Screening Model Optimization for Panay River Basin Planning in the Philippines

by

John Henry Millspaugh

B.S., Civil Engineering
University of Virginia, 2009

Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Civil and Environmental Engineering

at the
Massachusetts Institute of Technology

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ABSTRACT

The state of the water resources of the Panay River Basin have motivated studies and initial basin planning to mitigate flood damages, to produce hydroelectricity, and to increase irrigated rice areas. The goal of this study was to provide the optimal design parameters for facilities potentially to be placed in the basin and the water management variables associated with operating these facilities. This study considered four reservoirs, four hydropower facilities, and an irrigation facility. Screening model optimization produced results to provide insight for future water resources management in the basin. The modeling was completed in GAMS (General Algebraic Modeling System).

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There are many individuals that without their help, this thesis would not have been possible.

Before all others: my King, Jesus Christ. His grace was sufficient.

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1. Background

1.1 Capiz

The province of Capiz is located in the Western Visayas Region of the Philippines on Panay Island. It is located between the coordinate points 11° 09' to 11° 40' North and 122° 11' to 123° 05' East and represents 2,633.17 km^2 of the Panay Island of the Philippines. The province consists of its capital city, Roxas City, and sixteen municipalities (see Figure 1). The estimated population of the province is 773,300 individuals. 148,809 of these individuals reside in Roxas City (Provincial Planning and Development Office, 2010).

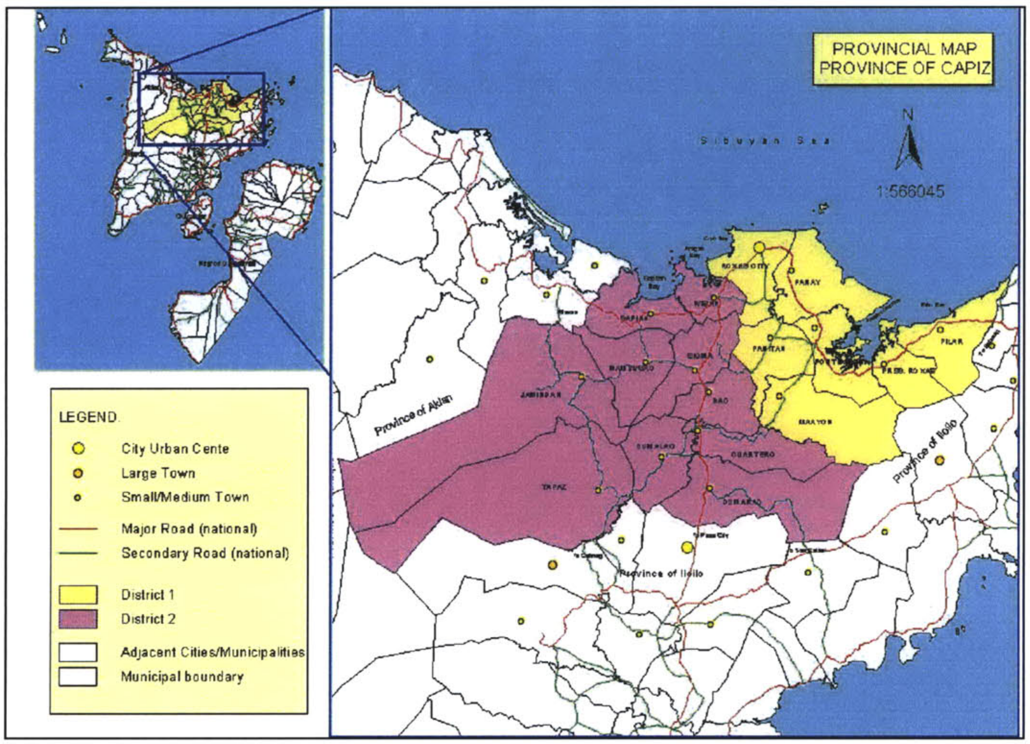

Figure 1: Capiz: Roxas City and Its Sixteen Municipalities (Provincial Planning and Development Office, 2010)

The economy of Capiz is heavily reliant on its agriculture and aquaculture industries. Eighty percent of Capizeños are income-dependent on these industries and forty-two percent of the province's land area is devoted to agriculture, primarily rice. The province produces on the order of 300,000 metric tons of rice per year. Despite the increase of commercialization in the province in recent years, these industries are predicted to remain as the critical components of the province's economy (Office of the Provincial Agriculturist and Department of Agriculture Bureau of Postharvest Research and Extension, 2008).

1.2 Farming in Capiz

To understand Capizeños necessitates understanding Capizeño farmers because of the ubiquity of farming in Capiz. Almost every male Capizeño has farming in his history. Most have been farmers since childhood. On average, farmers own 1.01 hectares of farming land and the majority of these farmers grow rice (Office of the Provincial Agriculturist and Department of Agriculture Bureau of Postharvest Research and Extension, 2008; Dela Cruz, 2010). Typical Capizeño farmers are poor and are very vulnerable to the productivity of their crops. The majority also rents their land for a fee each season (Virgilio, Badoles, & Abelardo, 2010). Consequently, farmers manage a tight budget each cropping in determining their expenditures on fertilizer, pesticides, and irrigation water. In addition to financial difficulties, farmers' highest vulnerabilities are the amount of water available to them for irrigation, flooding events, and pests (Amponin, 2010; Gicalde, 2010; Virgilio, Badoles, & Abelardo, 2010).

The Office of Provincial Agriculturists alongside the Offices of Municipal Agriculturist has been promoting more organic practices province-wide, coined "Integrated Pest Management (IPM)" (Department of Agriculture: Western Visayas, 2007). Disseminating knowledge and working alongside farmers in test trials has exhibited a promising start to alleviating the pest problem in Capiz through alternatives to mass chemical application, but water vulnerability still plagues farmers (Gicalde, 2010). Farmer's in lowland areas near the river are susceptible to the destruction of their crops from flooding while droughts can often result in substantial losses in a season's yield.

The author's investigation of irrigation systems while visiting Capiz resulted in some insights. Many irrigation systems were under-achieving and many were in need of repairs. The major problems noted were the abundance of illegal uses of irrigation systems, the need for maintenance, and the inability of many to afford access. Many farmers near the river rent generators to pump river water to irrigate their fields during periods when they can afford it. Nevertheless, the added benefits of irrigating one's land for a given cropping season was at most one metric ton per hectare for a municipality, but, the availability of irrigation water does allow farmers to more confidently plant more often, and thus can be a much added benefit to farmers in the short term (Hecita, 2010). On the other hand, the Municipality of Tapaz had marginal productivity improvement from irrigated lands, only an increase in productivity of 0.05 metric tons per hectare per season. The municipal agriculturists attributed this to high pest problems (Fecara, 2010). In summary, the province varied significantly in productivity from irrigation facilities.

1.3 Water Resources of Capiz

The majority of Capiz is located within the Panay River Basin and relies on the Panay River and the Mambusao River, the Maayon River, and the Badbaran River tributaries for much of its water needs (see Figure 2). The Panay River basin area is over 2,000 km^2 and its major river, the Panay River flows from the Southwest region of the basin to the middle North region of the basin. Along its route to the ocean, it gains water from the Badbaran River, the Mambusao River, and the Maayon River tributaries, respectively. The length of the river, 152 km, carries water through significantly flat terrain, resulting in siltation and flooding (Japan International Cooperation Agency, 1985). The middle and lower regions of the river area are subject to flooding from typhoons almost yearly. On average, Capiz experiences a typhoon once every two years (National Water Resources Council, 1977).

Figure 2: Panay Island with Panay River Basin Outlined (Image adapted from Japan International Cooperation Agency (1985))

Capiz's climate is defined as having neither a distinct wet nor dry season, although it usually rains more between June and December than between January and May (Turkulas, 2010). Rainfall in the region does vary significantly spatially. The meteorological investigation by JICA estimated yearly rainfall for the province in 1985 ranging from 3,500 mm in the mountainous west to 2,000 mm in the southeast region of the province (Japan International Cooperation Agency, 1985). Significant variations also occur between years due to El Niño and La Niña. La Niña means heavy rains and El Niño means drier conditions for Capiz.

During the rainier months of Capiz, especially during La Niña-occurring years, Capizeños have worries of flooding. The flooding history of Capiz is substantial grounds for Capizeños to fear with floods resulting in deaths and hundreds of millions of Pesos worth of damage (Japan International Cooperation Agency, 1985). Roxas City and twelve of the sixteen municipalities are heavily affected by floods occurring from typhoons. The areas that are most affected by flooding are those surrounding the Panay River and its tributary rivers. The lower elevation areas near the rivers bear the brunt of these catastrophic events. The flooding events have been devastating to lowland inhabitants and a major obstacle to the economic goals of the province (Provincial Planning and Development Office, 2010).

1.4 Motivation for Model

For at least the last thirty years, provincial planning has included investigations for alleviating flood damages, improving irrigation, and generating hydroelectricity. The most prominent example was the investigations and studies conducted by the Japan International Cooperation Agency (JICA) in the early 1980s. JICA proposed a solution for the Panay River Basin by completing "The Panay River Basin-wide Flood Control Study" in 1985. The study's main objective was to evaluate options for flood relief for the region; however, the proposal was also characterized by a solution that included benefits from hydropower and agricultural potential (Japan International Cooperation Agency, 1985). Nevertheless, to date, nothing has been actualized.

Flood protection, electricity generation, and irrigation expansion are presently still critical needs of the province of Capiz. Most recently, Typhoon Frank in June 2008 resulted in devastating damages for the majority of the lowland areas of Capiz. Typhoon Frank affected all 473 barangays of Capiz and at least 44% of the province's population. Over 25,000 houses and over 17,000 hectares of agricultural area were damaged (Provincial Disaster Coordinating Council, 2008). Capizeños remember the incident quite well and recount water levels being chest level in the roads and filling lowland homes with water (Turkulas, 2010; Gicalde, 2010). In regards to energy, the province is rapidly approaching the point of not being able to meet its energy demands and is in need of more sources (Abela, 2010). In regards to agriculture, a large number of farmers are constantly struggling to get consistent irrigation water for their rice fields to provide for their families and the market (Amponin, 2010; Fecara, 2010; Gicalde, 2010; Hecita, 2010).

Understanding the problem is the first step, but it must produce efforts to formulate a solution. The model in this study draws on the perceived problems of the province by the author from his investigation of past studies and his experiences during his site visit in January 2010 in order to provide insight towards a solution.

2. Project Overview

2.1 Objective

The research objective of this thesis was to provide an optimized solution through a screening model of the potential construction of dams, hydropower facilities, and an irrigation facility in the Panay River Basin and the subsequent water management. The model is based on the original ambitions proposed by JICA in 1985. The model is hoped to be an aid for decision makers as they potentially make large infrastructure decisions for the province in the future.

2.2 Scope

Although the JICA plan included holistic planning including river improvements, the model used in this study was simplified to the construction of dams for flood protection, hydroelectric power generation, and irrigation provision in the current basin. Many of the parameters used in the model used qualitative and quantitative data from regionally produced reports. The major reports were the "Draft Final Report on the Panay River Basin-Wide Flood Control Study: Main Report" (CS) produced by JICA and "Report No. 24A: Panay River Basin Framework Plan" (FP) produced by the National Water Resources Council (NWRC). The remaining parameters came from interviews and data collection during the author's visit to Capiz in January 2010. During this month the author accomplished the following:

- Completed site investigations of rice fields and irrigation facilities
- Held discussions with farmers and members of the Municipal Agriculturist
- Collected municipal rice production data from offices of the Municipal Agriculturist
- Obtained rainfall information from the weather authority, PAGASA
- Held interviews with members of the Office of Provincial Agriculturists (OPA)
- Obtained rice reports and data on rice from the OPA
- Held discussions with the projects' representatives from the Department of Public Works and Highways (DPWH) and JICA

The decision to construct the dams, hydropower facilities, and the irrigation facility and how to manage water was formulated as an optimization problem with the objective of maximizing the difference between the benefits and costs of the project.

The benefits were the electricity generated and the increased production from irrigated rice fields.

The costs were the construction of the potential dams, the irrigation facility, and the hydropower facilities, the operation and maintenance of these facilities, and the damage occurring from flood waters originating upstream of the proposed reservoir locations.

2.3 Model Approach

A screening model was used to conduct the optimization. The screening model in water resources planning is a model in which the possible options for the river basin are "screened" to determine the optimal solution based on a predetermined objective. The problem is often formulated as a mathematical programming problem with the objective to maximize or minimize some function that is dependent on the elements "screened" in the model (Cohon, 1978).

The resulting optimal system from the screening model was then scrutinized via a partially stochastic screening model. The results from this model and sensitivity analyses help depict possible options for decision makers for the region.

3. Screening Optimization Model

3.1 Model Overview

The previous studies for Panay River Basin planning seem to have only judged possible designs on feasibility; its constructability and economic internal rate of return (Japan International Cooperation Agency, 1985; National Water Resources Council, 1977). The purpose of using a screening model in this study was to conduct planning through the lens of optimizing the project's objective of benefitting Capiz while considering the previous constructability concerns and financial desires.

The analysis completed in this study was constrained to the optimization of the reservoir and hydropower facilities previously considered in regional studies and the potential for an irrigation facility adjacent to one of these reservoirs. The objective of building these facilities was posed to reflect the historical motivation for managing the basin: to primarily provide flood protection and then to provide electricity and irrigation for the province. The goal was to find facility sizes and river management decisions to maximize the difference between the benefits and costs associated with the project.

The screening model has historically been used for a mean hydrological year and then examined in simulation models to test the solution's robustness to varying hydrological years over the life of the project. For example, in the Rio Colorado case, the screening model was applied for a mean year with the costs discounted to get the net amortized benefit (Major & Lenton, 1979). The inclusion of floods in this study required a modification to this general screening model approach.

For this study's screening model, a mean hydrologic scenario was repeated for the entire project life[1], and return-year floods[2] were inserted into the model to account for probabilistic floods over the project's life. The life of the project was set at fifty years, *n*. Therefore, to account for major floods, floods were inserted within the fifty-year mean hydrologic scenario as shown in Figure 3, where the timeline indicates the mean hydrological data input for the model and the added floods are three day input data that characterizes the eight floods that were used in this study. Each of the eight floods was placed as three additional days at the end of June to represent typically occurring floods. Consequently, a 50-year flood was located in the middle of the 26th year, a 25-year flood in the middle of 13th and 39th years, and a 10-year flood in the middle of the 3rd, 8th, 18th, 31st, and 43rd years of the fifty years of the model. The damage from the floods was determined by the model from a relationship relating flood flows to flood damage for flood regions in the basin.

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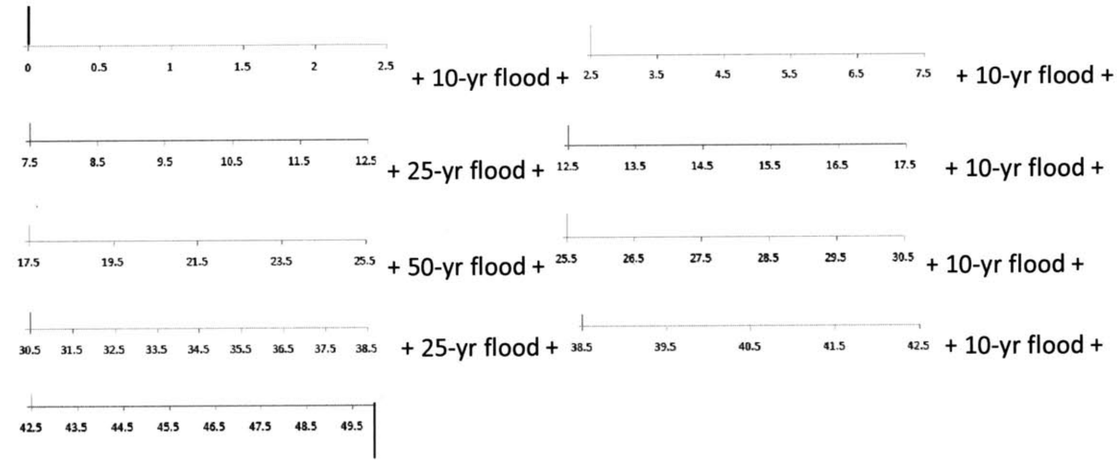
[1] An added benefit of running the screening model for the entire project life compared to only a mean year is that over-year storage is able to be accounted for. In the Rio Colorado case, the simulation model was used in part to handle their screening model's inability to handle over-year storage (Major & Lenton, 1979).

[2] Return period is the hydrological way of assigning a probability to a flood. (1/return flood period number)*100 is equal to the probability of that size flood occurring in a given year (Bedient, Huber, & Vieux, 2008).

Start: All Facilities Built = Year 0



End: End of Facilities' Life = 50 years

Figure 3: Timeline Showing Floods Added Throughout Project Life

Furthermore, these three-day flood periods were divided into 12-hour increments to more accurately reflect the changes in water flow over time due to a flood. The result was a model with 648 time steps, *t*. 600 time steps were months, *m*, and 48 were 12-hour long flood period increments. When the 48 12-hour time steps are looked at separately in this model, they are represented as 48 time steps, *v*, or eight flood periods[3], *u*.

The modified screening model also needed a unique objective function formulation. The benefits from the project were hydropower production and improved rice productivity. The capital costs of the project were amortized over the life of the project and the annual operation and maintenance costs were set as a percentage of the capital costs. Flood damages from water originating upstream of the proposed reservoir locations was considered as a cost in this model in order to design against flood damages. Project benefits and costs are shown in Tables 1-3 below.

Project Life Benefits	Project Life Costs
Total Hydropower Produced	Total Flood Damages from Flows Upstream of Reservoirs
Total Irrigated Rice Produced	Total Accrued Capital Cost Including Annual Interest Rate
	Total Operation and Maintenance Costs

Table 1: Project Life Benefits and Costs

Annual Benefits for Non-Flood Years	Annual Costs for Non-Flood Years
Hydropower Produced during Non-Flood Years	Amortized Capital Cost
Irrigated Rice Produced in Non-Flood Years	Annual Operation and Maintenance Cost

Table 2: Annual Benefits and Costs for Non-Flood Years

Annual Benefits for Flood Years	Annual Costs for Flood Years
Hydropower Produced during Flood-Years	Flood Damages from Flows Upstream of Reservoirs
Irrigated Rice Produced in Flood-Years	Amortized Capital Cost
	Annual Operation and Maintenance Cost

Table 3: Annual Benefits and Costs for Flood Years

[3] Each flood period consisted of six 12-hour time steps.

Since the actual occurrence of floods is only probabilistic, the objective function was formulated as maximizing the difference between the benefits and costs shown in Table 1. To find the total cost over the life of the project, the amortized amount for each year was found and then multiplied by the project length, 50 years. Since the majority of the model years were non-flood years, which all had the same input data, the contribution to the objective function during these years represent an annual floor for the objective function. Flood years were hoped to only introduce higher benefits due to increased hydropower production from more water, because it was hoped that flood damages from flows upstream of the reservoirs could be eliminated by facility implementation.

3.2 Facility Descriptions

The screening model was built to analyze the decision to construct four potential dams and subsequent hydropower facilities and an irrigation facility (see Figure 4). The four sites were the locations considered in CS (Japan International Cooperation Agency, 1985). The four sites, *s*, considered were named Panay 1, Panay 2, Badbaran, and Mambusao due to their location within the Panay River Basin.

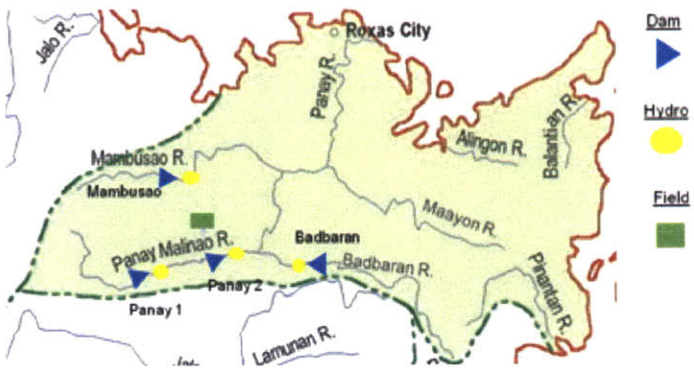


Figure 4: Panay River Basin with Proposed Facilities (Imaged adapted from Japan International Cooperation Agency (1985))

Reservoirs - In order to provide flood protection, hydropower production, and irrigation water, the four proposed reservoirs would collect water by damming sub basins within the Panay River Basin (see Figure 5). The basins were found using ArcGIS's hydrology toolbox (Economic and Social Research Institute, 2009) and Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) data for the region (ASTER GDEM, 2009)[4],[5].

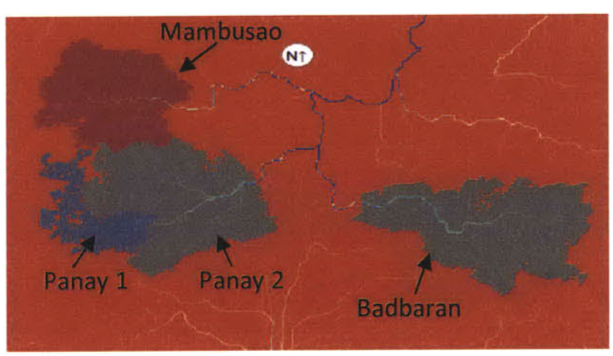


Figure 5: The Watersheds Contributing to the Proposed Reservoirs

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[4] The DEM's resolution was 30 m x 30 m resolution.

[5] ASTER GDEM is a product of METI and NASA. These data are distributed by the Land Processes Distributed Active Archive Center (LP DAAC), located at the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center (lpdaac.usgs.gov).

Figure 6 shows an approximately 7-meter-high by 100-meter-long dam currently operating in the lower reaches of Mambusao, Capiz. This reservoir serves only as an irrigation diversion dam with the start of the canal on the left side in Figure 6. The potential dams considered in this study differ from this dam in the way water is to be released downstream. Water would be released through an intake at the base of the dam as opposed to spilling over the crest of the dam. Dam release for the proposed dams would follow the example shown in Figure 7 to exploit the reservoir's head for hydropower generation.

Figure 6: Current Irrigation Dam

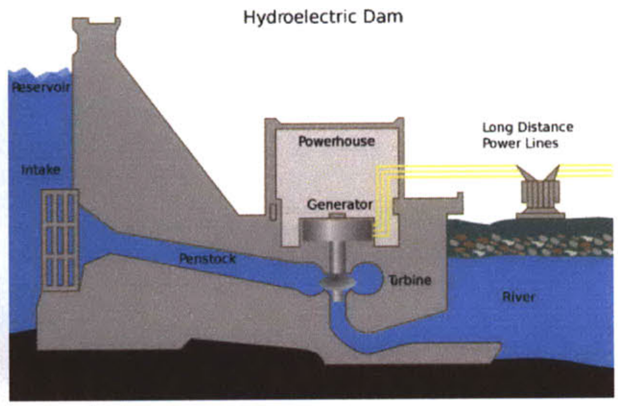

Figure 7: Generic Dam for Hydropower (Family, 2005)

Hydropower - The hydropower facilities would be a new technology introduced to the province. The hydropower facilities would create energy from turbines immediately downstream of each reservoir. The release at the bottom of the dams provides the head and flow for the turbines to produce energy. The energy produced at the power stations would then transmit the electricity throughout the region based on need to supplement its current energy supply.

Irrigation - The irrigation facility would originate similarly to the facility shown in Figure 6 and supply water to land area designated for growing rice. Some of the reservoir water would be diverted from the dam by means of a canal to designated rice fields that are adjacent to the reservoir. A network of irrigation canals would be used to deliver water to individual fields. Figure 8 exhibits an example of an irrigation canal in Capiz delivering water to rice fields.

Figure 8: Pontevedra's Municipality Irrigation System

3.3 Model Description

System Diagrams:

Figure 9 illustrates the potential facilities and model variables for each site.

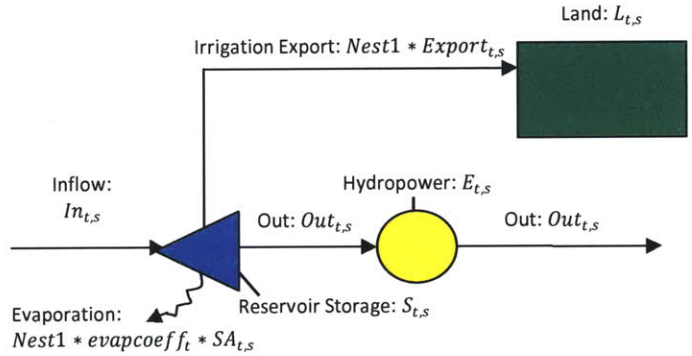

Figure 9: Network Diagram of Facility Sites

Figure 10 illustrates the five regional flow locations, j, where local flows, $Floodflowspot_{u,j}$, were used by the model to calculate regional flood damage, $FloodCost_{u,j}$ during flood periods, u.

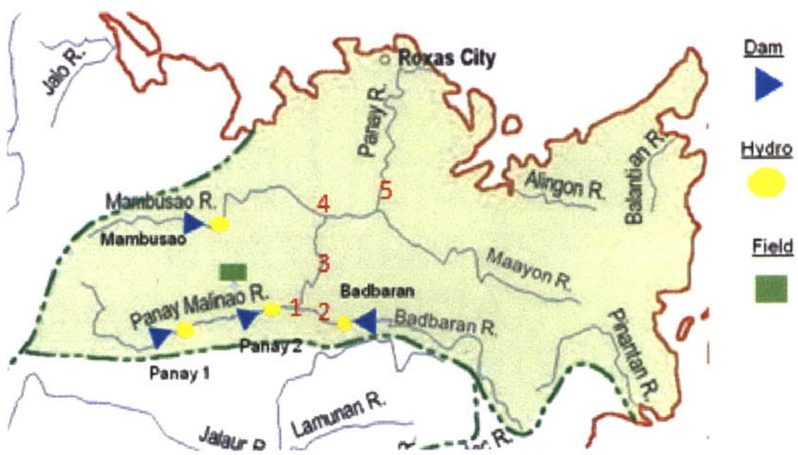

Figure 10: Flood Regions (Image adapted from Japan International Cooperation Agency (1985))

The following were the main decision variables of the model:

The capacities of the facilities at each site (Reservoir, Hydropower, and Irrigation Land): $CAPRes_s$ (MCM), $CAPPower_s$ (KW), and $CAPLand_s$ (ha)

Water management at each site and time increment (Storage, Release, and Irrigation Export): $S_{t,s}$ (MCM/time), $Out_{t,s}$ (MCM/time), and $Export_{t,s}$ (MCM/time)

Energy produced at each site per time increment: $E_{t,s}$ (KW*hr)

Flow volumes at locations representative of the five flood regions: $Floodflowspot_{u,j}$ (MCM/time)

Model Equations[6]:

Equation 1: Objective Function

$$[\sum_{t=1}^{648}\sum_{s=1}^{4} B_{t,s}] - [\sum_{u=1}^{8}\sum_{s=1}^{4} PreventableFloodCost_{u,s}] - [SummedAmortization * C] - [O\&M]$$

Equation 2: Benefits

$$B_{t,s} = IrrBen_{t,s} + HydroBen_{t,s}$$

Equation 3: Irrigation Benefit

$$IrrBen_{t,s} = Nest1 * \alpha * CAPLand_s * \Delta t$$

Equation 4: Energy Benefit

$$HydroBen_{t,s} = \beta * E_{t,s}$$

Equation 5: Capital Cost

$$C = \sum_{s=1}^{4}(ResCost_s + HydroCost_s + IrrCost_s)$$

Equation 6: Amortization Term

$$SummedAmortization = n * [r/(1 - \left(\frac{1}{1+r}\right)^n]$$

Equation 7: Operation and Maintenance Cost

$$O\&M = O\&MPercentage * C * n$$

Equation 8: Reservoir Capital Cost

$$ResCost_s = k_s * CAPRes_s$$

Equation 9: Hydropower Capital Cost

$$HydroCost_s = q_s * CAPPower_s$$

Equation 10: Irrigation Capital Cost

$$IrrCost_s = \mu_s * CAPLand_s$$

Equation 11: Preventable Flood Cost

$$PreventableFloodCost_{u,s} = \delta_s * Out_{u,s}$$

Equation 12: Total Flood Cost

$$FloodCost_{u,j} = \omega_j * Floodflowspot_{u,j}$$

---

[6] The mathematical programming formulation was based on the Rio Colorado screening model formulation (Major & Lenton, 1979; McLaughlin, 2009)

Equation 13: Mass Balance at Reservoirs

$$S_{t+1,s} = S_{t,s} + In_{t,s} - \ Nest1 * Export_{t,s} \ - \ Out_{t,s} - \ Nest1 * evapcoeff_t * SA_{t,s}$$

Equations 14-21: Mass Balance at Junctions and Flood Spots

$$Junction_{t,1} = out_{t,2} + \ flow_{t,3} + out_{t,3} + flow_{5,t}$$

$$Junction_{t,2} = Junction_{t,1} + flow_{t,6} + flow_{t,7} + out_{t,4} + flow_{t,9}$$

$$Junction_{t,3} = Junction_{t,2} + flow_{t,10} + flow_{t,11}$$

$$Floodflowspot_{t,1} = out_{t,2} + flow_{t,3}$$

$$Floodflowspot_{t,2} = out_{t,3} + flow_{t,5}$$

$$Floodflowspot_{t,3} = Junction_{t,1} + flow_{t,6}$$

$$Floodflowspot_{t,4} = out_{t,4} + flow_{t,9}$$

$$Floodflowspot_{t,5} = Junction_{t,3}$$

Equation 22: Monthly Flooding Prevention

$$Floodflowspot_{m,j} \le Maxmonflow$$

Equation 23: Reservoir 1 Inflow

$$In_{t,1} = flow_{t,1}$$

Equation 24: Reservoir 2 Inflow

$$In_{t,2} = flow_{t,2} + \ Out_{t,1}$$

Equation 25: Reservoir 3 Inflow

$$In_{t,3} = flow_{t,3}$$

Equation 26: Reservoir 4 Inflow

$$In_{t,4} = flow_{t,4}$$

Equation 27: Reservoir Capacity Constrained

$$CAPRES_s \le Resmax_s$$

Equation 28: Storage Constrained by Reservoir Capacity

$$S_s \le CAPRes_s$$

Equation 29: Storage-Head Relationship

$$H_{t,s} = \Psi_{1,s} S_{t,1}^2 + \ \Psi_{2,s} S_{t,1} + \Psi_{3,s}$$

Equation 30: Storage-Surface Area Relationship

$$SA_{t,s} = \Phi_{1,s} S_{t,1} + \Phi_{2,s}$$

Equation 31: Energy Produced (Major & Lenton, 1979)

$$E_{t,s} = \gamma * effic_s * Out_{t,s} * H_{t,s} * \Delta t$$

Equation 32: Hydropower Facility Size Constrained

$$CAPPower_s \leq Hydromax_s$$

Equation 33: Energy Constrained by Turbine Capacities

$$E_{t,s} \leq CAPPower_s * Nest2 * Y$$

Equations 34-36: Efficient Energy Constraints (Major & Lenton, 1979)

$$Hmin_{t,s} \leq H_{t,s}$$

$$Hmaxt_{t,s} \geq H_{t,s}$$

$$Hmax_{t,s} \leq 2 * Hmin_{t,s}$$

Equation 37: Irrigation Land Constraint

$$CAPLand_s \leq Landmax_s$$

Equation 38: Exported Irrigation Water

$$Export_{t,s} = watreq * CAPLand_s * \Delta t * Nest1$$

Equations' Variable and Symbol Definitions:

a – Major river junctions (1 - Panay River-Badbaran River junction, 2 - Panay River-Mambusao River, and 3 - Panay River-Maayon River junction)

f – Basin Reaches (See Section 3.4, Figure 15 for Eleven Reaches)

j – Flood Regions (1-5)

n – Project years: 50

m – Monthly time steps: 600 months

s – Facility Sites: 1- Panay 1, 2 – Panay 2, 3 – Badbaran, and 4 – Mambusao

t – Total time steps for the model: 600 months + 48 12-hour flood increments

u – Flood Periods: 8 3-day flood periods

$B_{t,s}$ - Benefits from irrigation ($IrrBen_{t,s}$) and hydropower ($HydroBen_{t,s}$)

C - Capital cost from reservoir facilities ($ResCost_s$), hydropower facilities ($HydroCost_s$), and the Irrigation facility ($IrrCost_s$)

$CAPRes_s$ - Reservoir facility size

$CAPPower_s$ - Hydropower facility size

$CAPLand_s$ – Irrigation land size

$E_{t,s}$ - Energy produced

$effic_s$ – Efficiencies of the hydropower turbines

$evapcoeff_t$ - Coefficient to convert reservoir surface area to volumetric evaporation

$Export_{t,s}$ - Irrigation export water volume

$FloodCost_{u,j}$ – Regional flood damage costs from all flood waters

$Floodflowspot_{u,j}$ - Flow volume for flood regions during flood periods

$flow_{t,f}$ – Flow volume for a given reach

$H_{t,s}$ - Head at reservoirs

$Hmin_{t,s}$ – Minimum head at reservoirs

$Hmaxt_{t,s}$ - Maximum head at reservoirs

$Hydromax_s$ – Maximum allowable hydropower facility size

$In_{t,s}$ - Reservoir inflow volume

$Junction_{t,a}$ – Flow volume at major river junctions

k_s - Linear proportionality constant for the relationship between reservoir cost and size

$Landmax_s$ - Maximum allowable irrigation facility size

$Maxmonflow$ - Maximum allowable monthly flow volume to ensure that flooding does not occur during monthly time increments.

Nest1 – Array to handle nesting of flood water management equations in the model

Nest2 - Array of hours for each model time step, *t*

$O\&M$ - Operation and maintenance cost for the project's life

O&MPercentage – Yearly operation and maintenance cost as a percentage of capital cost

$Out_{t,s}$ - Reservoir release volume

$PreventableFloodCost_{u,s}$ – Flood damage costs from flood waters upstream of proposed reservoirs

q_s - Linear proportionality constant for the relationship between hydropower facility cost and size

$Resmax_s$ - Maximum allowable reservoir size

$S_{t,s}$ - Reservoir storage volume

$SA_{t,s}$ - Reservoir surface area

$SummedAmortization$ - Factor of increased capital cost due to amortization over the life of the project

$watreq$ - Irrigation water requirement

Y - Factor of utilization

γ - Conversion factor for energy

δ_s - Linear proportionality constant for the relationship between reservoir release and flood damage

μ_s - Linear proportionality constant for the relationship between irrigation facility cost and size

Φ_s – Linear coefficients for the relationship between storage and surface area at the reservoirs

Ψ_s – Quadratic coefficients for the relationship between storage and head at the reservoirs

ω_j - Linear proportionality constant for the relationship between total regional flood cost and regional flow

Model Assumptions:

1) The model assumes that the floods produce a triangle shape hydrograph over a three-day period in between June and July with a peak flow in the 36^{th} hour. Floods primarily happen once at most per year and a typical time for a typhoon to hit the island is June (Turkulas, 2010; Provincial Planning and Development Office, 2010). For example, in late June Typhoon Frank brought heavy rains for three of four days, in the amounts of 75.5 mm/day, 300 mm/day, 232.5 mm/day, no rain, respectively (Turkulas, 2010). The model also assumes that the flood flow occurring in the lower basin can be evenly distributed among the basin based on the proportion of the basin that those locations represent (see Appendix D).
2) The life of the project was fifty years
3) All facilities were able to be built at the beginning of the fifty years and their life cycle ends at the end of the fifty years.
4) Every month was considered to be thirty days long.
5) Model consistency was considered not to be significantly affected by adding three days in the middle of flood years.
6) Mass balance equations were considered adequate to account for flood flows. A mass balance equation is not truly sufficient for flooding (Loucks, Stedinger, & Haith, 1981), but the lack of significant river characteristics made the use of flood routing equations unreliable. Therefore, the simplification of using mass balance equations for estimating flood flows was used.
7) The water is homogenous in quality and properties throughout the basin. Water properties in the model were only considered for the mass balance equations.
8) Seepage at the dams was considered negligible.
9) The cost of the reservoirs was assumed to be linearly proportional to the needed materials.
10) Material costs for the dams were only taken as a function of the dam's dimensions of length and height. It was assumed that width of the dam would vary linearly to product of the crest length and height of the dam.
11) The costs from operation and maintenance were assumed to be a yearly need represented as a percentage of the capital costs. This expense was deemed to be critical to project implementation based on the author's visits to other regional water projects, therefore a pricing

scheme based on capital costs was used in hopes of ensuring that larger projects would be given sufficient funding to carry out operation and maintenance.

12) The cost of the hydropower facilities was assumed to be linearly proportional to capacity size. No other data was available to assume a different relationship.
13) The pricing estimates from the 1985 reports were increased by 13%. This was based on an informal question to a regional authority on the project in regards to a reasonable present cost estimate (Abela, 2010).
14) The irrigation facility at Panay 2 was assumed to cost the same per hectare as the extension project in Pontevedra per hectare. The irrigation facility at Panay 2 was proposed to be a simple canal system near the reservoir that is similar to the extension project in Pontevedra. The land was assumed to be close enough to the reservoir that aqueducts or long transport canals were unnecessary.
15) Irrigation productivity for the past was considered representative of the productivity potential for every year of the life of the project.
16) All of the water exported for irrigation was assumed to be consumed. No water is returned to the river after it is exported.
17) Irrigation water needed at Panay 2 was assumed constant throughout the year. Farmers seemed to be constantly needing irrigation water as they were on a rotating schedule with other farmers throughout farming seasons.
18) Exported irrigation water need was assumed to be zero during the flood periods. The high precipitation associated with the typhoons means that farmers do not need irrigation water during this period.
19) All energy produced was assumed to be usable.
20) The head received by the turbines was equivalent to the height of water at the dam. The turbines are hoped to be placed as low as possible in elevation in order to benefit from the head created by the dams.
21) Operators were considered to have perfect knowledge of the amount and timing of the water resources in the basin. In reality, operators would not be able to act to achieve optimal operation, but with improvements in flood forecasting and more stream flow data, operation could be done efficiently.
22) Pan evaporation in Iloilo was considered representative of the pan evaporation at all of the reservoir locations.
23) Evaporation at the reservoirs was assumed to be zero during the flood periods. The cloud cover and the short time period of the flood periods make the evaporation negligible in comparison to all of the other terms in the mass balance equation.

3.4 Model Inputs

Reservoir Parameters:

The potential reservoir locations were analyzed in ArcGIS using the elevations from the ASTER DEM data. The dams were positioned so as to achieve the greatest benefit from the regional topography. Figures 11-14 show the crest lengths for the maximum-sized-dam at each site drawn in ArcGIS.

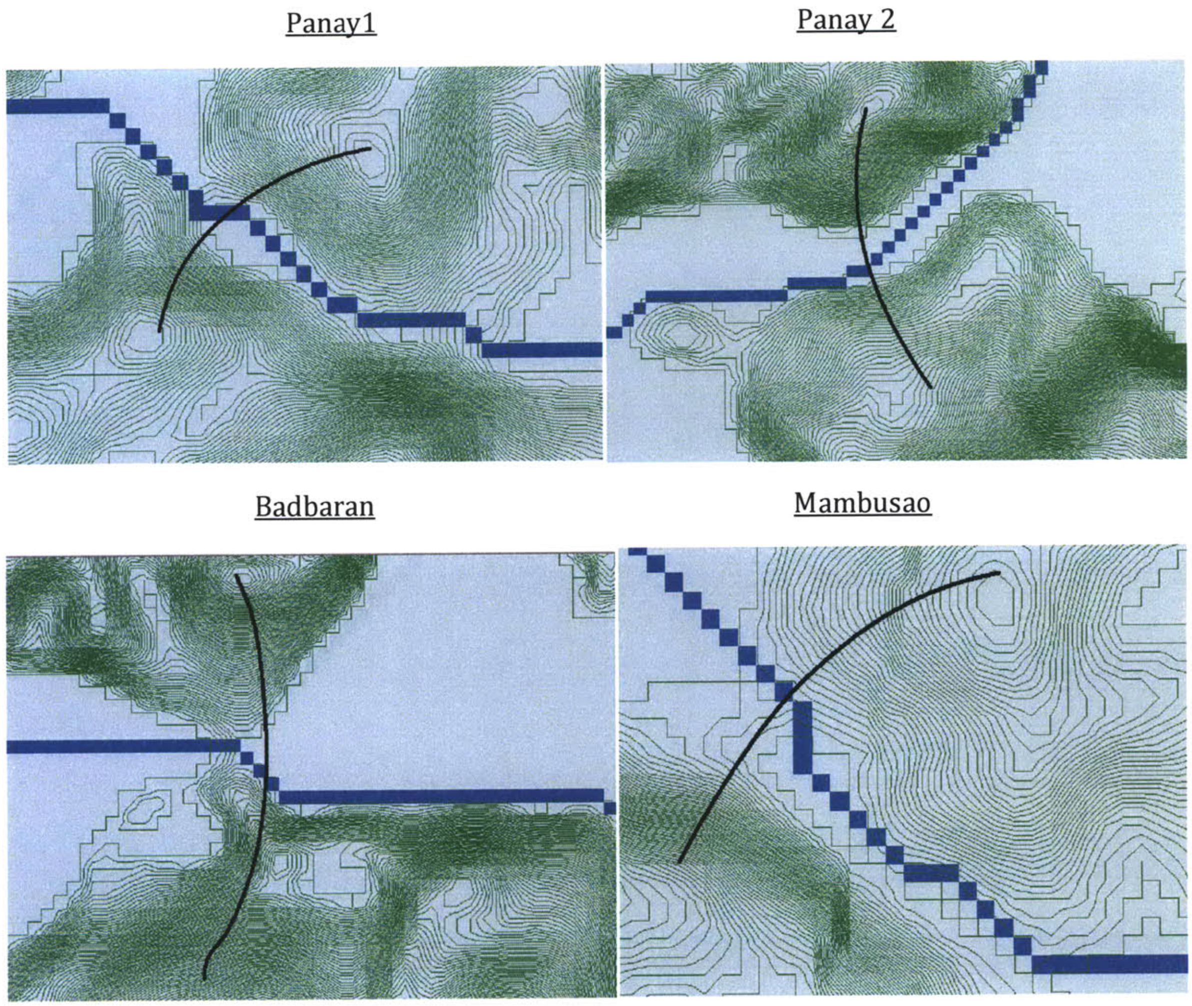

Figure 11: Maximum-Sized-Dam Crests

Analysis within ArcGIS was completed to calculate the parameters of the reservoirs at each site for varying heights of dams (see Tables 4-7)[7]. This data was used to compute reservoir costs, reservoir surface areas, storage volumes, and reservoir heads.

Dam height (m)	Reservoir Area (km^2)	Reservoir Volume (MCM)	Crest Length Needed (m)
45	9.632	182.224	588
40	8.694	146.066	466
35	6.619	111.062	400
30	5.745	80.630	370
25	4.549	55.424	320
20	3.605	35.603	309
15	2.984	19.440	269
10	2.226	6.821	197
5	0.930	1.7955	155

Table 4: Parameters for Varying Sized Dams at Panay 1 Site

[7] "Terrascope", a ArcGIS hydrology program written by Daniel Sheehan (MIT's GIS Lab), was used to obtain the effects of building certain size reservoirs at the proposed reservoir locations.

Dam height (m)	Reservoir Area (km^2)	Reservoir Volume (MCM)	Crest Length Needed (m)
35	117.240	1976.451	529
30	103.073	1543.760	440
25	83.543	1085.508	394
20	66.352	719.258	311
15	54.605	423.111	293
10	40.155	189.451	255
5	28.226	29.041	190

Table 5: Parameters for Varying Sized Dams at Panay 2 Site

Dam height (m)	Reservoir Area (km^2)	Reservoir Volume (MCM)	Crest Length Needed (m)
30	55.967	734.547	622
25	49.460	526.724	494
20	38.627	313.652	404
15	25.449	158.730	355
10	15.762	66.601	313
5	5.526	28.645	279

Table 6: Parameters for Varying Sized Dams at Badbaran Site

Dam height (m)	Reservoir Area (km^2)	Reservoir Volume (MCM)	Crest Length Needed (m)
35	44.959	743.065	668
30	40.650	574.133	559
25	33.215	356.520	464
20	25.643	239.068	426
15	18.522	134.708	362
10	13.023	58.570	305
5	7.117	10.970	225

Table 7: Parameters for Varying Sized Dams at Mambusao Site

Irrigation Benefit Coefficient:

The benefit from irrigation, *IrrBen*, was derived solely from increased productivity of rice crops for farmers in Dumalag, the municipality of the potential irrigation facility at Panay 2. The difference in rice productivity between lowland irrigated fields and lowland rain-fed-only fields in the region was derived from an interview with the Municipal Agriculturist. According to the Municipal Agriculturist in Dumalag, for the current year, good seeds planted on irrigated fields produced 3.6 metric tons per hectare, while good seeds on rain-fed-only fields produced 3.15 metric ton per hectare (Dumalag, 2010). Therefore, the benefit from this new irrigation facility was based on the difference in these productivities, the current average market price for this type of rice, 13.50 Pesos per kilogram, and the author's finding that irrigated fields can usually yield five harvests every two years, while rain-fed-only fields can usually only yield two harvests each year (Dumalag, 2010). From this information, a proportionality coefficient of $\alpha = 0.004809 \frac{MPesos}{ha*month}$ was used to compute the benefit from added irrigation land in Dumalag.

Hydropower Benefit Coefficient:

The current price of electricity in the province is 12.5 Pesos/KW*hr (Reyes, 2010). This price was used as the direct measure of the benefit from the energy produced. Therefore, $\beta = 0.0000125 \frac{MPesos}{KW*hr}$.

Capital Cost Linear Proportionality Coefficients:

The costs for the construction of the dams and the hydropower facilities were extrapolated from the cost estimates in CS. Prices for the chosen hydropower and reservoir capacities were found in CS and assumed to be linearly proportional to capacity and material costs, respectively. The prices were then increased by thirteen percent to reflect more present cost estimates (Abela, 2010). The relationship between reservoir capacity and costs was found by determining the size of dam needed from ArcGIS for a range of reservoir capacities by assuming that materials were linearly proportional to the product of the crest length and height of dam (see Tables 4-7). Then, these sizes were fit to a linear relationship between the quantity of materials needed for each sized dam and the cost of the dam (see Appendix C). The relationship between the size of the irrigation facility and its costs was determined from the costs of a current irrigation proposal in Pontevedra, Capiz and the assumption that the costs varied linearly to facility size. The current project is for an extension of an irrigation system (Amponin, 2010). The proposed irrigation land at Panay 2 site is assumed to be near the dam's release location and to only require irrigation canals to transport the irrigation water to nearby rice fields in order to match the known price of the Pontevedra project as best as possible.

The results of the linearly fitting of the reservoirs', hydropower facilities', and irrigation facility's cost estimates are shown below.

Site	k_S (MPesos/MCM)	q_S (MPesos/KW)	μ_S (MPesos/ha)
Panay 1	5.1004	0.0304	0
Panay 2	0.6783	0.0324	0.0292
Badbaran	1.3102	0.0596	0
Mambusao	1.5093	0.0546	0

Table 8: Linear Proportionalities for Facility Capital Costs

Interest Rate:

For the original screening model, an interest rate, *r*, of 6% was used. This percentage was based on the author's perception of a reasonable interest rate for the region based on his site visit in January 2010.

Operation and Maintenance Percentage:

For the original screening model, a percentage of 10% of the capital costs, $O\&M\ Percentage$, was used as the annual operation and maintenance cost. This was decided by the author as a percentage that would hopefully prevent the current problems occurring from lack of maintenance observed by the author during his site visit in January 2010.

Preventable Flood Cost Linear Proportionality Coefficients:

The Preventable Flood Cost, *PreventableFloodCost,* was derived from flood cost predictions for the year 2009 found in CS (Japan International Cooperation Agency, 1985). Flood costs predictions were available for 1, 1.1, 2, 5, 10, 25, 50, and 100 return year floods. These flood costs were then divided to represent the five main flood regions in the basin. Coefficients were given to each of these regions based on the percentage that each contributed to flood costs according to CS (see Appendix D). The resulting accumulating flow for each of these regions during a flood was found for each of the return flood years based on flood flow estimates and hydrograph assumptions. Then, the amount of water that each reservoir site contributes to the flood regions was used to relate the amount of water released from the reservoir sites to the amount of preventable damage from the discharge during floods. The results were fit to a linear curve (see Appendix C). The results of the linear fitting are shown in Table 9. δ_1 is zero because Panay 2 reservoir is still between Panay 1 reservoir and the flood regions.

Site	δ_s, Preventable Flood factor (MPesos of damage/summed MCM outflow for 3 day flood period)
Panay 1	0
Panay 2	2.3533
Badbaran	1.9817
Mambusao	2.7846

Table 9: Linear Proportionality Constants for Preventable Flood Cost

Flood Cost Linear Proportionality Coefficients:

To measure the total damage incurred from floods, proportionality coefficients were found relating the estimated summed flow of water during floods in the five main flood regions, *Floodflowspot*, to 2009 estimated damages from CS, *FloodCost*, weighted by the regional coefficients (see Appendix D). See Appendix C for the curve fitting for these proportionality constants. The result of the linear fitting is shown in Table 10.

Flood Region	ω_j, Flood Factor (MPesos/Summed MCM for 3 days)
1	0.5663
2	0.453
3	1.377
4	1.7062
5	1.0784

Table 10: Linear Proportionality Constants for Total Flood Costs

River Flows:

The entire system was constrained to mass balance equations to ensure conservation of mass. All terms in the mass balance equations are over a consistent time step, and thus flows were reduced to resulting cumulative flow volumes for the given time step. Eleven reaches were chosen for flow inputs into the model and for computing model flow outputs. The reaches are illustrated in Figure 15.

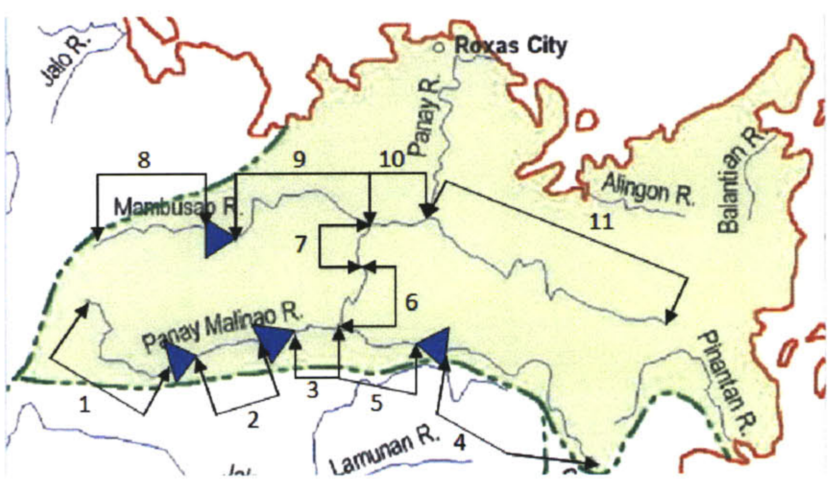

Figure 12: Eleven Reaches for Flow Model Inputs

The eleven river reaches, f, represent regions contributing volumes of water to the river per time step. The flow volumes of the reaches were based on mean monthly stream flow data from 1951 to 1974 from stream gages in Cuartero (Panay River), Mambusao (Mambusao River), and Maayon (Maayon River) from FP (National Water Resources Council, 1977). Because of the lack of stream gages at the sites of interests, an augmented version of the method of estimating streamflows based on basin areas was used[8]. The values from CS were adjusted based on the unique basin areas of each location (see Appendix D) and area rainfall distribution[9]. The resultant eleven flow volumes contributing to the river, $flow_{t,f}$, were repeated every year by months for the mean hydrological scenario. Figure 16 shows the eleven flow volumes, $flow_{t,f}$, for the mean hydrological scenario.

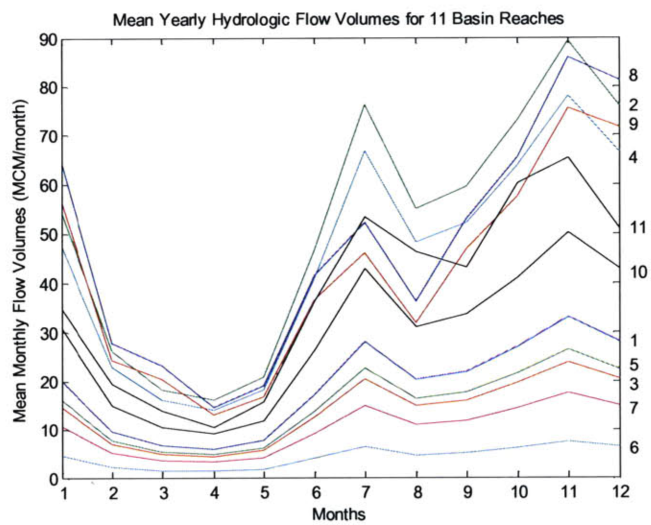

Figure 13: Eleven Monthly Reach Volume Input as *flow* in the Model

Eight significantly-sized floods were added to allow the model to account for sizable floods. The eight flood flows were generated from peak stream flow data for return flood periods found in CS (Japan International Cooperation Agency, 1985). First, the flood hydrograph for the lower Panay region, the endpoint of all accumulating eleven flow volumes was created using the peak stream flow as the peak of an isosceles-triangle hydrograph (see Appendix A.8). This hydrograph's flow was then distributed to the eleven locations of *flow* based solely on each location's sub basin contribution to the lower Panay region's streamflow[10] (see Appendix D). Then, the curve was divided into 12-hour increments and the flow volume of water for each increment was found by estimating the area under the curve by means of the trapezoidal rule (Stewart, 2003) . The mean flow volumes for each of the 12-hour increments were represented by the flow volumes used in the trapezoidal estimation, the mean flow volume for that period. These flows were inserted into the model as the 11 flood flow volumes, $flow_{u,f}$.

This process was completed for a 10-year flood, a 25-year flood and 50-year flood. Figure 17 shows the resulting flood flow volumes for the eleven reaches, $flow_{u,f}$.

[8] P. 230 of Loucks, Stedinger, & Haith, 1981 discusses the appropriateness of using the fraction of basin area to estimate an unknown streamflow from a known streamflow.

[9] The basin areas were found using the hydrology toolbox of ArcGIS and the rainfall distribution was estimated using an isohyetal map retrieved from CS by JICA (Japan International Cooperation Agency, 1985).

[10] Although this does not accurately account for such characteristics of a flood as backwater, the above flood flow simplification was done due to the lack of data to model the river more accurately during a flood.

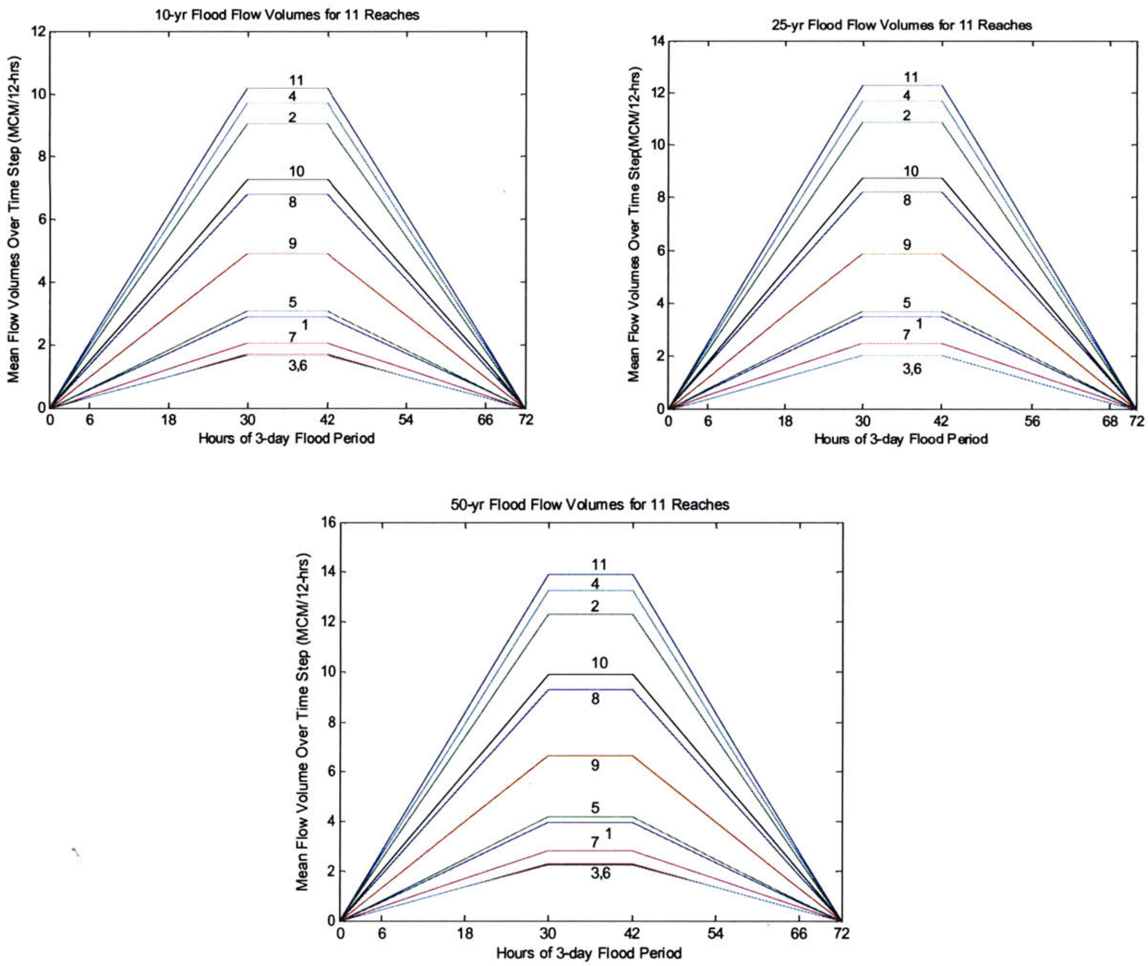

Figure 14: Mean Flood Flow Volumes

Reservoir Inflows:

The inflows, $In_{t,s}$, into reservoir Panay 1, Badbaran, and Mambusao were equivalent to the $flow_{t,s}$ upstream of the reservoirs: $flow_{t,1}$, $flow_{t,4}$, $flow_{t,8}$, respectively. The inflow into reservoir Panay 2 was equal to the outflow at Panay 1 reservoir, $Out_{t,1}$, plus the added flow from the basin between the Panay 1 outflow and Panay 2 reservoir, $flow_{t,2}$.

Maximum Reservoir Sizes:

The reservoirs chosen sizes, *CAPRes*, were constrained by maximum sizes, *Resmax* (see Table 11). They were all limited based on the site's topography, but Panay 2 reservoir site was also constrained so as to not interfere with Panay 1's dam.[11]

[11] When Panay 2's reservoir was allowed to be built larger, it still did not exceed this smaller constraint in the original optimized solution.

Site	$Resmax_s$(MCM)
Panay 1	182.22
Panay 2	535.47
Badbaran	734.55
Mambusao	743.07

Table 11: Reservoir Maximum Sizes

Maximum Hydropower Facility Sizes:

The size of each hydropower facility was constrained by a maximum size, *Hydromax* (see Table 12). The maximum sizes for these facilities were chosen as the sizes chosen in CS, because the feasibility of building larger facilities was assumed to be doubtful (Japan International Cooperation Agency, 1985).

Site	$Hydromax_s$ (KW)
Panay 1	7000
Panay 2	6000
Badbaran	2550
Mambusao	2250

Table 12: Maximum Hydropower Sizes

Storage-Head Coefficients and Storage-Surface Area Coefficients:

The relationship between the head of water at the dam, *H*, and the storage at the reservoir, *S*, was found running scenarios in ArcGIS for different size dams. A quadratic curve was fit to the data (see Appendix C). Table 13 shows the coefficients found from this curve fitting.

Site	$\Psi_{1,s}$	$\Psi_{2,s}$	$\Psi_{3,s}$
Panay 1	-0.0011	0.406	4.8876
Panay 2	-0.00003	0.044	1.9019
Badbaran	-0.00005	0.0714	2.9572
Mambusao	-0.00005	0.0809	3.4238

Table 13: Storage-Head Relationship Coefficients

The surface area of the reservoirs was needed to find the total volume of evaporation given the pan evaporation. The relationship between surface area and reservoir storage was found running the iterations in ArcGIS. A Linear curve was fit to the data (see Appendix C). Table 14 shows the coefficients found from this curve fitting.

Site	$\Phi_{1,s}$	$\Phi_{2,s}$
Panay 1	0.0484	1.4077
Panay 2	0.0765	17.054
Badbaran	0.0741	7.8962
Mambusao	0.0561	8.0456

Table 14: Storage-Surface Area Relationship Coefficients

Evaporation:

Mean monthly pan precipitation data for the years 1957-1974 in Iloilo, the neighboring province was retrieved from FP (see Table 15).

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
168.1	177.3	215.6	218.7	211.8	169.0	155.3	161.9	153.8	149.8	147.3	161.5

Table 15: Mean Monthly Pan Precipitation in Iloilo from 1957-1974 in millimeters (NWRC, 1985)

The mean pan evaporation was converted to meters and multiplied in the model (See *Equation 13*) by the surface area of the reservoir for each month (km^2) to obtain the volume of water evaporating from each reservoir per month (MCM).

Hydropower Conversion factor:

Gamma, $\gamma = 2725$, was used to convert the energy equation from MCM*m to KW*hr.

Hydropower Turbine Efficiencies:

The hydropower facility's efficiencies, $effic$, were back-calculated from the design plans in CS (Japan International Cooperation Agency, 1985).

Site	$effic_s$
Panay 1	0.6814
Panay 2	0.5983
Badbaran	0.64
Mambusao	0.64

Table 16: Hydropower Turbine Efficiencies

Hydropower Factor of Utilization:

In this model all energy produced could be used; therefore, the factor of utilization, *Y*, was 1

Efficient Energy Constraint:

Equations 34-36 ensure that the head at the dams does not vary too much, resulting in efficient energy production. The maximum head at a given reservoir is not allowed to be greater than twice the minimum head at that reservoir (Major & Lenton, 1979).

Irrigation Land Maximum Sizes:

The maximum land area, *Landmax*, was set at 500 hectares for Panay 2 to reflect data in CS (Japan International Cooperation Agency, 1985) and zero hectares for the other sites because irrigation facilities at the other sites were not considered in this model.

Site	$Landmax_s$ (ha)
Panay 1	0
Panay 2	500
Badbaran	0
Mambusao	0

Table 17: Maximum Irrigation Land Sizes

Irrigation Water Requirement:

The policy constraint was included that ensured that each month enough water was supplied to the irrigated land to satisfy the entire land size chosen. $watreq = 0.000259 \frac{MCM}{ha*month}$, the amount of water required per hectare for each month for irrigation was derived from approximate irrigation requirements from data in CS (Japan International Cooperation Agency, 1985).

Maximum Allowed Monthly Flow:

The monthly flows for the five flood flow spots were constrained so as to not exceed monthly values that would result in flooding. A safe flow estimation of 350 m^3/sec was set as the river capacity based on general river characteristics from CS (Japan International Cooperation Agency, 1985). When this estimate is converted to 10^6 cm^3 each month, $Maxmonflow = 907.2\ MCM$.

Arrays Factors for Distinguishing Flood Period Terms:

Some equations in the model were adjusted by arrays, *Nest1* and *Nest2*, to modify the equations to account for whether that time step is a monthly time step or a 12-hour flood time step. *Nest1* is equal to 1 for months and 0 for flood time steps. *Nest2* is equal to the number of hours for that given time step, 720 for months and 12 for 12-hour flood increments.

3.5 Screening Model Sensitivity Analyses

The screening model was completed with the inputs described in Section 3.4. Basin flows, the interest rate, and the operation and maintenance costs were considered by the author as the model inputs that were most probable of differing in reality. In the screening model, mean monthly flows, an interest rate of six percent, and an annual operation and maintenance cost equal to ten percent of the facilities' capital costs were used for these inputs. However, basin flows will certainly vary annually and the interest rate and the operation and maintenance cost inputs had little support in their estimations. Therefore, perturbations were completed on each of these inputs to test the screening model's sensitivity to changes in these inputs.

Screening Model's Sensitivity to Varying Flow Volumes - Mean historic flow data was used in the screening model because streamflow variation is difficult to predict and the placement of floods were hoped to be as unbiased as possible. To decide how sensitive the screening model would be to annually varying flows, flow volumes were synthetically generated to run through the screening model.

The synthetic flow volumes to replace the previously used $flow_{t,f}$ were generated from the flow volume distribution proportions for the eleven reaches used in Section 3.4 and monthly stream flow data from 1951 to 1974 from the stream gage in Cuartero (Panay River) found in CS. The twenty-four years of monthly data was divided into the eleven flow volumes, $flow_{t,f}$, by distributing flow volumes by the same monthly proportions used in Section 3.4. The result was 24 years of monthly data for the eleven reaches based on this model's method of distributing flow volumes within the basin.

Then, random flow values were generated using MATLab's random lognormal distribution function, LOGNRND[12], and the 24 years of monthly data. The output from the function was new values for $flow_{t,f}$ for the entire fifty years for each reach and month. Appendix H shows the new $flow_{t,f}$ terms for the eleven reaches over the life of the project. The screening model was rerun with this input to see how these varying flows would affect the solution. The same flood input from Section 3.4 was used for the flood periods.

Screening Model's Sensitivity to O&M and Interest Rate - The screening model was also rerun for varying operation and maintenance costs and interest rates. The streamflows in these runs were the inputs

[12] LOGNRND is found in MATLab's Statistics Toolbox (The MathWorks, 2010).

from Section 3.4. Perturbations were made on the interest rate and the operation and maintenance costs. The annual operation and maintenance cost was varied from 5% to 20% of the capital cost in 5% increments, while the interest rate was varied from 4% to 8% in 2% increments.

4. Results

4.1 Optimal Facility Sizes

The programming model was run in GAMS and solved using a nonlinear solver, CONOPT (Drud, 1996). The global maximum solution was sought over any local maxima by running the model for several different initial conditions and choosing the optimal condition that resulted in the maximum objective function. The resulting optimal solution produced the facility sizes shown in Table 18. The sizes were chosen in order to maximize the objective function of the model. The table also shows the resulting areas that would need to be reserved for inundation, Surface Area, and the height of the dam constructed, Dam Height.

Site	Reservoir (MCM)	Surface Area (km^2)	Dam Height (m)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	88.506	5.69	32.20	2393.972	N/A
Panay 2	517.676	56.66	16.85	5609.582	500
Badbaran	206.122	23.17	15.55	2550	N/A
Mambusao	150.946	16.51	14.50	2250	N/A

Table 18: Optimally-Sized Facilities

The areas that would need to be designated for the reservoirs are shown inside of the areas of each reservoir's basin in Figure 18. As seen in the figure, these areas reserved for inundation would vary significantly from Panay 1 to Panay 2. Plans should take into account what currently is located in these areas. Planners should be allowed to adjust the model to consider present and desired land use in these regions.

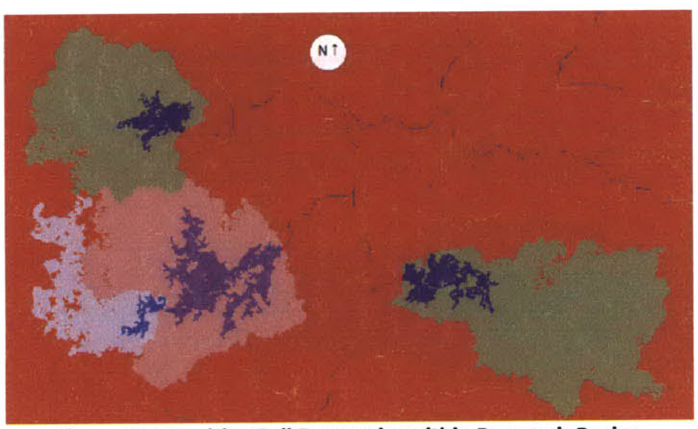

Figure 15: Resulting Full Reservoirs within Reservoir Basins

Table 19 shows the facilities chosen as a percentage of their maximum allowable size. Some of the facilities were actively constrained (see Appendix A.3) in the model by the site characteristic knowledge as seen by an entry of 100% in Table 19. Nevertheless, all of the reservoirs were built large enough to handle upstream floodwaters.

Site	Reservoir Chosen	Hydropower Chosen	Irrigation Land Chosen
Panay 1	48.6%	34.2%	N/A
Panay 2	96.7%	93.5%	100%
Badbaran	28.1%	100%	N/A
Mambusao	20.3%	100%	N/A

Table 19: Facilities Chosen as Percentage of Maximum Potential Size

Panay 1 - Panay 1 facilities were significantly less than its size constraints. This low proportion is due to the higher benefit from the Panay 2 reservoir just downstream. Overall it was shown to be more beneficial to invest more in the Panay 2 reservoir than in the Panay 1 reservoir. However, if for some reason Panay 2 facilities were not an option (e.g., Panay 2 reservoir land area is reserved for uses that would be ruined by inundation), Panay 1 facilities should be built much larger.

Panay 2 - Panay 2 was the only reservoir that came close to its size constraint. The Panay 2 reservoir chosen was also significantly larger than the reservoirs at the other sites. This high proportion can be partially accredited to site characteristics that allowed the size constraint at this site to be constrained at a higher value, but the fact that the other sites did not come close to their maximum potential sizes indicates a unique high potential at Panay 2. The topography at and upstream of the Panay 2 site produce significantly larger reservoir sizes for the same dam heights in the range considered for an optimal solution. Therefore, Panay 2 seems to be the site where the most the benefit is to be gained per investment for this proposed project.

Badbaran and Mambusao - The reservoir sizes at these sites were large enough to store water during floods, but were not built any larger due to the low size constraints on the hydropower facilities at these sites. Building the reservoirs larger would have incurred more costs than benefits.

4.2 Optimal Water Management and Energy Production

The screening model managed water to maximize the model's objective function while remaining within the constraints posed by the mathematical programming problem.

Flood Management - The reservoirs stored all upstream flood waters in order to minimize flood damage for the entire basin. The storage of water during the flood periods resulted in no flood damage in Flood Regions 1, 2, 3, and 4. Unfortunately, the source of a significant amount of the floodwaters for Flood Region 5 is from portions of the basin downstream of the dams, and thus the dams were unable to fully relieve Flood Region 5 of flood damages. As a result, overall flood damage was reduced by only 46% due to flood damage in Flood Region 5 being reduced only by 19%. Figure 19 shows the flow in each of the five flood regions during the 8 modeled floods over the entire 48 time steps, v.[13]

[13] Each flood was 3 days or 6 12-hour increments. Therefore, the 8 floods correspond to 48 12-hour time steps.

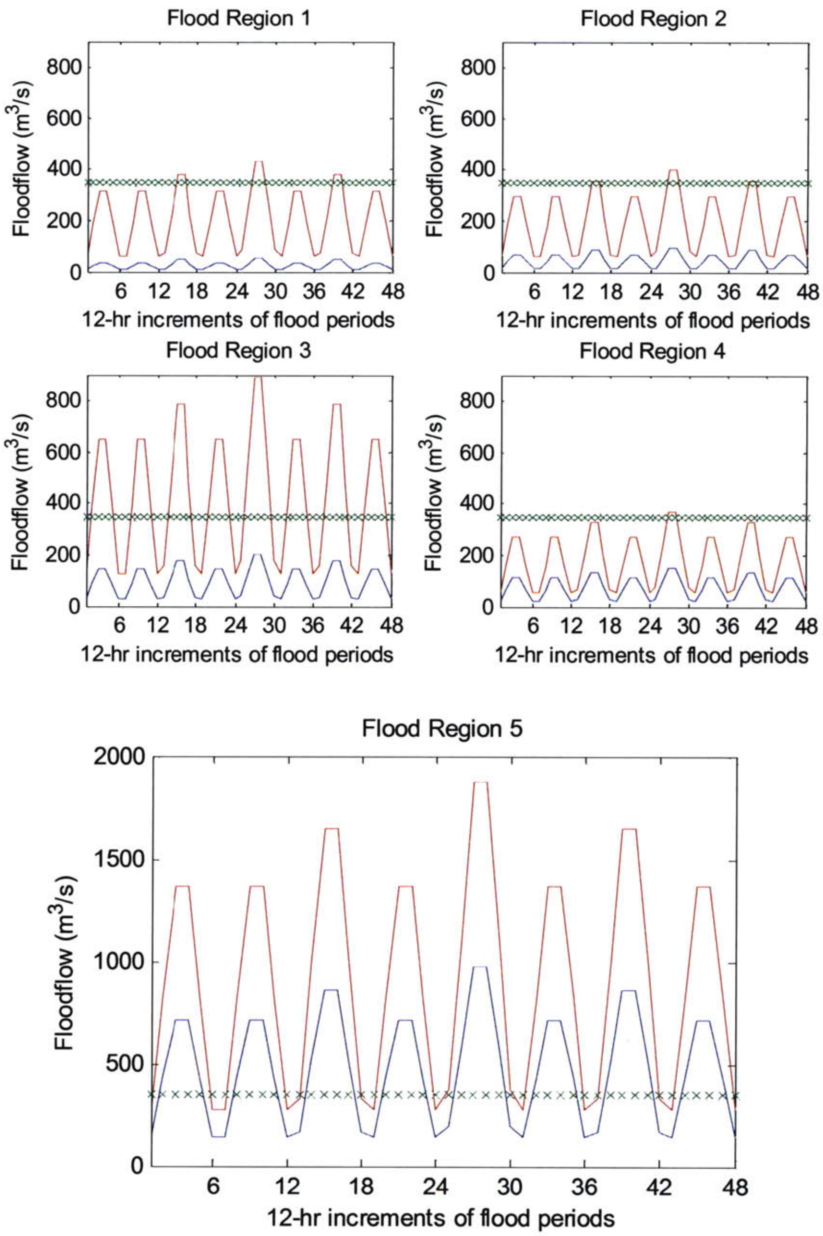

Figure 16: Flood Flow Reductions due to Reservoir Storage: without (red) and with (blue), green Xs represent safe flow

Irrigation Export – Water was exported for irrigation at a rate of 0.13 MCM/month except during flood periods, when no water was exported. This export rate was the estimated amount needed in order to provide for the 500 hectares of land area chosen for Panay 2.

Reservoir Release and Energy Production – Water was stored and released in order to maximize the energy produced over the project's life without making the sacrifice of incurring flood damages. Water was withheld to increase head and flow in order to maximize energy generation given knowledge of future inflows. The use of mean repeating hydrologic data resulted in water management being nearly the same for all non-flood years. The nearly consistent release of water also resulted in the nearly consistent production of energy during non-flood years because energy production depends on water release.

The optimal solution had periods where energy was not produced in order to gain head and flow for higher production at other times. In particular, flood years had long stretches of zero energy production before and during floods. Large energy production immediately followed the storm due to the release of the stored water from this time. This solution is suitable if other energy is available when energy is not produced from this system.

See Appendix F for detailed water management at the sites for non-flood years and flood years. Energy's dependence on outflow can be clearly seen from the non-flood years. Energy production similarly depends on outflow during flood years. The graphs also show how exploiting storage volume at all of the reservoirs handles the increase of flows during floods.

4.3 Objective Function

The globally-sought optimal solution to the objective function for the screening model was 23,404.365 MPesos, of which 91.6% was from hydropower benefits. The objective function divided by yearly contribution is shown in Figure 20. The floor of yearly contribution to the objective function (x's in Figure 14) is 455.5 MPesos. This floor represents a guaranteed yearly objective achieved from the project. The floor occurs from consistent annual production of energy and irrigated rice throughout the life of the project. The major increase in year 50 is due to the release of water before the end of the life of the project. Peaks during flood years occur from the extra hydropower generated from the extra water during those years. No downward dips occur because no preventable flood costs were incurred over the life of the project.

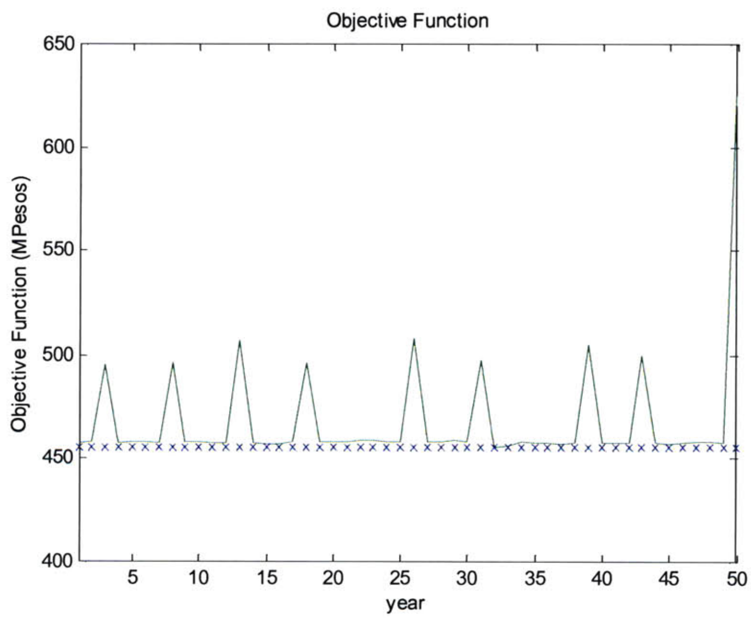

Figure 17: Objective Function for the Screening Model

4.4 Sensitivity Analyses

<u>Completing the Screening Model with Annually Varying Flows</u> - The synthetic flows were run in the screening model with all other parameters remaining the same. Table 20 shows the results of the optimized screening model using the synthetic flows. The objective function for this scenario was 23, 048.046 MPesos. This amount is a decrease of 1.5% from the originally run screening model.

Site	Reservoir (MCM)	Dam Height (m)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	89.668	32.45	2394.529	N/A
Panay 2	520.578	16.89	5535.088	500
Badbaran	222.599	16.37	2550	N/A
Mambusao	134.211	13.38	2250	N/A

Table 20: Screening Model: Synthetic Flows

Table 21 shows the percent change in facility sizes from the mean hydrologic scenario's optimized solution to the annually varying flow scenario's optimized solution.

Site	Reservoir (MCM)	Dam Height (m)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	+1.3%	+0.8%	+0.02%	N/A
Panay 2	+0.6%	+0.2%	-0.01%	0%
Badbaran	+8.0%	+5.3%	0%	N/A
Mambusao	-11.1%	-7.7%	0%	N/A

Table 21: Percentage Change from Screening Solution using Mean Data to Synthetic Data

The results show that all of the hydropower facilities size decisions and the irrigation land size decision are robust to annually varying flows. The results also show that the reservoir sizes chosen at Panay 1 and Panay 2 locations are also highly insensitive to the annually varying flows. However, reservoir sizes at Badbaran and Mambusao were sensitive to the varying flow scenario. This sensitivity suggests that the reservoir sizes chosen at these sites from the original screening model will achieve less than ideal benefits under the situation of varying flows.

Sensitivity to Operation and Maintenance Parameter Changes - Operation and maintenance cost and the interest rate for amortization were the parameters with the least confidence in their estimation. The effects of perturbations on these parameters on the objective function are shown in Figure 21.

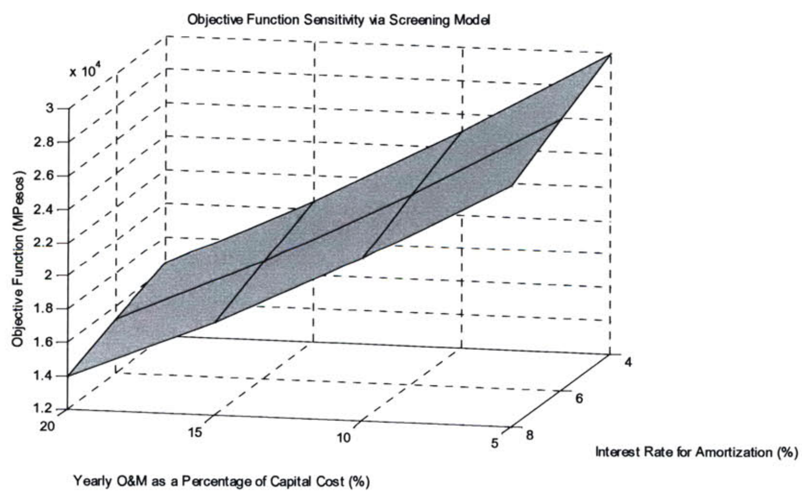

Figure 18: Objective Function Sensitivity in Screening Model Results: Interest Rate and O&M Cost

As shown in Figure 17, the objective function remained positive within the range of perturbations used on the operation and maintenance cost parameter and interest rate parameter. Therefore, the project is still beneficial, but for optimal benefit, the facility sizes would need to be changed, in some cases significantly (see Appendix G). Therefore, these parameters are essential for ensuring optimal benefits from this project. Project implementation should be initiated and sequenced so as to achieve a low interest rate and operation and maintenance should be planned for carefully.

5 Conclusions

5.1 Potential Benefits

Reservoir Potential – Capiz is a primarily water-rich province, yet much of the potential from managing its water resources has been unexploited. The reservoir sites examined in this study are rich in potential for benefitting Capiz in providing electricity via hydropower, providing flood protection during typhoons, and providing reliable irrigation. This study showed how facilities that are dependent on reservoir creations could be a very beneficial investment for Capiz.

Flood Protection Potential - The optimal scenario had no water released from the dams during flood periods. Therefore, the flooding damage was minimized as much as possible by the facilities. The proposed reservoir sites reduced overall flood damages by an estimated 46%. This reduction would greatly help inhabitants and Capiz's economic progress. This flooding reduction would also aid other flood-prevention projects in aims of approaching zero flood damage for the entire province. Flood damage still occurred in the Panay Region, Flood Region 5, because a large portion of the basin is downstream of the proposed reservoir sites. Consequently, the built facilities were reduced the flood damage by approximately 19% in this region, thus and 1,677.711 MPesos worth of flood damage was still incurred over the life of the project. Therefore, to fully eliminate flood damage, further basin development is needed. The CS's original proposal of river improvement via increasing the river's capacity appears to be a necessary action in fully providing the province with flood protection (Japan International Cooperation Agency, 1985). The option of only doing river improvement work should receive consideration, but the hydropower and irrigation potentials suggest that reservoirs should be used in order to exploit these other benefits.

Hydropower Potential - Capiz is almost exceeding its demand for electricity (Abela, 2010). The abundance of electricity generated through this project's implementation would help Capiz provide for its increasing energy demand. The generation of hydropower was the largest benefit from the project. For the original screening model, the financial benefits from hydropower production were 91.6% of the total benefits, including the benefits from reducing flood costs. Therefore, it is advisable to obtain highly accurate parameters for hydropower in order to best assess the project's benefits. This high energy production also makes building dams the preferential option in basin planning if other factors do not pose a large enough deterrent to dam building.

Irrigation Potential – In every sensitivity run of the model, the irrigation facility was built to its largest allowable size. This maximization exhibits the high potential benefits for irrigation from the creation of reservoirs like the ones analyzed in this study. The use of reservoirs for irrigation purposes has already been successful in some parts of the basin, such as Mambusao. The use of future reservoirs could be a key component in satisfying the water needs of farmers and should be investigated further as an alternative to pumping water from the Panay River.

5.2 Model Discussion

Design for Hydropower vs. Flood Protection - No tradeoff between releasing water and storing water during a flood period existed. Energy benefits and flood protection parameters needed to be relaxed well beyond realistic parameters in order for any tradeoff to be present. The model results show that the storage of water during flood periods not only reduces the cost incurred from floods, but also creates hydropower benefits from the additional storage of water.

Parameter Sensitivity – The two least supported parameters used in the model were the interest rate and operation and maintenance terms. The sensitivity analysis showed that although knowing these two parameters is important for project planning, the project was still financially beneficial for the ranges considered. When these parameters can be solidified, the model should be run with the more accurate parameters.

Timing of Project Implementation – The pricing estimates are subject to many variables that are likely to change with time. For example, the pricing of electricity and rice is subject to the market. The timing of the project as well as the possibility of sequencing the building of the facilities should be completed to match the best interest rate as well as correspond to a ready market.

5.3 Author's Advice

Farming Dynamics – The author advises that the advocacy for more organic farming should be intertwined with the development of new irrigated rice field areas. The majority of organic farming practices are dependent on joint efforts. Neighboring fields likely share water, runoff, and pests. The actions on one field affect the neighboring fields. It is the author's suggestion that organizing clusters of rice fields to practice consistent organic practices may be much more probable at the inauguration of the provision of irrigation water. Irrigated rice field owners already have to arrange scheduling for when they receive water, and thus it seems reasonable that organic practices could be better enforced by including rules to encourage crop rotations, fallow periods, and healthy pesticide/fertilizer application timing and quantities.

With regards to the current irrigation systems, the author's opinion is that irrigation is not providing optimal benefits due to the lack of constant access caused by breaks and poor management. These problems seemed attributable to the lack of designation of funds for systems beyond capital cost. For example, the Municipality of Pontevedra's community irrigation system (CIS) has no money for repairing its facilities, but is being given money to expand its facilities (Amponin, 2010). Operation and maintenance costs must be better considered in the planning and management of facilities in the region.

Important Factors Not Modeled – The model shows an optimal solution given the parameters and constraints placed on the model; however, several other important factors should be considered in planning for the basin. The cost associated with inundating current residential areas was not included in the model. This cost could be divided into both a relocation cost and a social cost. Recent years have produced dam plans that have been opposed by local inhabitants, such as the Three Gorges Dam in China (Sullivan, 1999). The infringements on people's rights have occurred usually in the name of holistic development for the region. These stakeholders must be given an adequate voice in the decision to build the Panay River Basin facilities. Sensitive regional planning may allow for a solution that would relocate people so as to provide those affected by dams with benefits from the project. The author noted that the regions of proposed inundation are the poorer regions of the province. Many of the sites are occupied by squatters who may be happy to be relocated if consequently provided a home and property. Such relocation should also be done in consideration of the basin's new condition. After project implementation, the province may have new land that is better fit to be used as residential and fit for growing rice.

Capiz relies on a large aquaculture industry. The aquaculture industry has already suffered from a decrease in water quality from upstream users (Belargo, 2010). Pastel (2007) argues that the decisions of water management should account for four factors; "environmental flows, source water protection, water quality and groundwater management" (p. 54). The building of dams and regulating of river flows in the Panay Basin should account for these factors. After facilities are built, the natural flow of the water would be drastically changed throughout the year so as to maximize power, reduce flood damage, and maximize rice profits. At the same time, ecological bodies may exist that are dependent on the natural hydrological cycle of the basin. Despite the current poor water quality of the rivers, an implemented solution should take into consideration any dependent species and include parameters to aid the health of the river, such as minimum-allowable flows for the river and its tributaries to create a healthy river and to provide a consistent ecological environment for the basin.

The project may also produce difficult-to-quantify benefits. The provision of electricity to families that have never had it before as well as providing a more consistent supply of electricity could have very large beneficial impacts on people's productivity and opportunities. Likewise, the reduction in flood damages may allow for economic endeavors never able to be accomplished by Capiz due to their current need to constantly rebuild infrastructure following typhoons.

All of these possible results need to be considered in the decision process. Even a much larger model accounting for these factors is likely to fail in adequately recognizing these factors. Decision makers and stakeholders must be integrally involved in discussing the possible solutions and the consequential results. It is highly likely that compromise will be needed from all parties as large parts of the province would be significantly changed by the implementation of this project.

Data Needs - Much of the primary data was derived from a study conducted twenty-five years ago. Much of the data in that study was estimates as well due to the lack of original data twenty-five years ago. The CS and FP both mentioned the need for investing in infrastructure for better data availability for basin-wide planning; however, such recommendations as increasing the number of stream and rain gages have yet to come to fruition. It is the author's extreme recommendation that the province should invest in such infrastructure to better assess decisions for water resources planning and management and to provide outside actors with the parameters to conduct studies in the region.

Simulation Model Needs – The varying-flow-sensitivity test proved that the overall screening model solution was fairly robust, but Badbaran and Mambusao reservoirs were shown to be sensitive to flow variations. Therefore, Badbaran and Mambusao should be further scrutinized in simulation models. Additionally, future events may require an even more robust system than the one found and tested in the screening models. The author's discussion with farmers and citizens of Capiz revealed their felt vulnerability to climate change (see Figure 22). Responses indicated that the majority of Capizeños attributed the weather and farming changes to global warming. Citizens also felt obligated to do what they could to combat global warming despite their expressed inability to change their actions due to their personal finances (Virgilio, Badoles, & Abelardo, 2010). Data from the Intergovernmental Panel on Climate Change (IPCC) suggests that the Philippines will be affected by climate change (Cruz, et al., 2007). Therefore, the Panay River Basin's sensitivity to climate change should be modeled as data becomes available and placed in simulation models to account for climate change in basin planning.

Figure 19: Global Warming Street Painting in Capiz

Summary – The model's optimal solution of facility sizes was proven to be both financially beneficial for the province and fairly robust to sensitivity analyses. Overall, the locations of the facilities are very profitable for meeting the electricity, irrigation, and flood protection needs of the province, and the locations show high potential for basin management. Despite the simplifications completed for the model, the results provide enough evidence to make it worthwhile to perform a more thorough analysis in considering the model's solution as a potential solution for basin management. Further studies and models should aim to include more accurate hydrology and land use information, while planning discussions should aim to include all stakeholders in the province.

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Appendix A: Literature Review

A.1 Water Resources Planning and Management

A general consensus has emerged for the need to consider the many aspects of water resources as the resources of the world undergo increasing amounts of stress. Proper planning and management of water resources is particularly needed for scenarios that involve a shortage of water or an excess of water. Regardless of whether a top-down or bottom-up method of planning and management is used, past attempts show that local stakeholders must be included in planning. Integrated Water Resources Management (IWRM) has become an important bottom-up planning that is a part of many nations' strategy for managing its water (Loucks & van Beek, 2005; Lenton & Muller, 2009).

Water resources experts such as Roberto Lenton and Mike Muller maintain that water crisis scares are unnecessary. They argue that both current and future water conditions can be handled with proper water resources management. The world's water continues to undergo an increase in stress due to population growth and high water consumptions around the globe, in many cases contaminating the water. Furthermore, climate change is changing the world's water situation (Lenton & Muller, 2009).

Higher climate temperatures are resulting in variable precipitation occurrences; producing more extreme scenarios (Arnell, 2003). This variability of water can leave nations in vulnerable states. Yearly average rainfalls may remain the same, but if precipitation variations lead to more flooding and droughts, the results can be devastating. Consequently, it is important for nations to conduct the necessary water resources evaluations in response to such predictions.

The evaluation and decision making for planning and management of water resource systems include technical, economical, and institutional components. Competent groups are needed in each of these arenas to achieve success. This creates a very large and multidisciplinary system in which options are needed to be assessed by experts and displayed to the decision makers. Experts often exploit modeling in order to produce easy to understand results for the decision makers. With quick advances in computers and technology, models have grown in their importance in water resources planning and management to be able to emulate real world situations and to simulate the modeled world under prescribed scenarios. Therefore, models can be an extremely effective way for decision makers to understand the effects of potential water resources actions (Loucks & van Beek, 2005).

Models are tremendous aids in what can be a very complicated decision process, but models have several limitations. Models are intended to replicate the real world, but models are based on available data and scientific relationships that may not perfectly match the real world. Unaccounted for factors could also severely alter the similarity of the model to the real world. Furthermore, models are usually created on certain assumptions. If the model is extended to scenarios where these assumptions are no longer valid, the model is very likely to produce inaccurate results. These are only a few of the limitations of models. Consequently, it becomes important for the decision makers to understand that the model is not a replacement for reality, but simply a tool to aid them when treated properly.

Good modeling should express all reservations about the complexity of the model and any simplifications completed in its creation. The model's unique assumptions and approach need to be verified and accurately presented to the decision makers. However, most problems have components similar to past solved problems which helps determine the accuracy of the current model. Therefore, verified historical approaches in the field are an integral part of modeling. Understanding an approach's past successes is advantageous for current projects. In order to benefit from past endeavors, much of the literature that was reviewed for this thesis relates to the application of models in solving problems of water resources planning and management.

A.2 Integrated Water Resources Management (IWRM)

IWRM took off as an approach for water resources management in the early 1980's and became further established by the Dublin Principle No. 2 of 1992.[14] According to Lenton & Muller (2009), IWRM seeks an "economic efficient, socially equitable, and environmentally sustainable" solution to water stress problems (p. 4). In order to do this, IWRM must be applied within the contextual bounds of each particular water problem; there is no one 'silver bullet' that can be universally applied. The solution will entail both infrastructure projects and institutional actions that are specific to a region.

Building facilities to store and transport water is often necessary and ensuring the proper use of water resources via incentives and institutional arrangements is vital. IWRM requires that these infrastructural and institutional decisions include all stakeholders. It also requires funding and efficient use of what is already available for water management. These factors' importance have been learned through the successes and failures of past water management efforts. Therefore, a solution accounting for these factors in addition to the physical constraints is the hope of IWRM (Lenton & Muller, 2009).

IWRM is essentially an approach for optimizing the use of water resources; however, it has proven to be more difficult in practice than in theory. Although IWRM is dependent on context, IWRM champions the idea of a holistic solution that includes all the different users of water in the solution. Therefore, the solution will often involve trade-offs, and thus, the multiple uses of the resource must be included. This necessitates comprehensive basin-wide planning and management of water resources (Lenton & Muller, 2009).

A.3 Water Resource Planning Via Optimization

A common historical approach to optimizing the use of water resources is to mathematically solve the problem by maximizing an objective function, which represents society's benefits, that is constrained by equations that represent the physics, politics, economics, etc. conditions of the problem. The objective function and the constraints are equations with decision variables. The solution set of these decision variables will produce the desired outcome expressed in the objective function. Such a problem creates a boundary containing a set of feasible solutions, where solutions on one side of the boundary still have optimizing potential and solutions on the other side are infeasible. At the boundary, some constraints will be at their limit, while others may still have flexibility. When a constraint is at its limit, it is referred to as being an active constraint (McLaughlin, 2009).

Solving optimization problems is an iterative method that solves via an algorithm until no better solution is found. A caveat in solving such problems is that such an approach may produce a local maximum instead of a global maximum. The best way to avoid the problem of a local maximum being confused as the global maximum solution is to formulate the optimization problem as a convex programming problem. The convex programming problem is created by formulating the objective function as a concave function and the constraint equations forming the feasible region as a convex function. A problem formulated this way meets sufficient criteria to ensure that local maxima solutions are global maxima solutions. Nonlinear programming problems are often not able to be formulated as such and their solved solutions are inherently local maxima (McLaughlin, 2009).

[14] Dublin Principle No. 2 states that "Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels (Zaag, 2002)." The recommendation of this principle supports IWRM's dogma of the essential need to include all stakeholders in holistically planning and managing water resources.

To be a local maximum, a solution must pass the Kuhn-Tucker conditions. The first condition requires that the solution lie in the feasible region created by the constraints. The second condition necessitates that the gradient of the active set of constraints and the gradient of the objective function at the given solution are in the same space. The third requirement is that the Lagrange multipliers of the active constraints at the solution are non-negative numbers. The last requirement, which is not always relevant, checks the curvature. This requirement is not applicable if the number of variables and the number of active constraints are equal. The curvature of the active constraints and the objective function should be opposite in direction to ensure a maximizing solution. The curvature can be found by comparing the Hessian of the objective equation with the Hessian of the active constraints. A convex programming problem will always satisfy this last condition because the objective function and the active constraints will have opposite Hessian matrix signs (Kuhn & Tucker; McLaughlin, 2009).

A.4 Simulation and Screening Models

According to Loucks, Stedinger, & Haith (1981), simulation and optimization are the two methods for solving water resource planning when posed as a mathematical problem. Deciding solely via simulation involves running several options through the equations and comparing the results to make the planning decision. Optimization seeks to find the best solution from all feasible options. Optimization was a concern historically, but the advancement of computers has alleviated the fear of handling numerous equations and variables for large feasible sets.

A screening model is an optimization approach, where the decision variables are "screened" for the set of variables producing the optimal objective. Screening models are often built for a simplified scenario (e.g., same yearly hydrological scenario). After a screening model has narrowed down the solution set, a simulation model can be used to test how well the solution does under a more complicated scenario (e.g., a varying hydrological scenario). Conducting water resources planning by following the path of a screening model before a simulation model is highly encouraged in literature such as Stedinger & Sule (1983), Jacoby & Loucks (1972), and Chaturvedi & Srivastava (1985). The importance of using stochastic parameters in models is discussed in literature such as Loucks, Stedinger, & Haith (1981), Lall & Miller (1988) and Sastri, Feiring, & Sim (1998).

A.5 The Rio Colorado Case

The Rio Colorado case provides an excellent example for a screening and simulation model setup. In the early 1970's, members of the Ralph M. Parson's Laboratory at the Massachusetts Institute of Technology (MIT) partnered with the Argentine government for a strategic planning solution to be applied to the Rio Colorado River. The objective was to maximize the country's gross national income by means of river management through constructing dams, hydropower facilities, and irrigation facilities. The solution was sought through studying the area and using mathematical programming models to provide decision makers with an understanding of the implications of their possible decisions. The problem was constructed as a mixed-integer programming problem to be run through three models; a screening model, a simulation model, and a sequencing model (Major & Lenton, 1979).

The screening model was used to help make decisions for the variables concerning the river basin management. The purpose of the screening model was to produce the optimal solution from a set of possible river basin infrastructure projects and operational uses for a mean hydrologic scenario. The simulation model was used to analyze the screening model solution's robustness. Finally, a sequencing model was used to decide on when parts of the infrastructure should be built (Major & Lenton, 1979).

These models produced plans for development on the river. Several site locations were determined in advance for possible reservoirs, hydroelectric power facilities, and import and export facilities for controlling the water. The models were multi-objective as the Argentine Republic expressed numerous goals to their MIT partners. For multi-objective optimization problems, either the objective function can be made increasingly complex by including these objectives in the primary equation or one objective can serve as the objective function, while the other objectives act as constraints to the problem. The Rio Colorado team took this latter approach (Major & Lenton, 1979).

The primary objective function for the Rio Colorado case was the discounted difference between the benefits and costs to the nation's income due to the development decision. The possible benefits from the river were irrigation productivity, exporting benefits, and hydroelectric power production. The costs were both the fixed and variable costs of the facilities needed to gain these benefits (Major & Lenton, 1979).

The screening model was formulated to decide if proposed facilities should be built and to what size under the objectives set by the model. The screening model was run under a mean hydrological scenario. Historical data was the primary source of data in creating the parameters for this run. To include the possibility of facilities not being built, the optimization problem included binary decision variables. The binary decision variables were zero if the facility was not built and one if the facility was built. By including the binary decision variables in both the costs and benefits of the problem statement, the solution was able to produce a solution set of binary decision variables that allowed for facilities not being built (Major & Lenton, 1979).

The decision variables for the Rio Colorado were the capacities of the reservoirs, the irrigation areas, the power facilities, the import/export facilities, and the variables associated with water allocation with each of these facilities. The capacities were given an upper bound based on site constraints and Argentinean development goals. The screening model's solution was facilities built at varying sizes, including several facilities not being built. In reality, availability of water resources varies by year and seasons. This would result in Argentina not always receiving their expected yearly benefits predicted by the screening model, thus simulation models were needed (Major & Lenton, 1979).

The simulation models were used to test the durability of solutions produced from the screening model. This durability refers to handling the variance of hydrological conditions from year to year. The simulation models consisted of a 50 year period that had fluctuating river inflows. The simulation model showed how some of the top solutions from the screening model would perform in maximizing the objectives (Major & Lenton, 1979).

The simulation model added another dimension to basin planning by including river inflow shortage periods. The shortage was defined as a period where the amount needed to satisfy the screening model objectives was unmet. In the case of the Rio Colorado, a shortage was considered to create a loss in benefits, while a season of excess created no added benefit. An operation rule was needed to handle the seasons where the target flow was not met. For the Rio Colorado case, the standard operating rule was the primary rule used, which simplifies to specifying a release amount at reservoir sites due to the previously decided target release amount and the current availability of water. The final storage rule was the secondary rule that was used for comparison. The final storage rule chooses actions to allow for storage at the end of seasons to meet the target amount for the following season (Major & Lenton, 1979).

The simulation model further characterized some of the best solutions for river development. After passing through this model, the solution set was reduced to a set of optimal and durable solutions. The sequencing model was then used as the final model to narrow down planning options. The sequencing model was used to decide for four time periods when the facilities should be built. The sequencing was to take place so as to achieve the greatest benefit considering projects' financial sensitivity to time and the facilities' operational dependence on other facilities (Major & Lenton, 1979).

In the course of creating the models to represent the river area, several simplifications were completed. For the screening model, complex situations in reality were simplified in order to complete the models; however, these simplifications potentially raise questions about the validity of the solutions. The screening model's limitation of not being able to account for over year storage was handled by the simulation model. On the other hand, when nonlinear relationships were simplified to piece-wise linear relationships for relationships in the constraint equations, local optima solutions became potential traps for the problem solvers. These imperfections of the model called for improvements. The solutions needed to be supported by real data and checked to minimize the errors that could have resulted from oversimplifying the problem (Major & Lenton, 1979).

Some of the hurdles faced in the Rio Colorado case have been shrunk in the present. The computing that took rooms of computers can now be completed quickly on a laptop using software such as General Algebraic Modeling System (GAMS). The template used in the Rio Colorado was well-thought out and provides for a good template for river basin screening models. Screening models such as the one in the Rio Colorado case gave a solution based on a mean hydrological case, thus it did not give an accurate account of what will actually happen in a world that has fluctuating water availability. A simulation model was used to test the results of future varying hydrological scenarios. Future water conditions used can be either synthetic or historical. Synthetic data is easily changed based on future predictions, but whether such data is realistic is debatable.. Historical data has credence due to its tangibility, but future conditions don't necessarily mirror history, especially with recent predicted effects from climate change (McLaughlin, 2009).

A.6 GAMS

GAMS is modeling software designed to solve "linear, nonlinear, and mixed integer optimization problems" (GAMS). Through solvers GAMS produces local solutions. It is up to the modeler to point the solution to a global solution. GAMS has been used for a wide range of applications from efforts to resolve the water conflict between Jordan, Israel, and Palestine to solving for the optimal planting procedure for rural farmers in Burkina Faso.

For the case in the Middle East, Frank Fisher from MIT with many partners has used GAMS to produce an easy to use interface, Water Allocation System (WAS), for decision makers. Behind the interface GAMS is solving the nonlinear optimization problem representing the water use objectives and physical constraints of the region. The WAS model allows policy makers to decide certain constraints of the problem that represent their objectives. Then, GAMS produces the optimal allocation procedure under the specified constraints. This process allows for the different agendas of the decision makers to be easily modeled by WAS and viewable by decision makers (Fisher & Hubert-Lee, Liquid Assets: An Economic Approach for Water Management and Conflict Resolution in the Middle East and Beyond, 2005; Fisher & Hubert-Lee, WAS-guided cooperation in water management: Coalition and gains, 2006).

The case on the Middle East provides an important reality lesson in water planning. The shadow price of relaxing a constraint, the Lagrange multiplier of a constraint, is the benefit gained by the objective function by relaxing that constraint by one unit. In a perfectly private market, this would correspond to the price that consumers should pay for an additional unit of water; however, institutions and/or governments may impose agendas that skew this practice by fixing prices, thus taking on the remaining cost of additional water. Consequently, the optimization capabilities of GAMS are proving to be an important component of the discussion on water allocation decisions in the Middle East as every decision in the region is laced with political implications (Fisher & Hubert-Lee, Liquid Assets: An Economic Approach for Water Management and Conflict Resolution in the Middle East and Beyond, 2005; Fisher & Hubert-Lee, WAS-guided cooperation in water management: Coalition and gains, 2006).

For the case in Burkina Faso, GAMS has been used to help benefit farmers. Rural Burkina Faso farmers have higher than normal pressure to plant the proper crops at the right time. Burkina Faso is subject to drastic differences in their water availability due to its long dry season. Farmers act according to their predictions of rainfall to plant so as to have the most productive year. GAMS was used to help the farmers by using probabilistic forecasting models and formulating the needs of the farmers as an optimization problem. In this case study, the primary objective function was minimizing the calorific deficit of the farmers' families. A secondary objective of maximizing the farmers' income was also included in the objective. This secondary objective was severely discounted in the optimization problem in comparison to the primary objective (Maatman, Schweigman, Ruijs, & Van der Vlerk, 2002).

The problem was formed as a mixed integer problem. Binary integer variables were used to decide whether certain land should be cultivated. The input climate conditions were predictive in nature based on global surface sea temperatures and placed in categories to replicate historical rainfall conditions. The problem solved for the best actions to be taken by farmer's given the rainfall predictions (Maatman, Schweigman, Ruijs, & Van der Vlerk, 2002).

In further modeling the agricultural practices in Burkina Faso, a rare model was used that incorporated the dynamic practices of the farmer's based on rainfall knowledge. The model showed the differences between the model's solution and the current farming practices. Discrepancies arise from either the model's shortcomings or non-optimal farming practices. The discrepancies were small, thus it was safe to conclude that the model was appropriately formed and that the farmers were practicing at near optimal behavior. The model also showed the active constraints on the farmers. This shed light on policy potentials such as relaxing the land constraint placed on the farmers (Maatman, Schweigman, Ruijs, & Van der Vlerk, 2002).

The confidence in the model led to creating an additional model that showed how possible technological changes could help the farmers. This new scenario took on farming capabilities that exceeded indigenous farming abilities. Modeling for different aids to the farming sector becomes important when considering climate change. Indigenous farming strategies may not be able to cope with climate change effects. Exploring technologies to help farmers cope with climate change is crucial (Maatman, Schweigman, Ruijs, & Van der Vlerk, 2002).

A.7 Climate Variability in the Philippines

According to the Intergovernmental Panel on Climate Change (IPCC), the Philippines has recently received an increase in average rainfall along with an increase in its variability. Over this recent history, floods and droughts have also occurred more frequently. Droughts due to El Niño-Southern Oscillation (ENSO) resulted in the loss of many crops in 1997 and 1998. Between 1990 and 2003, the Philippines witnessed an average increase of four cyclones per year. Climate forecasting predicts these trends to continue in the future. In addition to these increases in extreme water supply scenarios, coastal areas are expected to continue to experience rises in sea-level. This will be a major flood source for low-lying areas as well as instigate salt inundation problems (Cruz, et al., 2007).

With growing concern and evidence for the future effects of climate change, the Philippines has begun responding (Jose & Cruz, 1999). The Philippines is already a part of the world that must plan and manage water based on flooding. But the climatic changed world necessitates that the Philippines plan for even more floods and possible drought scenarios. The Philippines must act to handle the water issues that are already known, but they must also plan for the future as large infrastructure takes time to fund and build.

A.8 Flood Estimation

Using synthetic unit hydrographs is the primary means of relating a flood's peak flow to flow over time for basins with poor or absence of streamflow and/or rainfall data. One of the most primitive methods in the field of synthetic unit hydrographs was fabricated by the Soil Conservation Service. The method entails replicating a flood flow as a triangle. The peak of the triangle is located somewhere between the start and the end of the flood. The total volume of runoff is the total area of the triangle (Bedient, Huber, & Vieux, 2008).

Appendix B: GAMS Code for Screening Model

```
$offlisting
$offsymxref
$offsymlist
option
    limrow=1000
    limcol=1000
    reslim = 2500
        ;
option NLP = CONOPT;
sets
    t monthly increments for 25 yrs + 6 months /1*648/
    f flow locations /1*11/
    s sites(1-P1 2-P2 3-Bad 4-Mam) /1,2,3,4/
    p projects (1-reservoirs 2-hydropower 3-irrigation) /1,2,3/
    n number for coefficient polynomial tables /1*3/
    i number for coefficient for exponential tables /1*2/
    j flood region (1-Dumalag 2-Badbaran 3-Cuartero 4-Sigma 5-Lower Panay) /1*5/
;
Parameters
resmax(s) Reservoir maximum sizes (MCM)
/
1    182.22
2    535.47
3    734.55
4    743.07
/
```

Parameter

landmax(s) Irrigated land maximum sizes (ha)

/

1 0

2 500

3 0

4 0

/

Parameter

hydromax(s) Maximum hydropower sizes (KW)

/

1 7000

2 6000

3 2550

4 2250

/

Parameter

effic(s) efficiency of each hydropower facility

/

1 0.6814

2 0.5983

3 0.64

4 0.64

/

Parameter

hydrocost(s) Proportionality Constants (MPesos per KW of capacity)

/

1 0.0304

2 0.0324

3 0.0596

4 0.0546

/

Parameter

rescost(s) Proportionality Constants (MPesos per MCM of capacity)

/

1 5.1004

2 0.6783

3 1.3102

4 1.5093

/

Parameter

Nest1(t) 1s for months 0s for 12-hr flood periods (*Nest1* in the report)

/

/

Parameter

Nest2(t) 0s for months 1s for 12-hr flood periods (To not count cost for safe monthly flows)

/

/

Parameter

Nest3(t) 720 hours in a month 12 hours in a 12 hour period (*Nest2* in the report)

/

/

Parameter

eloss(t) pan evaporation losses m for each month 0 for flood periods (see Section 3.4)

/

/

Table

flow(f,t) 11 x 648 matrix of water added to the river at each location (see Section 3.4)

Table

storhead(s,n) Coefficients for Storage (MCM) – head (m) relationship

	1	2	3
1	-0.0011	0.406	4.8876
2	-0.00003	0.0444	1.9019
3	-0.00005	0.0714	2.9572
4	-0.00005	0.0809	3.4238

Table

areavolume(s,i) Coefficients for Storage (MCM) – Surface Area (km^2) relationship

	1	2
1	0.0484	1.4077
2	0.0765	17.054
3	0.0741	7.8962
4	0.0561	8.0456

Table

floodcostcoeff(s,i) Dam release flood cost (MPesos per MCM of total floodwater for 3 days)

	1	2
1	0	0
2	0	2.3533
3	0	1.9817
4	0	2.7846

Table

floodcostcoeff2(j,i) Regional Flood Cost (MPesos per MCM of total floodwater for 3 days)

	1	2
1	0	0.5663
2	0	0.453
3	0	1.377
4	0	1.7062
5	0	1.0784

Scalar

watrequ water requirement MCM per ha per month /0.000259/

energytomoney KW*hr to 10^6 pesos /0.0000125/

costirrig 1x10^6 P per ha /0.0292/

econvert to get KW*hr /2725/

ricetomoney ha irrigated to 10^6 pesos per month /0.0048098/

discount amortization factor 6% for 50 years /0.063444286373864/

payment actual multiplier for capital amount (*SummedAmortization* in 3.3) /3.1722/

positive variables

in(s,t) flows into dam (MCM)

out(s,t) discharge from dams (MCM)

storage(s,t) storage at each dam (MCM)

ex(s,t) water exported for irrigation (MCM)

capres(s) reservoir capacity (MCM)

capland(s) land capacity (ha)

cappower(s) power capacity (KW)

h(s,t) head at dams (m)

Rescosts(s) cost of dam 10^6 P

```
SurfaceArea(s,t) surface area of reservoir km^2
E(s,t) energy produced (KW*hr)
IrrBen   Irrigation Benefit (1x10^6 P)
HydroBen   Hydrobenefit (1x10^6 P)
Summedhydroben Total hydrobenefit (1X10^6 P)
summedirrben   Total irrigation benefit (1X10^6 P)
Hydrocosts(s) Hydropower facility costs (1X10^6 P)
Irrcosts Irrigation Costs (1x10^6 P)
OandM   Operation and Maintenance Costs (1X10^6 P)
Ben    Benefits (1X10^6 P)
Cost   Costs (1X10^6 P)
floodcost(s,t)  Preventable Flood Cost each time step (1x10^6 P)
floodcost2(j,t) Total Flood Cost each time step (1x10^6 P)
Summedfloodcost Summed Preventable Flood Cost (1x10^6 P)
Summedfloodcost2 Summed Total Flood Cost (1x10^6 P)
floodflowspot(j,t) Flow Volume in 5 flood regions (MCM)
junction(n,t) Flow Volume at river junctions (MCM)
hmin Minimum head (m)
hmax Maximum head (m)
;
free variable
z
;
*initialize variables
storage.l(s,t) = 10;
capres.l('1') = 20;
capres.l('2') = 35;
capres.l('3') = 30;
```

```
capres.l('4') = 40;

capland.l('2') = 500;

cappower.l('1') = 1000;

cappower.l('2') = 1000;

cappower.l('3') = 550;

cappower.l('4') = 250;

z.l = 40000


Equations

Inflow1(t) P1 inflow

Inflow2(t) P2 inflow

Inflow3(t) Badbaran inflow

Inflow4(t) Mambusao inflow

Storage1(s,t) storage

Storage2(s,t) storage 2

Flow1(s,t) Flow at Pan-Badbaran

Flow2(s,t) Flow at Pan-Mambusao

Flow3(s,t) Flow at Pan-Maayon

Flow4(s,t) Floodspot at Dumalag

Flow5(s,t) Floodspot at Badbaran

Flow6(s,t) Floodspot at Cuartero

Flow7(s,t) Floodspot at Sigma

Flow8(s,t) Floodspot at Panitan

Capresequ(s) reservoir capacity constraint

storagehead(s,t) storage to head

Costtocapacity(s) cost to reservoir capacity

Areatovolume(s,t) Relating surface area and storage

Caphydroequ(s) hydropower constraint
```

Energyprod(s,t) energy produced

Energylimit(s,t) Limit of energy

Enben Energy benefit

Costhydroequ(s) Cost of hydropower facilities

sumhydro Summing hydropower benefit terms

hydromin1 Low end of head

hydromax1 High end of head

hydrovar1 Minimize head variation

Caplandequ(s) Irrigable land constraint

Irrneed(s,t) Water need for irrigation

Irrbenefit Irrigation benefit

Irrcost(s) Irrigation cost

sumirr Sum irrigation ben

Floodcostequ Preventable flood cost

Floodcostequ2 Total preventable flood cost

Summedfloodcostequ Total flood cost

Summedfloodcostequ2 Summed total flood cost

Flowduringmonths Ensures that monthly flows do not exceed safe flows

Costequ Capital costs

Costequ2 Operation and Maintenance Cost

Benefitequ Hydropower and irrigation benefit

Objective(t) Objective function

;

```
*********************************************************************************
*********************************************************************************
*Equations
*********************************************************************************
*********************************************************************************
*Inflows at each Site
*********************************************************************************
*P1 site
Inflow1(t)..      in('1',t) =e= flow('1',t);
*P2 site
Inflow2(t)..      in('2',t) =e= flow('2',t)+out('1',t) ;
*Badbaran site
Inflow3(t)..      in('3',t) =e= flow('4',t) ;
*Mambusao site
Inflow4(t)..      in('4',t) =e= flow('8',t) ;
*Flow at Pan-Bad Jct
Flow1(s,t)..      junction('1',t) =e= out('2',t) + flow('3',t) + out('3',t) + flow('5',t);
*Flow at Pan-Mam Jct
Flow2(s,t)..      junction('2',t) =e= junction('1',t) + flow('6',t) + flow('7',t) + out('4',t) + flow('9',t);
*Flow at Pan-Maayon
Flow3(s,t)..      junction('3',t) =e= junction('2',t) + flow('10',t) + flow('11',t) ;
*Flow at Dumalag
Flow4(s,t)..      floodflowspot('1',t)=e= out('2',t) + flow('3',t)  ;
*Flow at Badbaran
Flow5(s,t)..      floodflowspot('2',t)=e=out('3',t) + flow('5',t);
*Flow at Cuartero
Flow6(s,t)..      floodflowspot('3',t)=e=junction('1',t) + flow('6',t)  ;
*Flow at Sigma
```

```
Flow7(s,t)..      floodflowspot('4',t)=e=(out('4',t) + flow('9',t))  ;

*Flow at Panitan

Flow8(s,t)..      floodflowspot('5',t)=e= junction('3',t) ;

**********************************************************************************

*Storage equations

**********************************************************************************

*Storage at dams

Storage1(s,t)..    storage(s,t+1) =e= storage(s,t) + in(s,t) - ex(s,t)*Nest1(t)- out(s,t)-
eloss(t)*SurfaceArea(s,t);

*Relating reservoir area to volume

Areatovolume(s,t).. SurfaceArea(s,t) =e= areavolume(s,'1')*storage(s,t)+areavolume(s,'2');

*storage, head relationship

storagehead(s,t)..

h(s,t) =e= (storhead(s,'1')*storage(s,t)*storage(s,t))+(storhead(s,'2')*storage(s,t))+storhead(s,'3');

*Reservoir constraint

Storage2(s,t)..     storage(s,t) =l= capres(s);

Capresequ(s)..      capres(s) =l= resmax(s);

*Cost of dam to capacity of reservoir

Costtocapacity(s).. Rescosts(s) =e= rescost(s)*capres(s);

**********************************************************************************

*Hydropower

**********************************************************************************

Energyprod(s,t)..         E(s,t) =e= econvert*effic(s)*h(s,t)*out(s,t);

Energylimit(s,t)..        E(s,t) =l= cappower(s)*Nest3(t);

hydromin1(s,t)..          hmin(s) =l= h(s,t);

hydromax1(s,t)..          hmax(s) =g= h(s,t);

hydrovar1(s)..            hmax(s) =l= 2*hmin(s);

*Hydropower constraint
```

```
Caphydroequ(s)..          cappower(s) =l= hydromax(s);

*Energy benefit

Enben(s,t)..              Hydroben(s,t) =e= energytomoney*E(s,t);

*Cost of hydropower

Costhydroequ(s)..         Hydrocosts(s) =e= hydrocost(s)*cappower(s)  ;

************************************************************************************

*Flooding

************************************************************************************

Floodcostequ(s,t)..       Floodcost(s,t) =e=  Floodcostcoeff(s,'2')*out(s,t)*Nest2(t);

Summedfloodcostequ..       Summedfloodcost =e= (sum(s, sum(t, Floodcost(s,t))));

Floodcostequ2(j,t)..      Floodcost2(j,t) =e=  Floodcostcoeff2(j,'2')*floodflowspot(j,t)*Nest2(t);

Summedfloodcostequ2..      Summedfloodcost2 =e= (sum(j, sum(t, Floodcost2(j,t))));

************************************************************************************

*Irrigation

************************************************************************************

*Irrigable land constraint

Caplandequ(s)..           capland(s) =l= landmax(s);

*Irrigation need

Irrneed(s,t)..            ex(s,t) =e= capland(s)*watrequ*Nest1(t);

*Irrigation benefit

Irrbenefit..              Irrben =e= capland('2')*ricetomoney;

*Cost of irrigation facilities

Irrcost(s)..              Irrcosts  =e= costirrig*capland('2')   ;

************************************************************************************

*Ensuring safe monthly flows

************************************************************************************

Flowduringmonths(j,t)..    floodflowspot(j,t) =l= 907.2  ;

************************************************************************************
```

```
*Objective Function
************************************************************************************
*Benefits 10^6 P
Sumhydro..     SummedHydroben =e= sum(s, sum(t,Hydroben(s,t)));
Sumirr..       SummedIrrben =e= Irrben*600 ;
Benefitequ..   Ben =e= SummedHydroben + SummedIrrben  ;
*Costs 10^6 P
Costequ..      Cost =e= sum(s,Rescosts(s)) + sum(s,Hydrocosts(s)) + Irrcosts ;
Costequ2..     OandM =e= 0.1*Cost*50;
*Objective function: Maximize benefits - costs
Objective(t)..  z =e= (Ben -payment*Cost - OandM - Summedfloodcost) ;
************************************************************************************
*Solver
************************************************************************************
Model panaybasin /all/;
solve panaybasin using NLP maximizing z;
```

Appendix C: Graphs for Curve Fitting

Reservoir Cost Curves

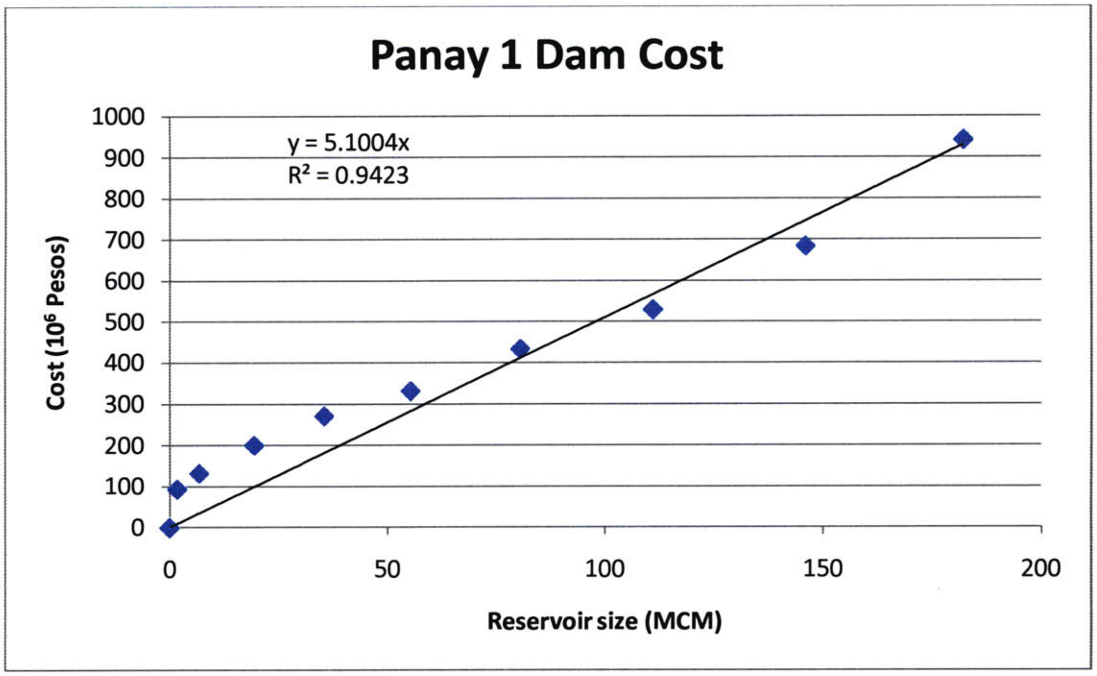


Figure 20: Dam Cost for Panay 1

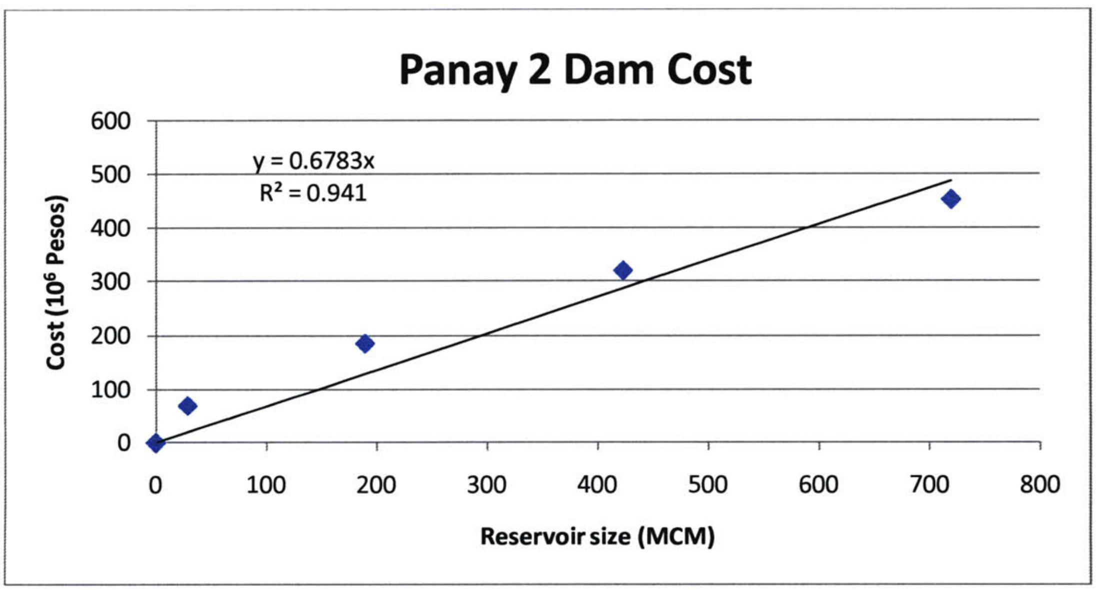


Figure 21: Dam Cost for Panay 2

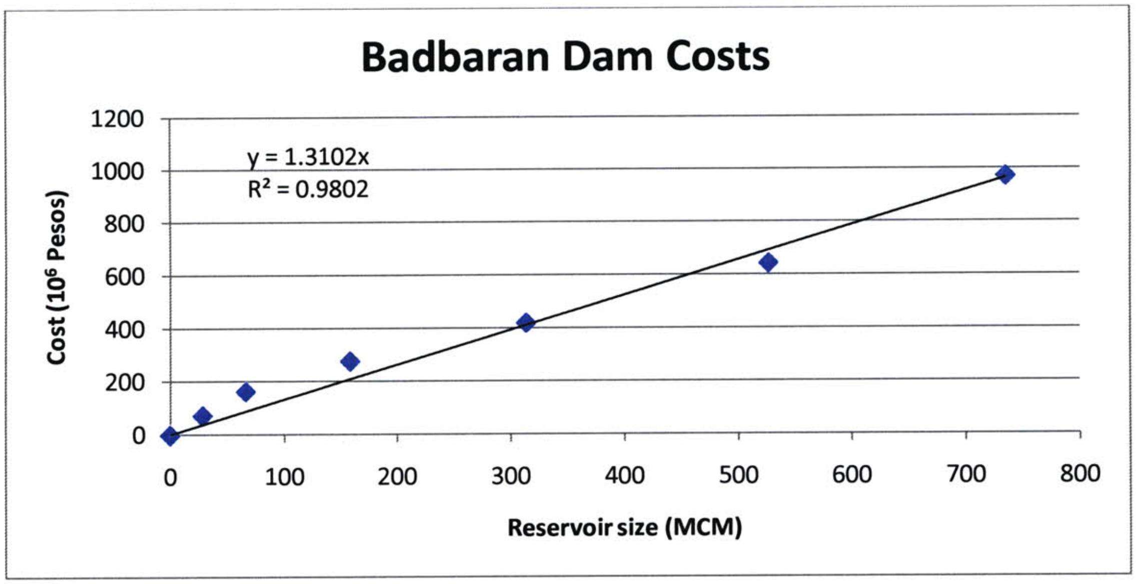


Figure 22: Dam Cost for Badbaran

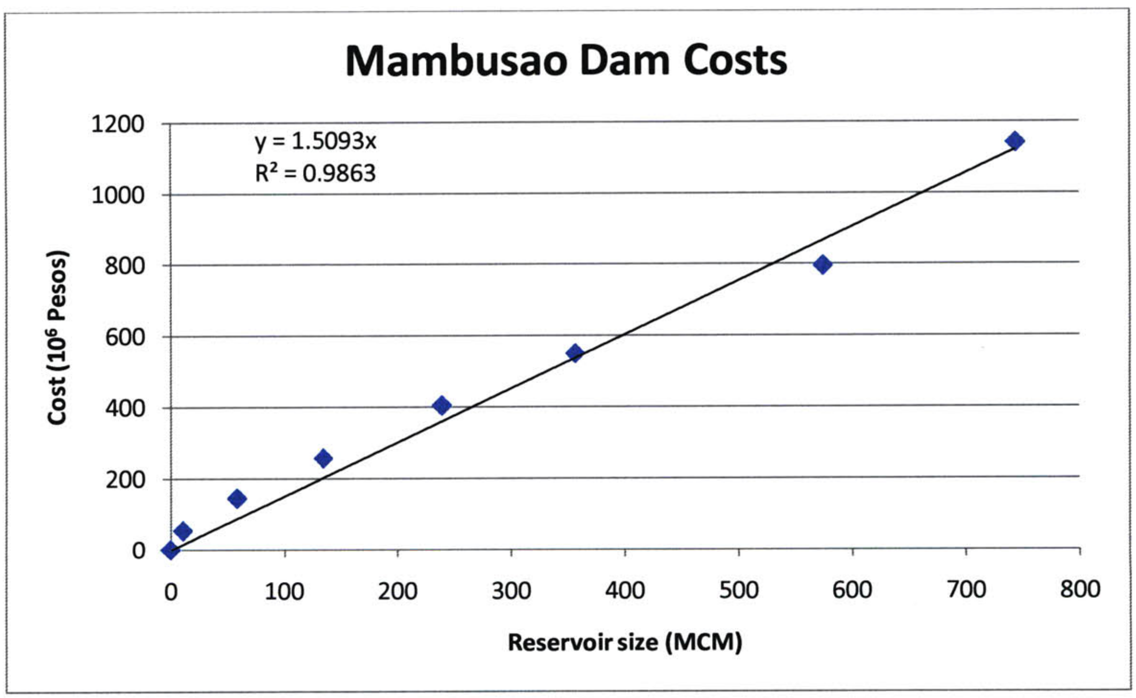


Figure 23: Dam Cost for Mambusao

Storage-Head Relationship Curves

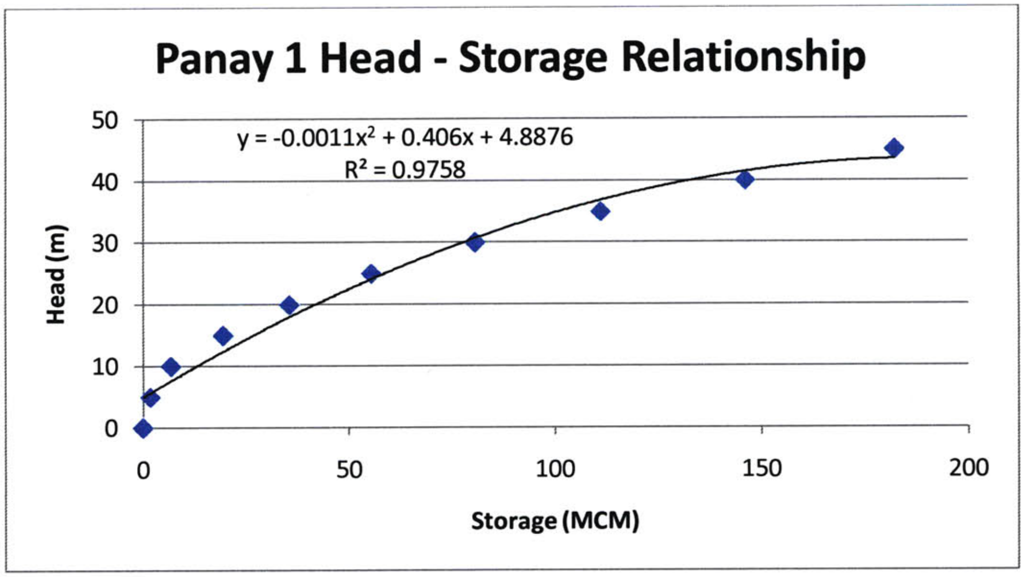


Figure 24: Head-Storage Relationship for Panay 1

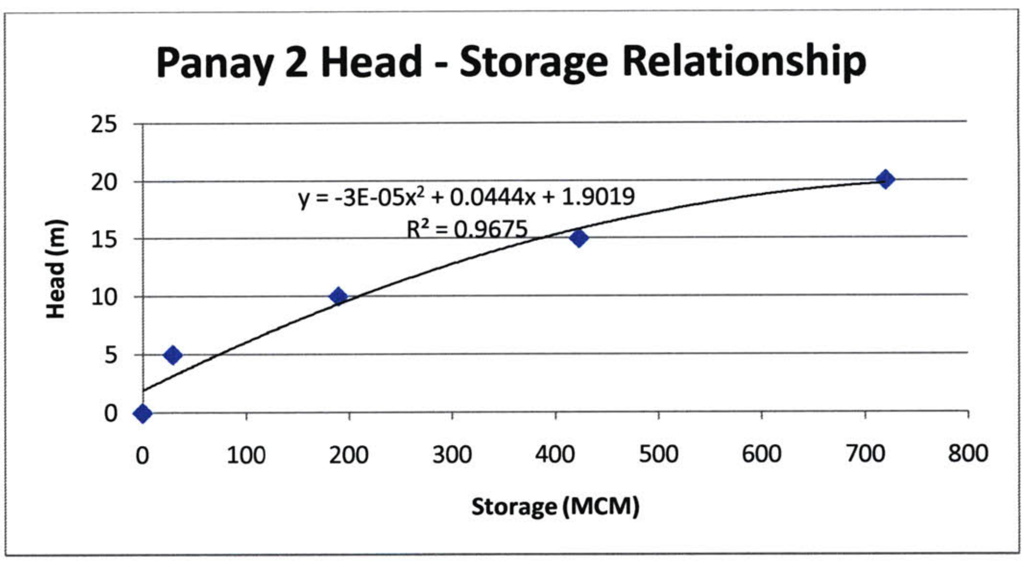


Figure 25: Head-Storage Relationship for Panay 2

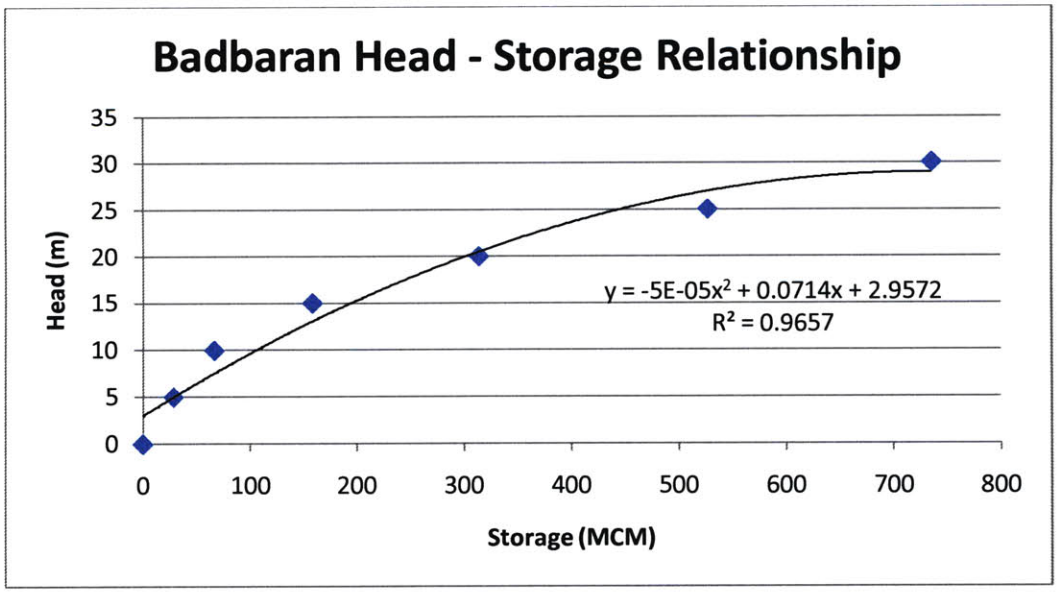


Figure 26: Head-Storage Relationship for Badbaran

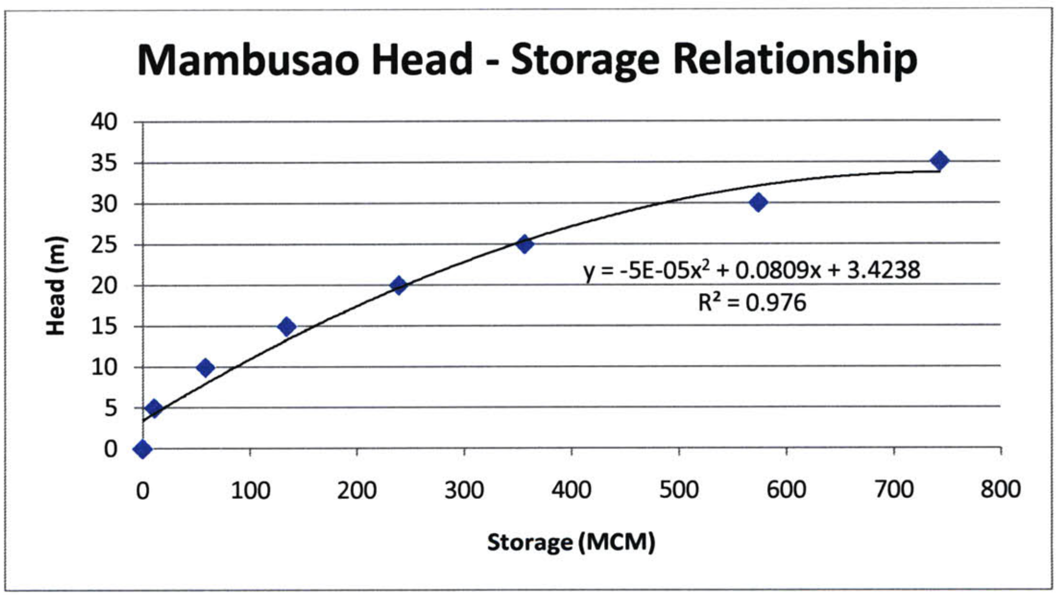


Figure 27: Head-Storage Relationship for Mambusao

Storage-Surface Area Relationship Curves

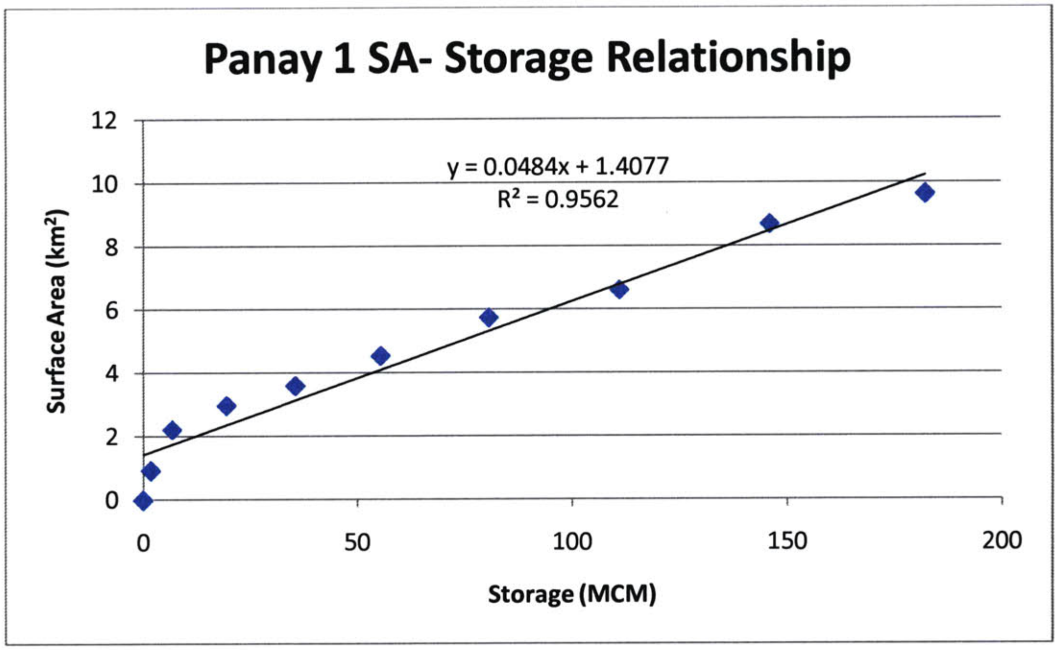


Figure 28: Surface Area-Storage Relationship for Panay 1

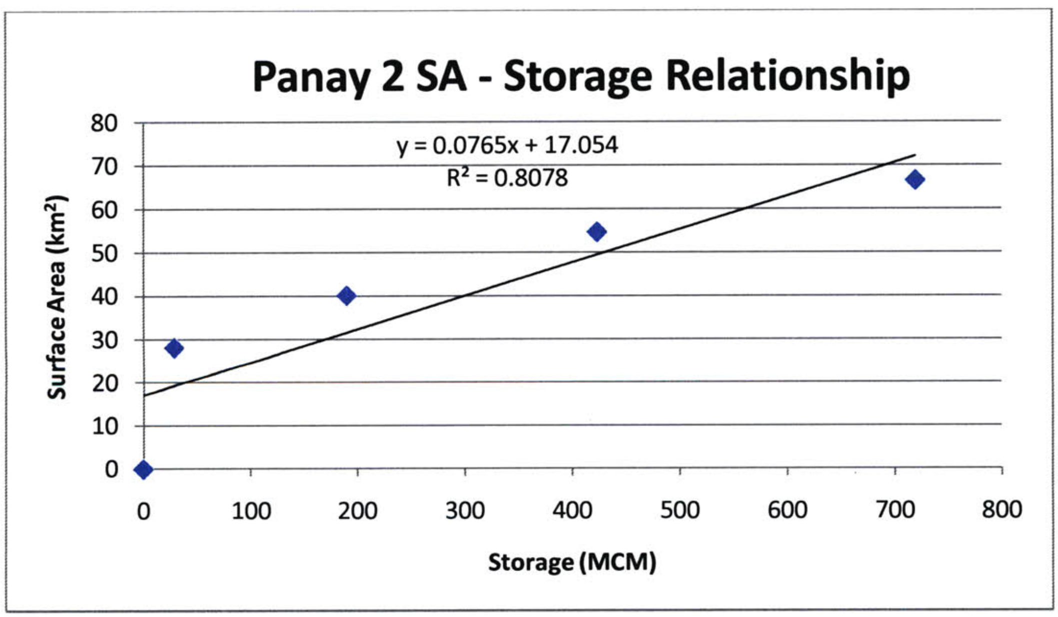


Figure 29: Surface Area-Storage Relationship for Panay 2

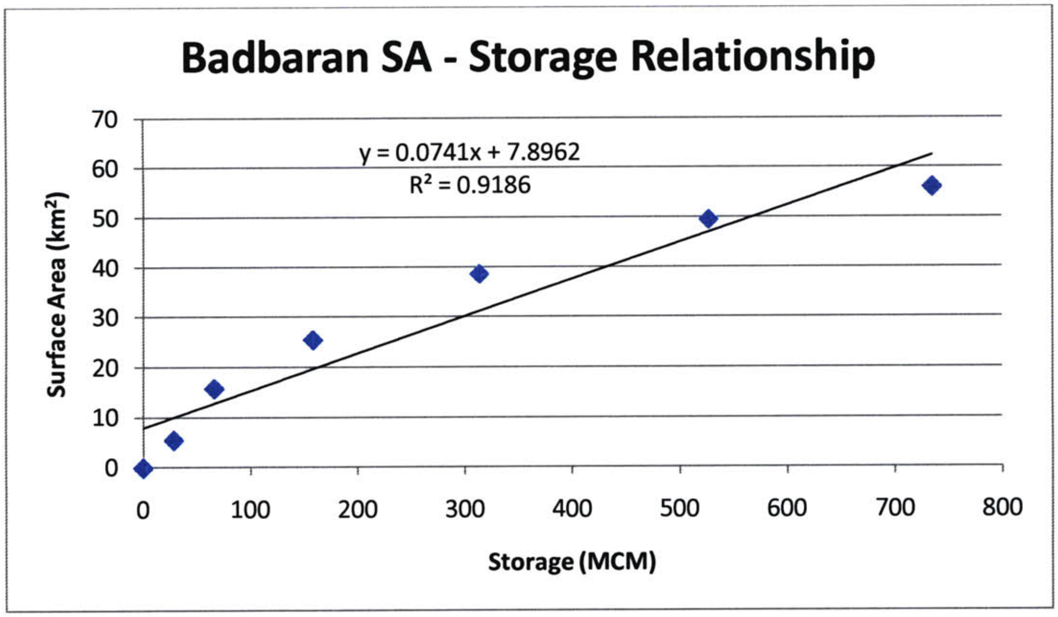


Figure 30: Surface Area-Storage Relationship for Badbaran

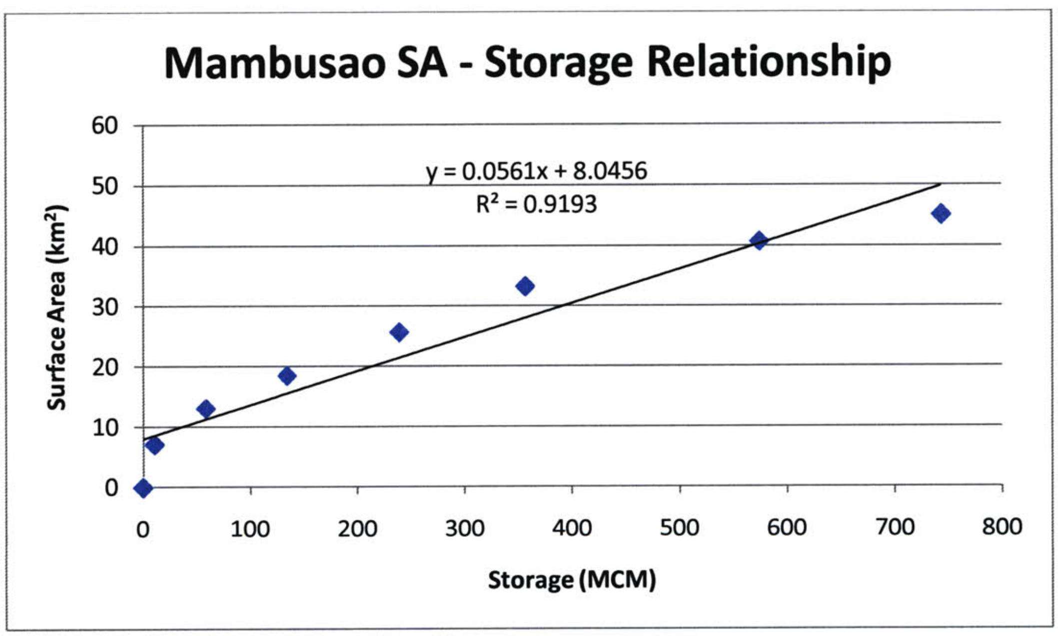


Figure 31: Surface Area-Storage Relationship for Mambusao

Reservoir Release-Flood Damage Relationship Curves

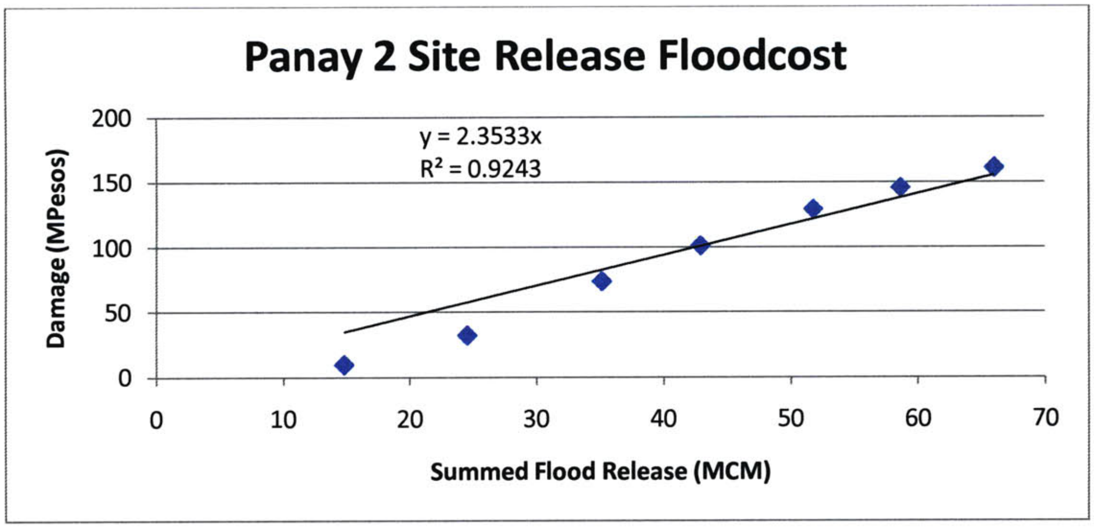


Figure 32: Flood Cost Curve for Panay 2

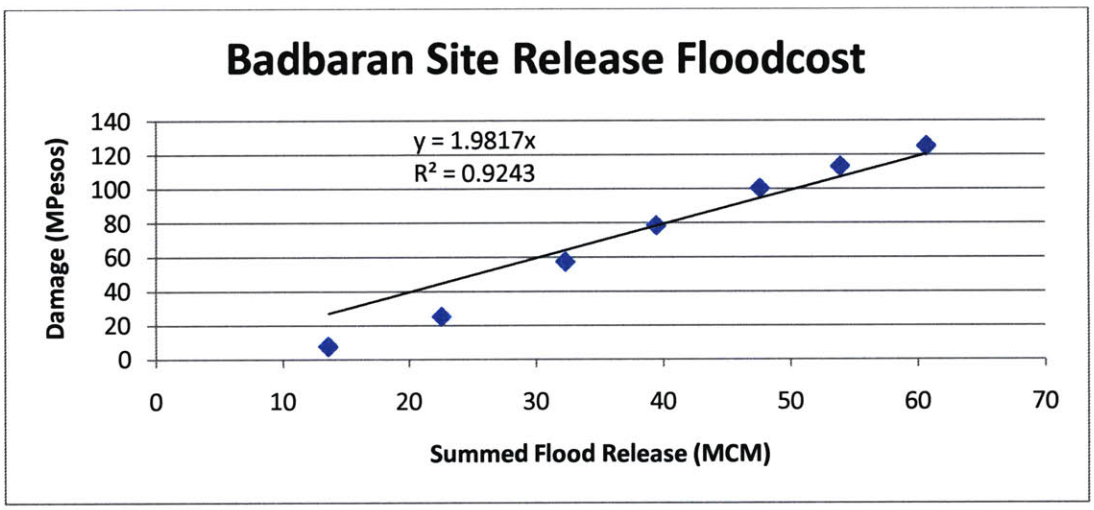


Figure 33: Flood Cost Curve for Badbaran

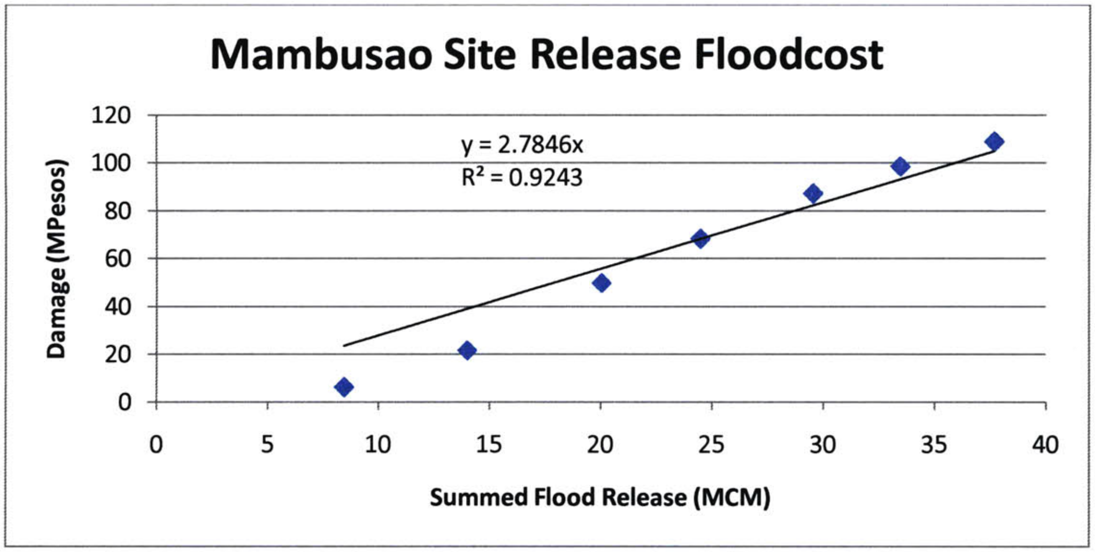


Figure 34: Flood Cost Curve for Mambusao

<u>Flood Region Flow-Flood Damage Relationship Curves</u>

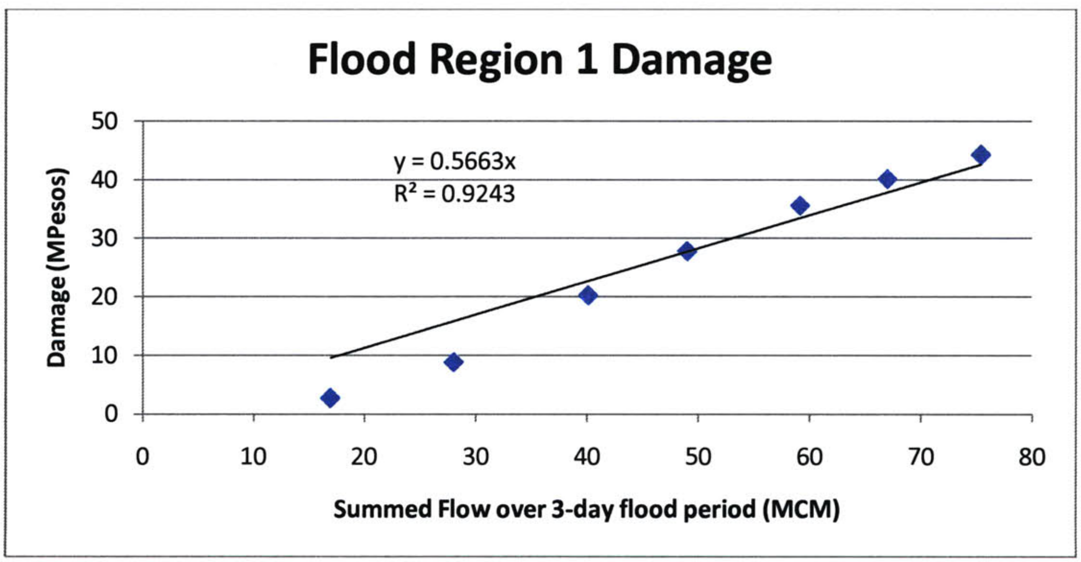


Figure 35: Flood Cost Curve for Region 1

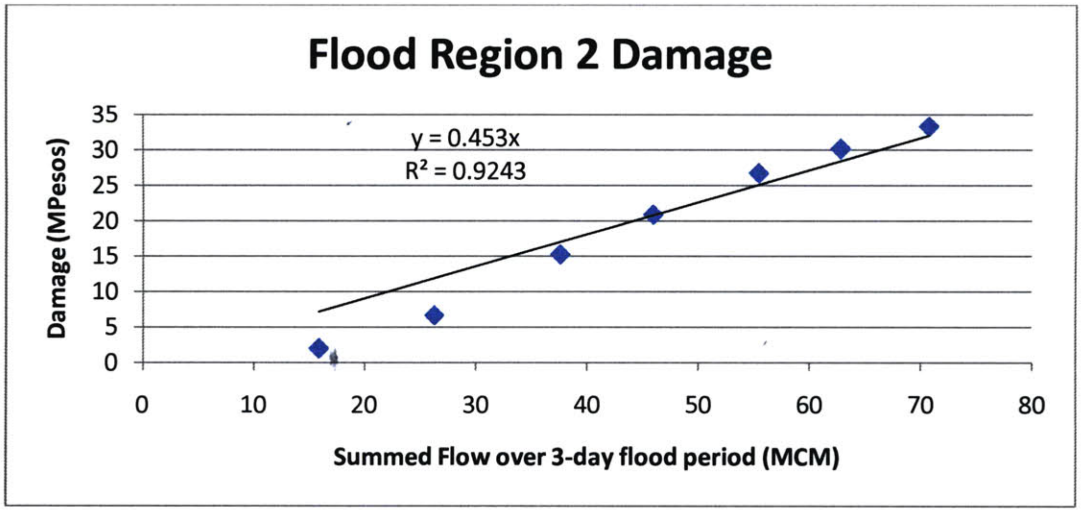


Figure 36: Flood Cost Curve for Region 2

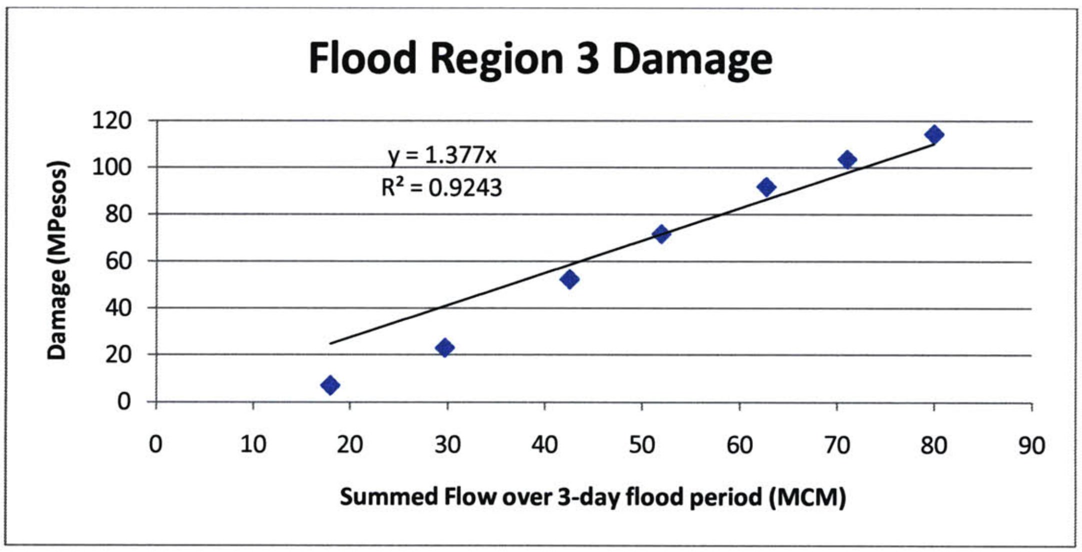


Figure 37: Flood Cost Curve for Region 3

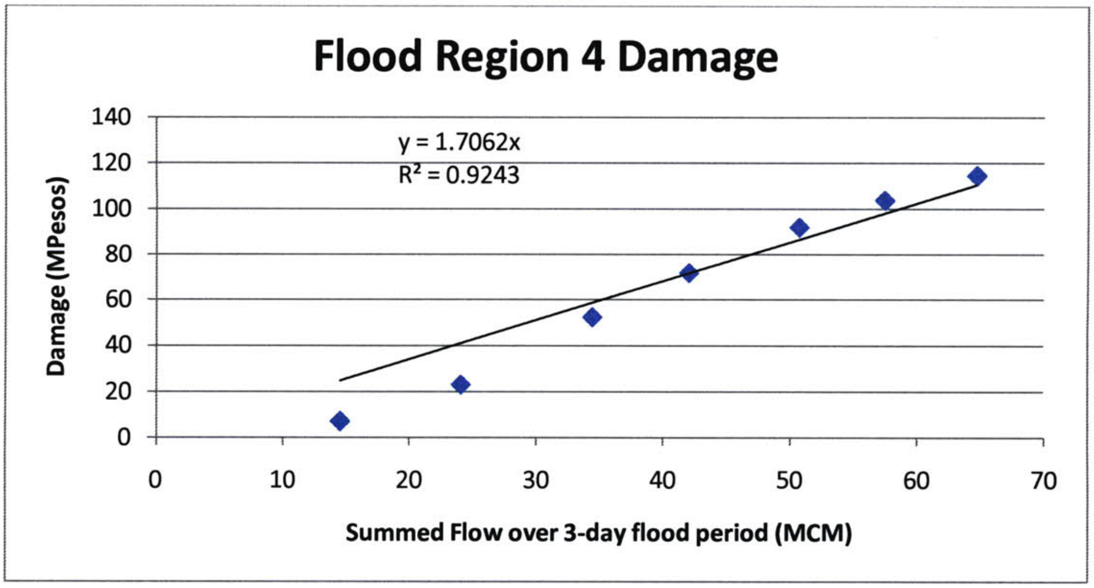


Figure 38: Flood Cost Curve for Region 4

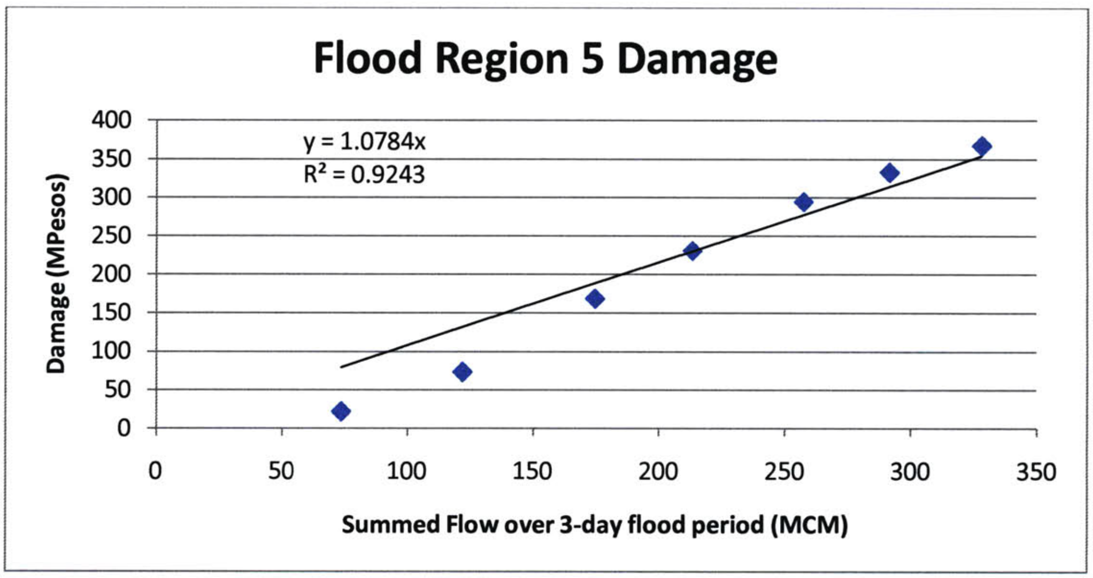


Figure 39: Flood Cost Curve for Region 5

Appendix D: Percentages for Sub Basins and Regional Damages

River Reach	Unique Basin Area (m^2)	Percentage of Lower Panay Basin, %
1	105.9400	4.89
2	329.8456	15.23
3	61.94222	2.86
4	354.3133	16.36
5	112.4711	5.19
6	60.83556	2.81
7	75.17333	3.47
8	248.6133	11.48
9	178.3611	8.24
10	265.1422	12.24
11	372.8622	17.22

Table 22: Percent Contribution to the Basin for Each of the Eleven Locations Found from ArcGIS

Flood Region	Percentage of Total Damage, %
Flood Region 1	6.58
Flood Region 2	4.94
Flood Region 3	16.96
Flood Region 4	17.01
Flood Region 5	54.52

Table 23: Flood Regional Damage Percentage (Derived from Japan International Cooperation Agency (1985))

Appendix E: Closer Images of Full Reservoirs

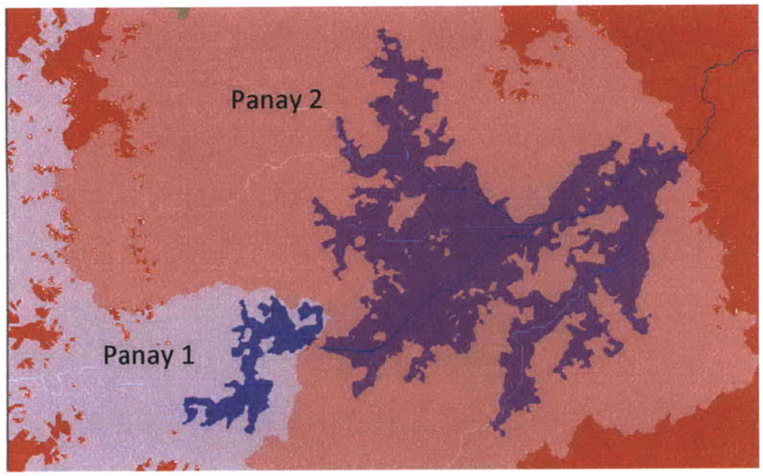


Figure 40: Resulting Full Reservoirs within Reservoir Basins for Panay 1 and Panay 2

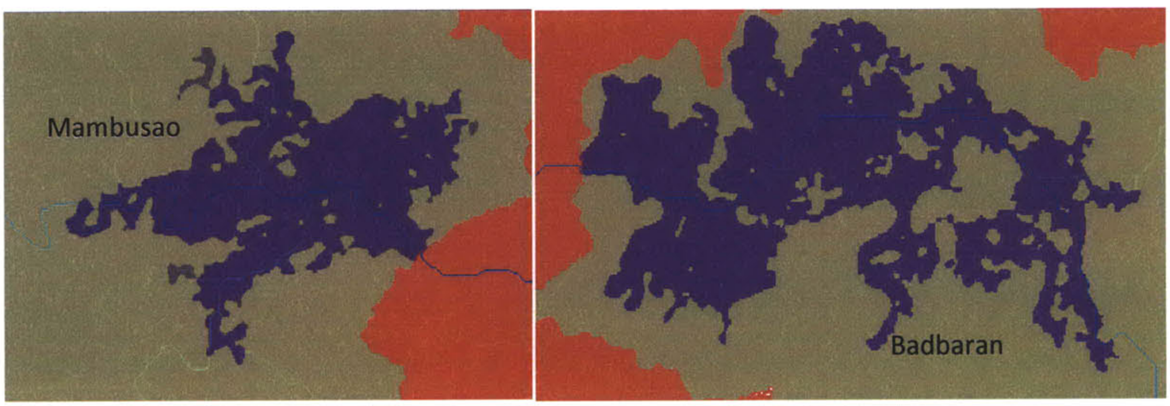


Figure 41: Resulting Full Reservoirs within Reservoir Basins for Mambusao and Badbaran

Appendix F: Screening Model's Water Management and Energy Production Solution

Panay 1

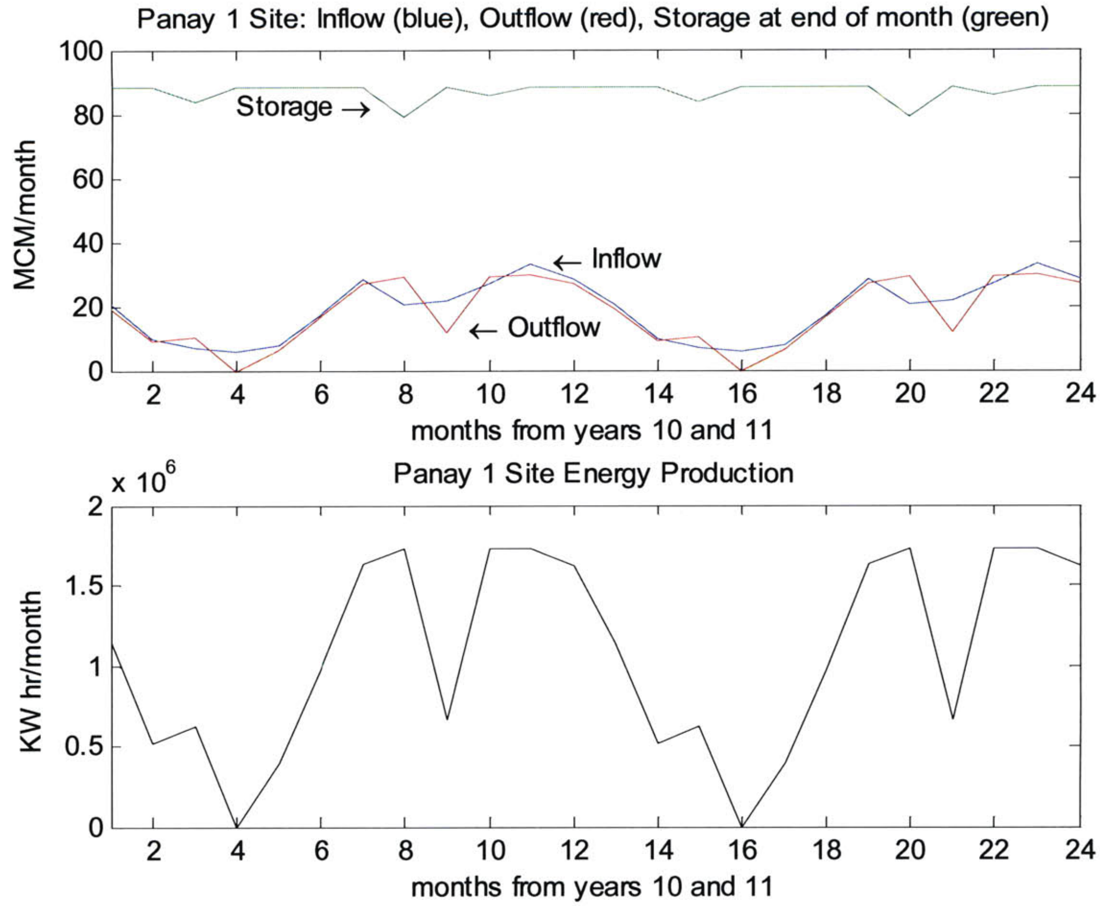
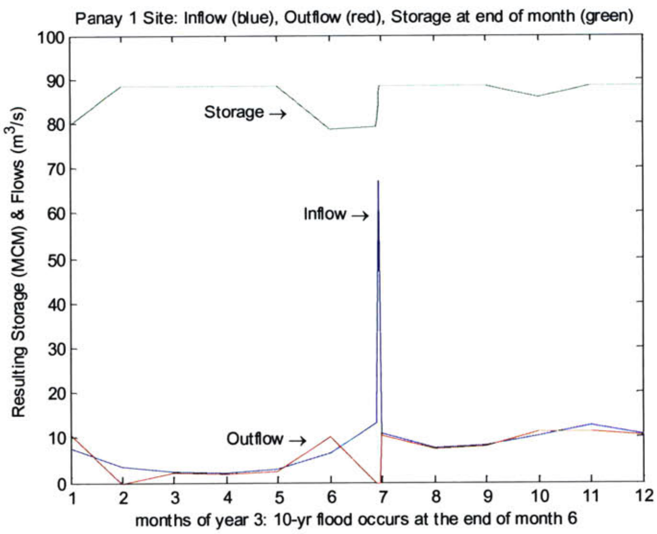
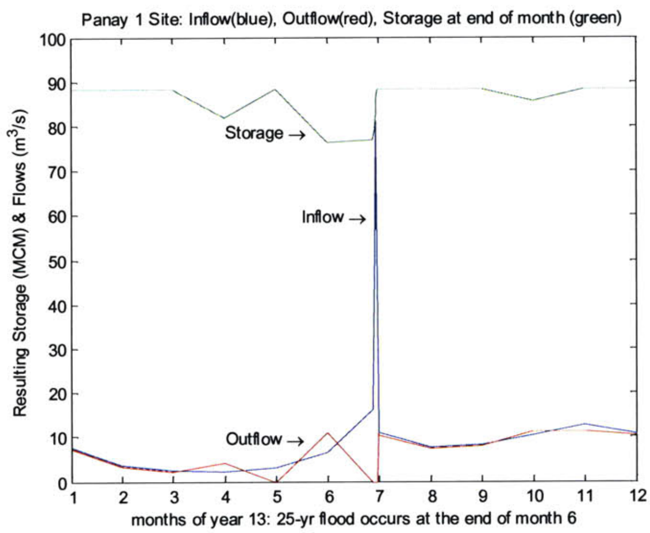


Figure 42: Mean Screening Operation and Energy Production for Panay 1





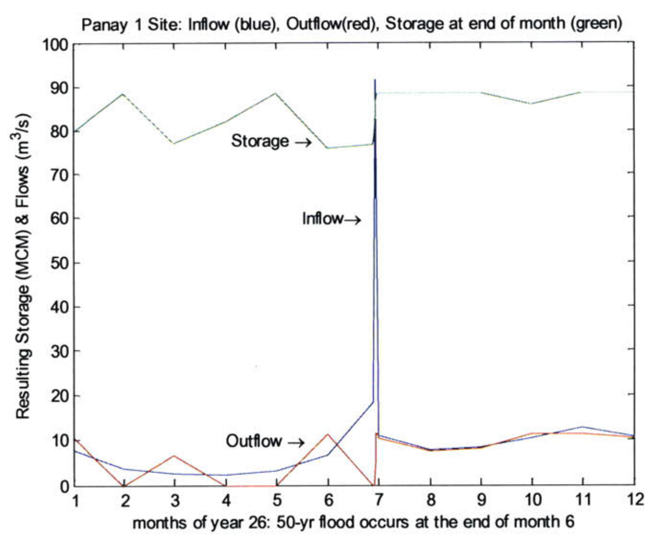


Figure 43: Panay 1 Screening Operations for Floods

Panay 2

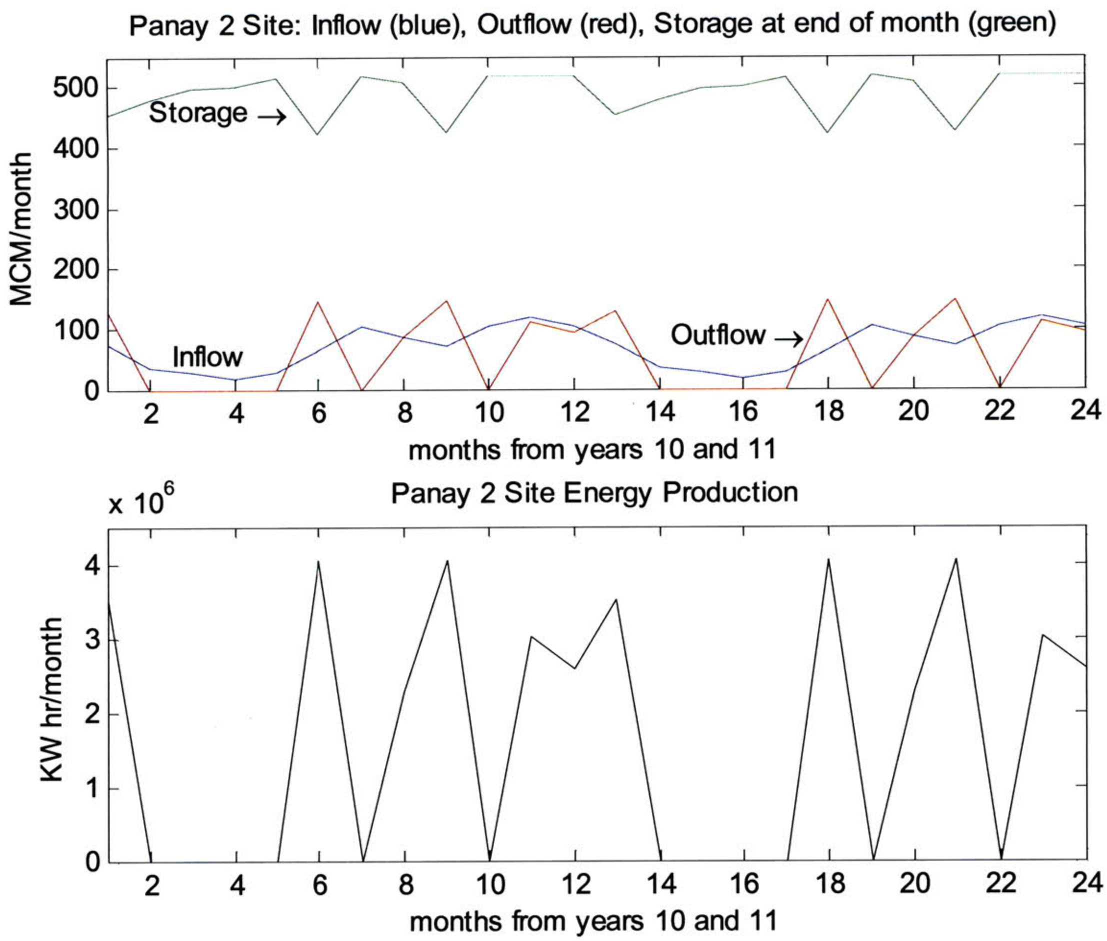


Figure 44: Mean Screening Operation and Energy Production for Panay 2

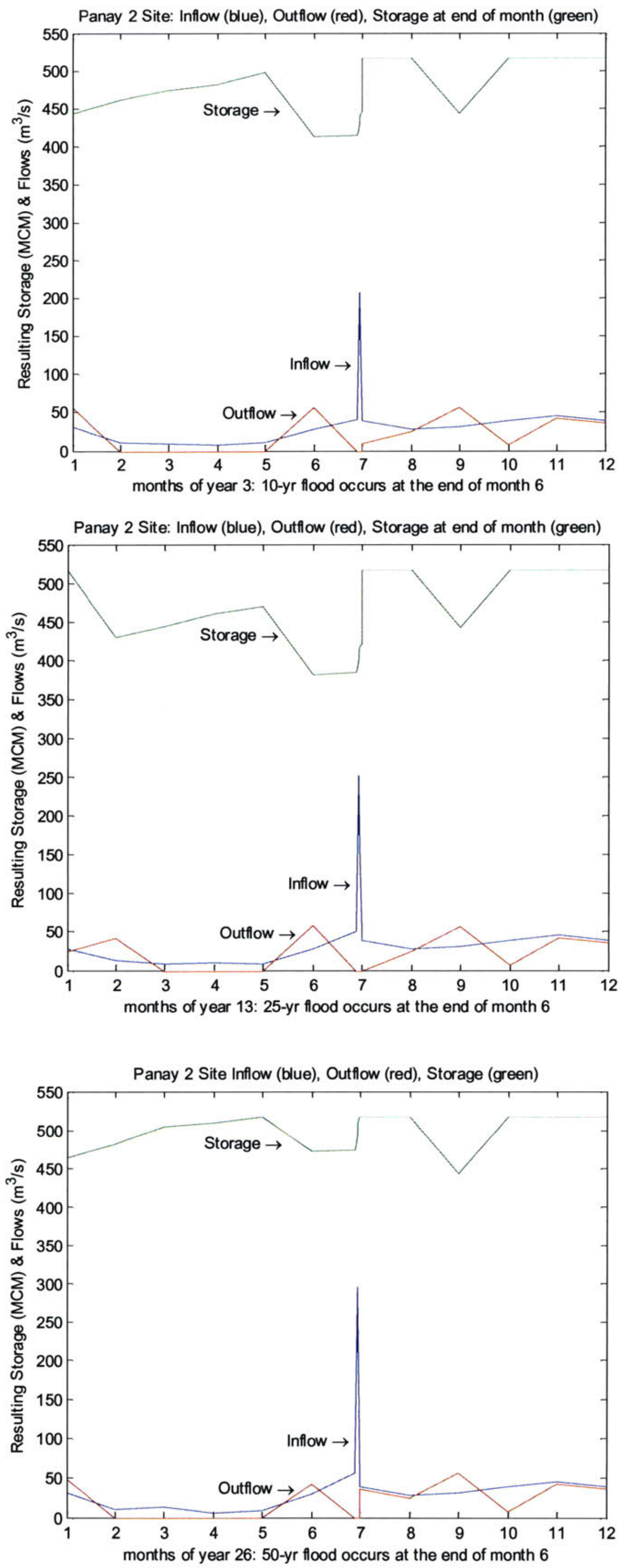


Figure 45: Panay 2 Screening Operations for Floods

Badbaran

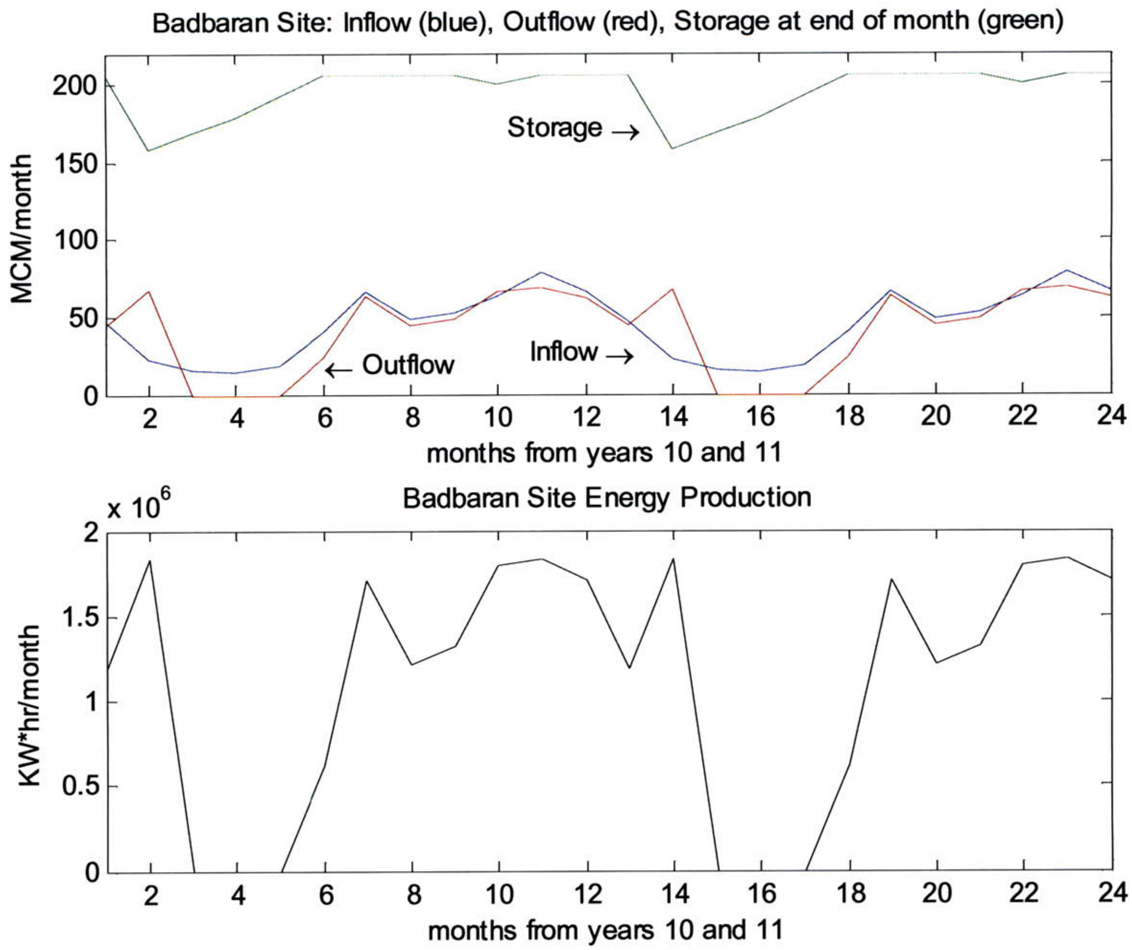


Figure 46: Mean Screening Operation and Energy Production for Badbaran

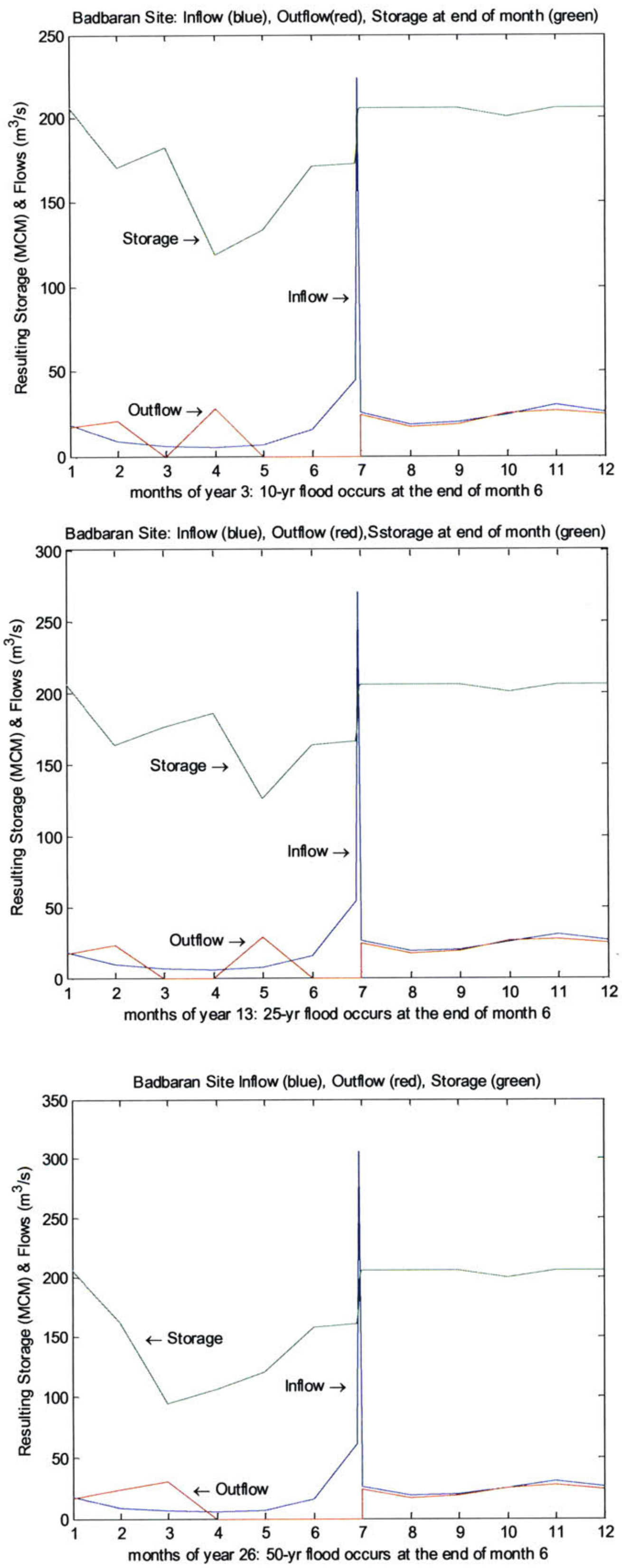


Figure 47: Badbaran Screening Operations for Floods

Mambusao

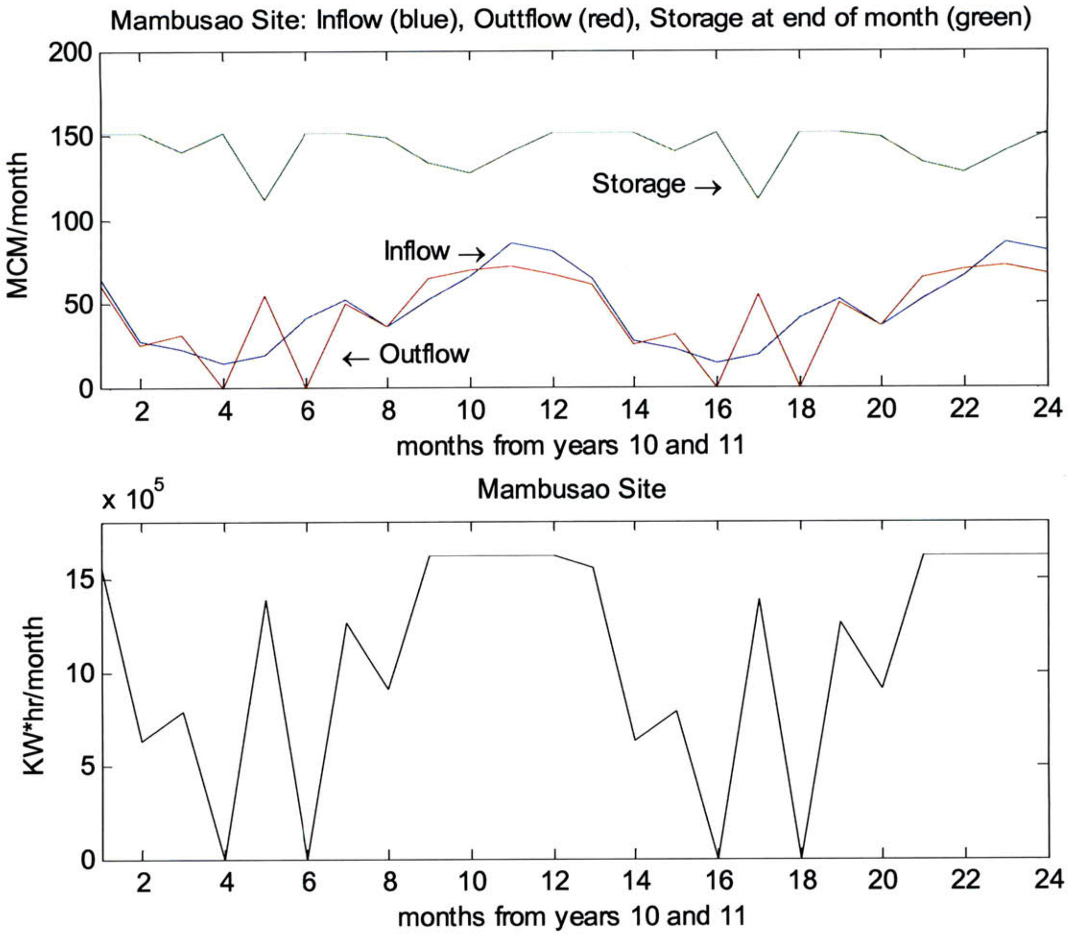


Figure 48: Mean Screening Operation and Energy Production for Mambusao

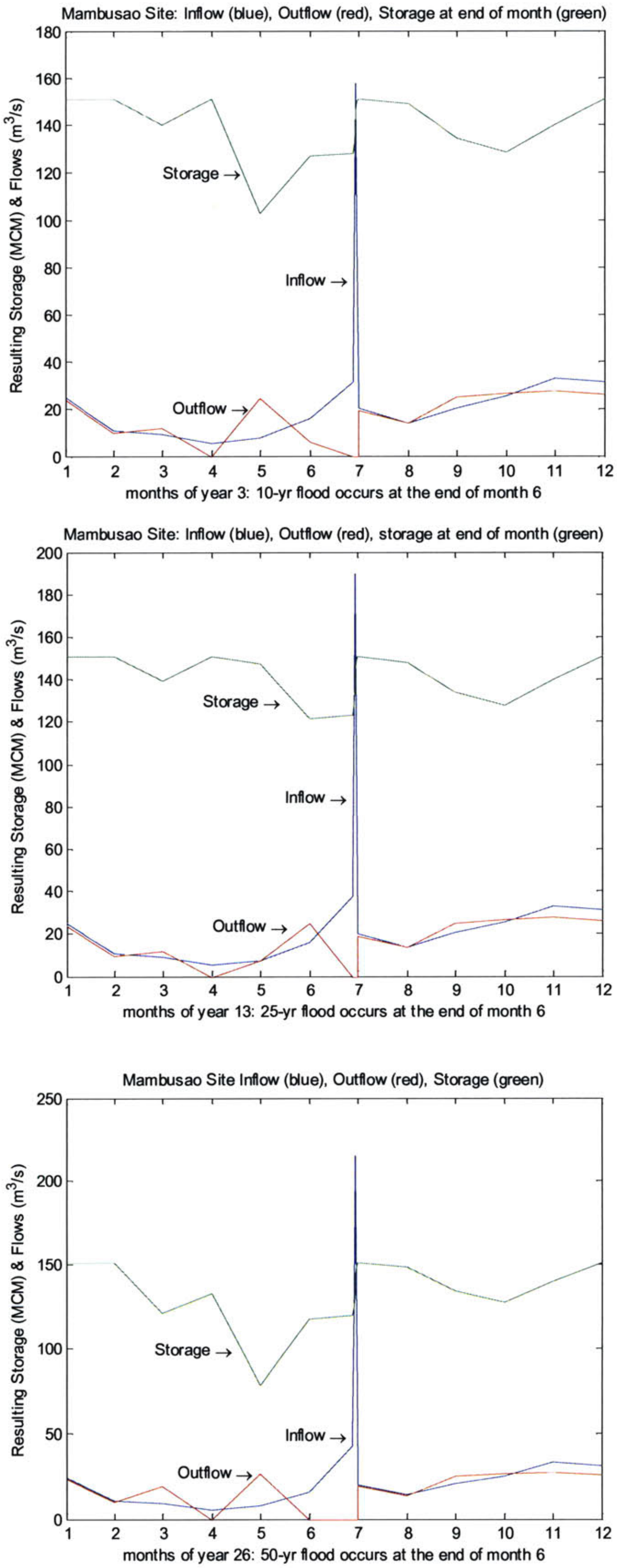


Figure 49: Mambusao Screening Operations for Floods

Appendix G: Facility Sizes' Sensitivity to O&M and Interest Rate

Site	Reservoir (MCM)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	124.581	3315.599	N/A
Panay 2	535.47	5928.913	500
Badbaran	206.122	2550	N/A
Mambusao	150.946	2250	N/A

Table 24: Interest Rate = 4%, O&M = 5% of Capital Cost (Objective Function = 29,946.082 MPesos)

Site	Reservoir (MCM)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	97.222	2638.015	N/A
Panay 2	534.151	5788.738	500
Badbaran	206.122	2550	N/A
Mambusao	150.946	2250	N/A

Table 25: Interest Rate = 4%, O&M = 10% of Capital Cost (Objective Function = 24,984.137 MPesos)

Site	Reservoir (MCM)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	75.023	2056.988	N/A
Panay 2	479.707	5201.292	500
Badbaran	206.122	2550	N/A
Mambusao	150.946	2250	N/A

Table 26: Interest Rate = 4%, O&M = 15% of Capital Cost (Objective Function = 20,452.020 MPesos)

Site	Reservoir (MCM)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	47.426	1613.899	N/A
Panay 2	426.301	4505.227	500
Badbaran	200.349	2459.860	N/A
Mambusao	150.496	2250	N/A

Table 27: Interest Rate = 4%, O&M = 20% of Capital Cost (Objective Function = 16,398.987 MPesos)

Site	Reservoir (MCM)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	114.807	3092.555	N/A
Panay 2	535.470	5887.326	500
Badbaran	206.122	2550	N/A
Mambusao	150.946	2250	N/A

Table 28: Interest Rate = 6%, O&M = 5% of Capital Cost (Objective Function = 28,233.639 MPesos)

Site	Reservoir (MCM)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	88.506	2393.972	N/A
Panay 2	517.676	5609.582	500
Badbaran	206.122	2550	N/A
Mambusao	150.946	2250	N/A

Table 29: Interest Rate = 6%, O$M = 10% of Capital Cost (Objective Function = 23,404.365 MPesos)

Site	Reservoir (MCM)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	66.228	1906.084	N/A
Panay 2	462.272	1983.459	500
Badbaran	206.122	2550	N/A
Mambusao	150.946	2250	N/A

Table 30:Interest Rate = 6%, O&M = 15% of Capital Cost (Objective Function = 19,011.727 MPesos)

Site	Reservoir (MCM)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	38.73	1410.07	N/A
Panay 2	402.90	4204.70	500
Badbaran	184.4	2215.02	N/A
Mambusao	150.95	2250	N/A

Table 31: Interest Rate = 6%, O&M = 20% of Capital Cost (Objective Function = 15,171.8495 MPesos)

Site	Reservoir (MCM)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	105.874	2869.083	N/A
Panay 2	535.470	5844.476	500
Badbaran	206.122	2550	N/A
Mambusao	150.946	2250	N/A

Table 32: Interest Rate = 8%, O&M = 5% of Capital Cost (Objective Function = 26,401.040 MPesos)

Site	Reservoir (MCM)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	82.189	2212.038	N/A
Panay 2	495.458	5385.418	500
Badbaran	206.122	2550	N/A
Mambusao	150.946	2250	N/A

Table 33: Interest Rate = 8%, O&M = 10% of Capital Cost (Objective Function = 21,732.265 MPesos)

Site	Reservoir (MCM)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	55.854	1797.052	N/A
Panay 2	443.973	4738.276	500
Badbaran	206.122	2550	N/A
Mambusao	150.946	2250	N/A

Table 34: Interest Rate = 8%, O&M = 15% of Capital Cost (Objective Function = 17,520.788 MPesos)

Site	Reservoir (MCM)	Hydropower (KW)	Irrigation Land (ha)
Panay 1	28.719	1160.244	N/A
Panay 2	384.394	3939.744	500
Badbaran	182.693	2189.192	N/A
Mambusao	150.946	2250	N/A

Table 35: Interest Rate = 8%, O&M = 20% of Capital Cost (Objective Function = 13,955.598 MPesos)

Appendix H: Synthetic Flow Volumes

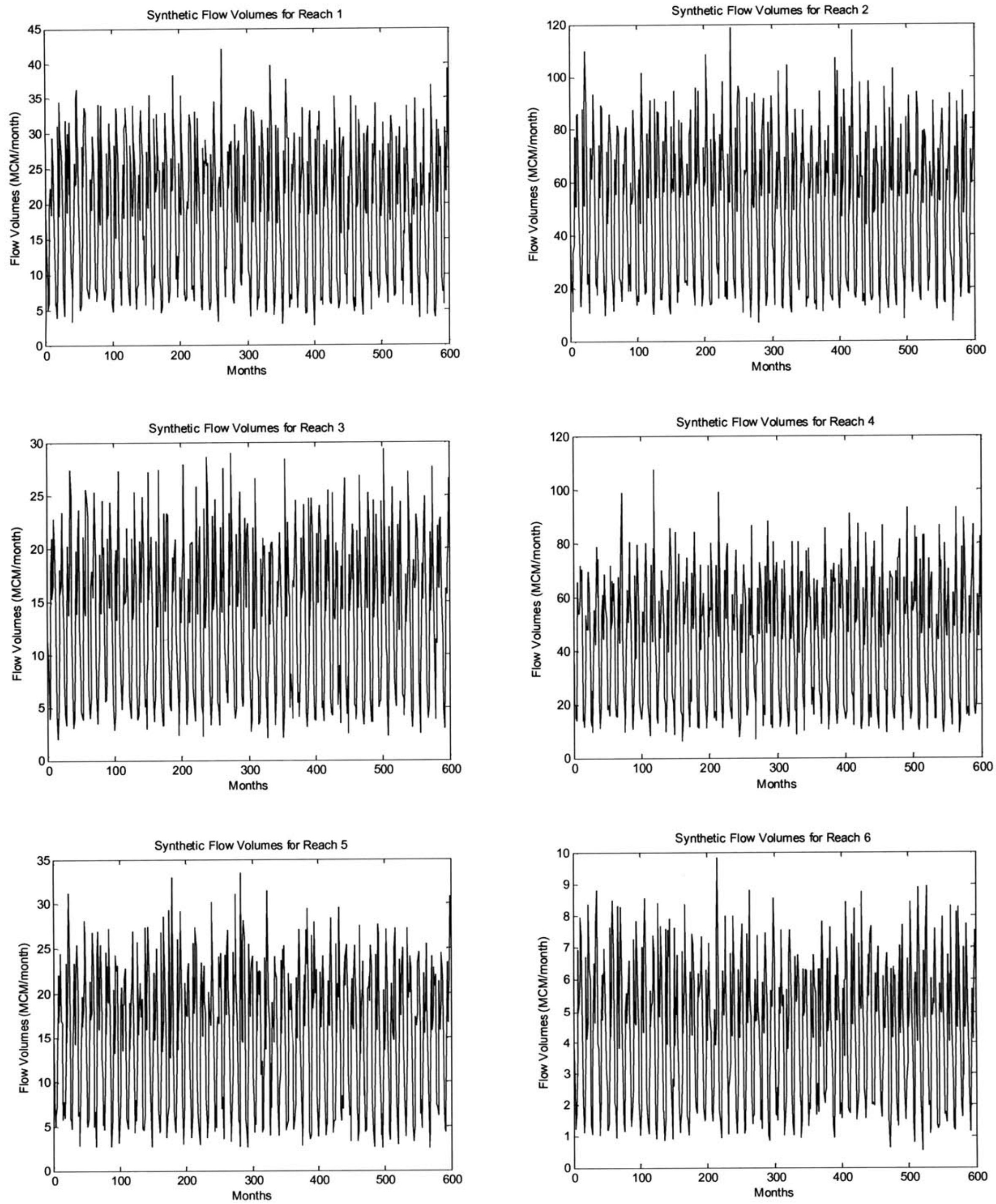


Figure 50: Synthetic Flow Volumes for Reaches 1-6

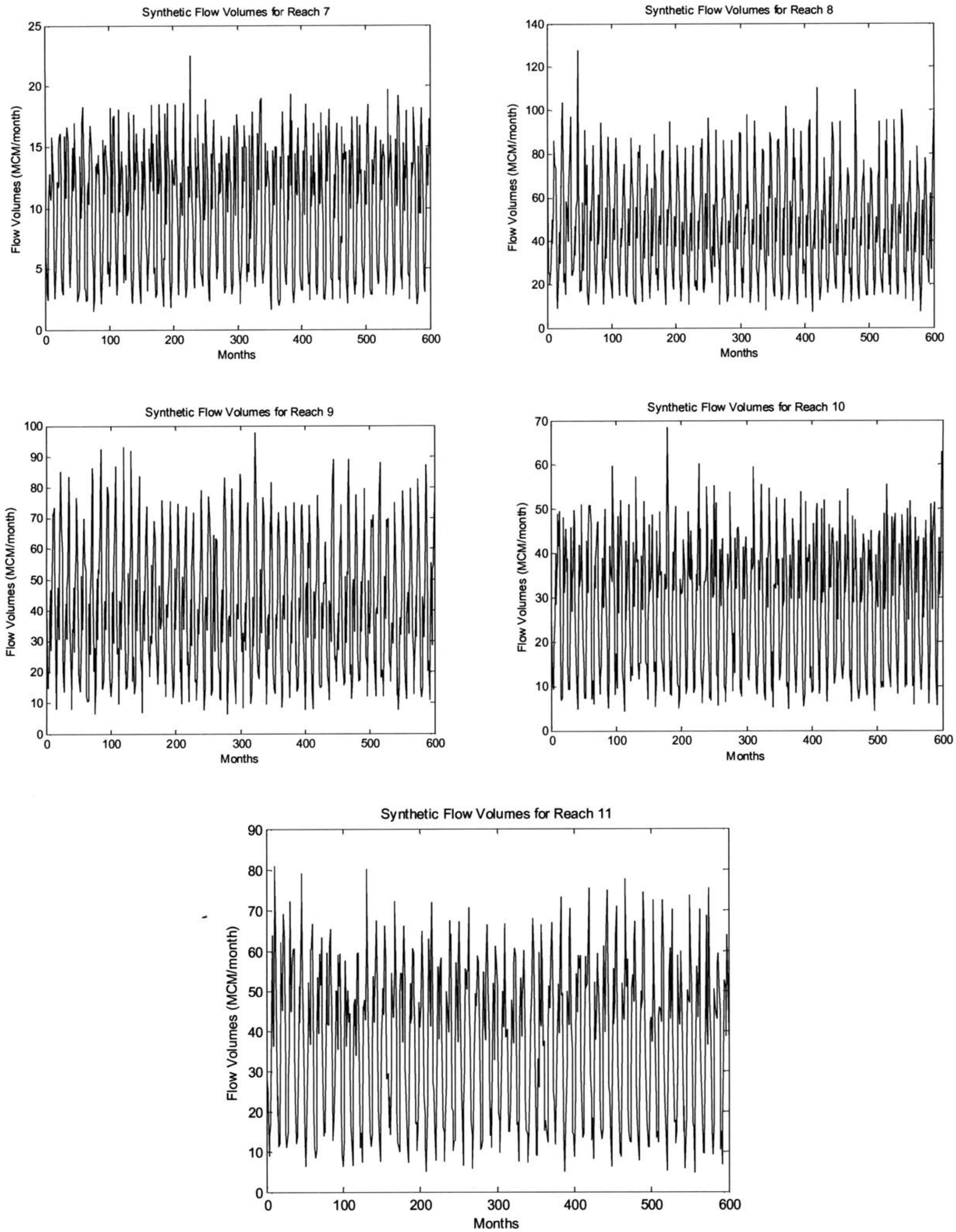


Figure 51: Synthetic Flow Volumes for Reaches 7-11