times.
10. Water temperature.

The samples were taken has collected between 86 and 895 samples in conditions of high flow rates during the period 1987-2007, which represents between 2% and 20% of the total collected.

3.2.1 US DH-48 Depth integrating suspended hand line sampler

The US DH-48 is a lightweight hand-held depth-integrating sampler used for the collection of suspended-sediment samples in wadeable streams. The US DH-48 was one of the first samplers designed by FISP. Like all FISP suspended-sediment samplers, it is designed to sample isokinetically, meaning that water and sediment enters the nozzle at the same velocity as the stream being sampled in order to collect a representative sample. The sampler is made of aluminum, weighs 3.5 lbs. and is approximately 10 in long. A pint milk bottle is used as the sample container. The pint milk bottle container is held in place and sealed against a rubber gasket by a hand operated, spring tensioned clamp at the rear of the sampler. A brass 1/4-in internal diameter intake nozzle extends horizontally from the nose of the sampler body. A streamlined projection on the side of the sampler that points toward the rear of the sampler accommodates the air exhaust port that allows air to escape from the sample bottle as it fills with sample. (USGS 2015)

A standard 1/2-in diameter wading rod is threaded into the top of the sampler body for suspending the sampler. To sample to depths greater than can be waded, wading rod extensions in 1- and 3-ft lengths can be added to the sampler. With the extensions, the sampler can be deployed from a low bridge or boat. The unsampled zone using the US DH-48 is 3.5 in. The sampler can be used in velocities that range from 1.5 to 8.9 ft/sec.

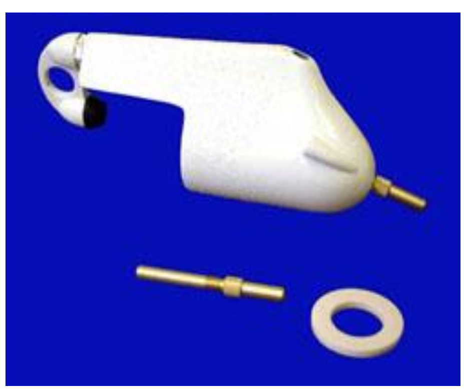

Figure 1. US DH-48 Depth integrating suspended hand line sampler (USGS 20015).

3.2.2 US DH-59 Depth integrating suspended hand line sampler

The US DH-59 is a medium-weight hand-line suspended-sediment sampler. The sampler can be lowered and raised, hand over hand, with a flexible suspension line. It can be used in stream depths up to 15 ft and in steam velocities ranging from 1.5 to 5.0 ft/sec. The sampler is a streamlined bronze casting that is 15 in long and weighs 22 lbs. The sampler uses a pint glass milk bottle. The bottle container is sealed against a gasket in the head cavity of the casting by pressure applied to the base of the bottle by a hand operated, spring tensioned, pull rod assembly at the rear of the sampler. The sampler uses a 3/16- or 1/4-in internal diameter intake nozzle that projects horizontally upstream from the head of the casting. As a sample is collected, the displaced air in the bottle is ejected downstream through the air exhaust tube integrally cast into the body and protected by a streamlined projection on the side of the head of the sampler. The unsampled zone using the US DH-59 is 4.5 in. The sampler is calibrated and supplied with nozzles having 1/4" and 3/16" bores. Sample container bottles and the suspension are not furnished with the hand line suspended sediment sampler. The sampler can be used in stream depths up to 15 ft. and in stream velocities ranging from 1.5 to 5.0 ft./sec. The unsampled zone using the US DH-59 is 4.5". Includes case, hanger bar, 2 gaskets, and 2 ea. of 3/16" and 1/4" red plastic nozzles. (USGS 2015)

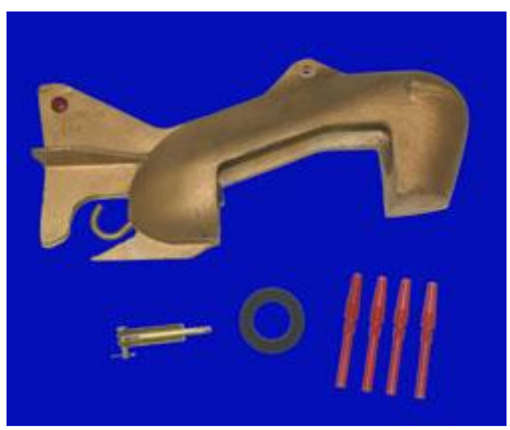

Figure 2. US DH-59 Depth integrating suspended hand line sampler (USGS 2015).

3.2.3 US DH-74 Depth integrating suspended sampler

The US D-74 is a cable-suspended suspended-sediment sampler. The sampler is lowered and raised by means of a suspension system such as a reel and crane or bridge board. It could also be used with a cableway. The sampler can be used in stream depths up to 15 ft and in stream velocities ranging from 1.5 to 6.6 ft/sec. The sampler has a cast bronze, streamlined body that is 24 in long and weighs 62 lbs. A pint or quart glass bottle sample container is used with the sampler. The head of the sampler is hinged to permit access to the sample container. Tail vanes are provided to orient the instrument into the stream flow. The US D-74 uses 3/16- and 1/4- in internal diameter intake nozzles that project into the stream current for collecting a sample. A port, which points downstream, is located on the side of the sampler head from which air escapes as it is displaced by the sample filling the container. The unsampled zone using the US D-74 is 4.1 in. (USGS 2015)

The sampler has a cast bronze, streamlined body in which a round or square pint or quart bottle sample container (not furnished) is enclosed. The head of the sampler is hinged to permit access to the sample container. Tail vanes are provided to orient the instrument into the stream flow. The head of the sampler is drilled and tapped to receive the 1/4 inch, 3/16 inch or 1/8-inch intake nozzle which projects into the current for collecting the sample. A port, which points downstream, is provided on the side of the sampler head from which air escapes as it is displaced by the sample being collected in the container. The instrument is suspended on a hanger bar attached to a 1/8-inch steel cable and is lowered and raised by means of a reel mounted on a crane. (none of the equipment for suspension of the sampler is furnished.)

Figure 3. US DH-74 Depth integrating suspended sampler (USGS 2015).

3.3 Sediment yield – sediment rating curve

Sediment yield by a stream or the stream sediment load is the total sediment delivered past a point of interest or the watershed outlet during any given time (Borah et al. 2007). The stream sediment load can be determined using either a short-term or a long-term analysis. The short-term analysis of sediment load is performed generally on a daily basis expressing often the magnitude and variability of sediment transport during rainstorm or snowmelt events (Julien 2010). On the other hand, the long-term sediment load analysis estimates the amount of sediment yielded by a stream. On an annual basis, it gives the mean annual sediment load of a stream (Julien 2010). The long-term sediment is utilized for reservoir sedimentation, sediment budget and degradation studies. Soil erodibility factor (K) The K value or the soil erodibility factor depends on the percentage of sand and organic matter in the soil. Soil information was provided by the Panama Canal the K[0.0864] values were determined with the percentages of sand, silt and organic matter along with soil structure and permeability to generate a representative value of a soil's ability to erode. Reference values were used to ensure that the calculated values were logical. The reference values were as follows: 0.05 – 0.15 for soils high in clay; 0.05 – 0.20 for soils that are high in sand; and 0.25 – 0.65 for soils high in organic matter (Jones, n.d.) Soil erodibility factor (K) is related to the integrated effect of rainfall, runoff, and infiltration on soil loss. This factor accounts for the influences of soil properties on soil loss during storm events on upland areas (Renard et al. 1997). In practical sense, K is a lumped parameter representing an integrated relationship between annual average erosion, profile reaction to erosion, and hydrological processes. A unit plot is 72.6 ft long, with a uniform lengthwise slope of 9 percent, in a continuous fallow, tilled up and down the slope (Weesies, 1998).

The laboratory method used by the unit of water quality for the determination of the concentration of suspended sediments in the Program of flow measurement of suspended sediments is the established by the "Standard Methods", edition 21: SM 2540-D.19

The method SM 2540-D is to filter a sample of water through a glass fiber filter with pores of 1 micrometer (μm) in size, previously weighed and then dried in an oven at a temperature between 103°C and 105°C until a constant weight of the filter more sediment retained.

The sediment rating curve daily total sediment discharge in tons per day is the product of the daily mean water discharge, flux-averaged total sediment concentration, and a unit conversion; finally, the instant solid flow is obtained by applying the following equation. (Julien 2010). **(Tables 1-2)**.

$$\boldsymbol{Qs}_{(\boldsymbol{metric\ tons/day})} = \boldsymbol{k} * \boldsymbol{C}_{[\frac{\boldsymbol{mg}}{\boldsymbol{l}}]} * \boldsymbol{Q} \quad , \qquad [eq.1]$$

Where:

$\boldsymbol{Qs}$: $Instant\ solid\ flow\ in\ tons\ per\ day\ (tons/day)$

$\boldsymbol{k}$: $coefficient\ equal\ to\ 0.0864\ for\ the\ international\ system$

$\boldsymbol{C_{mg/l}}$: $average\ concentration\ of\ suspended\ sediments\ in\ miligrams\ per\ liter\ \left(\frac{mg}{l}\right), got\ in\ the\ lab$

$\boldsymbol{Q}$: $instant\ flow\ in\ cubic\ meters\ per\ second\ \left(\frac{m^3}{s}\right), got\ it\ from\ each\ hydrometeorological\ networks$

3.3.1 Annual sediment yield load

Two essential approaches can be used to determine the long-term average sediment load of a river: [a] the summation approach; and [b] the flow duration curve approach. The summation approach utilizes the mass curves method to determine the cumulative sediment load as function of time in years. The second approach combines a sediment-rating curve between total sediment discharge or flux-averaged concentration, and water discharge; and a flow-duration curve (Julien 2010).

3.3.2 Specific Degradation of the Panama Canal Basin

As determinant, sediment yield Y is the total sediment delivered past a point of interest or the basin outlet over a specified period of time and it is generally measured in tons per year. For a given watershed or basin, the specific degradation [SD] is obtained by dividing the yield [Y] by the drainage area A of the watershed. (Table 3) Therefore:

$$\boldsymbol{SD} = \frac{\boldsymbol{Y}}{\boldsymbol{A}} \quad , \qquad [eq.2]$$

Where:

SD= specific degradation in metric tons/km^2*year.

Y= sediment yield.   A= drainage area in km^2.

3.4 Coefficient of determination (r^2) of flow rate and production of suspended sediments in sub-basins

In the area between gauging sections, the production and flow rate of suspended sediments were determined, on the basis of a simple linear regression between the average value of the flow rate and the production of specific suspended sediments of the 7 hydrometric stations, for the period 1998-2007, included the calculation of final sediment yield **(Figure 21)**.

The Coefficient of determination between Sediment yield and flow rate ($\mathbf{r^2}$= 0.9557) is expressed by:

$$\boldsymbol{qs = 9.1471\, q - 184.7538} \qquad \textit{[eq.3]}$$

Where

$\boldsymbol{qs}$: $average\ production\ of\ suspended\ sediments\ yield\ in (\frac{\frac{t}{year}}{km^2})$

$\boldsymbol{q}$: $average\ specific\ flow\ in\ (\frac{\frac{l}{s}}{km^2})$

Chapter 4

Literature Review

This chapter provides an overview of the background literature on soil erosion processes before providing a review of Panama Canal, finally the erosion and sediment yield.

4.1 Description of the Panama Canal Basin

The Panama Canal is a critical international trade route and pathway for global commerce. Yet, despite the critical transportation services that the waterway provides, most accounts focus on the heroic tale of its construction. Consequently, many of us imagine the Panama Canal as an excavated channel between the Atlantic and Pacific Oceans that was finished nearly a century ago. Open nearly any historical work on the canal and you will read of a monumental engineering project completed in 1914 by virtue of American political will, technological innovation, and migrant labor. Panama occupies an isthmus connecting North and South America and separating the Atlantic and Pacific Oceans. The nation has a land area of approximately 29,000 square miles; the canal is oriented northwest-to-southeast and bisects mountains that run east-west along the spine of the isthmus. These mountains, the Cordillera Central, are flanked by upland plains that descend to rolling hills and coastal plains. The coastal plains are the country's best agricultural land, but 75% of an estimated 3.5 million inhabitants live in urban areas, particularly Panama City (population: ~1.4 million), which is located at the waterway's approximately 80 kilometers long connecting the Atlantic and Pacific Oceans. This waterway was cut through one of narrowest saddles of the isthmus that joins North and South America.

The Canal uses a system of locks compartments with entrance and exit gates. The locks function as water lifts: they raise ships from sea level (the Pacific or the Atlantic) to the level of Gatun Lake (26 meters above sea level); ships then sail the channel through the Continental Divide.

Each set of locks bears the name of the town-site where it was built: Gatun (on the Atlantic side), and Pedro Miguel and Miraflores (on the Pacific side).

The lock chambers steps are 33.53 meters wide by 304.8 meters long. The maximum dimensions of ships that can transit the Canal are: 32.3 meters in beam; draft their depth reach 12 meters in Tropical Fresh Water; and 294.1 meters long (depending on the type of ship).
The water used to raise and lower vessels in each set of locks comes from Gatun Lake by gravity; it comes into the locks through a system of main culverts that extend under the lock chambers from the sidewalls and the center wall. **(Figure 4,5)**.

4.1.1 Gatun Lake

Gatun Lake (Sp. Lago Gatún) is a large artificial lake to the south of Colon, Panama. It forms a major part of the Panama Canal, carrying ships for 33 km (21 mi) of their transit across the Isthmus of Panama, coordinates: 9°11´N 79°53´W, type: artificial lake, primary inflows: Chagres River, surface elevation 26 m. **(Appendix 2)**.
The lake was created between 1907 and 1913 by the building of the Gatun Dam across the Chagres River. At the time it was created, Gatun Lake was the largest man-made lake in the world. Gatun Dam was also the largest of its kind.
The lake is situated in the valley of the Chagres River. It was formed, and the river widened and deepened, by the construction of the Gatun Dam about 10 km (6.2 mi) from the river's estuary in the Caribbean Sea in 1907–1913. The geography of the area was ideal for the creation of a large lake here; the hills bordering the valley of the Chagres open up widely around the area of the lake, but come together to form a gap just over 2 km (1.2 mi) wide at the location of the dam. The damming of the river flooded the originally wooded valley; almost a century later, the stumps of old mahogany trees can still be seen rising from the water, and submerged snags form a hazard for any small vessels that wander off the marked channels.
Gatun Lake has an area of 425 km^2 (164 sq mi) at its normal level of 26 m (85 ft) above sea level; it stores 5.2 cubic kilometers (183,000,000,000 ft^3) of water, which is about as much as the Chagres River brings down in an average year. With the creation of the lake many hilltops became islands. The biggest and best known of them is Barro Colorado Island, home of the world famous Smithsonian Tropical Research Institute (STRI). The lake has given its name to the Gatun structure, which may be an eroded impact crater.

Gatun Lake forms a major component of the Panama Canal; the lake, including the flooded arm extending up the Chagres River, makes up 32.7 km (20.3 mi) of the raised part of the waterway, the other part being the 12.6 km (7.83 mi) Culebra Cut.

The canal follows a clearly marked route around the lake's islands, following the deeper water south from Gatun Locks, and then east. A small "shortcut" channel, the "Banana Cut", runs between the islands, providing a slightly shorter route through the lake; this is used by canal launches and yachts to cut a little time off the crossing, and to avoid the heavy ship traffic. The lake is also important as a reservoir of water for the operation of the canal locks. Each time a ship transits the canal 202,000 m^3 (53,400,000 US gal) of water is passed from the lake into the sea; with over 14,000 vessel transits per year, this represents a very large demand for water. Since rainfall is seasonal in Panama, the lake acts as a water store, allowing the canal to continue operation through the dry season.

A major factor in water regulation is the ability of the rainforest in the lake's watershed to absorb rainfall, releasing it gradually into the lake. However, significant deforestation of the watershed has cleared away much of the vegetation, and reduced the area's water capacity. This has resulted in falling water levels in the lake during the dry season. Coupled with the massive increase in canal traffic since its opening, and the resultant increase in water usage, this is an ongoing problem for the canal, and the actually problem with erosion and sediments yields (1998-2007).

The impassable rain-forest around Gatun Lake has been the best defense of the Panama Canal. Today these areas have endured practically unscathed by human interference and are one of the few accessible areas on Earth that various native Central American animal and plant species can be observed undisturbed in their natural habitat.

World famous Barro Colorado Island, which was established for scientific study when the lake was formed and is today operated by the Smithsonian Institution, is the largest island on Gatun Lake. Many of the most important ground breaking scientific and biological discoveries of the tropical animal and plant kingdom originated here. Lake Gatun encompasses approximately 180 square miles (470 km^2), a tropical ecological zone part of the Atlantic Forest Corridor and Eco-tourism on Gatun Lake has become a worthwhile industry for Panamanians. Gatun Lake also serves to provide the millions of gallons of water necessary to operate the Panama Canal locks each time a ship passes through and provides drinking water for Panama City and Colon.

4.1.2 Alhajuela Lake

Alajuela Lake (Spanish: Lago Alajuela) is an artificial lake on the Chagres River created by the Madden Dam and linked to the Panama Canal, Location: Panama, Coordinates 9°14´04´´N 79°34´32´W, lake type: reservoir, catchment area: 1,026 km^2, surface elevation 78.8 m. (Appendix 2) Lake Alajuela serves as a reservoir for the canal, which lies to the lake's southwest. The Chagres, Pequení, Boquerón, Salamanca, Indio, Piedras, San Cristóbal and Escandaloso rivers flow into the lake. At present, Alhajuela Lake ensures continued operation of the canal during the dry season and during years of drought. However, in recent decades there has been concern that the water storage capacity of Alhajuela Lake is decreasing due to the accumulation of sediment in the lake, the source of which is the surrounding watersheds (Heimsath et al.,2002; Perg et al.,2003; Phillips et al., 1998). Others worry that future decreases in runoff (perhaps driven by human-induced climate change or by land use) might be more important than sedimentation (Condit et al., 2001). In any case, decreased water storage in Alhajuela Lake due to either sedimentation or decreased runoff from the watershed could hinder canal operation.

Alhajuela Lake, in upper Chagres River basin, provides up to 45% of the water necessary to operate the Panama Canal (Larsen and Albertin, 1984). Even though the storage capacity of the lake is vital to the operation of the canal and thus, the global economy, little is known about the rate and processes of sediment production in tributary drainage basins. Transportation of this sediment into Alhajuela Lake is steadily reducing its water storage capacity.

Little is understood about the upper Chagres basin and its headwaters because the watershed is thickly vegetated and there are no established transportation routes. The Panamanian government protects the basin from development. Human disturbance is minimal and is mostly confined to the lower elevations and to the Piedras River tributary in the southern portion of the watershed.

The 466 km^2 upper Chagres basin has a total relief of ~800 m. The basin is dominated by steep hill-slopes. Aerial and ground observations suggest that sediment is delivered to the channels by both biologically driven soil creep and by landslides. Field observations show that in much of the lower and mid-basin, the river flows on bedrock suggesting little sediment storage. However, in the upper reaches of the Chagres, Esperanza, and Chagricito rivers, local areas have up to 2 m of boulders and alluvium overlain by floodplain deposits. In general, once sediment is delivered from the hill-slopes to the channel, it is quickly transported out of the drainage basin as suggested by the extensive reaches of bedrock-floored channels and small aerial extent of sediment storage. The mean annual precipitation for the Alhajuela Lake watershed is 2840 mm per year (Larson and Albertin, 1984). Most precipitation falls from mid-April to mid-December; January through March are the dry months. **(Appendix 4)**.

The climate of central Panama over the past 14,000 years, inferred from analysis of sediment cores from two lakes ~200 km east of the Chagres basin, changed from drier to wetter near the Pleistocene – Holocene climatic transition ~10,000 years ago (Bush et al., 1992). Additional dry periods (~3800 to 3700 yr BP, ~3400 to 2500 yr BP, and ~1900 yr BP to the present) may have occurred in central Panama during the Holocene as suggested by evidence from two swamps in the Darien province east of the Chagres basin (Bush and Colinvaux, 1994). Although much of central Panama may have experienced limited fluctuations in climate over the past 10,000 years, dated sediment cores from lakes west of the upper Chagres basin suggest that sedimentation rates have remained constant except for a slight increase in the sedimentation rate between 7,500 to 5,000 years ago (Bush et al., 1992).

4.1.3 Previous studies

Previous studies on sediment production and reservoir sedimentation in the Panama Canal Basin, have focused on the basin of Alhajuela reservoir:

Kellog, H. F., 1931: From measurements of suspended sediment in the Chagres River in Alhajuela, between September 1929 and February 1931, he estimated a solid suspension flow 0.056 MMC / year.

Wadsworth, F.H., 1978: It established that deforestation has caused sedimentation of the reservoir Alhajuela results in a loss of more than 5% in the capacity of useful storage volume and trends to keep usage land that time, it would result in a loss of 40% capacity Original total water storage for 2000.

Larson, C. L., 1979: He estimated a solid suspension flow 2,595 MCM / year.

Alvarado, Luis A., 1985: He estimated a solid suspension flow 0.774 MMC / year.

Tutzauer, Jack R., 1990: He estimated a solid suspension flow 0.890 MMC / year.
Note: MMC= million cubic metre.

4.1.4 The Geological History of Panama

Topography the arrangement of natural and artificial features of an area plays a key role in the following discussion. Before proceeding, then, it will be useful to explain current scientific knowledge of the geological history of the Panamanian isthmus. As we now understand plate tectonics, the isthmus emerged over a subduction zone where two oceanic plates the Caribbean Plate and Pacific Ocean Plate met and formed a volcanic arc in a contiguous American tropical ocean. The deep water connection between the Pacific Ocean and Caribbean Sea began to close in the early Miocene, fifteen to twenty million years ago. Magma rose up through plate fissures, creating a broad underwater ridge that was still under a thousand meters of water. By eleven million years ago, an island archipelago with marine and coastal habitats appeared across what is today the southern half of Central America. Sediment runoff gradually filled in the spaces between the islands. Only three corridors remained connecting Pacific and Caribbean waters at the end of the Miocene: The Atrato basin in northwestern Colombia, the San Carlos Basin in northern Costa Rica and southern Nicaragua, and the Panama Canal Basin. By four million years ago, the water at these points was fifty meters deep. The closure of the Panamanian isthmus took place three and a half million years ago, dividing a single American tropical ocean.

The division of the seas was an event of great paleoclimatic, paleogeographic, and paleobiological importance. However, the division of the land bridge between North America and South America through the construction of the Panama Canal would also prove to be an event of lasting historical, political, and technical significance. The Panamanian isthmus created a barrier to the inter-oceanic movement of marine life, even as it facilitated the movement of a flood of terrestrial organisms between the North and South America. The Panama Canal follows the orientation of a northwest-southeast depression – roughly 20 miles wide with a maximum altitude of 650 feet – shaped by volcanic and sedimentary processes. As one of the lowest-lying and last connecting points on the Central American land bridge, the basin is defined by marine and terrestrial deposits sediment on top of volcanic basement rock.

4.1.5 Soil Characteristics

The geological formations discussed in the previous section presented the parent material for the soils that are found in the Panama Canal area. Acidic soils are dominant due to the volcanic origins of the igneous conglomerates. The types of soils found in the area influence drainage, fertility, and subsequently erosion in the canal. Therefore, this section provides an identification and description of the types of soils and how they are classified by the Panama Canal Authority.

The Panama Canal Authority Geotechnical Department identifies four main types of acidic soils found in the area. The first type is the ultisols, which are acidic, infertile soils, most of which have lost their top layer by erosion. The typical soil profile has two to three horizons, including ocrico, umbrico and argilic. Due to the erosion of the surface horizons, the argilic horizon subsurface becomes exposed. This horizon is an accumulation of clay that is much more leached and acidic than the ocrico and umbrico horizons (URS Holdings, Inc., 2007).

The second soil type is the alluvial soils that are found on the flood plains of the rivers Chagres, Gatun, Chilibre, Gatuncillo, and their tributaries. The alluvial soils have only one horizon that consists of a few stones. They are less clayey and more fertile then ultisols. They are classified as entisols because they originate from the very recent alluvial plains and have no defined horizons in their soil profile (URS Holdings, Inc., 2007).

The third soil type is the sedimentary origin soils that are from the Gatun, Gatuncillo, Caraba and Bohio formations. This soil type is less acidic and has greater levels of organic matter. It is the most fertile of all the soil types in the Panama Canal area, but it has a greater capacity for erosion due to the low aluminum content (URS Holdings, Inc., 2007).

The fourth soil type is the anthropic soils, which is also classified as entisols because they are derived from the recent formations and do not have defined horizons in the soil profile. There is also a greater concentration of algae, due to the deposit of dredged materials from the Gatun Lake. The influence of human activities makes it difficult to give a detailed description due to the variability of deposited materials (URS Holdings, Inc., 2007).

Soils in the Panama Canal basin expansion area are also classified according to their capacity and capability for uses in the construction of the canal. The capacity for use of the soils is determined according to factors such as slope, erosion, effective depth, texture, stone content, drainage and fertility. The best soils are those of Class I because they have no restrictions on their use. The higher classification numbers indicate more restrictions on the use of the soil. Therefore, Class VIII soils would not be used for any other activities pertaining to the building of the locks except protection (sealant for new access dam to the third set of locks). An example of a Class VIII soil is clay because it has poor drainage and fertility. Soils with a higher usage capacity are the alluvial type soils (Classes III and IV), plains and soils of limestone origins (URS Holdings, Inc., 2007).

4.1.6 Climate

The Panama Canal is located on the narrow and low Isthmus of Panama. The potential for erosion of the existing channels and those being excavated is dependent on the climate and geography of the area. Panama has a tropical climate. The average temperature for 2010 was 26.4°C (79.5°F) with a high of 34.5°C (94.2°F) and a low of 8.7°C (47.8°F), as recorded by the Tocumen weather station. Temperatures are higher on the Caribbean side than the Pacific side (Meditz and Hanratt, 1987).

Locally, three types of climates are experienced in the Panama Canal area: very humid tropical climate, humid tropical climate, and tropical grass lands climate. The very humid tropical climate is found to a limited extent in the northern end of the Panama Canal area. It is defined by abundant rainfall all year round, with the driest month of February usually having more than 60 mm of rainfall. The humid tropical climate covers the entire area and is found over the Atlantic area and a large portion of the Pacific sector. This type of climate is characterized by an annual rainfall greater than 2,500 mm and a dry season that lasts for 3 months from January to March. The annual average temperature ranges between 24°C and 26°C. Lastly, the tropical grass lands climate is found on the Pacific side, with annual rainfall below 2,500 mm and the median temperature of the coolest month (November) is 18°C (URS Holdings, Inc., 2007).

Precipitation usually occurs in the form of rainfall. The annual average precipitation recorded by Panama Canal Basin stations within or near the Panama Canal area (Limon Bay, Gamboa and Balboa) varies between 1,891 mm and 2,787 mm. Rainfall mostly occurs during the wet season from May to November. The cycle of rainfall depends on the moisture from the Caribbean Sea deposited by the north and northeast winds and the Continental divide, which acts as barrier for the Pacific lowlands. In general, rainfall occurs more frequently on the Caribbean side than on the Pacific side of the Continental divide. **(Table 4**, **Figure 15**, **Appendix 4)**.

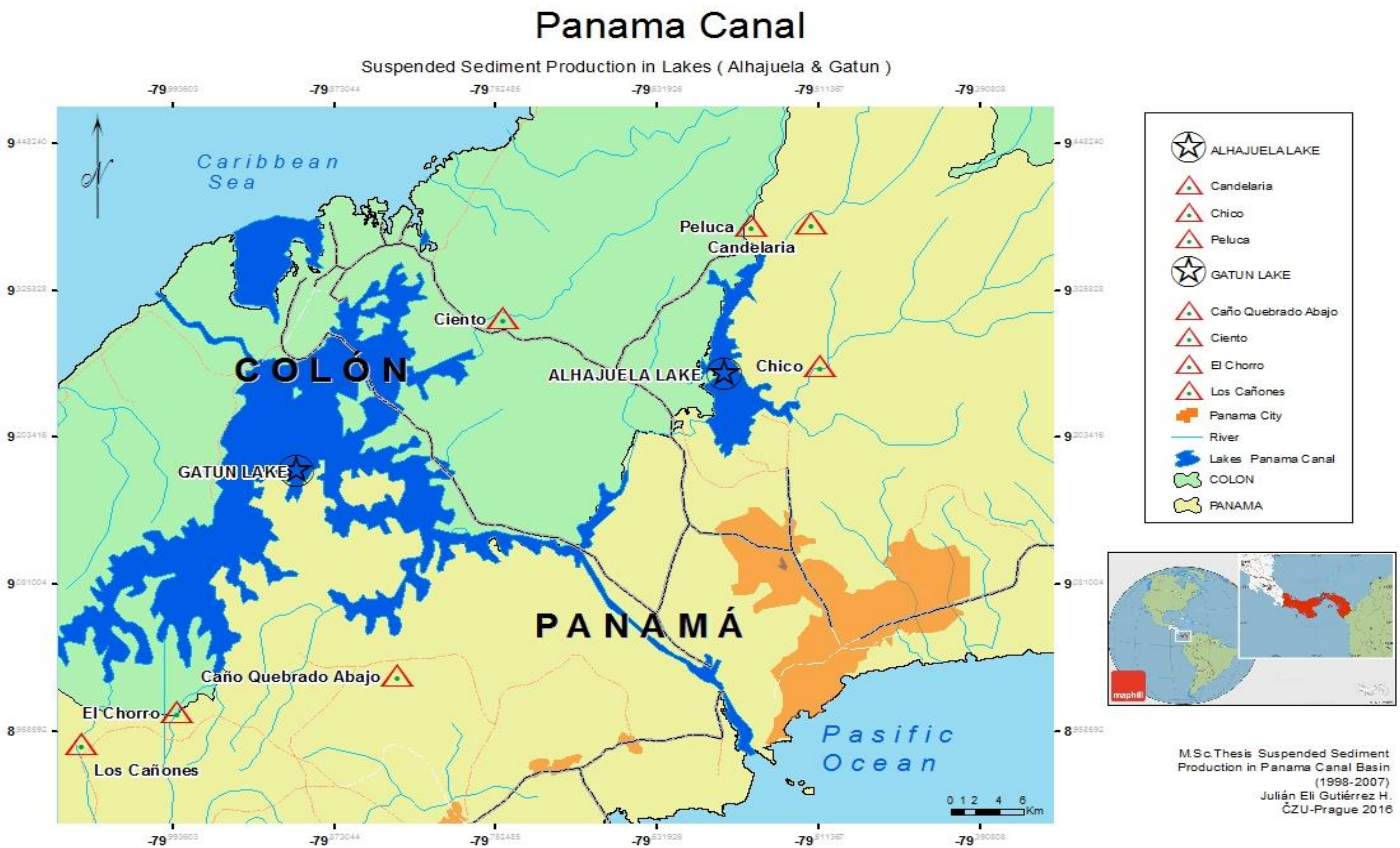

Figure 4. List of the gauging section in the Panama Canal Basin, lakes (Alhajuela & Gatun). (Julián Gutiérrez 2016).

Figure 5. Panama Canal Authority (Panama Canal 2016).

4.2 Soil erosion processes

Erosion is the process whereby earth or rock material is loosened or dissolved and removed from any part of the earth's surface. Whereas weathering involves only the breakdown of rock, erosion additionally entails the detachment and transport of weathered material from one location to another, denuding the earth's surface and delivering sediment to the fluvial system. Erosion rates are frequently measured on small fractional-hectare plots. The landscape and associated fluvial transport system may be divided into zones where either erosive or depositional processes dominate. Erosion processes predominate in mountainous environments, while deposition predominates on floodplains, although both erosion and depositional processes occur simultaneously in virtually all environments. Thus, materials eroded from mountain slopes may be deposited in valleys and floodplain deposits are eroded by stream channels (Morris and Fan, 1997).

Soil erosion may be classified according to the erosive agent (water flows, human activity, land use, rainfall, wind, and others phenomenon), the erosion site (splash, sheet, rill, gully and channel) or the erosive process (e.g., raindrop, channel, mass wasting) (Morgan, 1991; Chankao; 1996; Tangtham, 2002). **(Figure 6)** explains the mechanism of soil erosion processes; at the first stage, splash erosion initially takes place when the falling raindrops hit bare soil dislodging soil particles. Once the rainfall amount accumulating on the land surface exceeds the infiltration capacity of the soil, surface runoff or overland flow is generated. The dislodged or loosened soil particles will then be removed by surface runoff in a thin layer, flowing down to a point of deposition (called sheet erosion). While sheet erosion is difficult to see due to the fact that water does not cut any channel when carrying away soil particles, rill erosion leaves visible scouring on the landscape. Rill erosion is formed when runoff from sheet erosion begins cutting small, separate channels as it travels a downward slope. Gully erosion is an advanced stage of rill erosion; it occurs when the water in rill concentrates to form larger channels. Unlike rill erosion, the gully cannot be removed by normal cultivation methods (Poesen *et al*., 2003; Aksoy and Kavvas, 2005; Morgan, 2005). Gully erosion and channel erosion may refer to either the gradual or the massive erosion of the beds and banks of gullies and stream channels. Mass wasting refers to erosion associated with slope failures, including landslides and similar slope movements. Wind erosion refers to movement of soil particles by wind. Wind erosion may be important in arid or semiarid regions as an agent that can transport sediment from ridges into depressions from which it can subsequently be transport by runoff (Rooseboom, 1992).

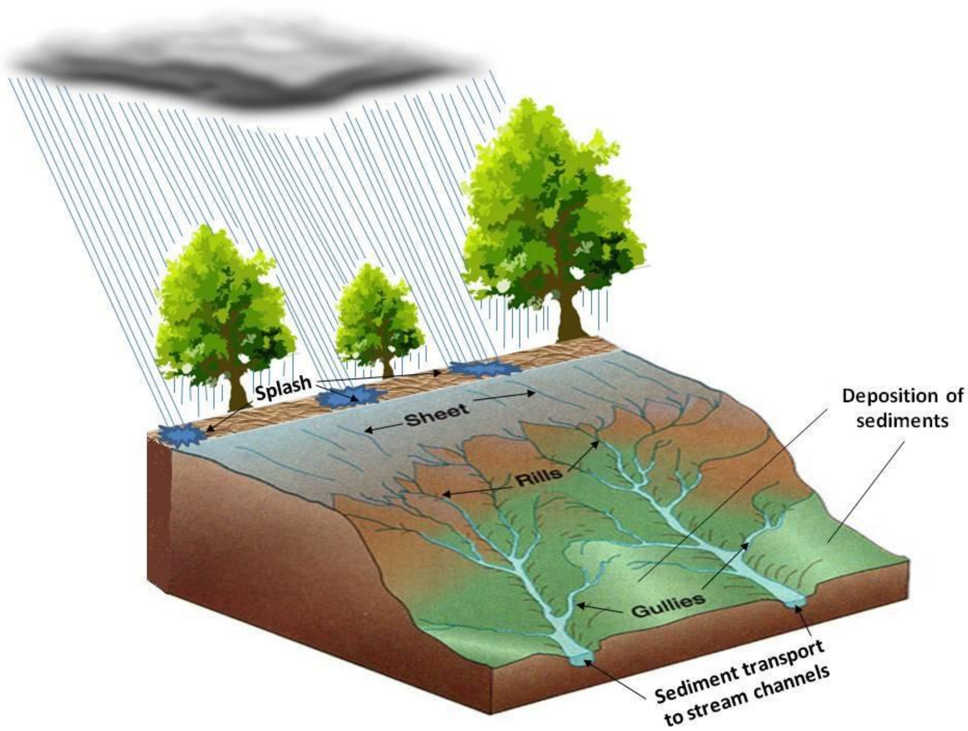

Figure 6. Schematic diagram of soil erosion processes. (Rooseboom, 1992).

4.3 Soil erosion and sediment export to rivers and lakes

Soil erosion and sediment export to rivers and lakes cause important environmental problems. Soil erosion irreversibly deteriorates soil quality, which often results in reduced soil productivity and may even drive land-use change (Bakker et al., 2004 and Bakker et al., 2005). Eroded sediment is often polluted with fertilizers, leading to eutrophication and the disturbance of fragile aquatic ecosystems. Increased sediment loading to rivers can lead to excessive sedimentation in lakes and reservoirs, thereby threatening aquatic biota and hydroelectric power generation (Douglas, 1995, Vanacker et al., 2003 and Wilkinson et al., 2009). Land use changes can have a large impact on watershed hydrology and erosion, and soil erosion is often affected by the cultivation of arable land and, depending on climate, on intensive grazing, especially in sloping areas. To a large extent, soil erosion is determined by the absence of protective vegetative land cover. The rapid abandonment of traditional agricultural practices and the large extent of areas affected by vegetation recovery have changed the hydrological response and sediment delivery dynamics (Gallart and Llorens, 2004 and Lopez Moreno et al., 2006). Many studies have illustrated the importance of human induced land use changes on the fluxes of water and sediment (McIntyre, 1993, Slaymaker, 2001, Van Oost et al., 2000, Boix-Fayos et al., 2008, García-Ruiz et al., 2008, Fiener et al., 2011, Manuel et al., 2011, Yan et al., 2013 and Shi et al., 2014).

4.4 Sediment Yield Measurements

Sediment yield is the amount of sediment load passing the outlet of a catchment, that is the sediment load normalized for the drainage area and is the net result of erosion and deposition processes within a basin (Jain and Das, 2010; Restrepo and Syvitski, 2006; Verstraeten and Poesen, 2001). These materials are of three different kinds; dissolved load (consisting of soluble materials carried as chemical ions); suspended load (containing clay and silt held up by the turbulent flow), and bed load which includes larger particles moved by saltation, rolling and sliding (Nagle, 2000). However, on the basis of transport processes, measurement principles, and morphological/sedimentary associations, fluvial sediments are often classified into two; bed materials and washed materials. Bed material is often conflated with bed load (makes up the bed and lower banks of the river channel), and wash material moves in suspension and travels out of the reach once entrained (measured load), but the two classifications are not congruent (Church, 2006). Depending on discharge, the medium grain sand particles (saltation materials) could become unmeasured sediments if the popular Helley Smith sampler is used. Generally, the size of material that moves as bed or suspended load in the flow depends upon the power and turbulence of the flow (Gomez and Church, 1989). In relatively deep streams of high flows, with bed material that consists of fine sand, the suspended bed material may be 90% or more of the total sediment discharge. However, in shallow streams with medium to coarse sand beds, the unmeasured sediment discharge may represent 50% or more of the total sediment discharge (Andrews, 1981).

4.5 Field Measurements of Sediment Yield

Measuring and estimating suspended sediment yields in rivers has long been subject to confusion and uncertainty (Thomas, 1985) because various methods have been developed to measure suspended sediment yield and they include the measurement of suspended sediment load and water discharge (Akrasi, 2005; Khanchoul et al., 2010; Kusimi, 2008), measuring total eroded soil and deposited sediments in small catchments (Verstraeten and Poesen, 2001), and measuring sediment volumes in ponds, lakes or reservoirs (Nichols, 2006; Verstraeten and Poesen, 2001). For the measurement of sediment volumes in ponds, lakes and reservoirs, radiometric techniques using 210Pb or 137Cs as tracer elements can be employed to reconstruct sediment budgets over a period of time (Foster et al., 1990; Govers et al., 1996; Walling, 1990 cited in Verstraeten and Poesen, 2001). The ideal situation to estimate the suspended sediment yield of rivers would be to measure suspended sediment concentration and water discharge continuously and use the product function as an estimate of suspended sediment discharge (Lane et al., 1997; Thomas, 1985). Obtaining continuous records of concentration however is practically impossible owing to cost, number of samples and sampling frequency among others (Edwards and Glysson, 1999; Thomas, 1985). The use of sediment discharge rating curve to estimate sediment yield is however problematic because suspended sediment concentrations are known to be variable for a given discharge because storm flow hydrographs usually, but not always, are characterized by higher suspended sediment concentrations during the rising limb than the falling limb. Further, the timing between storm events also influences availability of fine-grained sediment from the watershed, such that an initial storm flow following relatively dry conditions usually has a greater suspended-sediment concentration than subsequent flows of similar magnitude (Edwards and Glysson, 1999). Consequently, statistical considerations show that the sediment load of a river is likely to be underestimated when concentrations are estimated from water discharge using least squares regression of log-transformed variables (Asselman, 2000; Cohn et al., 1992; Ferguson, 1986; Jansson, 1985; Singh and Durgunoglu, 1989). Also regardless of how the samples are collected, there remain questions of when the measurements of concentration should be made, how they should be used to estimate the total yield, how close can samples be spaced in time and still be meaningful among others (Edwards and Glysson, 1999; Thomas, 1985). According to Edwards and Glysson, (1999), spatio temporal variations in sediment transport can be captured by collecting depth/point integrated suspended sediment samples that define the mean discharge weighted concentration in the sample vertical and collecting sufficient verticals to define the mean discharge weighted concentration in the cross section. Verticals of samples could either be taken using Equal Discharge Increment or Equal Width Increment Methods. Though both methods have their advantages and disadvantages, if properly used, they yield similar results. Also the biases in the estimation of sediment loads by rating curve due to using log transformed estimates can be significantly reduced by using nonlinear regression. Further improvements can be achieved by identifying seasonality's and breaks in slopes of the rating curves and taking samples at the right time. Finally, the underestimation caused by using average daily flows with the rating curve can be eliminated by using sub-daily flow data, if available (Singh and Durgunoglu, 1989). The many methods that have been developed for collecting data and estimating suspended sediment yields indicate each method is characterized by one limitation or the other, thus the method that one employs is subject to availability of equipment, cost, convenience, the kind of results that is sought among others.

Chapter 5

Results

This chapter presents, the results about the annual average sediment yield, precipitation, slope range, distribution of vegetation cover of the basins of the rivers to the hydrometric stations, outflow, in the Panama Canal Basin, for the periods of 1998-2007; and make some comparative analysis based on the results. Very briefly I can say that the sub-basin with more apportation of sediment yield is the Alajuela Lake, where also steeper slopes, and precipitation amount occurs, in comparison with the Gatun Lake.

It's very important to mention that for the years 1999 and 2007 higher precipitation (wet years) was recorded and for the years 2001 and 2005 the dry years of El niño event occured. My thesis highlights the importance of proper watershed management in order to reduce the sedimentation.

A summary of specific production flow and suspended sediment in the Panama Basin is provided in the Table 1. This table show the collections of suitable time series of the Years (1998-2007), Flow rate Q [m^3/s], production sediments suspended [tons/year], and Area [Km^2], all this information are coming from the rivers Chico, Candelaria and Peluca in the Sub-basin Alhajuela Lake.

The development of sediment yield throughout the years was graphically depicted **in Figure 7**. Sediment Yield vs Years, the **Figure 8**. Flow Rate vs Years and in the **Figure 9**. The box-plot, Sediment Yield.

Table 1. Summary of specific production flows and suspended sediment at stations hydrometric Sub-basin Alhajuela Lake. Period (1998-2007).

	Sub-basins of Alhajuela Lake					
	Chico A= 414 km^2		Candelaria A= 135 km^2		Peluca A= 91 km^2	
Years	Flow rate Q [m^3/s]	Production sediments suspended (tons / year)	Flow rate Q [m^3/s]	Production sediments suspended (tons/ year)	Flow rate Q [m^3/s]	Production sediments suspended (tons / year)
1998	26.6	113235	12.4	76896	6.16	43872
1999	43.1	206635	18.1	126732	10.3	80593
2000	36.4	343424	14.3	83880	8.12	45254
2001	24.7	55705	11.9	66390	6.44	38452
2002	29.5	122776	14.4	116229	7.24	50810
2003	26.7	44047	11.9	56122	6.31	24147
2004	37.5	389896	15.2	141522	9.71	101581
2005	26.6	48462	10.9	15906	6.26	26854
2006	39.6	343341	14.4	118652	7.68	69472
2007	40.1	676722	16.9	178648	8.72	99261

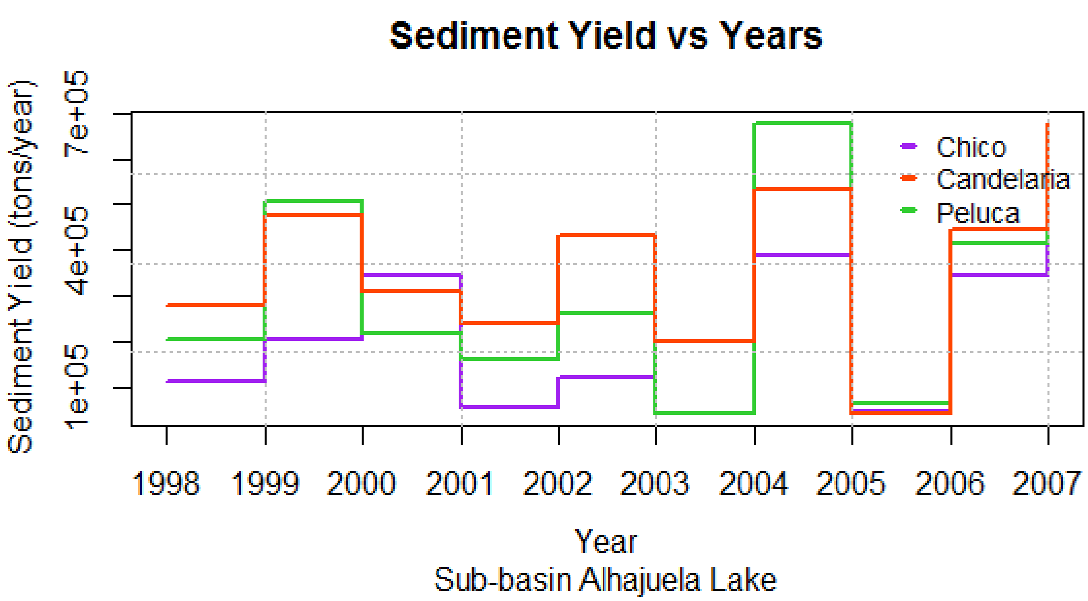

Figure 7. Transport of sediments yield in the Sub-basin, of Alhajuela Lake (1998-2007).

Here in the graph briefly I can say that the river with more sediments yield apportions are first one Caldera, second one Peluca, and the last one Chico; the years with higher values are in 2004,2005, 2007, and lowest in 2001,2002,2003.

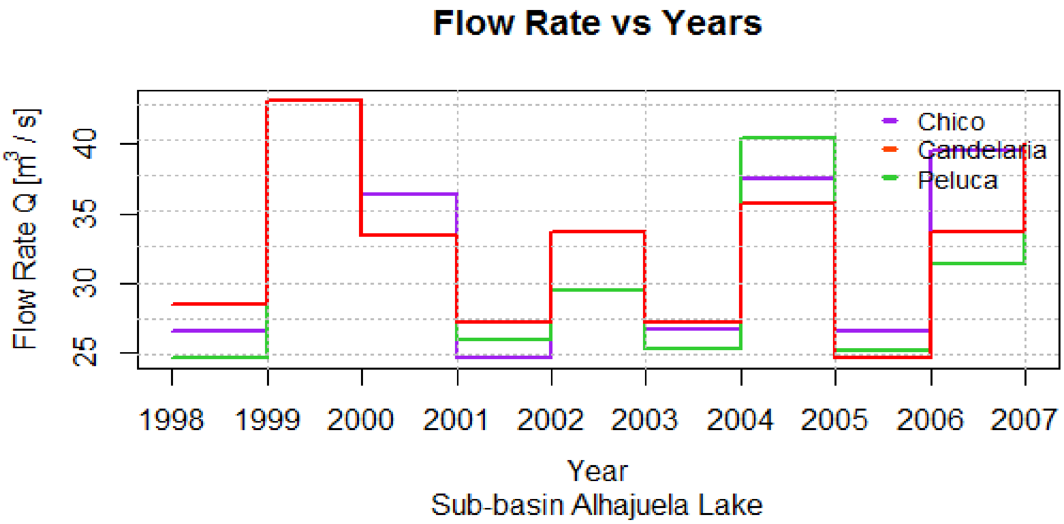

Figure 8. Flow rate Q [m^3/s] vs years, in the Sub-basin, Alhajuela Lake (1998-2007).

Here in the graph I can evaluate that the river with more flow rate apportions are first one Caldera, second one Chico, and the last one Peluca: the years with higher values are in 1999 and 2007 and lowest in 2001-2005.

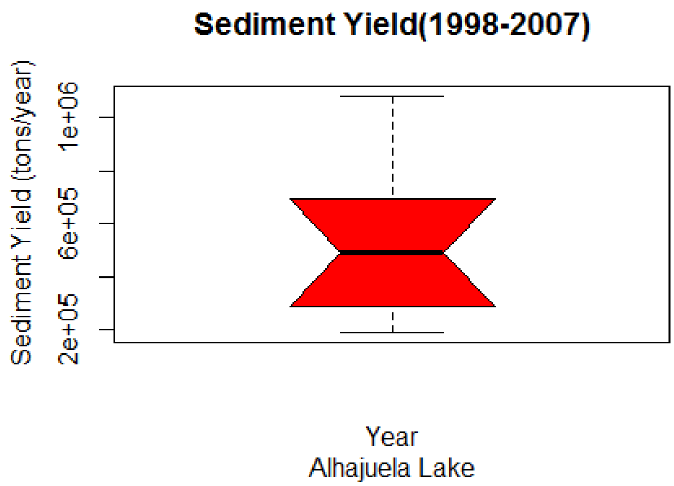

Figure 9. The box-plot, Sediments Yield, Alhajuela Lake (1998-2007).

It´s can be said that here the sediments Yield in the Alhajuela Lake, had its highest concentration of sediments between 28,000 tons to 70,000 tons/year.

A summary of specific production flow and suspended sediment in the Panama Basin is provided in the Table 2. This table show the collections of suitable time series of the Years (1998-2007), Flow rate Q [m^3/s], production sediments suspended (tons/year), and Area (Km^2), all this information are coming from the rivers Ciento, El Chorro, Los Cañones and Caño Quebrado in the Sub-basin Gatun Lake.

The development of sediment yield throught the yea The development of sediment yield throughout the yars was graphically depicted in **Figure 10**. Sediment Yield vs Years, the **Figure 11**. Flow Rate vs Years and in the **Figure 12**. The box-plot, Sediment Yield.

Table 2. **Summary of specific production flows and suspended sediment at stations hydrometric the Sub-Basin of Gatun Lake. Period (1998-2007).**

	Sub-basins of Gatun Lake							
	Ciento A= 117 km^2		**El Chorro** A= 174 km^2		**Los Cañones** A= 186 km^2		**Caño Quebrado Abajo** A= 67 km^2	
Years	Flow rate Q[m^3/s]	Sediment Yield [tons / year]	Flow rate Q[m^3/s]	Sediment Yield [tons / year]	Flow rate Q[m^3/s]	Sediment Yield [tons / year]	Flow rate Q[m^3/s]	Sediment Yield [tons / year]
1998	6.21	29476	4.64	22496	6.28	11134	70.8	388633
1999	10.1	83569	8.72	51660	12.9	49496	77.7	451807
2000	7.15	42448	6.60	22269	9.10	25615	68.9	371111
2001	4.90	16039	4.58	13988	7.71	21003	39.8	105358
2002	5.07	16553	7.40	43522	11.1	54199	50.9	206878
2003	6.30	34412	8.98	71814	11.7	55553	74.3	420660
2004	6.97	49001	6.27	29143	7.96	16320	61.1	300468
2005	4.35	14617	5.66	24046	7.39	14920	50.4	202532
2006	6.35	54311	8.22	74034	11.3	84541	63.5	322211
2007	7.67	70020	8.47	46763	12.0	56601	76.6	442107

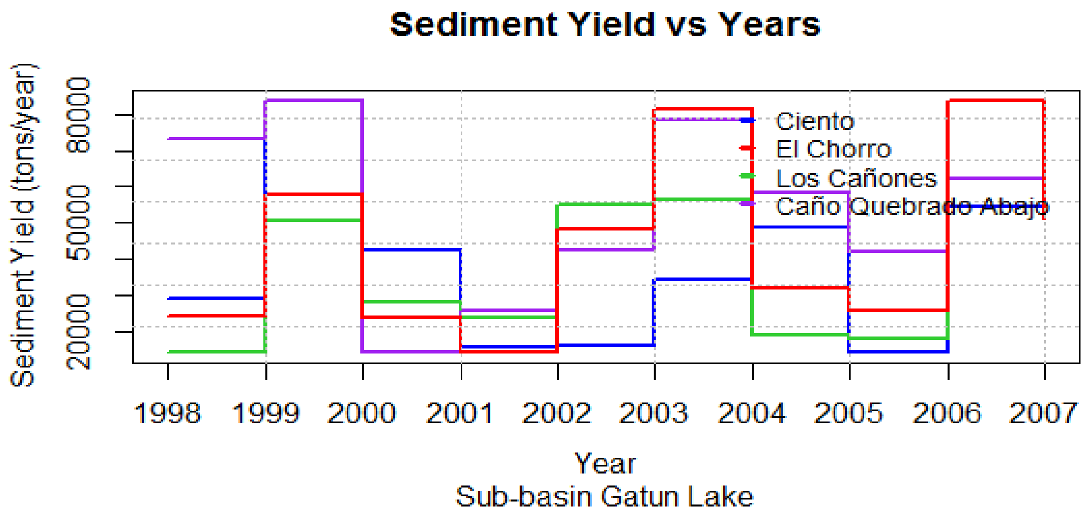

Figure 10. Transport of sediments yield in the Sub-basin, of Gatun Lake (1998-2007).

Here in the graph briefly I can say that the river with more sediments yield apportions are first one is Caño Quebrado Abajo, second one is El Ciento, the third one is El Chorro and the last one is Los Cañones; the years with higher values are in 1999,200,2003-2004, and 2007; and lowest years was in 2001,2002,2006.

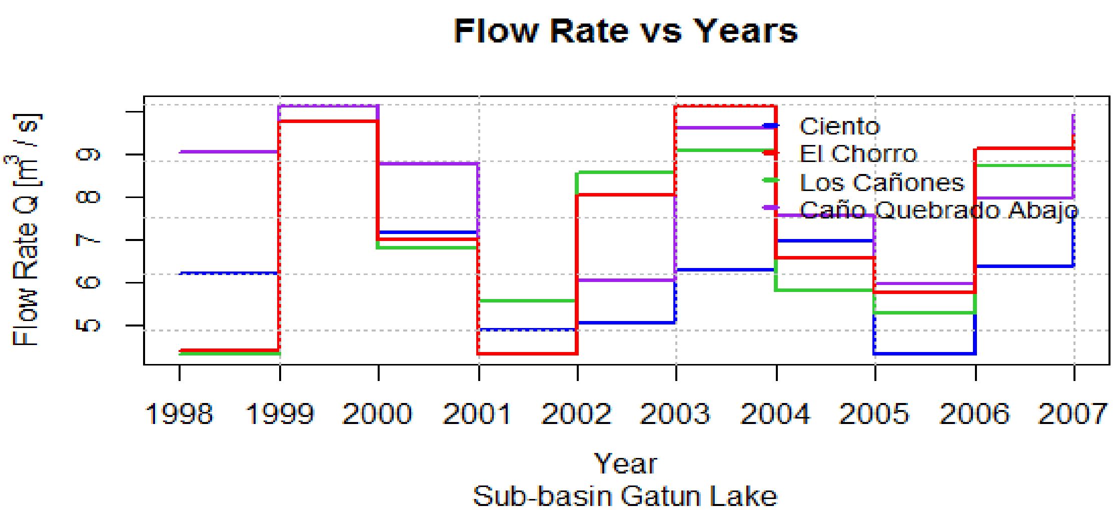

Figure 11. Flow rate Q [m^3/s] vs year, in the Sub-basin, Alhajuela Lake (1998-2007).

Here in the graph I can evaluate that the river with more flow rate apportions are first one Caldera, second one Chico, and the last one Peluca: the years with higher values are in 1999 and 2007 and lowest in 2001-2005.

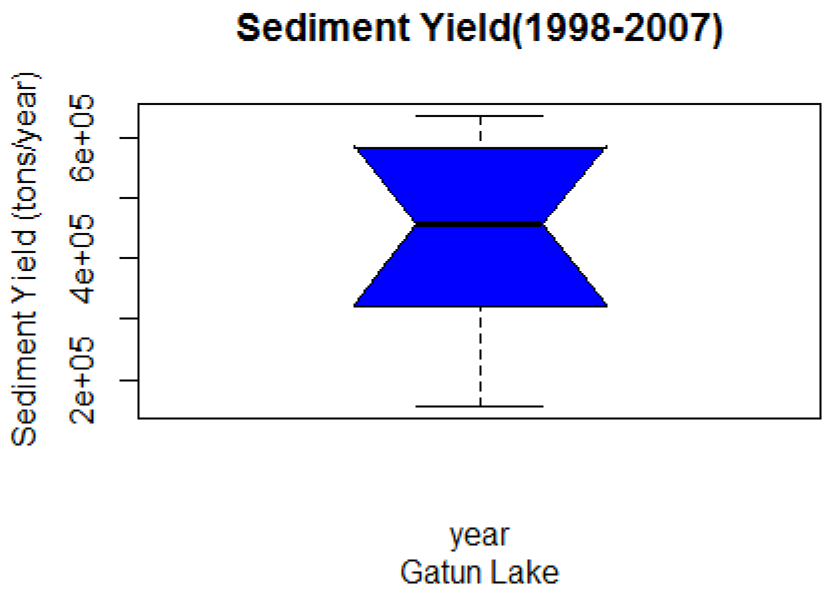

Figure 12. The box-plot, Sediments Yield, Gatun Lake (1998-2007).

Let´s say that here the sediments Yield in the Gatun Lake, had its highest concentration of sediments between 32,000 tons to 60,000 tons/year.

Table 3. Flow specific vs Sediment Yield in the Panama Basin

Panama Canal Basin								
	Alhajuela Lake				Gatun Lake			
		Sediment Yield				Sediment Yield		
Years	Flow rate Q[m^3/s]	[tons/year]	[tons/km^2/year]	MMC/ year	Flow rate Q[m^3/s]	[tons/year]	[tons/km^2/year]	MMC/ year
1998	65.4	356586	365	0.368	87.9	451738	241	0.467
1999	106	671220	688	0.694	109	636532	339	0.658
2000	79.4	598617	613	0.619	91.7	461443	246	0.477
2001	63.7	287268	294	0.297	57.0	156387	83.3	0.162
2002	68.2	383314	393	0.396	74.5	321153	171	0.332
2003	68.6	279065	286	0.288	101	582439	310	0.602
2004	84.1	769764	789	0.795	82.3	394932	210	0.408
2005	61.3	190129	195	0.196	67.8	256115	136	0.265
2006	86.1	692677	710	0.716	89.4	535097	285	0.553
2007	86.4	1082314	1109	1.12	105	615492	328	0.636

Note: for the years 1999 and 2007 were the higher precipitation (wet years) and for the years 2001 and 2005, were the dry years El Niño event.

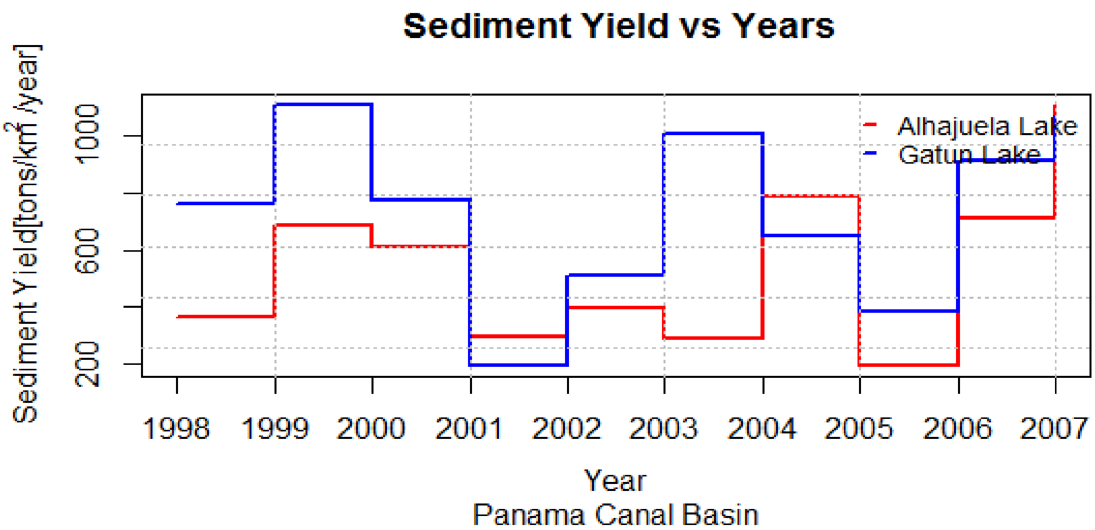

Figure 13. Transport of sediments yield in the Panama Canal basin, (1998-2007).

Here in the graph briefly I can say that the sub-basin with more sediments yield apportions in the Panama Canal basin were Gatun Lake, with higher apportion in the years 1999,2003,2007; but in the year 2007 the more apportions were Alhajuela Lake. The lower apportions were in the year 2001.

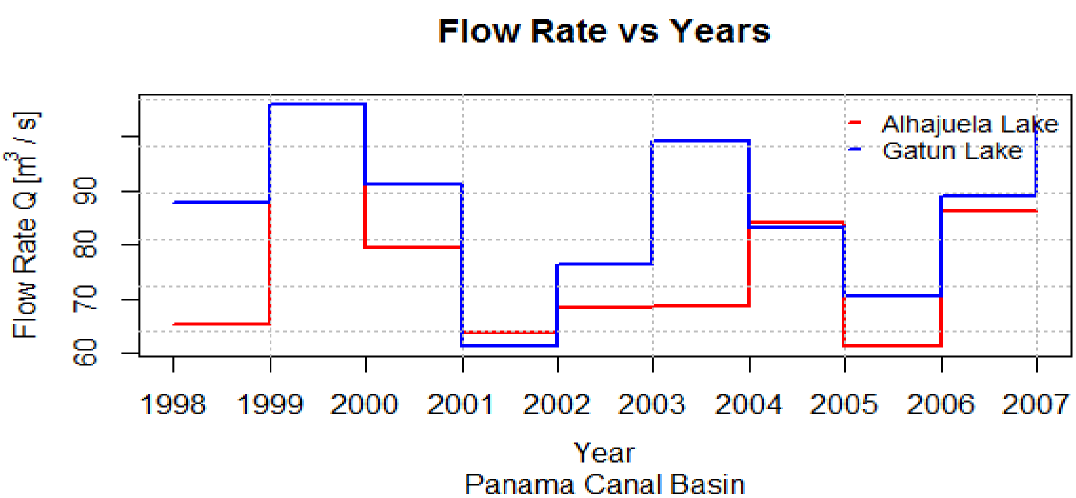

Figure 14. Flow rate (Q= m^3/s) vs year, in the Panama Canal basin (1998-2007).

Here in the graph I can say that the sub-basin with more flow rate apportions was Gatun Lake nevertheless the Alhajuela Lake the values it is very significant as well.

In the **Table 4**, **Figure 15**, and **Appendix 4,7**. We can see the clime of the Panama Canal Basin. The Panama Canal is located on the narrow and low Isthmus of Panama. Panama has a tropical climate; the average temperature is 26° (79.5°F) with a hight of 35°C (94.2°F), temperatura are higher on the Caribbean side tan the Pacific side. The precipitation ussually occurs in the form of rainfall, in the Panama Canal Basin varies between 1900 mm and 2800 mm. Rainfall mostly accurs during the wet season from May to November. The cycle of rainfall depends on the moisture from the Caribbean Sea deposited by the north and northeast winds and the Continental divide, which acts as barrier for the Paacific lowlands.

Table 4. Average rainfall in the basins of the reservoirs Alhajuela Lake and Gatun Lake (1998-2007)

Panama Canal Basin		
Years	**Alhajuela Lake** Precipitation [mm]	**Gatun Lake** Precipitation [mm]
1998	8633.46	9857.74
1999	10360.66	12024.36
2000	8569.96	10568.94
2001	7416.8	8956.04
2002	7772.4	8572.5
2003	8862.06	10261.6
2004	877.24	9972.04
2005	7442.2	8796.02
2006	8912.86	9880.6
2007	9242.12	10215.66

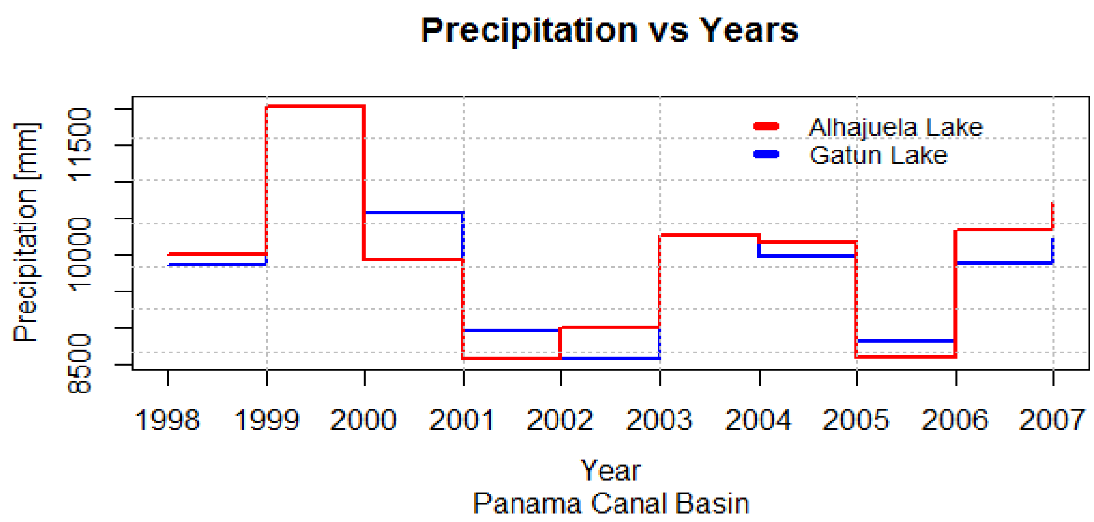

Figure 15. Precipitation [mm] in the Panama Canal basin (1998-2007).

Here we can see that the sub-basin with higher percent of precipitation was Alhajuela Lake, the reason is that in this area, the curves of rainfall are from 10215.66[mm/year] to more of 4551 [mm/year]; and for the Gatun Lake the curves of rainfall are from 1751 [mm/year] to 3500 [mm/year]. **(Appendix 4)**.

Here in the Table 5. I describe the Physical Features (Alhajuela & Gatun) Lakes. The Panama Cana cuts throught one of the narrowest saddles of the isthmus joins that joins North and South America to provide a direct between the Atlantic and Pacific Oceans. The canal route is approximately 80 km in leght and uses a system of locks in order for the ships to traverse this continental divide. (**Figure 4, Appendix 1**).

Table 5. Physical Features (Alhajuela & Gatun) Lakes.

Sub-basin	Geographical coordinates		Area of drainage	Average gradient	Length Mainstem	Density drainage
	Latitude N	Longitude W	[Km²]	[%]	[km]	[km/km²]
Chico	09° 15' 49"	79° 30' 35"	414	56	48.3	2.22
Candelaria	09° 22' 58"	79° 30' 59"	135	47	26.5	2.27
Peluca	09° 22' 48"	79° 33' 40"	91	47	22.3	1.99
Ciento	09° 17' 52"	79° 43' 41"	117	37	36.5	2.26
El Chorro	08° 58' 32"	79° 59' 25"	174	26	46.9	1.44
Los Cañones	08° 56' 56"	80° 03' 45"	186	23	42.7	1.34
Caño Quebrado Abajo	09° 00' 17	79° 49' 34"	67	10	19.7	1.96

The soils in the Panama Canal Basin are also classified according to their capacity and capability for uses in the operation of the canal. The capacity for use of the soils is determined according to factors such as slope, erosion, effective depth, texture, stone content, drainage and fertility, in the **Table 6, Appendix 3**, we can see the Slope ranges of the basins of the rivers to the hydrometric stations; and after we can see the graphically (**Figures 16-20**).

Table 6. Slope ranges of the basins of the rivers to the hydrometric stations.

Sub-basin	Slope ranges: Nearly level 0-12 %		Gently sloping 13-25%		Strongly sloping 26-50%		Moderately steep 51-75%		Steep >76 %	
	Km²	%	Km²	%	Km²	%	Km²	%	Km²	%
Chico	33,0	8,0	95,7	23,1	229,0	55,3	53,5	12,9	2,8	0,7
Candelaria	21,7	16,0	41,6	30,8	58,3	43,2	12,1	8,9	1,3	1,0
Peluca	12,8	14,0	24,4	26,9	41,6	45,8	10,7	11,8	1,4	1,5
Ciento	16,1	13,7	37,5	32,0	52,6	44,9	9,9	8,5	1,0	0,8
El Chorro	34,7	19,9	57,9	33,3	64,1	36,8	15,6	9,0	1,7	1,0
Los Cañones	50,6	27,7	59,9	32,2	60,6	32,6	13,0	7,0	1,9	1,0
Caño Quebrado Abajo	50,8	75,5	14,8	22,0	1,7	2,6	0,0	0,0	0,0	0,0

Here I can describe that the sub-basin with high range slopes are: Chico, Candelaria, Peluca from the Alhajuela Lake sub-basin; and the less range slopes for the Ciento, El Chorro, Los Canones, Cano Quebrado Abajo from the Gatun Lake sub-basin.

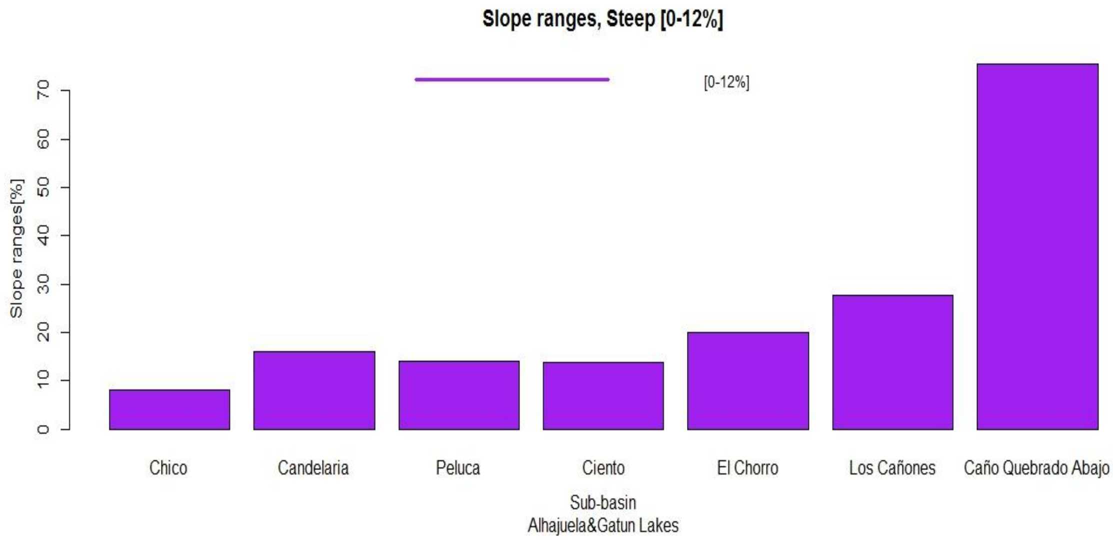

Figure 16. Slopes ranges- Nearly Level [0-12%] in the Panama Canal Basin (1998-2007.)

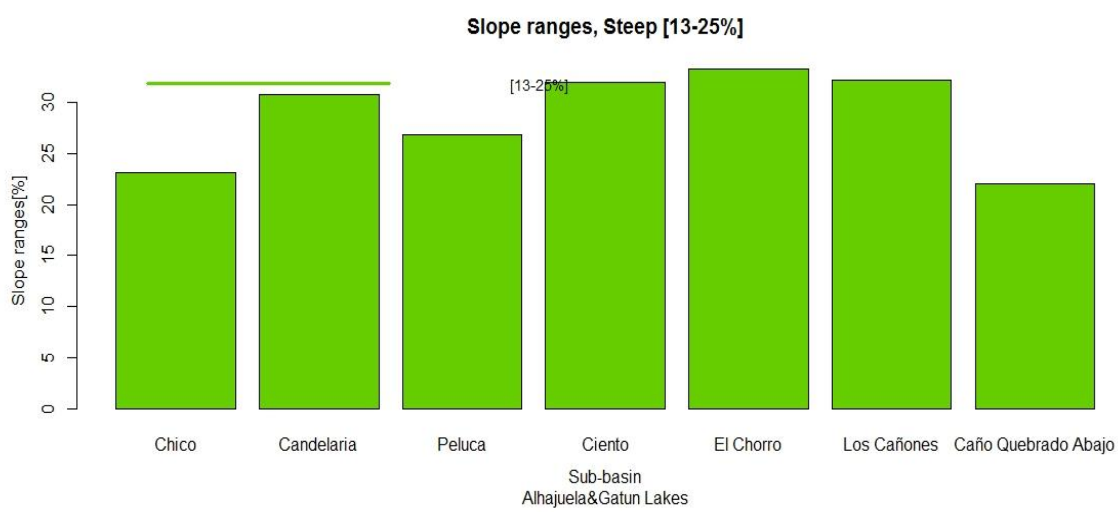

Figure 17. Slope ranges-Gently sloping [13-25%] in the Panama Canal Basin (1998-2007).

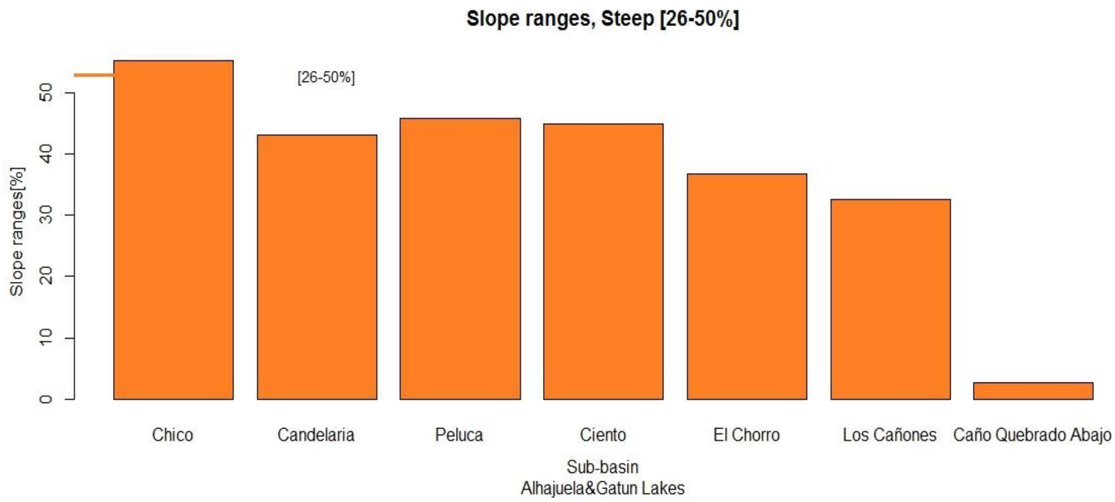

Figure 18. Slope ranges- Strongly sloping [26-50%] in the Panama Canal Basin (1998-2007).

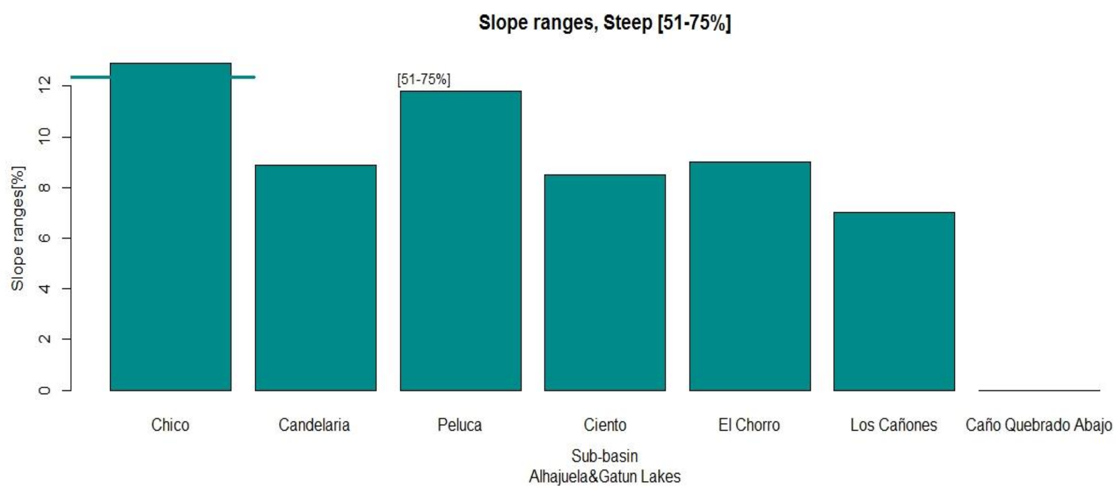

Figure 19. Slope ranges- Moderately steep [51-75%] in the Panama Canal Basin (1998-2007).

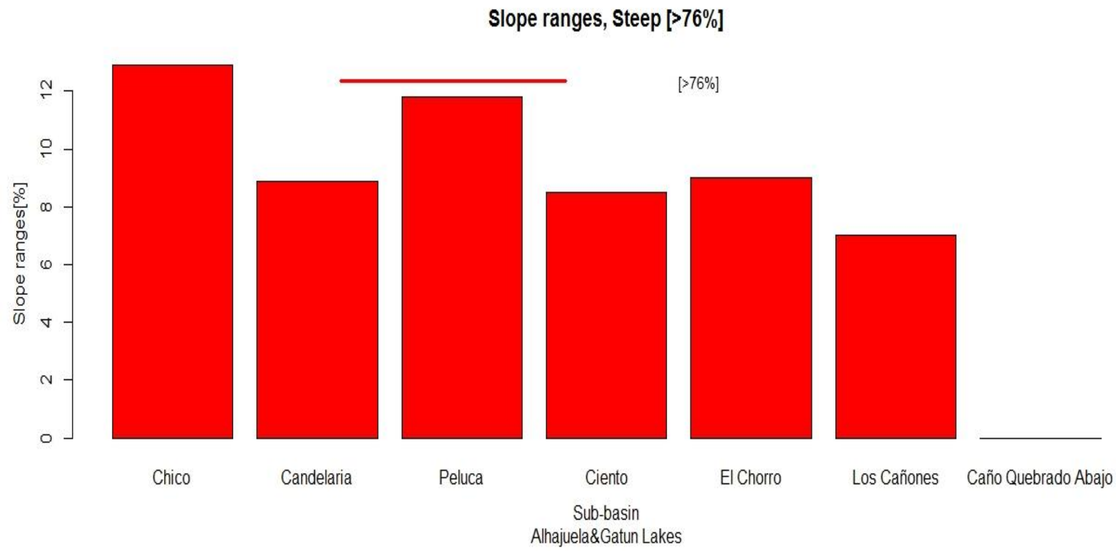

Figure 20. Slope ranges- Nearly Level [>76%] in the Panama Canal Basin (1998-2007).

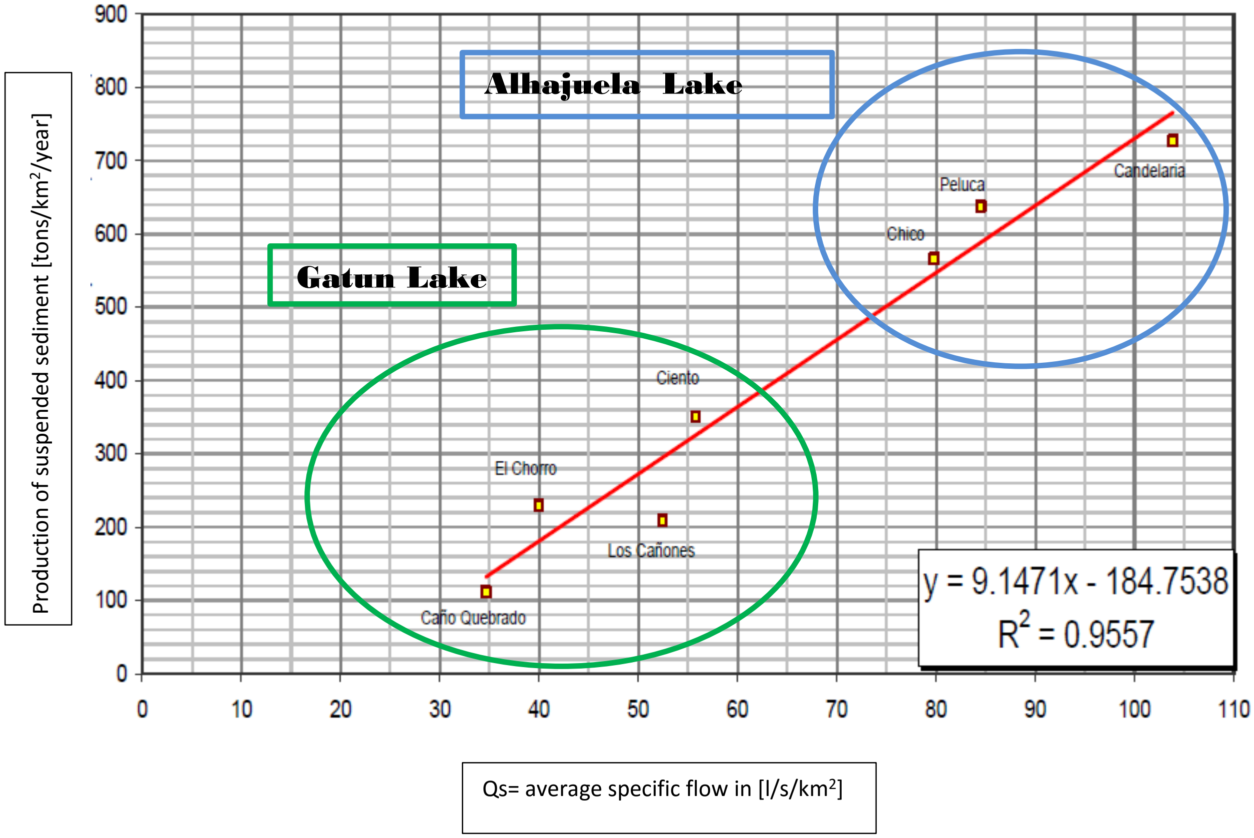

Figure 21. The coefficient of Determination of production of suspended sediment yield [tons/km^2/year] vs Specific Flow [l/year/km^2].

The coefficient of Determination, in the Panama Canal basin indicates that for the sub-basin Alhajuela and Gatun Lake say:

Interpretation: R^2=0.9557≈ 95.6% between the production of sediment [tons/km^2/year] and the specified flow rate [l/s/km^2], which allows to estimate indirectly the production of sediments in sub-basin, and the linear relationship is direct, at high precipitation the sediment yield It tends to increase.

Here in the Table 7. We can observe the distribution of vegetation cover of the rivers in the sub-basins (Alhajuela Lake & Gatun Lake). The flora of the Panama Canal Basin consists of a variety of plant species present in that given area. The diversity of climatic conditions, soil, and degree of human intervention determine the presence of different types of forests, grasslans, agricultural crops, etc; which possess different types of physiognomy and associated plant species.

Table 7. Distribution of vegetation covers of the basins of the rivers to the hydrometric stations. (Panama Canal Authority 2015).

Distribution of vegetation cover of the basins of the rivers to the hydrometric stations.

Sub-basin	Mature forest		Secondary Forest		Scrub and Stubble		Canal Grass		Grasslands		Soils without Vegetation		Urban Areas		Forest plantations		agricultural crops	
	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%
Chico	391.3	94.5	16.0	3.9	5.3	1.3	0.7	0.2	0.6	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Candelaria	126.7	93.9	6.5	4.8	1.4	1.0	0.1	0.1	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Peluca	54.4	59.9	25.5	27.5	8.9	9.8	1.1	1.2	1.5	1.6	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Ciento	33.3	28.4	34.7	29.7	29.7	25.4	4.7	4.0	12.4	10.6	0.2	0.2	0.1	0.1	1.9	1.6	0.0	0.0
El Chorro	3.8	2.2	35.3	20.3	49.1	28.2	0.0	0.0	83.4	47.9	0.0	0.0	2.5	1.5	0.0	0.0	0.0	0.0
Los Cañones	0.9	0.5	35.4	19.0	56.0	30.1	0.0	0.0	93.7	50.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Caño Quebrado Abajo	0.1	0.1	4.0	5.9	11.3	16.9	0.0	0.0	48.5	72.4	0.0	0.0	0.7	1.1	0.1	0.1	2.4	3.5

The distribution of vegetation cover of the basins of the rivers to the hydrometric stations, i can say that the most area cover is Chico, Candelaria, Peluca with hight percent in Mature forest, after secundary forest and scrub and strubble in the Alhajuela sub-basin; but for Ciento, El Chorro, Los Canones and Cano Quebrado Abajo the percent are normal for to Gatun Lake.

It is good that the Alhajuela Lake sub-basin have a high percent of Mature forest and Secundary Forest, but in other part it is very dangerous as the woodcutters are causing big dangerous in this zone for to get the wood.

Chapter 6

Discussion

Soil erosion by water continues to be a serious global issue, especially in the Panama Canal Basin, where climatic and topographic conditions accelerate the process of erosion and sedimentation. This research was focused in the study the soil erosion and sediment yield, over the periods (between 1998 to 2007).

Specifically, this thesis came to the following discussion:

I. Soil erosion is a major issue because the frequency of rainfall in Panama promotes transport of soil from disposal sites into the canal channel. Increased erosion means the canal channel needs to be dredged more frequently to keep the channel operational, even now with the expansion of the Panama Canal.

II. According to the results of this study, soil erosion in the Panama Canal Basin has increased in mean annual soil erosion rate from 365 [tons/km^2/year] (in 1998) to 1107 [tons/km^2/year] (in 2007), for the Alhajuela Lake, and 241[tons/km^2/year] (in 1998) to 328 [tons/km^2/year] (in 2007), for the Gatun Lake, with high percent probability that it will increase in future years.

III. Also this analysis suggests that the sediment yield generation rates of 195 to 1109 [tons/km^2/year] for the Alhajuela Lake with the Flow rates of 61.3 to 106 Q[m^3/s] and then to Gatun Lake the rates 136 to 339 [tons/km^2/year] with the Flow rates of 57.0 to 109 Q[m^3/s].

IV. Extreme rains in the years 1998 and 2007 had a severe effect on values of the concentrations of suspended sediments that are normally recorded in the rivers that discharge into the Alhajuela Lake. In the sub-basins of these rivers, which were the most affected by the storm, the forest coverage covers more than 85 % of the drainage areas and much of the land dominated by the steep slopes of more than 15 degrees (26%), then unleash mudslides, the sediment yield measured was 5442[tons/km^2/year]. During this event, the sub-basin Alhajuela Lake received average rainfall between 173 and 442 mm in 24 hours and between 366 and 775 mm for duration of three days, which contributed to the saturation of the soil. These conditions were conducive to the development of numerous landslides.

V. The sub-basin of the Panama Canal basin with higher production of sediments is the Alhajuela Lake (5442[tons/km^2/year]), followed by the Gatun Lake (2349.3 [tons/km^2/year]).

VI. A regression (r^2=0.95) was determined between the production of sediment [tons/km^2/year] and the specified flow rate [l/s/km^2], which allows an estimate to be indirectly determined by the production of sediments in the sub-basin, and the linear relationship is direct, at high precipitation the sediment yield It tends to increase.

VII. It is likely that there are still sediments retained in basins and channels of the main rivers, to continue for a time high concentrations of sediment in rivers during the rainy season. It can be expected in the next few years by condition moist tropical forests, the natural regeneration of the vegetation cover sites of bare soil exposed by landslides and production rates of sediment and sedimentation decreasing to satisfactory values of 500[tons/km^2/year] and 0.07% year, respectively.

VIII. The effect of rainfall in the soil erosion and sediments yield, between 1998 and 2007, indicates that rainfall affecting soil erosion mostly occurs in the virgin evergreen forest. In other words, it means that soil erosion increased when rainfall increases.

IX. The most critical area for soil conservation planning is Alhajuela Lake Sub-basin.

X. The Soil Erosion and Sediments Yield increased when rainfall occurs more soil deposits in the lakes, which affects channel navigation and can cause damage to marine life.

XI. The level of the sediment yield rates is in the permissible level for sustainable operation of the Panama Canal so the Panama Canal Authority has many contingency plans for the management of the Panama Canal Basin. The Panama Canal Authority carried out dredging of the Alhajuela&Gatun Lakes, this technique is often used to keep waterways navigable in the Panama Canal.

XII. The situation of sediments yield rates is Okay and sustainable in long term.

Chapter 7

Conclusion

Accelerated soil erosion by water is a worldwide problem because of its economic and environmental consequences, especially in the Panama Canal Basin. The study and measurements of sediment is very difficult because of many factors influence the erosion rates, careful field observations such as sediments, soil properties, rainfall duration and intensities, vegetation density and agricultural practices are needed. Sediment yield should be taken in adequate frequency especially during high discharges. Slopes steeper than 10% cause much erosion. The best erosion control practice is good farming, and before planning any soil and water control program socio-economic conditions should be studied.

Specifically, this thesis came to the following conclusions:

I. This study evaluated the vulnerability to soil erosion the Panama Canal Basin with the purpose of determining areas that carry high rates of soil loss, sediment runoff (Alhajuela Lake and Gatun Lake), affecting the operations of the Panama Canal Authority. In actuality The widening and deepening of the canal channel and the excavation of the new locks involve the relocation and storage of soil in other locations. The removal of vegetation cover leaves soil exposed and more susceptible to erosion. The process of sediment yield being predominantly occurs due to runoff from rainfall, which is prevalent in the Panama Canal area; when deforestation takes place. Under these conditions, erosion rates are increased compared to land with natural vegetation. This is because there are limited root systems to hold the soil in place or canopy cover to protect the soil from raindrop splash impact and overland flow.

II. In the Panama Canal Basin, the primary factor that influence the rate erosion are climate, land use and geology; climatic factor include the amount and intensity of precipitation, seasonality, time of concentration is very important, wind speed and the typical temperature range.

III. In the sub-basin Alhajuela Lake this sub-basin has high-intensity precipitation and range slopes this event causes higher rate of erosion than in the sub-basin Gatun Lake.

IV. The factor that has the most influence on the potential for erosion is land use, which affects the ground cover from vegetation and drainage. Humans play a significant role in excessive or accelerated soil erosion based on land use practices. When ground cover provided by natural vegetation is removed for agriculture, urban development, or mining, the soil structure is damaged. The sediment yield measured below the Panama Canal basin, confluence from 1998 to 2007 (5442[tons/km^2/year] to Alhajuela Lake and 2349.3 [tons/km^2/year]) to Gatun Lake.

V. Currently soil conservation practices which can be included to mitigate soil are no-tillage or low-tillage, no deforestation, and crop rotation. On the other hand, there are practices such as partial, selective and progressive slash and prune, permanent soil cover, efficient use of fertilizer, live fences, and agricultural planning that have a low percentage of acceptance among the farmers of the subwatershed. Initiatives, such as the Integrated Management Program for the Panama Canal Basin, have been put in place to educate the inhabitants about water resources and conservation.

VI. Perform a bathymetry of the reservoir Alhajuela every 10 years and in the Gatun Lake in the short term, taking advantage of the most modern techniques exist that allow the quantification with better accuracy the volumes of sediment deposited and their distribution in the reservoirs. In addition, this information allows you to check the elevation curves-capacity, which is important for the correct calculation of the water balance of the reservoirs.

VII. Evaluate the land uses in the area outside of the Panama Canal, in order to determine their contributions and importance with regard to the erosion, since the rivers carry these sediments throughout their route since are born in the upper part of the basin till the large reservoirs of the Panama Canal.

VIII. The best erosion control practice is good land use; it is remarkable how often the management requiring good erosion control coincides with intensive efficient and human activity.

IX. Adjacent basins, heavily impacted by agriculture, have significantly higher contemporary sediment yields and are thus, no longer exhibiting steady landscape behavior. Alhajuela Lake is important to the operation of the Panama Canal; lowered average annual precipitation combined with a modest additional loss of storage capacity could significantly affect the number of ships that can be conveyed through the canal. It is apparent that more intensive land use within the Alhajuela Lake sub-basin and the accompanying increase in sediment yield, could have adverse effects on storage capacity and thus, on the economy of Panama Canal Authority and possibly the world.

X. From these estimates, it is evident that further reduction in reservoir capacity, from sedimentation combined with either successive dry years or from a change in climate to less precipitation, would have significant effects on the canal operation and on the economy of Panama and possibly the world. Such filling of the reservoir however, could be countered by expensive dredging to regain storage capacity. Thus, it is apparent that proper watershed management in the Alhajuela Lake and Gatun Lake basin is necessary to maintain sufficient water storage capacity.

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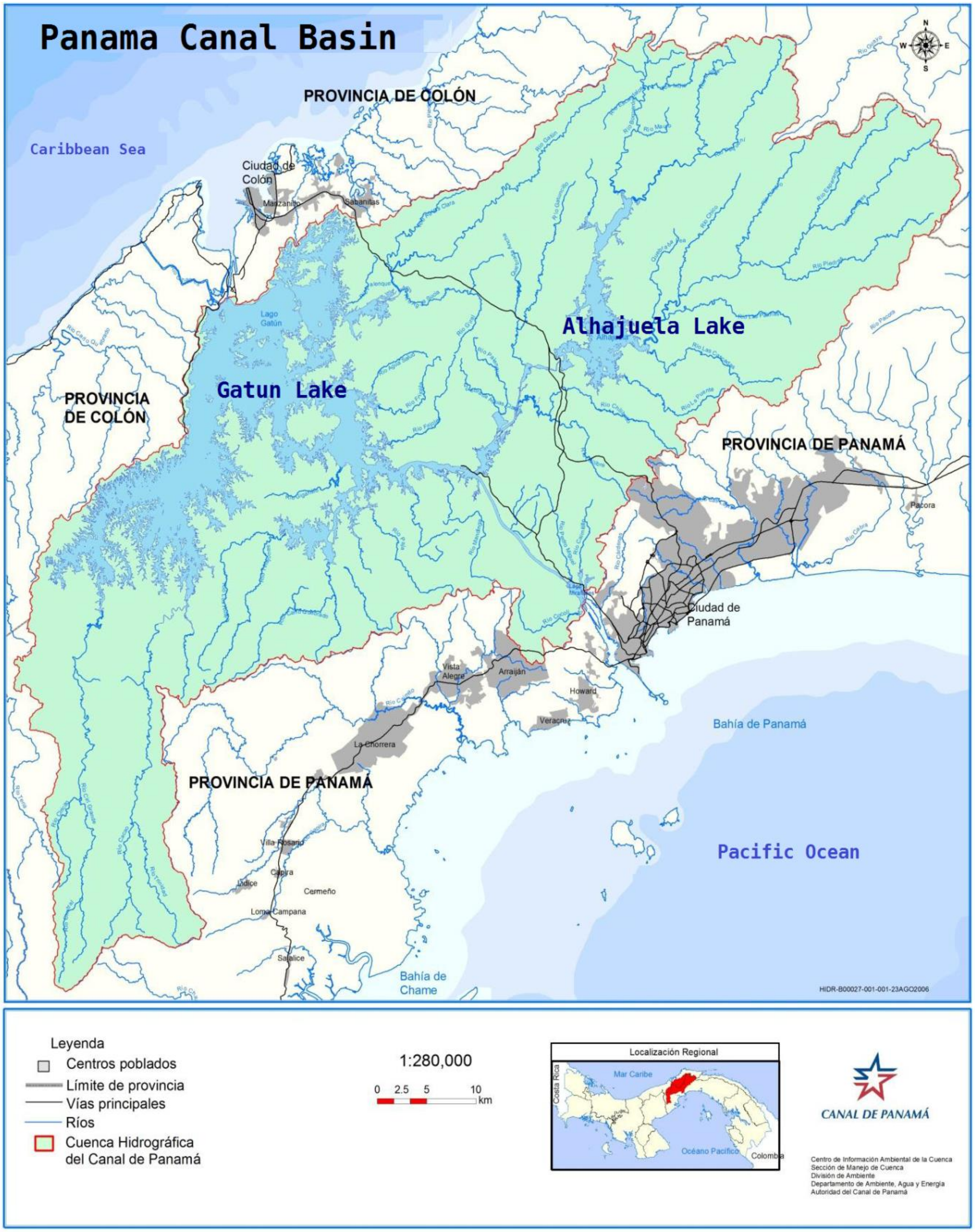
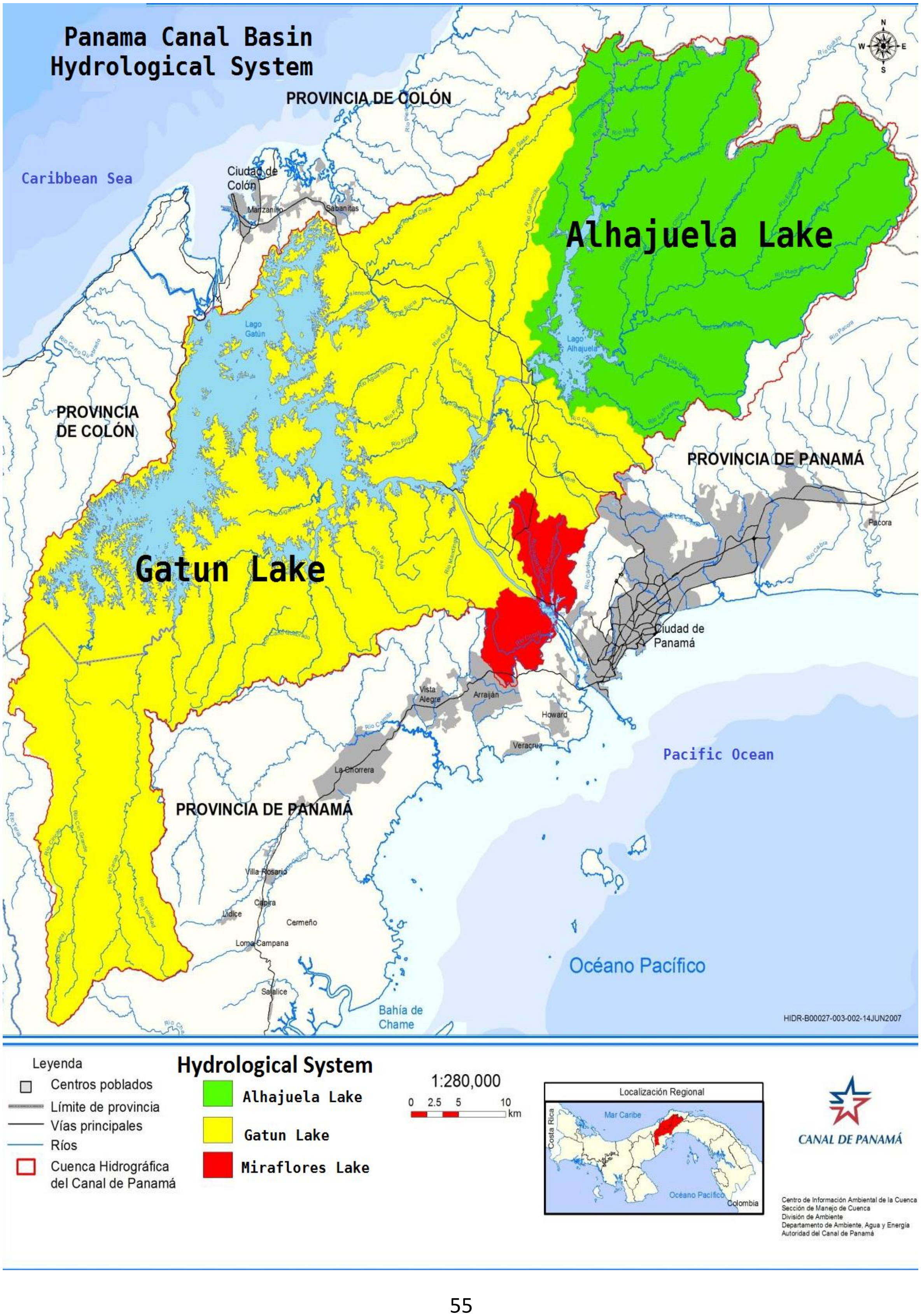
Appendices

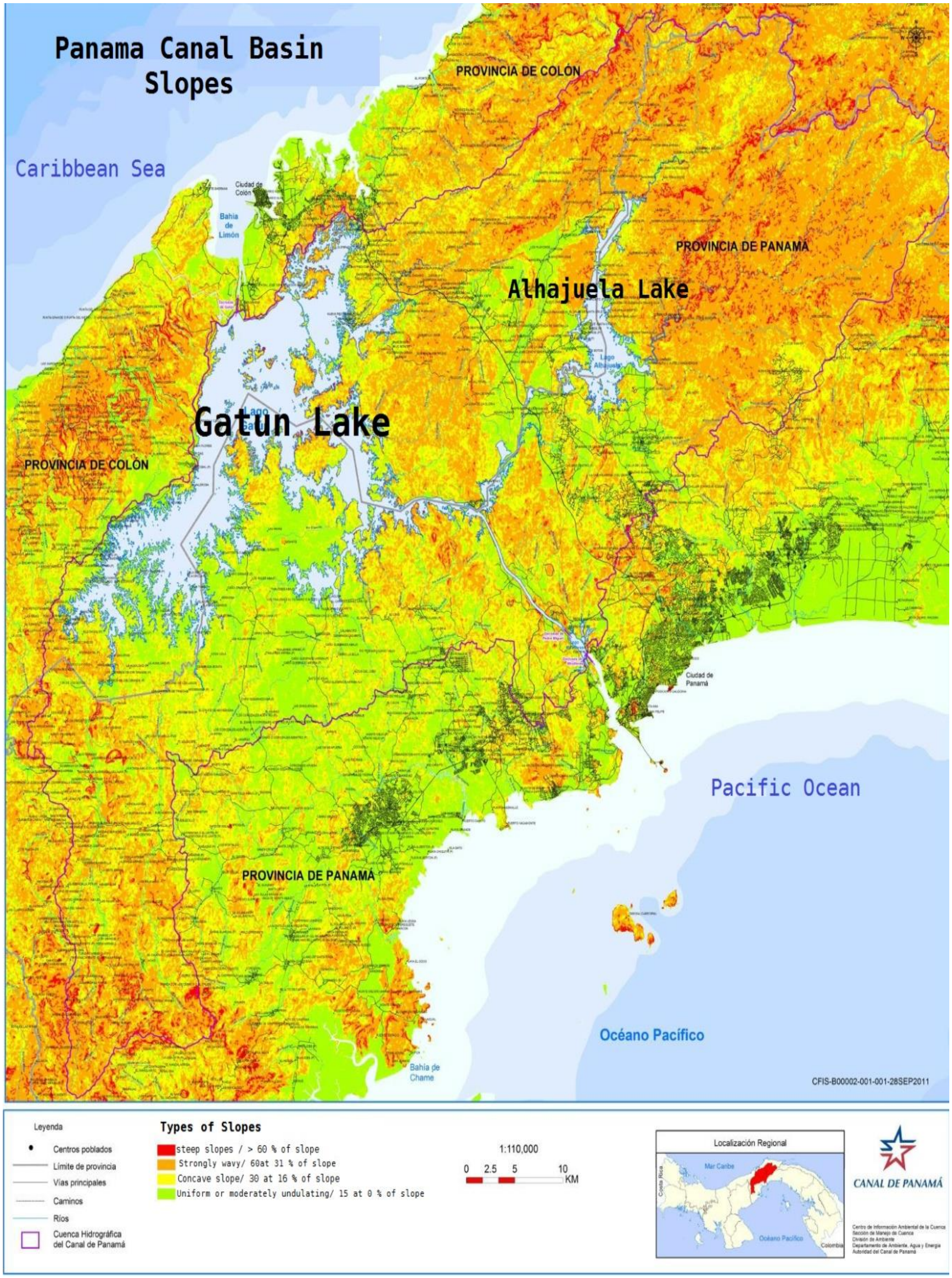
Appendix 1. Panama Canal Basin. By Panama Canal Authority. (2015).



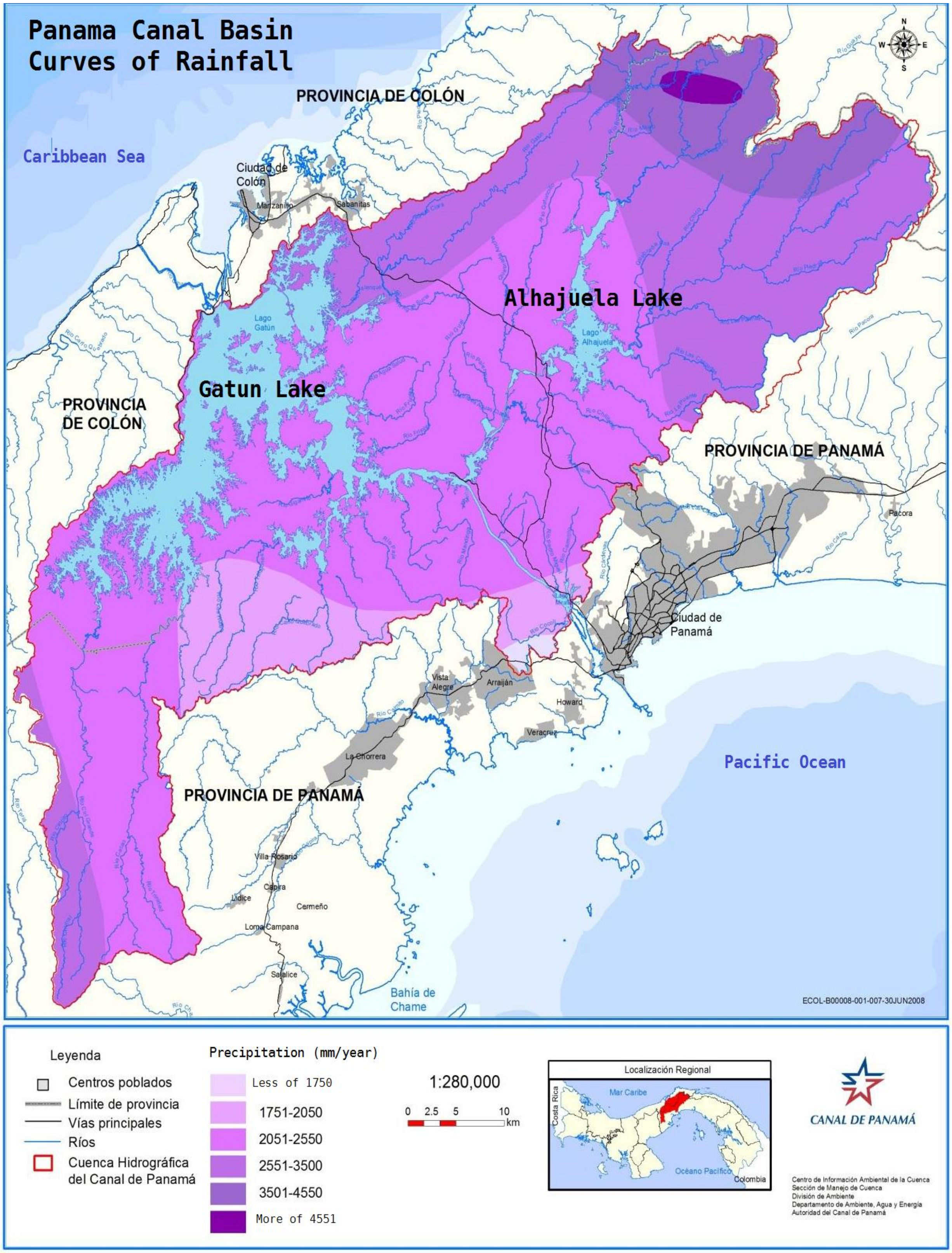
Appendix 2. Panama Canal Basin, Hydrological System. By Panama Canal Authority. (2015).



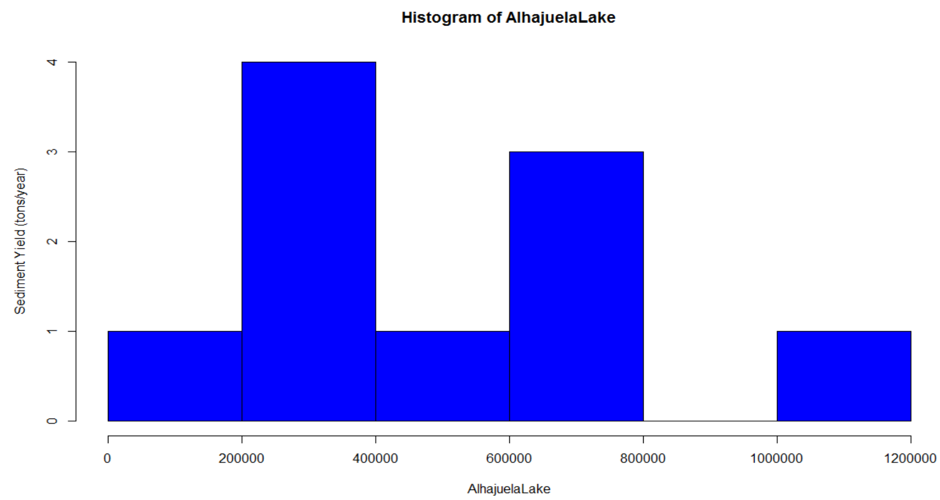
Appendix 3. Panama Canal Basin, Slopes. By Panama Canal Authority. (2015).



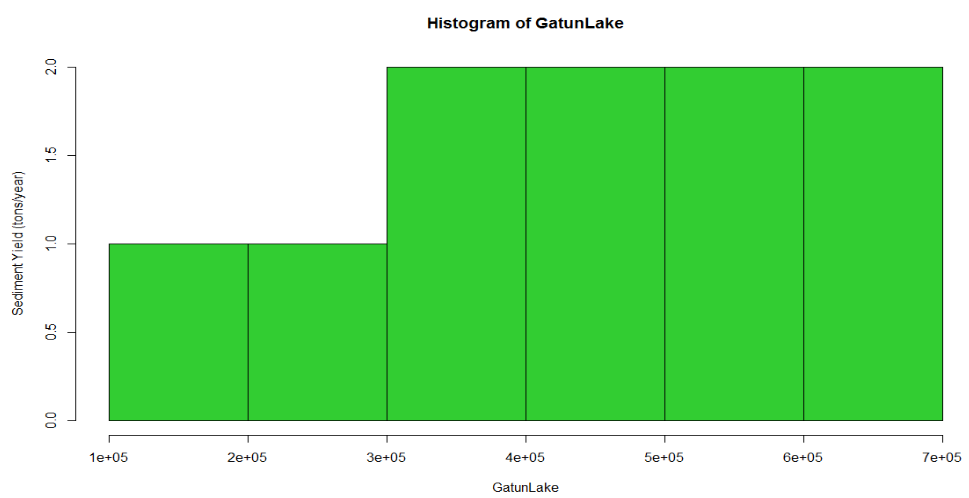
Appendix 4. Panama Canal Basin, Curves of Rainfall. By Panama Canal Authority. (2015).



Appendix 5. The Histogram of sediment yield, Alhajuela Lake (1998-2007).



Appendix 6. The Histogram of sediment yield, Gatun Lake (1998-2007).



Appendix 7. Precipitation (mm) vs Temperature (T°C) in the Gatun Lake & Alhajuela Lake. (Julian Gutierrez 2016).