Addressing Lake Gatun's Uncertainty:
Deterministic and Flexibility in Engineering Design (FIED) Methods

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Abstract

This project involved work for the Panama Canal Authority from July-October 2017, the results of which remain confidential, and a subsequent study that assessed the Panama Canal's water resources management planning methods. A hydraulic model and floodplain maps were created to analyze downstream impacts of a proposed construction project. Later work considered deterministic and flexibility in engineering design methods. A framework is provided to incorporate flexibility in engineering design methods to Panama Canal water management project.

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This work is a continuation of term A17 Major Qualifying Project for the ACP in Panama and the results of that work remain confidential at the request of ACP. This work was partially funded by Grant #1357667, made available by the National Science Foundation's Office of International Science and Engineering, titled "IRES: Environmental Impact of the Panama Canal Expansion Project." This work was completed with Samantha Eaton, Brandon King, Jasmine Loukola, and Margaret Porter. The following report, which was completed in Term B17, builds on the general experience of the project in Panama and sets it in a wider context. The work in B term was completed individually.

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1. Introduction

Lake Gatun is a unique freshwater body, with significant water demands. Panama City relies on Lake Gatun to provide its drinking water. The Panama Canal draws large quantities of water from Lake Gatun to transit ships. The uninterrupted transit of ship requires Lake Gatun's water level to be maintained at a specified level. The *Autoridad del Canal de Panama* (ACP, the Panama Canal Authority) has raised the water level of the lake 1.5 ft (0.45 m) since the opening of the new set of locks, and the ACP predicts that they will need to continue to raise the water level with increasing water demands from the canal operations and Panama City. The ACP projects that the demands and complexity of the management of Lake Gatun will continue to grow significantly in the next century.

Large scale infrastructure projects have been proposed, designed, and constructed to aid the management of Lake Gatun's water level. Currently, the water level of Gatun Lake is controlled by Madden and Gatun Dams[redacted]

In large-scale infrastructure projects, such as the Panama Canal, engineers attempt to design systems that intentionally account for a range of future possibilities (McCarthy, 2015). The operations of the Panama Canal, global climate change, and demands for drinking water in Panama City are all significant categories of factors that influence the future uncertain water level of Lake Gatun (Appendix A: *Factors Influencing Lake Gatun Water Level*).

The Panama Canal demands significant quantities of freshwater from Lake Gatun, suggesting that any significant changes in shipping patterns will have significant impacts on the water level of the lake. These shipping rates through the canal are dependent on a multitude of other factors such as the global economy, demand for goods, transportation modes, and location of factories. The opening of a fourth set of locks, which the feasibility of is currently being studied, would have dramatic impacts on Lake Gatun's water level. The opposite could occur, with the future emergence of a technology that reduces demand for large ship transits. This would have the impact of reducing water demands on the canal and prevent a future project such as the fourth set of locks.

Rainfall patterns, the frequency of heavy flooding, and prolonged droughts due to climate change may also impact the water level of Lake Gatun. Sea levels are predicted to rise between 80 and 90 cm (31 and 35 in) with a change of global temperatures from 1.4 to 2ºC (34.5 to 35.6 ºF) (Triole, 2016). Extreme storm events in Central America, such as the 2010 flooding that forced the closure of the Panama Canal as well as the 2015/2016 drought have led to increased unpredictability in hydrologic modeling (Ranson, 2016).

The Panama City water supply is primarily provided by Lake Gatun through a public-private management partnership. The ACP is contracted by the public water company, *Instituto de Acueductos y Alcantarillados Nacionales* (IDAAN) to provide water, making the ACP responsible for predicting future water demands. In addition to predicting water demands influenced by population growth, the ACP must also account for behavioral changes of the population, industry changes, or other factors that would influence the amount of water consumed from Lake Gatun.

Engineers at the ACP have the responsibility of anticipating the range of future circumstances. Each factor, however, is interconnected with the other factors. Balancing the many factors to estimate what that change will actually be and the probability of the concurrent events is difficult to predict. The challenge for the ACP in the management of Lake Gatun's water level is to appropriately incorporate predictions of how factors will impact the water level and design infrastructure to meet the future demands.

2. Background

Uncertainty, defined as the inability to be confident of the outcome of future events, creates challenges in designing infrastructure systems that adequately meet future needs. Changes in policies, economies, environments, technologies, and needs influence the uncertainty of the future (Wong, 2011). Designing infrastructure that will meet the needs of the future has required the development of tools and methods to predict these changes.

There are many factors that may play a role in influencing the future water level of Lake Gatun. These uncertainties include global climate change, local water demands, and canal operations to facilitate global shipping. The ability of engineers to design for future water needs at Lake Gatun requires making predictions. Inaccurate predictions can result in the over or under designing of infrastructure, often wasting resources in capital-intensive projects (Bourani, 2015).

2.1 Deterministic Infrastructure Planning

The most conventional approach of predicting uncertainty is through deterministic methods. In the deterministic planning approach, a planner assesses the present conditions and calculates over time what the rational scenario for the future outcome will be based on the current conditions (Figure 1) (Wong, 2011). Historically, traditional river basin planning for dams has depended on the "most-probable" forecast of critical system variables including population, water demand, and average streamflow (Baker, 2014).

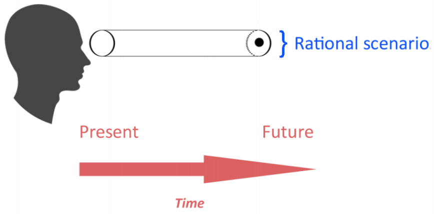

Figure 1: Deterministic Planning Approach (Wong, 2011)

For example, using the deterministic planning method, if the current population of a community is 1000 people and the current growth rate of the community is 1.5%, then the future population in the rational scenario would be 1,160 people. This makes a linear prediction about the future event. A linear event predicts that the current conditions will be the same in the future or that the current conditions will continue to change at the same rate, given as 1.5% in this example. The resulting infrastructure design in this rational scenario would plan for a population of 1,160 people.

Deterministic forecasting methods rely on most-probable or average scenarios. Most-probable scenarios for a river basin would include values such as average streamflow or precipitation forecasts (Baker, 2014). Using these most-probable scenarios, however, result in the "*flaw of averages*" (Cardin, 2015). The "*flaw of averages"* is the process of forecasting an event that is most-likely to occur or an average scenario. When all of the most-likely events are averaged together the predicted future value is suboptimal (Cardin, 2015). In the previous case this would include averaging the rational scenario of population growth as well as other anticipated linear predictions. System responses, however, are not typically linear events, making the estimation inaccurate (Cardin, 2015). Taking average linear values potentially misses a wide range of future events (Baker, 2014).

Jensen's Law, which is applied to non-linear systems, states that the net present value (NPV) with the expected demand of something does not equal the actual expected NPV (Baker, 2014). Jensen's Law predicts that the average or expected demand scenario will not properly value a design, providing incorrect best solutions (Cardin, 2015). When the false assumption that the event is a linear function is made there is a significant chance that the designs will be too large and result in a loss of money or that the design will be too small resulting in missed opportunities (Cardin, 2015).

While Jensen's Law predicts that the average or expected value of the rational scenario will be inadequate to describe the future scenario, economic and resource uncertainties are traditionally accounted for in a deterministic model (Baker, 2014). These uncertainties are incorporated through sensitivity analyses. In a sensitivity analysis, probabilities to parameters, safety, or contingency funds are incorporated into construction plans (Baker, 2014). The sensitivity analysis may include the addition of a safety factor for a design to account for a project being in an earthquake zone, or the expansion of a project's capacity based on the probability of intense flooding.

The standard method for water resource practitioners to design potable water systems is by projecting future population to determine future water demands. This standard method follows the deterministic infrastructure planning method, making the assumption that an area's future hydrology will follow a linear change and be similar to past hydrology (Milly, 2008). Future hydrology, as well as population growth, however, follow a non-linear system. New Delhi, India, has proven that the deterministic method is ineffective at predicting and properly sizing drinking water treatment plants. The population forecast of New Delhi in 2007 was 22.5 million people by 2025, a population that was surpassed four years later. This has forced the 2025 projection up to 32.9 million people, 46% higher than the initial forecast (Wong, 2011). Globally, the water resource divisions are beginning to transition their perception and planning methods for designing infrastructure that accounts for the uncertainty of water, using alternative methods of planning (Wong, 2011).

2.2 Flexibility in Engineering Design Method of Planning

The flexibility in engineering design (FIED) method is an emerging method of infrastructure planning that aims to address the limitations of deterministic planning and accommodate future uncertainty. Rather than taking the linear deterministic approach of future planning, the FIED method looks at a collection of rational scenarios that may occur over time in the future and how infrastructure should be adapted over time to meet those potential scenarios (Figure 2) (Wong, 2011).

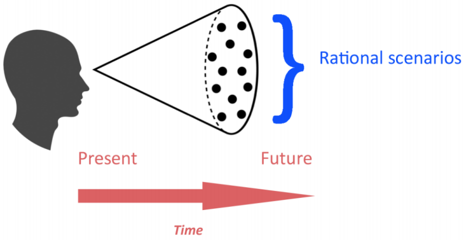

Figure 2: Flexibility in Engineering Design Approach (Wong, 2011)

Using the previous example of a community with a population of 1000 people and the FIED method, a set of rational scenarios would be developed based on assessing conditions that would influence the population of the community. The current growth rate of 1.5% may be a factor in determining the future rational scenarios, however, the rational scenarios will incorporate other factors that may influence the growth rate. These factors could include the assessment of how the economy is impacting the birth rate or how environmental or political conditions in a region are encouraging migration. More importantly, the rational scenarios would not look only at the expected population in 10 years, but would also set benchmarks at different years before the 10-years of the developed rational scenarios that would enable engineers to adapt their plans continuously to the size of the community that presently exists.

The benchmark years within the FIED method incorporates flexible modular designing into infrastructure planning. Over time, infrastructure designed using the FIED method can be adapted to the current conditions (Cardin, 2015). Using flexible modules, instead of needing to build to a midpoint of the range of possibilities that could occur for a “most likely scenario,” the engineer can continuously adapt the design to appropriate sizes (McCarthy, 2015). The FIED method enables planners to improve the economic value of systems under uncertainty by using options that have the ability to adapt and respond to desirable situations (Cardin, 2015 & Wong, 2011). Having infrastructure developed with the ability to adapt and current parameters, infrastructure can capitalize on good opportunities and be more resistant and responsive to losses (Baker, 2014).

It is impossible to analyze all possible combinations of evolutions and flexible ways in which a system can adapt over time (Cardin, 2015). However, using the FIED method, flexible strategies can be used to tell a planner how to continue to design and plan future infrastructure as new information becomes available. This assessment can be completed using a screening model (Figure 3).

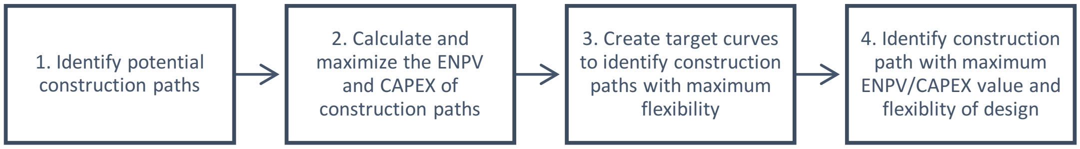

Figure 3:Steps to develop a screening model

A screening model requires the planner to first identify all of the potential construction paths for the project. Using those construction paths, the expected net present value (ENPV) and the discounted capital expenditures (CAPEX) are calculated. The ENPV is calculated for each sequence based on the probability of the event occurring providing an expected value that the project will be worth. The CAPEX calculates the amount of capital needed to be spent on the infrastructure and is accounted for because many infrastructure projects are capitally constrained. The ENPV and CAPEX values can then be maximized for each construction sequence. The third step of the screening model, after the value and capital expenditures are maximized, is to create target curves. Target curves indicate which construction plans are the most flexible in their design strategies. On average, flexible design strategies have better outcomes when compared to inflexible or less flexible design strategies. These target curves can look at each construction sequence and using the NPV and probability of each path to occur with the anticipated price per path, can identify which path is most flexible (Baker, 2014).

Using the ENPV, CAPEX, and target curves, the most appropriate construction path can be determined. Once the screening model has determined a construction sequence that minimizes downside risks and maximizes upside gains, the screening model can be used to further study the most attractive design strategies. At the conclusion of step four, the screening model can be recreated with the optimal path determined from the first screening model. The new screening model can further refine the options within that model. This assists the screening model and FIED method in overcoming the limitation of computing power, by minimizing the total number of plans in study by removing alternative plans using the screening model method (Baker, 2014).

In conventional deterministic infrastructure planning, climate change, drinking water, and shipping demands cannot be simultaneously assessed, adequately quantifying the long term changes. This means that an alternative method of analysis for planning is necessary (Cardin, 2015). The FIED method addresses the problem engineers planning infrastructure problems face, knowing what, when, and to what size to build a project based on changing conditions surrounding a project (Wong, 2011). The FIED method raises the question if the water level of Lake Gatun, and as a result the Panama City drinking water supply and the Panama Canal shipping services can be better managed using the FIED method.

3. Methodology

The water level of Gatun Lake is uncertain, influenced by global shipping demands of the Panama Canal, water demands of Panama City, and global climate change. Deterministic methods can provide a rational scenario for infrastructure to be designed to meet, however, it is ideal to incorporate the flexibility in engineering design (FIED) method into the large scale infrastructure planning to account for the uncertainty of Lake Gatun's future water level. The goal of this project was to assess uncertainty and infrastructure planning methods [redacted], and to determine the feasibility of the ACP applying the FIED method for the management of Lake Gatun's water level.

To meet this goal the following two objectives were established:

1. Identify deterministic and FIED infrastructure planning methods used in the [redacted]
2. Determine the feasibility and a potential framework of applying additional FIED methods to Lake Gatun's water level management.

3.1 Assess Infrastructure Planning Methods

The method of infrastructure planning [redacted] was assessed by reviewing the [redacted]. Phrases and statements in the report were identified that predicted the future of the project, [redacted]. These phrases were then categorized as indicators of deterministic methods, FIED methods, or undeterminable according to the criteria in Table 1.

Table 1: Indicators of Planning Methods

Deterministic Method	FIED Method	Undetermined
Linear assumption that the conditions of today will be the future conditions	Incorporating a large range of potential future events that may impact future conditions	Values/rates provided do not specify how they were determined
Linear assumption that the growth rate today will be a sustained growth rate in the future	Incorporating benchmark years to assess and adapt plans	Unclear whether plans will/will not be adapted over time
Plans that do not allow for changes in the future	Construction plans that allow for changes in the future	Ambiguous regarding how the plan can change in the future

The total number of deterministic, FIED, and undeterminable methods were then summed to determine which method was more predominantly used in the feasibility study.

3.2 Determine Feasibility and Framework for FIED Methods

The phrases identified were grouped into categories of uncertainty factors and rational scenarios. These categories of uncertainty factors included hydrology (blue), agricultural (orange), economic (green), and energy (yellow). Based on the results of the assessment of the infrastructure planning methods used in the report, the need for FIED method was determined. This need was identified by comparing the categories of uncertainty factors and rational scenarios that were addressed in the report to the potential factors of influence that were identified in Appendix A: Factors Influencing Lake Gatun Water Level.

The feasibility of applying the FIED method was determined by developing a SWOT (Strengths, weaknesses, opportunities, and threats) analysis (Figure 3). The strengths describe how the FIED method would be beneficial to the management of Lake Gatun's water management. This looks at the advantages the FIED method has, such as what the method does better than the existing method used as well as the influence it may have on the future of Lake Gatun's water management. The weaknesses of the SWOT look at how the FIED method could be improved, what should be avoided, and what may be lost in using the FIED method. The opportunities looks at what can emerge as a result of using the FIED method, such as impacts beyond the intended impacts such as changes in technology, government policy, or social patterns. Threats of the SWOT analysis assess what could prevent the FIED method from working, as well as challenges that might impact the implementation of the FIED method. At the completion of the SWOT analysis, it can be determined by comparing the strengths/opportunities to the weaknesses/threats to determine if the FIED method is worthwhile to further purse as a potential approach to infrastructure planning.

Once the need and feasibility of the FIED method were identified, a framework for potentially applying the FIED method was developed. This framework focused on the application of the FIED method screening model to the water management of Lake Gatun.

4. Results

4.1 Assessment of Infrastructure Planning Methods

The assessment of infrastructure planning methods found that deterministic phrases were most common within the [redacted] (Table 4). These statements were deterministic because they either projected that the current conditions would continue to be the future conditions or they established a relationship on a non-linear system. These non-linear system relationships have the potential to obey Jensen's Law (Equation 1) that the net present value will not equal the expected net present value. While deterministic methods were most common, it was found that the [redacted] had some statements that lacked sufficient information to determine the method. The only statement that followed a FIED method was the projection of agricultural crops in the region, suggesting flexibility in the type of crop.

Table 4: Phrases and Planning Type

Phrase	D.	F.	U.	Justification
[redacted]	√			Assumes flooding of the past will be the same intensity of flooding for the future
[redacted]	√			Assumes flooding of the past will be the same intensity of flooding for the future
[redacted]	√			Looks at one set return period for the project
[redacted]	√			Assumes groundwater conditions will be the same for the future
[redacted]			√	Does not explain how the 99.6% is calculated
[redacted]	√			Assumes hydrology of the past will be the same intensity in the future
[redacted]			√	Does not provide details on the power market study
[redacted]	√			Projects a set growth rate for the future
[redacted]	√			Uses current energy demands for future energy demands
[redacted]	√			Transposes current energy values and capacity for the future
[redacted]			√	Does not specify how life-cycle analysis or rate of return is calculated
[redacted]		√		Acknowledges that crops may shift in the future
[redacted]			√	Does not explain how return percentage is calculated
[redacted]	√			Anticipates maintained financial inflation and interest rates
Totals:	**9**	**1**	**4**	

4.2 Feasibility and Framework for Applying FIED Method

Based on the analysis of the infrastructure planning methods used for the [redacted] the project is based on primarily deterministic methods with the need to further explore FIED methods. The project has progressed with a 'predict-plan' approach to raising the water level of Lake Gatun. Within the deterministic projections, the assessment focused results on four uncertainty factors; hydrology, energy, agriculture, and economics (Table 5). Noticeably absent from the feasibility study was the potential changes to water demand from Lake Gatun caused by either the Panama Canal or drinking water for Panama City demands.

Table 5: Deterministic Uncertainty Factors Addressed

Deterministic Uncertainty Factors Addressed
Hydrology • Probable maximum flood (PMF) • Groundwater flow • Storm return periods (i.e. 50-year storm)
Energy • Energy demands for growth scenarios
Agriculture • Crop selection
Economics • Inflation rate • Anticipated project cost • Project lifespan • Interest rate

A SWOT analysis (Figure 4) was created to show the feasibility of applying the FIED method to the project.

Table 4: SWOT Analysis

Strengths • Provides benchmarks to change engineering designs with conditions of the future • Incorporates a larger range of events in the assessment of probable events	**Weaknesses** • Requires re-assessment of current project and water management schemes • Will delay current development of water management strategies • FIED method may result in same predicted
Opportunities • Future savings, avoiding large infrastructure investments • Enables adaptation of infrastructure over time	**Threats** • Requires additional funding that may not be available for further analysis of the existing project • May require breaking an existing design-build contract

The SWOT analysis suggests that there may be benefits to apply the FIED method to the water management of Lake Gatun. The screening model, previously described in Chapter 2.2 was adapted as a framework for the ACP to apply the FIED method (Figure 4).

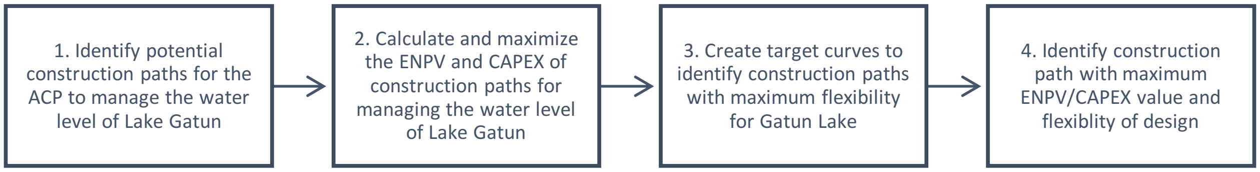

Figure 4: Screening Model for Lake Gatun Water Management

5. Conclusions and Recommendations

The FIED method provides many advantages to the conventional deterministic planning methods and have the potential of being incorporated effectively into the management of Lake Gatun's water. The assessment [redacted] indicates that there was very minimal use of the FIED method. This was demonstrated by the use of probable maximum flood values, storm return periods, water flows, and inflation rates. However, the assessment also indicated that there were some areas where the method used was undetermined. The SWOT analysis suggests that there are benefits to applying the FIED method to this project, however, the current status [redacted] which is currently contracted out threatens the ability to effectively implement this method without further delaying the implementation of a water management solution. Furthermore, the implementation of the FIED method would require the collaboration of the ACP with an expert in the FIED method to develop complex models, such as the screening model recommended.

The management of Gatun Lake is only one of many engineering infrastructure concerns that requires the ACP to make predictions about the future. The ACP could benefit significantly from adopting FIED methods to their other infrastructure plans. Specifically, the FIED method could have larger implications in the study of the feasibility study for the fourth set of locks, providing important benchmarking for engineering decisions and construction.

Based on the findings of this project, the following recommendations have been developed to address both the immediate project for the water management of Lake Gatun, as well as long term recommendations for the future management of the Panama Canal.

Immediate recommendations:

1. Further investigate the use of FIED methods in the planning and reports for [redacted]
2. Assess the feasibility of applying additional methods without impacting the transit of ships through the canal

Long term recommendations:

1. Further investigate the application of the FIED to large scale dam and canal projects
2. Incorporate analysts with expertise in FIED methods to assess current planned infrastructure projects and future ACP needs

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7. Appendix

A: Factors Influencing Lake Gatun Water Level

Category of Influence	Increase Water Level in Lake Gatun	Maintained Water Level in Lake Gatun	Decrease Water Level in Lake Gatun
Rainfall	• Increased storm/flood intensity • Return period storms are higher than MWH 1990's predicted values	• Maintained rainfall patterns • There are no changes to MWH 1990's predicted values	• Increased drought periods • Return periods are less than MWH 1990's predicted values
Sea Level Changes	• More salt intrusion occurs, preventing water being used by Panama City	• Sea level changes does not impact Lake Gatun	• Sea level change causes drop in Lake Gatun
Population	• Decreased population growth	• Maintained population	• Increased population growth
Industry	• Loss of water intensive industry	• No change in industries	• Increase of water intensive industry
Behavioral Changes	• Decreased water use per capita	• Maintained water use per capita	• Increased water use per capita
Water Pollution/ Increased Salinity	• Inability to use water for potable purposes	• No change to water quality	• Improved water quality
Water Economy	• Unaffordable water market prices	• Maintained water market price	• Inexpensive water market prices
Water Policies	• Stringent water policies	• No change to current water policies	• Less stringent water policies
Ship Transits	• Decreased # of transits • Substitution of old locks with new locks that use less water	• No change in current transit of ships and water demanded for canal purposes	• Increased use of water for canal • Construction of new set of locks demanding additional water
Global Economy	• Poor economy leads to fewer ships transiting •	• No changes to economy impacting shipping industry	• Strong economy leads to increase in ships transiting •
Panama Canal Policies	• Policy limiting number of transits	• No changes to policies	• Policy encouraging additional transits
Canal Technology	• New technology that demands less freshwater	• No changes to canal technology that influences water demand	• New technology that demands more freshwater