WATER HARVESTING THROUGH PONDS IN THE ARCO SECO REGION OF THE REPUBLIC OF PANAMA; DECISION SUPPORT SYSTEM FOR POND STORAGE CAPACITY ESTIMATION

by

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“Let not a single drop of water that falls on the land go into the sea without serving the people”

King Parakrama Bahu, Sri Lanka, 12th century

DEDICATION

This thesis is dedicated to my parents and my sister. Their love and support encouraged me throughout all the important steps of my life. These past two years have not been an exception. In part, this work is their achievement.

I also wish to dedicate this thesis to Panamanian campesinos interioranos (small-scale farmers of the Azuero Peninsula), who have struggled all their lives for a better future.

ABSTRACT

M.Sc. Anne Desrochers Bioresource Engineering

The 'Arco Seco' or 'Dry Arc' region of the Republic of Panama is considered to be the driest in the country, where many areas of this region experience severe water stress during the months of January through May. The region is known for its severe deforestation, extensive cattle ranching activities, water scarcity, and as the heartland of small-scale farming. Most research carried out in the region has focused on the improvement of large-scale farms, and not much attention has been given to small landholders. This study was conducted to develop a tool for the assessment of sustainable implementation of water harvesting through ponds for agricultural purposes in the region. A computer based Decision Support System (DSS) has been developed specifically for the Arco Seco region in order to facilitate pond storage capacity estimation. As part of the DSS, four computer programs have been designed for four different case scenarios; the first one is for sites that have high water demand and no topographical restrictions for pond size; the second is for fairly high water demand, no topographical restrictions for pond size, and for farmers who wish to have a backup of water to use mostly during drier years; the third is for low water demand, usage during the dry season only, and topographical restrictions for pond size, and finally the fourth is for constant water demand throughout the year, and for sites where runoff is the only water source.

To illustrate the DSS approach, emphasis was placed on a pond that was designed and constructed as part of the present study in the community of Tierras Blancas, Herrera province, Panama. The four programs were tested based on the site conditions. The pond site was characterized by various water sources, where the farmer was interested in collecting water for irrigation of a small plot during the dry season only, and for small-scale pisciculture. Therefore, based on the realities of the Tierras Blancas site, the Dry Season Demand versus Supply program was evaluated to be the best program for pond size estimation. Finally, the practice of (and equipment for) water harvesting is low-cost, which makes it accessible to small-scale low-income producers who predominate the semi-arid region of the Arco Seco.

RESUMÉ

M.Sc. Anne Desrochers Génie des Bioressources

« Arco Seco » ou « l'arc sec » de la République du Panama est considéré comme étant la région la plus sèche du pays où plusieurs zones sont atteintes de stress hydrique durant la période de janvier à mai. Cette région, située au cœur de l'agriculture à petite échelle, est connue pour sa déforestation sévère, ses activités d'élevage bovin, et sa pénurie d'eau. La plupart des recherches effectuées dans la région ont visé l'amélioration des fermes à grande culture tandis que les agriculteurs à petite échelle n'ont reçu que très peu d'attention. Cette étude fut menée avec le but de développer un outil pour l'évaluation de la mise en application renouvelable de la récolte d'eau au moyen d'étangs, pour fins d'agriculture dans la région. Un système interactif d'aide à la décision (SAD) fut développé spécifiquement pour la région Arco Seco et ce, pour faciliter l'estimation de la capacité de stockage de l'étang. Dans le cadre du SAD, quatre programmes d'ordinateur furent conçus pour quatre scénarios différents : le premier, pour les sites avec des besoins en eau élevés et aucune restriction topographique en ce qui à trait à la grosseur de l'étang; le deuxième, pour des besoins élevés, aucune restriction topographique et pour les agriculteurs désireux d'avoir une réserve d'eau disponible durant les années plus sèches; le troisième pour des besoins en eau plutôt bas et à être utilisé seulement durant la saison sèche, et avec des restrictions topographiques; enfin le quatrième scénario vise des besoins en eau constants tout au cours de l'année, et pour des sites où l'écoulement constitue la seule source d'eau.

Pour illustrer la méthode du SAD, l'emphase fut mise sur un étang conçu et construit dans le cadre de cette étude, dans la communauté de Tierras Blancas de la province de Herrera, au Panama. Basés sur les conditions du site, les quatre programmes furent mis à l'essai. Diverses sources d'eau caractérisent le site de l'étang où le fermier désirait recueillir l'eau pour fins d'irrigation d'un petit terrain seulement durant la saison sèche, et pour de la pisciculture à petite échelle. Selon les réalités du site de Tierras Blancas, il fut déterminé que le meilleur programme pour déterminer la grosseur de l'étang projeté était le programme 'Demande en Saison Sèche versus

Approvisionnement'. Finalement, les techniques reliées à la récolte d'eau (ainsi que l'équipement requis) est généralement une pratique peu coûteuse, ce qui la rend accessible aux producteurs à petite échelle et à faibles revenus qui prédominent la région semi-aride de l'Arco Seco.

ACKNOWLEDGEMENTS

I would like to express my appreciation to my thesis supervisor, Dr. Robert Bonnell for his support, advice and encouragement throughout this study. I wish to thank him for his confidence and patience. He never doubted the outcome, even though reaching the actual study site was a daunting task.

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My appreciation also to my dear friends Roni, Hirondelle, Sarra, Carolina, Tulio, Henri, Naro, Barry, Luís, Haroon, Jean-Francois, Joe, Celia, and Zuleika for their understanding and support throughout this period.

Many thanks to my father, Lucie, my mother, Sharon, my sister and Mike for their encouragement. Lastly, I would like to express my deepest gratitude to my mother for her patience and help in preparing this manuscript.

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Chapter 1. INTRODUCTION

1.1 Objectives

The global goal of this thesis was to establish an on-farm water-management research plot in the Arco Seco region of the Republic of Panama. Further goals included: the involvement of small-scale farmers in the development of a technology that would address their dry-season water needs, and the development of a tool for the assessment of sustainable pond water-harvesting. The specific objective was to develop a Decision Support System to facilitate estimation of pond storage volume requirement, which could be utilized for different case scenarios and site conditions.

1.2 Scope

In light of the annual water scarcity problem, an ever decreasing water table level, and increasing environmental degradation in the Arco Seco region of Panama, it is necessary to assess the viability of alternative methods of obtaining water for agricultural purposes instead of depending on water from wells. The introduction of water harvesting and management through the dry season can lead to improved farm income that could be used to increase household food security. In the long term, such a system can also lead to improved environmental protection by addressing the regional concern of land degradation due to poor vegetal cover during the dry season. This applies if the water collected is used for irrigation purposes. However, there have been no prior studies on the sustainability of water harvesting through ponds for small-scale farmers in the region. Therefore, this study will contribute to a better understanding and facilitation of pond sizing based on a variety of field conditions. In addition, this study will provide recommendations to improve the design for the implementation of ponds in the region.

The thesis will be distributed to two different Panamean institutions: the Centro del Agua del Trópico Humedo para América Latina y el Caribe (CATHALAC) and the Ministerio de Desarrollo Agropecuario (MIDA). In addition, Spanish and English copies of the Decision Support System will be distributed to extension agents working at the MIDA central branch in Santiago de Veraguas and to other institutions that may be interested. Results obtained from this study will also be submitted for publication in at least one journal. Finally, results obtained from this study have been presented at the 11th International Conference, in Mexico on Rainwater Catchment Systems, August 2003.

1.3 Site description

1.3.1 Introduction to the Republic of Panama

1.3.1.1 Geography

The Republic of Panama is located between 7°12'07" and 9°38'46" North latitude and between 77°09'24" and 83°03'07" West longitude (Comisión Nacional de Recursos Fitogenéticos de Panamá, 1995). The country is bordered by the Caribbean Sea to the north, the Pacific Ocean to the south, Costa Rica to the west, and Columbia to the east. Since the Isthmus of Panama is the narrowest land area between the Pacific and Atlantic Oceans, the Panama Canal was constructed within this country, which separates South America from North America. Panama occupies a total area of 78,000 km^2, with a topography that is characterized by three main mountain chains (one to the west, one to the east, and another in the central provinces), and plains in the coastal areas (Central Intelligence Agency, 2001).

1.3.1.2 Socio-economic context

Panama's population was estimated to be 2,882,329, with a growth rate of 1.26% for the year 2002 (Central Intelligence Agency, 2001). Slightly more of the population lives in urban areas (55.5%), than in rural areas (44.5%) (Autoridad Nacional del Ambiente, 1999b).

Panama's economy mainly relies on the service sector, which accounts for 76.5% of the country's gross domestic product (GDP). The industrial sector accounts for 16.5% and agriculture for 7% of GDP (Autoridad Nacional del Ambiente, 1999b; Central Intelligence Agency, 2001; Doggett, 2001). Income distribution within the country is extremely skewed and there are large income disparities between rich and poor.

1.3.1.3 Environmental conditions

Based on the Köppen climate classification, there are five different climates in the country, as shown in Figure 1.1. There is a very humid tropical climate on the north-western Caribbean coast, a humid tropical climate throughout the country but mainly on the south-western Pacific coast, a savannah tropical climate mainly on the coast of the Gulf of Panama and on the eastern coast of the Caribbean, a very humid temperate climate in the highlands in the western part of the country, and finally a humid temperate climate surrounding the Barú volcano near the border with Costa Rica.

In most of the country there are two distinct seasons: the wet and the dry season. The length of each season varies within the country, where the wetter Caribbean coastal area differs significantly from the drier Pacific coast. However, for most of the country, the wet season extends from mid-April to approximately mid-December, and the dry season from mid-December until mid-April. Rainfall patterns in the northern section of the country are markedly different from the ones in the south, where the Atlantic coast receives an annual average of 4,500 mm of rain, compared to the Pacific coast, which receives 2,000 mm (Comisión Nacional de Recursos Fitogenéticos de Panamá, 1995). Temperatures vary from 21° to 32° C in the lowlands and from 10° to 22° C in the mountains (Comisión Nacional de Recursos Fitogenéticos de Panamá, 1995; Doggett, 2001).

Twenty-five percent (25%) of the Panamanian territory is dedicated to protected areas (Autoridad Nacional del Ambiente, 1999b). However, due to insufficient enforcement measures, illegal logging and hunting activities are common in most of these areas. The main environmental problems that are currently occurring in the country include deforestation, soil erosion, water pollution, and mangrove destruction (Autoridad Nacional del Ambiente, 1999b; Central Intelligence Agency, 2001; Doggett, 2001).

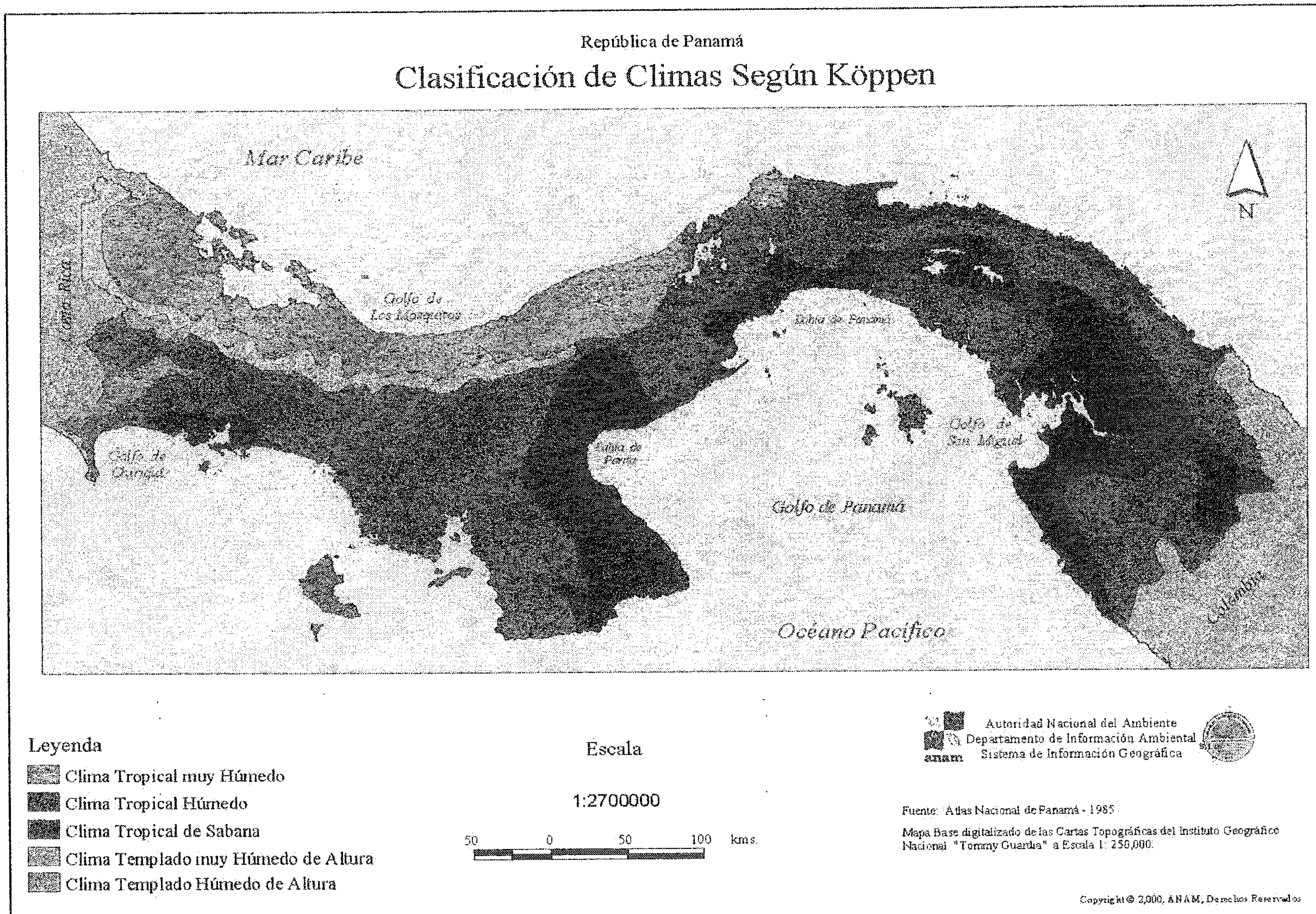


Figure 1.1 Panama's climates based on the Köppen Climate Classification (Instituto Geográfico Nacional Tommy Guardia, 1985).

1.3.2 Characterization of the Azuero Peninsula and Arco Seco

1.3.2.1 Geography

The Azuero Peninsula is a distinctive feature in the S-shaped country of Panama. It is described as a squared land segment protruding southward into the Pacific Ocean, as shown by the shadowed area in Figure 1.2. The peninsula was named after Vicente Azuero, a well-known Colombian political leader during the 19^{th} century when Panama was part of Colombia (Heckadon Moreno, 1984). The land mass is surrounded by the Gulf of Panama to the east, and the Gulf of Montijo to the west. The provinces of Herrera, Los Santos, and part of Veraguas occupy the peninsula. The physical features that characterize the territory include plains along coastal areas, rounded hills going inland, and more abrupt terrains constituting the Cordillera Occidental, stretching along the length of the peninsula.

As for the Arco Seco or 'Dry Arc' region, it is located to the east of the Azuero Peninsula, along the Gulf of Parita and the Gulf of Panama. The region is delimitated by the black dashed line shown in Figure 1.2, and includes the low-lying pacific coastal area of four provinces: Los Santos, Herrera, Coclé, and a small part of Panama. The Arco Seco covers a total area of approximately 4,000 km^2 and is mostly characterized by coastal plains and rolling hills (Universidad Tecnológica de Panamá, 2002).

1.3.2.2 Socio-economic context

The Azuero Peninsula is sparsely populated. Important cities located within the Arco Seco include: Chitré, Los Santos, and Las Tablas. There are approximately 250,000 inhabitants living within the Arco Seco, with the majority located in rural areas (Autoridad Nacional del Ambiente, 2000).

The economy of the region relies mostly on agriculture, although 60% of the Azuero territory is considered unsuitable for intensive agriculture due to its steep topography and the poor fertility of the soil (Heckadon Moreno, 1984). The provinces of Herrera and Los Santos have traditionally been recognized as "the heartland of Panamanian small-farm agriculture and areas of small-farm economies" (Jaen Suarez, 1978, as paraphrased in Jones, 1990). The main economic activity driving the region is cattle ranching for meat and mostly milk production, where 30% of the country's

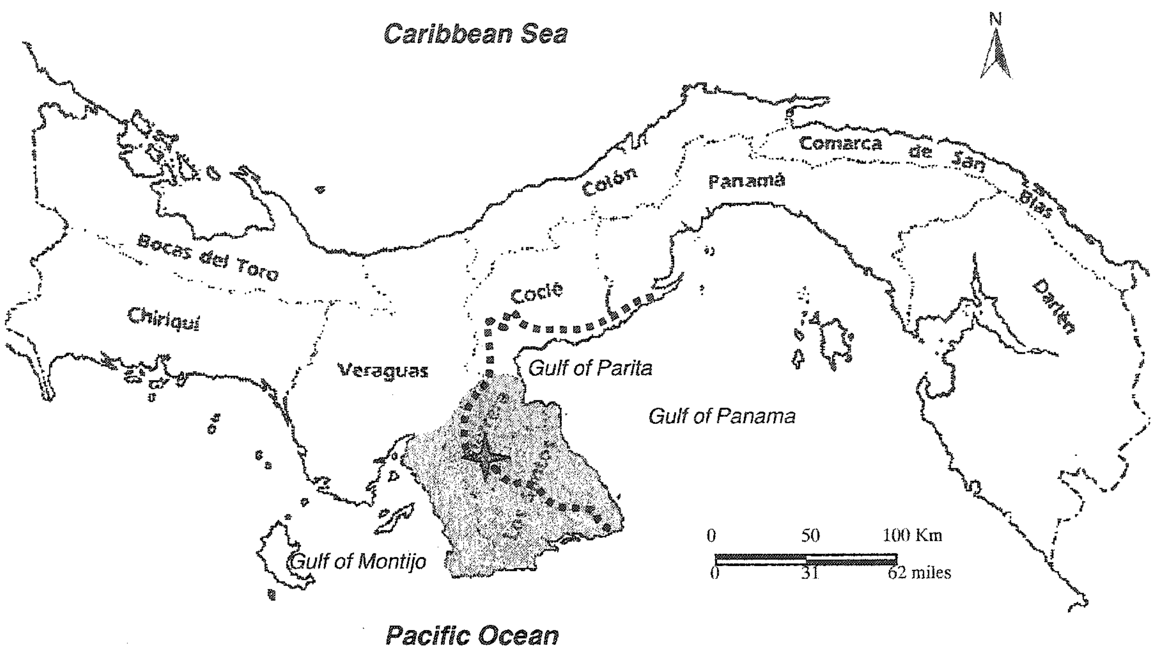


Figure 1.2 Map of the Republic of Panama. The shaded area indicates the Azuero Peninsula, the dashed black line the Arco Seco region, and the grey star the Tierras Blancas study site (map adapted from Comisión Nacional de Recursos Fitogenéticos de Panamá, 1995).

livestock inventory is located within the Azuero Peninsula (Castillo, 2001). The Arco Seco has been afflicted by water scarcity for several years, due to accelerated deforestation from the 1950s' until today (stronger influences from 1950 to 1970) in order to make place for livestock (Heckadon Moreno and McKay, 1984). This resulted in 50% of the area's pastureland drying up in 1998, followed by the death of 2,500 heads of cattle and 15,000 more suffering from malnutrition in 2001, in addition to significantly slowing down milk production (Castillo, 2001; Cortes, 2002; Cortes 2003). A total of over $14 million was lost mostly in maize, rice, and livestock due to water scarcity in the region (Consejo Agropecuario Centroamericano, 2001).

1.3.2.3 Environmental conditions

1.3.2.3.1 Climatic conditions and edaphic properties

Based on the Köppen climate classification there are two distinctive climates within the Azuero Peninsula, as shown in Figure 1.1: a savannah tropical climate to the east, on the coasts of the Gulf of Panama and Parita, and tropical humid climate to the west, along the Gulf of Montijo.

There are two distinctive seasons: dry and wet. The dry season extends from December until the beginning of May, and the wet season from May until the end of November. The Peninsula receives on average between 1000 mm and 1500 mm of precipitation annually, 1200 mm to 2000 mm of average annual pan evaporation, and temperatures varying between 28° and 34° Celsius (Food and Agriculture Organization of the United Nations, 2000; Instituto Geográfico Nacional Tommy Guardia, 1985). Some of the most critical regions within the Arco Seco receive even less than 1000 mm of precipitation annually (Autoridad Nacional del Ambiente, 2000). The Azuero Peninsula and especially the Arco Seco, as its name indicates, are well known for their severe droughts. Oceanographic and meteorological researchers have pointed to the El Niño current as a possible explanation for these recurring droughts (Heckadon-Moreno, 1984). The El Niño phenomenon is said to cause disturbances of the ocean and atmosphere in the tropical Pacific leading to important consequences in weather patterns around the globe (Diaz and Markgraf, 1992). During any El Niño, the central and western Pacific tradewinds decrease, which leads to a lowering of the thermocline (layer of water between surface and deep-water zone) in the eastern Pacific, and an elevation of the thermocline in the west. This results in a variation of rainfall patterns, where high precipitations follow the warm water eastward, with associated flooding in Peru and southern USA, and drought in Indonesia and Australia (Trenberth, 1997). While there is flooding in Peru and nearby areas caused by the El Niño current, some countries in Central America including Panama suffer from severe droughts (Comisión Económica para América Latina y el Caribe, 2002).

Soils within the Azuero Peninsula are generally characterized by their reddish colour, highly leached nutrient content, acidic pH, clayey texture, high erodibility, and suitability for forestry (Autoridad Nacional del Ambiente, 1999b; Heckadon-Moreno, 1984). Their exact soil classification depends on the document consulted; not all soil maps agree on the same soil taxonomical order. Soils in the region have been classified as Ultisols (United States Department of Agriculture, 2000), Latosols (Heckadon-Moreno, 1984; Striker, 1952), and Oxisols suborder Ustox (Comisión de Reforma Agraria de

Panamá, 1967). Soil classification in Panama generally follows the United States Department of Agriculture's soil taxonomy classification system (United States Department of Agriculture, 1999).

1.3.2.3.1 Main constraints and consequences

Crucial environmental limitations encountered in the Azuero Peninsula include erratic precipitation and infertility of soils. Since most of the cattle ranching activities of the country take place within the region, deforestation of the land to make room for pastureland has long been the cause of environmental degradation. This is partly due to destructive 'slash-and-burn' agriculture encouraged by Panamanian cattle ranchers, mismanagement of the natural resources (explained in next paragraph), and lack of political and economical enforcement for appropriate land use (Heckadon-Moreno 1984; Joly 1982; and Jones 1990). In addition, lack of technical assistance and financial support of subsistence farmers limit their ability to counteract the process of environmental deterioration on their land (Autoridad Nacional del Ambiente, 1999a). Also, poor sensitization of these farmers and the population in general regarding the use of agrochemicals is reflected in the excessive use of herbicides and other agrochemical agents, and in the lack of preventive measures taken to avoid the exposure of users to these chemicals.

Ledec (1992) demonstrated a strong inverse correlation between forest cover and the number of cattle in Panama, especially in the Peninsula. In 1998, forest cover was 4% for the province of Herrera and 7% for Los Santos, which represent by far the most deforested provinces in Panama (Autoridad Nacional del Ambiente, 1999b). Until the turn of the twentieth century, most of the Azuero Peninsula was covered with various types of tropical forests and savannah, however, the alteration of natural ecosystems by man during the past century has led to the destruction of most tropical forests. While deforestation is widespread, other land mismanagement practices include: utilization of inappropriate land for agriculture, indiscriminate slash-and-burn, cultivation on abrupt hills, and monoculture (Autoridad Nacional del Ambiente, 1999a; Hernández, 2003). These practices have accelerated processes of soil deterioration such as loss of fertility and reduced soil physical properties. Overgrazing, soil compaction, soil erosion, desertification, and sedimentation are other environmental concerns for the region (Autoridad Nacional del Ambiente, 1999b).

A multitude of consequences results from severe deforestation of the region. First of all, there is a decrease in soil fertility, since much of the organic matter was taken away with the trees. More precisely, there is deterioration in soil physical properties, such as decreased soil structure and porosity, and alteration in soil chemical properties including reduced cation exchange capacity (CEC) and reduced amounts of available nutrients. Extensive deforestation of watersheds has also led to severe detrimental effects on its hydrology; there is reduced soil water retention and gradual lowering of the water table, which of course lead to longer dry spells and decreased water availability for domestic and agricultural purposes. In the long term, these negative impacts affect provincial and local economies, entailing increased unemployment, poverty, migration to cities in search of employment, and further clearing of forested areas to find better land for agriculture (Autoridad National del Ambiente, 1999b).

1.3.2.4 Water-harvesting in the Arco Seco

As a response to water scarcity problems within the agricultural sector of the Arco Seco, in 2001 the Ministry of Agriculture of Panama (Ministerio de Desarrollo Agropecuario, or MIDA) implemented the Plan Agua or 'Water Plan' as an urgent solution to provide water for agricultural purposes, especially for the livestock industry. The plan's objective was to harvest rainwater and store it within ponds, tanks, water troughs, and small dams, in addition to constructing deep wells (Consejo Agropecuario Centroamericano, 2001; Ministerio de Desarrollo Agropecuario, 2001). However, one year later most of these rainwater-harvesting systems were left dry (Cortes, 2002; Cortes, 2003). The inefficient performance of the rainwater harvesting systems implemented with the Plan Agua is thought to be due to insufficient field studies prior to construction (Aizprúa, 2003) and lack of organization (González *et al.*, 2002). This resulted in low success, high costs, and negative environmental impacts. Therefore, the Ministry of Agriculture introduced another plan in 2002: Plan Sequía or 'Drought Plan'. This plan's objective was to focus on developing even more wells to exploit groundwater sources, rather than focusing on rainwater harvesting techniques (Cortes, 2002; González, 2003).

Most subsistence farmers still do not have sufficient amounts of water to produce crops and adequately water livestock during the dry season, which results in extensive migration of people to cities and large-scale farms during this period of time. Unfortunately, little quantitative work has been done to evaluate actual possibilities and predict the success of implementing water-harvesting techniques throughout the Arco Seco.

Local producers are concerned about the fact that groundwater tables are going down and that more and more wells are drilled in the area (Aizprúa, 2003; Berrocal and Cortes, 2003), where 60.2% of wells constructed (approximately 500 wells) are inefficient (Ruiz, 2000). Inefficient meaning that there is insufficient amount of water flow (less than 189.5 liters/min). Water conservation in the agricultural sector is a priority for the government, since 45-50% of the fresh water within the Arco Seco is currently used for agricultural purposes (Universidad Tecnológica de Panamá, 2002).

The reintroduction of water harvesting in a proper manner and management through the dry season can lead to improved farm income that could be used to increase household food security. Over the long term, these techniques can also lead to improved environmental protection by addressing the regional concern of land degradation through better resource management. The practice of (and equipment for) rainwater harvesting is low-cost, which makes it accessible to small-scale low-income producers who predominate the semi-arid region of the Arco Seco.

1.3.3 Description of construction site

1.3.3.1 Localization

The site chosen for construction of a water-harvesting system associated with this research project is located in the community of Tierras Blancas, which is part of the county of El Cedro, district of Los Pozos in the province of Herrera. The grey star in Figure 1.2 indicates the approximate location of the site on the map of the country. Figures 1.3 to 1.5 localize the district of Los Pozos, county of El Cedro, and community of Tierras Blancas. The water-harvesting scheme was implemented on private land owned by Gustavo González Trejos. Specifications on the criteria established for site selection will be given in more detail in a subsequent section. The area is located within the Cordillera Occidental, where abrupt hills predominate the landscape.

1.3.3.2 Socio-economic context

The county of El Cedro is sparsely populated with various communities extending throughout its boundaries, as shown in Figure 1.5. Communities are variable in size and may be as small as three houses. The largest community within the county of El Cedro is also named El Cedro, and is composed of approximately 44 houses. As for the community of Tierras Blancas, there are 13 houses.

The large majority of families are agriculturally based, where crops produced and animals raised are for household consumption. Therefore, these producers are considered subsistence farmers. Some families also raise livestock to produce milk which is sold directly to Nestlé's International Company. On average, producers own 15 to 30 ha of land and 20 head of cattle. As for Señor González, he owns a total of approximately 45 ha of land and 40 head of cattle. Some of the main crops produced in the area include maize (*Zea mays* L.), various types of beans (*Phaseolus vulgaris* L.), rice (*Oryza sativa* L.), cassava (yucca) (*Manihot esculenta* Crantz L.) and yams (name) (Dioscorea spp.). Other crops produced on a smaller scale include otoe (tannia) (Xanthosoma spp.), tomato (*Lycopersicon esculentum* M.), pepper (*Capsicum annuum* L.), pineapple (*Ananas comosus* L.), and sugar cane (*Saccharum officinarum* L.). Most of the agricultural work is done manually; there exist few machines for land preparation and none for crop harvesting.

The main problem in the region is lack of water during the dry season, since most streams passing through the area dry up. Therefore, producers cannot plant any crops or provide water in adequate quantity to livestock during the dry season. Men usually leave the communities during this period to go work for larger farms or municipal works, which engenders socio-economic instability in the area.

A highly successful rainwater-harvesting scheme (through ponds) for sustainable agriculture was implemented in Bolivia (Kuiper and Hudak, 2000b). The project area has similar conditions as the Arco Seco region; climatic, socio-economic, and history of resource mismanagement such as overgrazing, deforestation, and soil erosion (Kuiper and Hudak, 2000a).

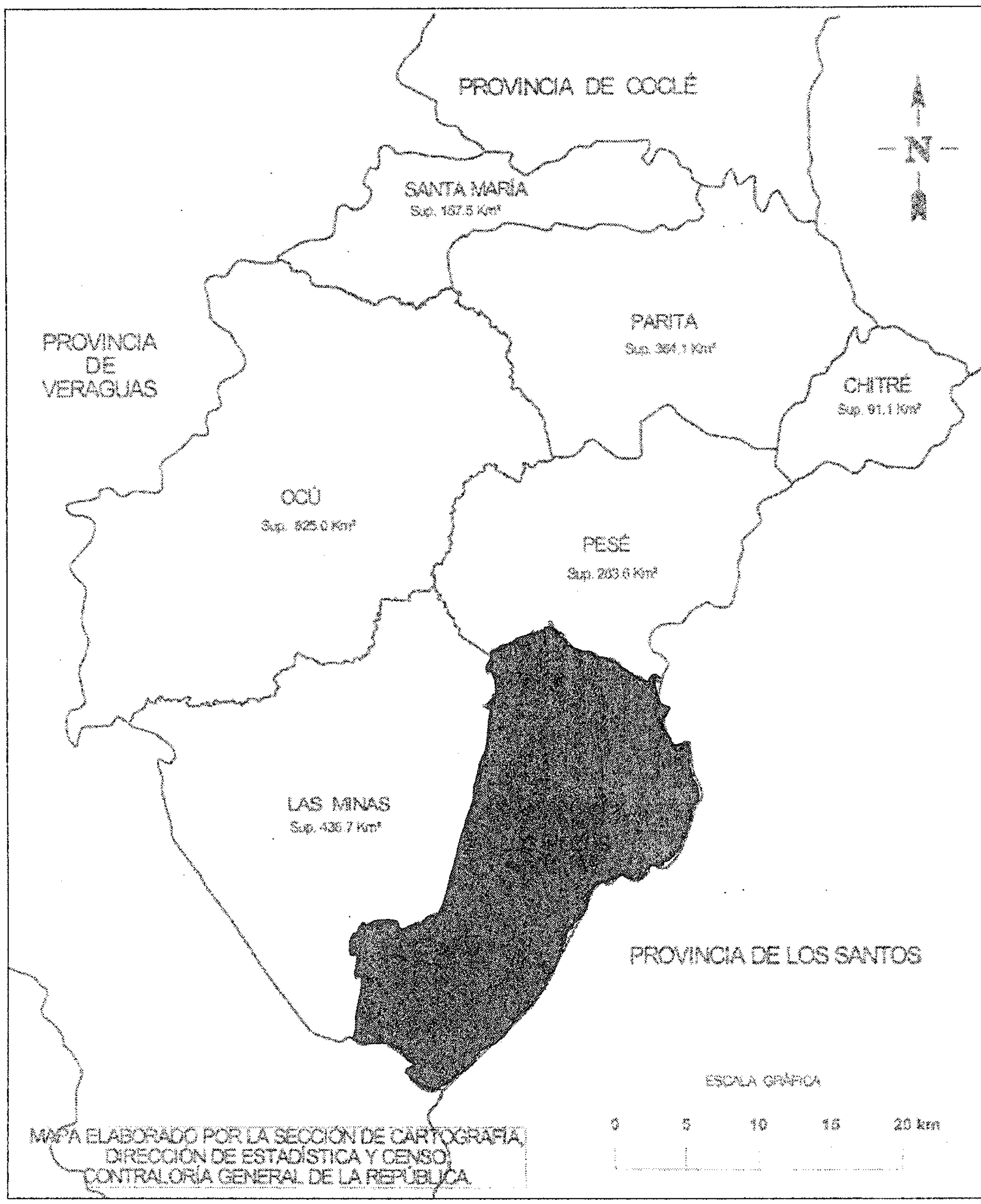


Figure 1.3 Map of the province of Herrera. Map indicates the location of the provinces' seven districts. The shaded area represents the district of Los Pozos (Instituto Geográfico Nacional Tommy Guardia, no date).

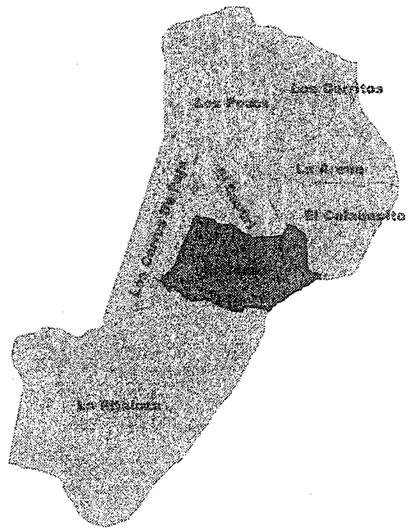


Figure 1.4 Map of the district of Los Pozos. Map indicates the districts' eight counties. The shaded area represents the county of El Cedro (Ministerio de Desarrollo Agropecuario, 2002).

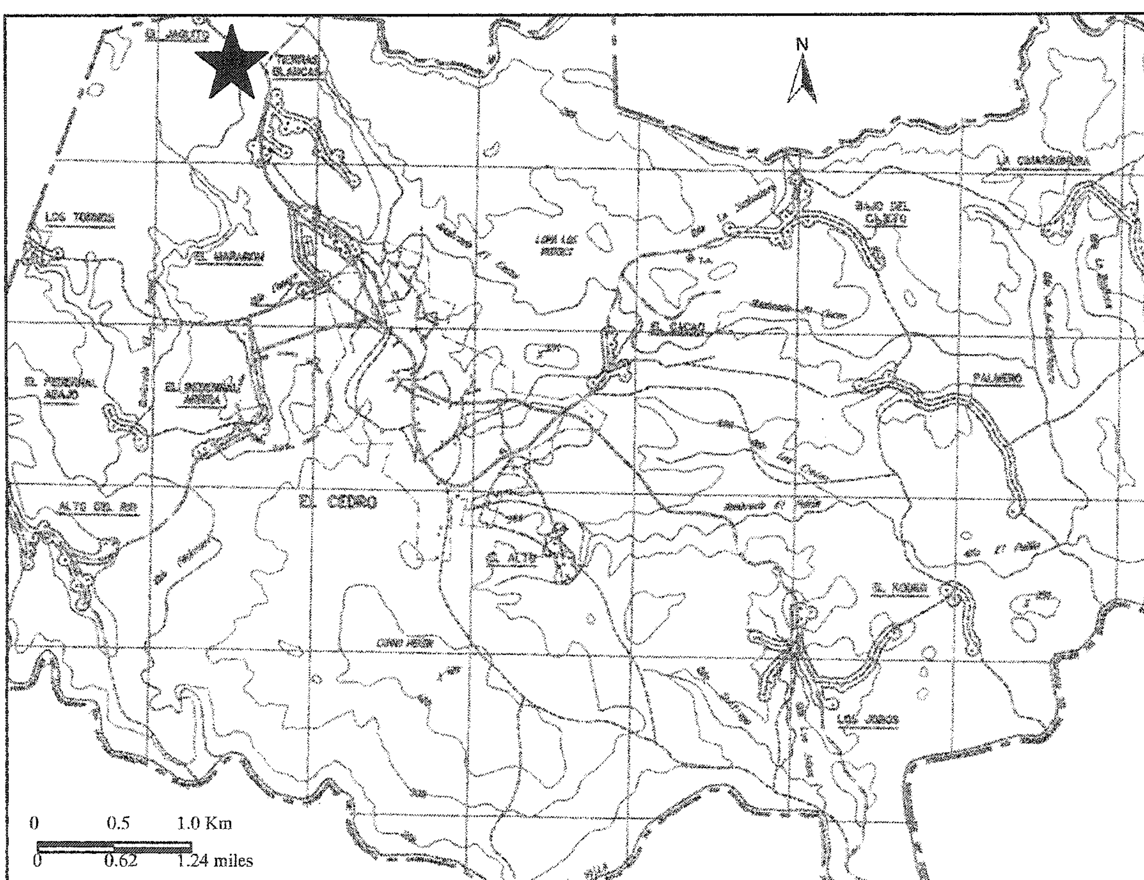


Figure 1.5 Map of the county of El Cedro. Map indicates county's various communities. The black star represents the location of the community of Tierras Blancas (Instituto Geográfico Nacional Tommy Guardia, 1996).

Chapter 2. LITERATURE REVIEW

2.1 Water scarcity

Freshwater supply is considered to be one of the most critical problems facing humanity today (Hinrichsen, 2003; World Water Assessment Programme, 2003). This is partially due to a continuous increase in population and to an increase in water demand per person. In addition there is an increased reliance on irrigation for agricultural production, and an increase in industrialization, both with its associated pollution (Johns Hopkins School of Public Health, 1998). In addition, access to and supply of freshwater is limited by various factors such as: climate, geography, and politics.

Freshwater represents 3% of all sources of water and only 1% is considered readily available (de Villiers, 1999; Shiklomanov, 1993). Most of the freshwater is unavailable, since it is in the form of glaciers, ice caps, and permafrost. Available freshwater is unevenly distributed worldwide, resulting in areas having less access than others during the whole year or for certain periods of the year (Chaturvedi, 1994). For example, almost one third of the world population is living in areas of severe water shortages (Falkenmark and Widstrand, 1992).

The unavailability or lack of water has drastic consequences on a country's economical development and its inhabitants' quality of life (Falkenmark and Widstrand, 1992). It is well known that throughout history, and increasingly more today, many political conflicts have emerged due to the inaccessibility of freshwater. For example, there have been many ongoing conflicts between four countries in the Middle East where the Jordan River basin drains: Israel, Jordan, Lebanon, and Syria. The three streams which form the Jordan River basin are located in different countries, however, since 1967 Israel has controlled the areas where these streams are located (McCaffrey, 1993). It has been globally recognized that the 1967 Arab-Israeli war conflicts were due in part to water politics (de Villiers, 1999). Dispute for water between these countries has given rise to violent political and military conflicts on various occasions in the region (Naff and Matson, 1984).

Freshwater is a finite resource which needs to be well managed and conserved, regardless of the purpose for which it is used: agricultural, domestic, or industrial.

Integrated management of water resources is an interdisciplinary approach that must take into account supply and demand. Mismanagement and over-exploitation of water supplies may lead to depletion of surface and subterranean water resources. This not only leads to water scarcity and/or water quality problems, but can also have long-term detrimental impacts on the environment.

2.2 Water-harvesting

2.2.1 Definition and benefits

Water harvesting is the collection and storage of water, either directly in the form of precipitation and runoff, or indirectly in the form of groundwater, surface spring, or river (Myers, 1975; Crichley and Siegert, 1991; Pacey and Cullis, 1991). The water is later used for domestic, agricultural, or industrial purposes (Schiller and Latham, 1982b). Water harvesting systems have existed for thousands of years in many parts of the world and are a main source of water for many communities.

The main benefits obtained from water harvesting systems are to secure water supply for use during dry periods of the year, to contribute to water and soil conservation, and to reduce erosion. More precisely, water harvesting reduces the dependence on groundwater supply for water uses, can reduce flooding in certain areas (capture and storage of runoff), and improve household economic situation on the long term.

When planning for water harvesting systems, associated costs must also be considered. Such costs include: loss of land for the implementation of the system, potential increase in the spread of water-borne diseases such as malaria and bilharzia, and monetary costs for construction, operation and maintenance.

2.2.2 General principles

Water harvesting schemes for agricultural purposes are composed of three main parts: 1) the catchment area which captures rain and runoff, 2) the storage device chosen to collect water, and 3) the plot of land that will receive water through irrigation (Pacey and Cullis, 1986). The catchment area contributes runoff from field and is usually located within the field, directly onto the soil surface. However, soil sealants are sometimes added in areas which experience low rain, and in areas with very high soil infiltration rates in order to increase amount of water harvested. These will be discussed more thoroughly in subsequent sections. If only a small plot of land is cultivated, rooftops can be used as catchment areas (Schiller and Latham, 1982b). As for storage devices, these vary in shape, size and composition. Most often, water storage devices will be made of available materials, and their size will depend on demand and quantity of water supplied. Ponds are usually used to store water for agricultural purposes.

When choosing a site for and building a water-harvesting system, a variety of factors need to be taken into consideration, such as: edaphic properties, climatic conditions, topography, socio-economic context of the region, water demand, and availability of labour and materials (Cooley *et al.*, 1975).

2.2.3 Historical perspectives,

Signs of early water harvesting practices have been discovered in ancient Iraq, which have been estimated to be up to 4500 years old (Hardan, 1975). These systems were used to provide water to caravans along the roads from the Arabian Gulf to Mecca (Hardan, 1975). Some of the oldest water harvesting systems thoroughly studied are located in the Negev desert of Israel (Evenari *et al.*, 1961). These systems have been estimated to date around 4000 years (2000 B.C.) and consisted mostly in collecting runoff from small to large watersheds for irrigation purposes (Evenari *et al.*, 1961). Over time, various other systems have evolved all around the world, especially in arid to semi-arid regions. Some examples of these systems include: water harvesting from floodwater practiced in Arizona and New Mexico for more than 1000 years (Critchley and Siegert, 1991), runoff collection through microcatchment practiced for centuries in North Africa (Pacey and Cullis, 1986), and the 'Khadin' water harvesting technique in India (Kolarkar, 1996). Recent water harvesting related research has been devoted mostly to methods and materials used to collect runoff and to increase efficiencies of existing systems.

People in arid to semi arid areas have been dealing with water shortages for centuries. Therefore ancient practices and systems that efficiently use and store water (when available) do exist. On the other hand, there are other areas which have depleted their freshwater supplies either due to mismanagement of the resource or to the occurrence of a natural disaster. Climate change and an increase in human-induced water scarcity in recent times have resulted in an amplified interest in water harvesting techniques.

2.2.4 Techniques

There is a multitude of water harvesting techniques; the choice of which to use is dependent upon the water source, catchment area, storage, and use, as shown in Table 2.1. There are a number of different classifications of water harvesting techniques (Reij, *et al.*, 1988).

Techniques based on water sources include: runoff, direct rainwater, snow, mist, dew, surface spring, river, and groundwater. Techniques based on catchment area include: small catchments (roofs of all kinds, and within the field directly on the ground or with micro-catchments), large catchments (on the ground within the field, treated or untreated surface). Techniques based on storage include: above-ground tanks of all kinds, cisterns, water troughs, ponds, reservoirs, and wells. Finally, techniques based on water use include: domestic use (drinking water, household purposes, and garden irrigation), agricultural use (irrigation, drinking water for animals, pisciculture), and industrial.

Table 2.1
Water harvesting techniques based on water sources, catchment area, storage and use.

WATER SOURCES:	Runoff Rainwater Snow Mist Dew Surface spring River Groundwater
CATCHMENT AREA:	Small → roofs → within field: - ground (treated or not) - micro-catchments Large → within field: - ground (treated or not)
STORAGE:	Tanks Cisterns Water troughs Ponds Dams Wells
WATER USE:	Domestic → drinking water → household purposes → garden irrigation Agricultural → field irrigation → animal watering → pisciculture Industrial

2.3 Water-harvesting through ponds

2.4.1 Methodology; pond design, construction, and use

2.4.1.1 Site Selection

There are many important aspects to consider when choosing a site for the implementation of a water-harvesting scheme. In this section, focus will be placed on a specific type of water-harvesting technique: through ponds. Firstly, it is important to make sure that the area meets certain physical characteristics. These characteristics include: topography, drainage area, and soil texture (Frasier and Myers, 1983; Missouri Department of Conservation, 1994). It is important that the area where the water-harvesting system is intended to be located be characterized by gentle slopes having less than 5% slope; to minimize soil erosion and sedimentation build-up (Kuiper, 1999). The soils of the area should be fine textured (clayey), which have slow permeability and low water infiltration rates (Foster, 1988). When searching for an adequate location, one should keep in mind that the system should be located at the lowest point in the contributing catchment area, and be located near the point of use in order to minimize piping and/or canal requirements (Ministry of Agriculture, 1977; Davidson and Van Vlack, 1940).

2.4.1.2 Preliminary considerations

Following site selection and prior to pond design, it is important to consider certain general conditions for the scheme to be cost-effective, well organized, and to meet farmer needs and expectations.

2.4.1.2.1 Environmental conditions

2.4.1.2.1.1 Data collection

Depending on time availability and budget restrictions, it is often suggested to set up an on-site micro-meteorological station. This allows for better accuracy of data collection and hence results. On the other hand, if installation setup is not possible, alternative sources of data should be forethought. Therefore, it is important to investigate the location of the nearest meteorological station, which variables are measured, at what time interval, and for how long the data has been recorded. These aspects are especially important for developing countries, since most often there are few meteorological stations, and these usually have a short history of data compilation (Gould and Nissen-Petersen, 1999). When using data reported by these stations, it is suggested to use variables that have been compiled for a period of at least 10 years (Schiller and Latham, 1982b; van Veenhuizen, 2000), or ideally 20 to 30 years (Gould and Nissen-Petersen, 1999).

2.4.1.2.2 Socio-economic conditions

Before beginning with pond design, it is essential to take into consideration the socio-economic conditions of the area. Level of education will determine optimal complexity and technological applicability of the scheme. Furthermore, access to site in addition to accessibility and availability of materials, labour, and equipment in the region are important economic aspects to consider (Frasier and Myers, 1983).

2.4.1.2.2.1 Farming Systems Research (FSR) approach

In this investigation the Farming Systems Research or FSR approach was used, which basically aims to involve small-scale farmers in the development of technologies in order to meet their needs. This type of approach focuses on finding ways where collected information about farmers' conditions and needs is used to orient investigation priorities, while ensuring that producers' point of views are taken into consideration (Tripp, 1991). The key components of FSR are: multidisciplinary approach for the diagnosis of current farming systems, laboratory and on-station analysis, design and analysis of technologies under farmers' current conditions, on-farm socio-economic analysis as well as in surrounding farming communities, and finally presentation of recommendations directly to farmers and extension agents (Stroup *et al.* 1993). This particular approach gives specific attention to the fact that very little research with small-scale farmers has been reported and published, thus the ability of extension agents to effectively give advice concerning the use of appropriate technologies to these farmers is put in doubt. When properly applied, the FSR approach is considered highly successful and appropriate for working with small-scale farmers. (Tripp 1991).

2.4.1.3 Pond design

Pond design is very technical and requires overall knowledge of soils, rainfall trends, characteristics of watershed, and water movement (Foster, 1988). Soil type, form and dimensions of watershed, topographical features, and climate vary from one region to another. The first step in pond design consists in selecting methods for catchment area management and pond construction (Frasier and Myers, 1983). Materials available within the area will play an important role on methods selection. When designing a pond, it is important to establish the period of the year during which the water collected will be used: year-round or seasonal. Furthermore, establishing the purposes for which water will be used once collected (irrigation, animal watering, pisciculture, or a combination) will help determine the quantity of water needed (Husenappa *et al.*, 1981; United States Department of Agriculture, 1971; Rodiek, 1988). Climatic conditions and crop type determine irrigation water requirements. Animal water requirements also vary according to climate. For it to be successful in the long run, it is essential that the scheme be well planned.

2.4.1.3.1 *Catchment area*

The size of the catchment area will depend on the quantity of water required, water sources available, and runoff coefficient of the catchment. If large amounts of water are required, then the catchment area will be large. Again, this is assuming that precipitation and runoff are the only water sources available for the system. An example of an alternative water source can be a spring.

There is no standard shape for a catchment area, however it most often follows the natural topography of the land (Frasier and Myers, 1983). Channels or ditches are sometimes used to concentrate runoff and convey water to storage area. The catchment area should have a gradient large enough to trigger runoff: 3 to 5 percent is sufficient (Frasier and Myers, 1983). Larger gradients cause soil erosion, and hence sedimentation buildup.

2.4.1.3.1.1 Soil sealants

Soil sealants are sometimes used in areas where rainfall is the only water source, but occurs infrequently and for short periods of the year. These will seal the macro and micro pores of the soil to reduce water loss through infiltration. These materials should be water insoluble and trapped within the soil profile, so that they do not contaminate runoff water (Frasier and Myers, 1983). Soil sealants have been extensively documented and can be classified into three categories; The first can be classified as clay blankets, for example addition of bentonite to the soil surface (Missouri Department of Conservation, 1994; Powell, 1977; United States Department of Agriculture, 1982). The second consists of waterproof membranes, such as asphalt, paraffin wax, rubber, sheet metal coverings, plastic liners, and concrete (Bohra and Isaac, 1987; Fairbourn *et al.*; Frasier and Myers, 1983; Frasier *et al.*, 1987; Missouri Department of Conservation, 1994; Powell, 1977; United States Department of Agriculture, 1982). The third category consists of chemical additives, for example sodium salts such as sodium carbonate, sodium polyphosphates and sodium chloride (Bohra and Issac, 1987; Frasier and Myers, 1983; Powell, 1977; United States Department of Agriculture, 1982). Other methods that have been reported include gravel-covered sheetings and simple compaction of the soil (Frasier and Myers, 1983; Missouri Department of Conservation, 1994). These materials can also be used to seal the water harvesting system, especially ponds, to prevent excessive seepage (Frasier *et al.*, 1979; United States Department of Agriculture, 1971). All these materials have different areas of suitability, durability, methods of application, maintenance requirements, and costs. Therefore, thorough investigation of the materials' properties should be performed before selection and application.

2.4.1.3.2 Storage capacity estimation

Storage capacity estimations are based on water supply and demand. Apart from rainfall and runoff, alternative water supplies include: surface water that can be diverted from streams, and springs that can be tapped and channeled into the system (Hamilton and Jepson, 1940; Kuiper, 1999).

Many factors have to be taken into consideration when estimating storage capacity of a water-harvesting system for agricultural purposes: expected rainfall, crop water requirements, effectiveness of irrigation technique used, water loss through evapotranspiration, seepage, and overflow. A system is able to provide year-round water supply if total water sources exceed demand, and if storage capacity is sufficient (Gould and Nissen-Petersen, 1999). There are various techniques to determine the size of water storage systems, which are great tools for system design optimization. Some of the common approaches used include: the graphical method, mass curve method, statistical methods, and computer-simulation methods, each to be discussed below.

2.4.1.3.2.1 Graphical method

The graphical method is a simple approach that consists in plotting the cumulative average monthly runoff using a bar graph. Cumulative water use is then represented on the graph by drawing a straight diagonal line from the origin (constant water use). Storage volume is determined by estimating the greatest difference between cumulative runoff and water use (Gould and Nissen-Petersen, 1999; Kuiper, 1999; Schiller and Latham, 1982b). The main disadvantages of this method are: lack of precision, assumption that water is used year-round as opposed to seasonal usage, water demand is constant, and assumption that runoff is the only source of water to the system. In order to use the Graphical Method, runoff has to be determined.

2.4.1.3.2.1.1 Runoff estimation

The precise amount of runoff generated by a catchment area is difficult to estimate since so many interrelated factors will influence yield: antecedent moisture content, land relief, water infiltration through soil, plant cover, and intensity and duration of storm rainfall (United States Department of Agriculture, 1971). Various methods and models have been developed to calculate runoff (Viessmen and Lewis, 1996). Examples of methods include the Soil Conservation Service Curve Number (Viessmen and Lewis, 1996), Cook's method (Dickinson, 1980) and Rational method (Dickinson, 1980; Linsley, 1976). There are also various computer models for runoff estimation, such as the Agricultural Non Point Source Pollution model (AGNPS) (Panuska *et al.*, 1991; Young *et al.*, 1987), and the Precipitation-Runoff Modeling System (PRMS) (Leavesley *et al.*, 1983). This section will focus on runoff estimation using the Rational method, since it requires little data input, is simple to use and can be widely applied under a range of climatic conditions.

The Rational method stipulates that the amount of runoff generated by a certain area is a function of the runoff coefficient, average annual rainfall, and size of catchment area:

$$Q = 0.0027CiA \tag{1}$$

Where Q is runoff in m^3s^{-1}, C is runoff coefficient, I is average peak rainfall intensity in mmh^{-1}, and A is catchment area in ha. C varies with topography, vegetation, and soil texture (Table 2.2).

Table 2.2

Determination of runoff coefficient C (table adapted from Dickinson, 1980).

Topography and vegetation	**Soil Texture**		
	Open sandy loam	**Clay and silt loam**	**Tight clay**
Woodland			
Flat (0-5% slope)	0.10	0.30	0.40
Rolling (5-10% slope)	0.25	0.35	0.50
Hilly (10-30% slope)	0.30	0.50	0.60
Pasture			
Flat	0.10	0.30	0.40
Rolling	0.16	0.36	0.55
Hilly	0.22	0.42	0.60
Cultivated			
Flat	0.30	0.50	0.60
Rolling	0.40	0.60	0.70
Hilly	0.52	0.72	0.82

2.4.1.3.2.2 Mass Curve method

The mass curve method consists in plotting cumulative yearly rainfall runoff over a period of a minimum of ten years. A diagonal line starting from the origin is drawn to represent cumulative water demand (constant). Critical periods are identified by finding the largest difference between cumulative rainfall runoff and water demand. This difference corresponds to maximum storage requirement (Gould and Nissen-Petersen, 1999; Schiller and Latham, 1982b). Disadvantages of this technique include: assumption that water demand is constant throughout the year, and rainfall runoff is the only water supply to the system.

2.4.1.3.2.3 Computer modeling and statistical methods

Computer models for water harvesting are used to predict the performance of a particular system and to simulate a set of site conditions. The main advantages of using computer models are: ability to analyze large amount of data in short periods of time, and transferability of models under a range of site conditions (Gould and Nissen-Petersen, 1999). However, performance of the modeling operation depends on accuracy of data and on how well the algorithm emulates the real world (Gould and Nissen-Petersen, 1999). Some models have been developed to estimate size of water harvesting system storage in many areas around the world; SimTanka is a model developed in Jaipur India to estimate tank storage capacity for rainfall runoff from roofs for domestic water use (Vyas, 1996). Another model was developed at the University of Dalhousie in Nova Scotia, Canada, to determine the probability of the system to meet daily domestic water requirements, where water is stored in cisterns (Scott *et al.*, 1995). A spreadsheet method acting as a water balance method was developed in Kenya to estimate the minimum tank volume to collect rainfall runoff from roofs in order to meet a specific domestic water demand (Burgess, 1996). Other modeling efforts in this field were carried out in Australia (Perrens, 1982a; Perrens, 1982b). Statistical analyses are sometimes included within certain computer models in order to calculate the probability of success or failure of a system (Ahmed and Fok, 1982; Schiller and Latham, 1982a).

2.4.1.4 Pond construction

When planning for pond construction, one should have an idea about the dimensions of the pond in order to estimate how deep and wide to excavate. Ponds can have various shapes: rectangular, circular, or irregular. Methods to estimate dimensions vary depending on pond form. These will be discussed below.

2.4.1.4.1 <u>Estimating pond dimensions</u>

2.4.1.4.1.1 Circular ponds

Ponds can be excavated as to have a cone shape. In order to estimate depth and length of pond, necessary volume needs to have been calculated previously with one of the methods described above. Dimensions of circular ponds are estimated using Equation 2, and are represented in Figure 2.1.

$$V = \pi h / 3(R^2 + r^2 + Rr) \qquad (2)$$

Where V is pond volume in m^3, π is equal to 3.1416, h is height (or depth) of pond in m, R is radius across the top of the pond in m, and r is radius across the bottom of the pond in m. For this method, pond depth is first specified. Both radiuses are then found by trial and error so that the volume equals the one calculated with one of the previous methods.

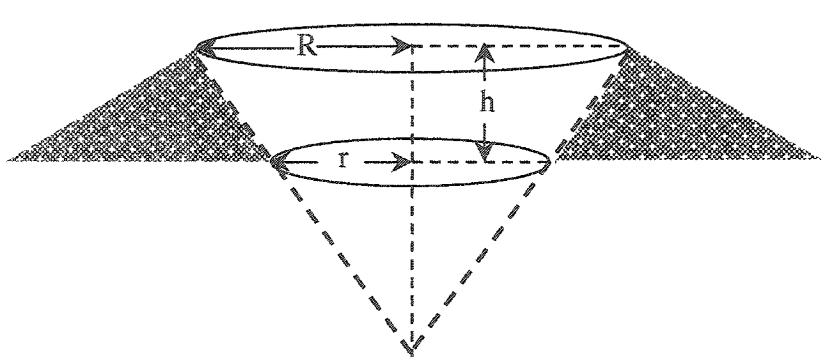


Figure 2.1 Profile view of a cone-shaped pond (Kuiper, 1999).

2.4.1.4.1.2 Rectangular ponds

Rectangular shaped ponds are the most common since it is easy for machinery to remove the fill material (United States Department of Agriculture, 1982). Again, required pond volume needs to be calculated prior to estimation of dimensions. The prismoidal formula is used for estimation of pond dimensions:

$$V = \frac{(A + 4B + C)}{6} \times D \tag{3}$$

Where V is pond volume in m^3, A is area at the ground surface in m^2, B is area at mid-depth (1/2 D) in m^2, C is area at the bottom of the pond in m^2, and D is average depth of the pond in m. Figure 2.2 illustrates the cross section and longitudinal section of a rectangular pond. For this method, pond depth needs to be established first. Length and width of the pond are then found by trial and error so that pond volume equals the one calculated with methods mentioned previously.

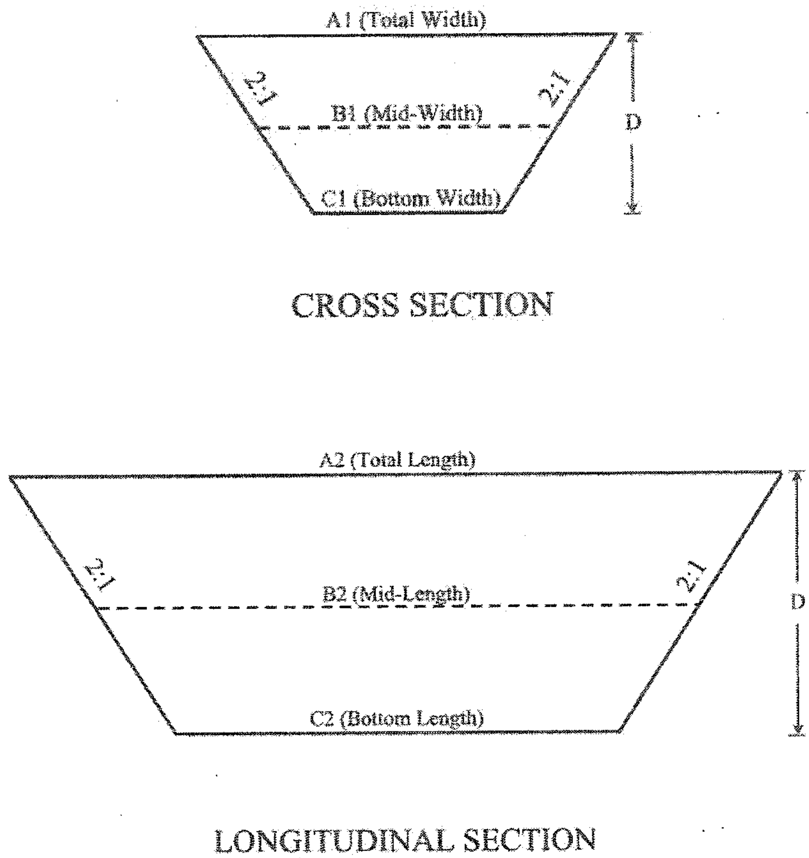


Figure 2.2 Cross and longitudinal sections of a rectangular-shaped pond (modified from United States Department of Agriculture, 1971).

2.3.1.4.2 *Excavation*

Ponds can be excavated either with machinery or by hand, depending on equipment available, accessibility of the site, and economic situation of farmer. Size and type of machinery used for excavation can restrict pond dimension, therefore knowledge of the equipment to be used is suggested (United States Department of Agriculture, 1971). Bulldozers, dragline excavators, and tractor-pulled wheeled scrapers are the most common machinery used for pond excavation (Nichols, 1966; United States Department of Agriculture, 1982). Ponds are usually excavated starting from the centre, going to the sides (Nichols, 1966). Deeper ponds with less surface area are preferred than large shallow ponds, since they lose less water through evaporation, and do not favour plant growth at the bottom (Nichols, 1966).

Interior walls of the pond should not be steeper than the natural angle of repose of the soil to be excavated so that sloughing can be prevented. Location where the excavated soil will be placed during pond construction should be considered before excavation begins. There are 3 common ways to place the fill material: stacked, spread, or removed. Figure 2.3 illustrates these three methods of placement.

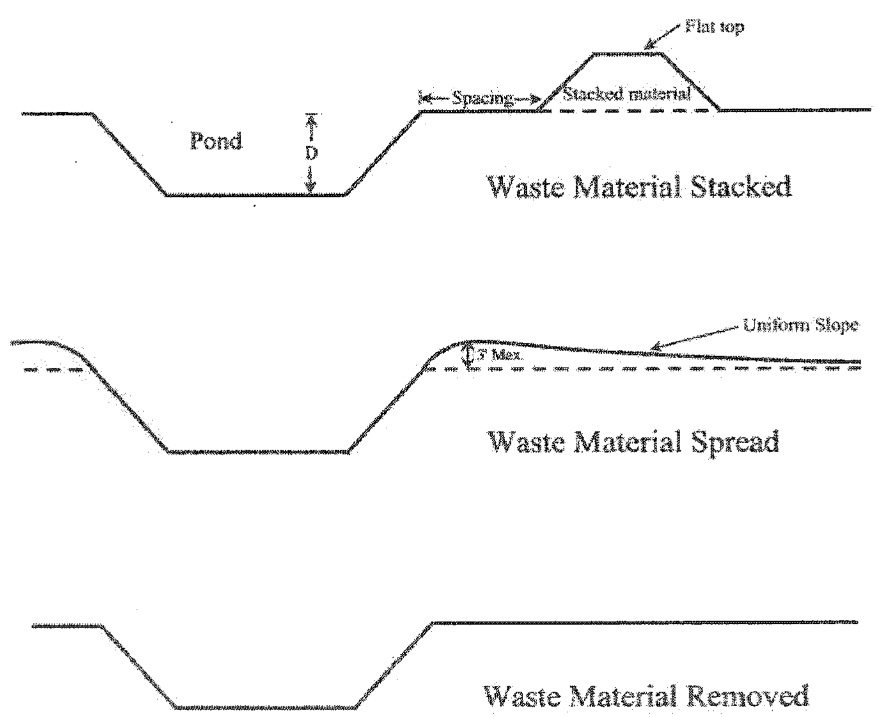


Figure 2.3 Cross section of a pond illustrating the three most common ways to place excavated soil (modified from United States Department of Agriculture, 1971).

2.3.1.4.3 *Methods to reduce evaporation*

Water lost through pond evaporation is significantly high, especially when high temperature, dry and windy climatic conditions prevail (International Commission on Irrigation and Drainage, 1967). There are various methods to reduce evaporation. These include: reducing surface area of pond, adding covers and films on the surface, and planting windbreaks (Hudson, 1987; International Commission on Irrigation and Drainage, 1967). Some common examples of covers consist of plastic sheets, rubber membranes, and roofs of various materials (Powell, 1977). Thin films composed of monomolecular layers of long chain fatty alcohols can be placed on the water surface to reduce evaporation (Powell, 1977). Windbreaks are also good to reduce evaporation since they reduce wind and provide shade. These techniques vary in cost and require thorough investigation before application or implementation.

2.3.1.5 Protection and maintenance

Adequate protection of pond and surrounding areas will lengthen the life of the water-harvesting system. Preventing sedimentation buildup and animal trampling, as well as promoting soil and moisture conservation practices are important protection measures that should be considered (Hamilton and Jepson, 1940). These will be discussed in further detail. Protection requires maintenance. Inspections should be performed on a regular basis in order to ensure good functioning of system, especially following high intensity rainfall (Husenappa *et al.*, 1981).

2.3.1.5.1 Sedimentation basins

A sedimentation basin located before ponds' inlet should be implemented if significant amount of sediments is carried with runoff (Frasier and Myers, 1983; United States Department of Agriculture, 1971; Williams, 1993). In order to prevent sedimentation buildup, proper erosion control measures should be implemented on the catchment area. Such measures include: planting permanent vegetation cover (trees and grasses), and sustainable agricultural practices (terracing, contour tillage, and strip-cropping) (Hamilton and Jepson, 1940).

2.3.1.5.2 Fencing

Animals should be discouraged from drinking directly from the water-harvesting system to avoid damage caused by trampling and contamination, and to avoid drowning of animals (Davidson and van Vlack, 1940; Hamilton and Jepson, 1940). Rather than allowing livestock to drink directly from pond, water should be conveyed to water troughs (Kuiper, 1999). The perimeter of the system should be fenced with material that is locally available, such as barbed wire or native thorny vegetation.

2.3.1.5.3 Soil and moisture conservation

Simple soil and moisture conservation practices that can be included in a water-harvesting scheme include: berms, terraces, rock check dams, infiltration ditches, windbreaks, and promoting the establishment of vegetation (Hudson, 1987; Faustino, 1986; Kuiper, 1999; Lal, 1990). Vegetation cover should be planted immediately following excavation in order to prevent erosion of bare soil surrounding pond. Sod-forming grasses that require low water are said to be preferable (Hamilton and Jepson, 1940). Such practices can be combined and integrated with other types of conservation practices in the fields.

2.3.1.5.3.1 Vetiver grass

Extensive study on *Vetiveria zizanioides* (Linn.), commonly known as vetiver grass, has been carried out over several years and is considered to play an important role in preventing soil erosion (Banco Mundial, 1995; La Red Latinoamericana del Vetiver, 1999; Smyle and Magrath, 1993). This perennial grass has many aspects that make it desirable for farmers, such as: adapts easily to a multitude of climatic and edaphic conditions, propagates easily, withstands drought, flood and fire, repels many pests, resists most diseases, is disliked by livestock, does not compete with other crops, and finally does not need much maintenance (Banco Mundial, 1995; Smyle and Magrath, 1993). Vetiver grass has an extensive array of long roots extending up to 3 metres, which enable to hold soil in place and to conserve soil moisture. There has been increasing interest for this plant in farming contexts in Latin America (La Red Latinoamericana del Vetiver, 1999).

2.4 Decision Support Systems in an agricultural context

One of the main problems with agricultural research is that successful management practices in one region are not necessarily transferable to another mainly because of soil characteristics, climate, and the socio-economic context. Agricultural Decision Support Systems (DSSs) and computer modeling have been developed and are used to facilitate information management, analysis, and sharing. These make agricultural systems and techniques more accessible, transferable and practical for guiding and advising scheme design and implementation. DSSs are also used to reduce numerous long-term field studies and are helpful for planners, policy makers, and extension agents in order to extrapolate trends (Jones *et al.*, 1993). Therefore, DSSs are tools that facilitate recommendations by taking many variables and possible scenarios into account and finding the most appropriate alternatives.

Various types of DSSs have been designed for specific agricultural purposes: pest management (Michalski *et al.*, 1983), fertilizer application (Hayman and Easdown, 2002), crop management (Carberry *et al.*, 2002; Plant, 1989; Welch *et al.*, 2002), pisciculture (Nath, 1996), irrigation management (Hearn and Bange, 2002), and animal nutrition (Stuth *et al.*, 2002; Donnelly *et al.*, 2002). Some DSSs are developed for a specific region and may need alteration in order to be transferable to other regions.

2.4.1 Difficulties in the implementation of DSSs

Extensive research on a multitude of DSSs for agricultural purposes has been carried out, however there is still resistance to adopting this type of technology. It has been demonstrated that successful DSS adoption may be associated with perceived usefulness of technology by end users, and ease of use or straightforwardness of the system (McCown, 2002).

Carberry *et al.* (2002) report that farmers' interest in DSSs is much higher when they have difficulties on the farm, rather than preventing them ahead of time. When designing a DSS, it is important to consider costs and risks of implementing a new practice or system. In addition, it is important to design models that represent realistic farming conditions

The future of DSSs in an agricultural context depends on the willingness to accept change in farming practices, and ease of use and accessibility of systems. Thus, farmers and agricultural extension agents need to see such information systems not only as a tool to help in making a better choice of actions, but also to facilitate the understanding of factors involved in the decision process (McCown, 2002).

Chapter 3. MATERIALS AND METHODS

3.1 Region Selection

Selection of the region for implementing a water-harvesting system was determined to be located in the district of Los Pozos, since contacts had already been established in this region. The construction site was to be implemented in either El Cedro or El Capuri county (see Figure 1.4). Ideally, the project would have been located on communal land so that all members of the community could participate actively and benefit from the project. Unfortunately, neither community had communal land where the project could be implemented, so the system had to be located on privately owned land. Although the project would not benefit all community members directly in the short term, it will by word of mouth benefit many producers of the region in the long term. The on-farm water-management research plot was implemented to ensure that the ponds could be beneficial in the region and adapted to conditions for long-term use and allow for implementation on a larger scale.

There is a high demand for this type of project in the area, which made the site selection task even more difficult. First of all, meetings were organized in both counties in order to determine exactly how many farmers would be interested in participating and willing to allocate part of their land for the implementation of a water-harvesting system. The next step was to visit the land of interested farmers in both counties to ensure that the area met the requirements for specific physical characteristics. The final important aspect considered for site selection was the interest and enthusiasm of the farmer; He had to be willing to invest land, time, and money into the project.

A total of fifteen farms were visited, but only one met all the above criteria. The main obstacle was topography; terrain was overly abrupt in most locations. A particular area on the land of Gustavo González Trejos seemed to be adequate for the implementation of a pond, and he seemed to be willing to participate actively in the project. His land is located in the community of Tierras Blancas, municipality of El Cedro. His main interest was to collect water to irrigate a small field and for small-scale pisciculture.

3.2 Preliminary analysis

Certain preliminary analyses of regional conditions were carried out before the actual scheme design. These included topographical, climatic, and socio-economical aspects. These aspects will be discussed in greater detail in the following paragraphs.

3.2.1 Topography

In order to analyze the topography of the area, small-scale maps were first used to look at the general topographical features of the county of El Cedro. Larger-scale maps and aerial photographs were then analyzed to locate the prospective pond construction site. Since the project was done on a very small-scale, ortho-photographs of the community of Tierras Blancas would have been ideal, but unfortunately none had been taken in the area.

3.2.1.1 Surveying and delimitation

The Technological University (Universidad Tecnológica de Panamá) of Santiago, province of Veraguas graciously provided surveying equipment and staff to perform surveying of the pond construction site. Surveying was carried out to determine the elevation of the pond compared to the fields to be irrigated so that a water conveying system could be selected. If pond area was to be higher than the fields, water could be conveyed to the fields by gravity. In addition, surveying was used to determine the slope and extent of the catchment area so that the amount of runoff generated could be calculated. Finally, topography of the area also played a role in determining accessibility for machinery to the construction site.

3.2.2 Climate

The installation of a small-scale on-field meteorological station was not possible due to time and financial constraints. Therefore, climatic variables gathered through nearby meteorological stations were used for the water-harvesting project. Variables that were provided included: average precipitation, temperature, pan evaporation, relative humidity, and average wind speed. The ETESA (Empresa de Transmisión Electrica S.A.)

graciously provided a daily record of this data over a thirty-one year period for the meteorological station of Los Santos, which is located at approximately 38 km from Tierras Blancas. This type A meteorological station (records various climatologic variables) is the closest one to the site. The ETESA also provided daily precipitation records for three type C meteorological stations (record only precipitation data): La Mesa de Macaracas, Los Pozos, and La Pitaloza Arriba. These are the three nearest type C meteorological stations from the water-harvesting site, which are located at approximately 5, 12, and 8 km from site, respectively. Since La Mesa de Macaracas is the closest to the site, its precipitation data was used for this project.

3.2.3 Socio-economic aspects

The socio-economic conditions of the area were determined by talking with residents of El Cedro county, Peace Corps volunteers working in the area, and through personal observations. Having an idea about the socio-economic conditions of the area in which a project is to be implemented will help the project be oriented more towards the inhabitants' interests, needs, and capabilities. In addition, taking into consideration the socio-economic constraints of an area might help in understanding existing imbalances within a region and finding possible solutions.

3.2.4 Soil and terrain analysis

3.2.4.1 Soil profile analysis and sampling

A pit was dug to 1.5 m in depth to examine the soil profile and identify the horizons. Each horizon's thickness was measured with a measuring tape and a sample was taken from each of them. Digging a soil profile is useful when planning for a water-harvesting scheme through ponds; lower soil horizons will determine if the area has a suitable soil texture for pond implementation, or if the pond will require lining. If a highly permeable layer (sand) were present, there would be much more water lost through seepage.

A set of soil samples was taken for each horizon within the soil profile. Three other soil samples were taken at an interval of 15 meters at the pond construction site, at a depth of 0 to 20 centimeters (below organic horizon). A final set of four soil samples was taken at an interval of 20 meters at the field to be irrigated, at a depth of 0 to 20 centimeters. Each soil sample weighed approximately 500 g. Soil samples were kept in paper bags and then air-dried.

3.2.4.2 Field and laboratory analysis

3.2.4.2.1 Field analysis

General soil and terrain description was carried out in order to know more about the general condition of the pond's area. This is an important step in order to avoid some unexpected failure of the project possibly due to an unaccounted for soil property. A series of aspects were evaluated, such as: soil profile description (see Table 3.1) and terrain description (Table 3.2).

Water infiltration tests

The Technological University (Universidad Tecnológica) of Santiago provided a double-ring infiltrometer to determine the water infiltration rate through soil at the pond construction site (Forsythe, 1974). The infiltrometer was placed on the floor of the soil profile, since measurements of infiltration rates at the bottom of the pond were needed. Therefore, infiltration rates for a depth of 1.5 metres were measured for a one-hour period for the site.

Table 3.1
Soil profile description (Ministry of Crown Lands Province of British Columbia, 1997)

Soil structure	Soil texture	Presence of roots	Presence of rocks
a) granular	a) moist cast test	a) none	a) none
b) blocky	- hard to squeeze	b) few	b) few
c) prismatic	- somewhat hard to squeeze	c) many	c) many
d) columnar	- easy to squeeze		
e) platy	b) ribbon test		
f) single grained	- long (5 cm)		
g) massive	- medium (2-5 cm)		
	- short (less than 2 cm)		
	c) feel test		
	- stickiness test		
	• really sticky		
	• somewhat sticky		
	• slightly sticky		
	- graininess test		
	• smooth with no grit		
	• somewhat gritty		
	• very gritty		
	- dry feel test		
	• more than 50 % sand		
	• less than 50 % sand		
	d) taste test		
	- smooth with no grit		
	- somewhat gritty		
	- very gritty		
	e) shine test		
	- very shiny		
	- moderately shiny		
	- not shiny		

Table 3.2
Terrain description (Canada Expert Committee on Soil Survey, 1982; Ministry of Crown Lands Province of British Columbia, 1997)

Slope	Site position	Soil drainage	Presence of mottles
Plain ($0-3^{o}$)	Crest	Very rapid	a) Abundance
Gentle slope ($4-15^{o}$)	Upper slope	Rapid	- few (< 2%)
Moderate slope ($16-26^{o}$)	Middle slope	Well	- common (2-20%)
Moderately steep ($27-35^{o}$)	Lower slope	Moderately well	- many (> 20%)
Steep (> 35^{o})	Toe	Imperfect	b) Dimension
	Depression	Poor	- fine (< 5mm)
	Level	Very poor	- medium (5-15mm)
			- coarse (> 15mm)

3.2.4.2.2 Laboratory analysis

Three soil samples were taken for every sampling point: one that would be analyzed in the laboratory of the Instituto de Investigación Agropecuaria de Panamá (IDIAP) located in Divisa, province of Veraguas, one that would be analyzed in the soil testing laboratory of McGill University, Macdonald Campus, and finally the last sample was kept for possible duplication analysis. Results from both laboratories were compared. Soil samples were ground using a mortar and pestle and passed through a 2 mm sieve. For each analysis, there was one control and a minimum of one duplicate. Table 3.3 indicates the soil analyses that were performed in addition to the method used.

Table 3.3
Soil analysis methods used for both the Instituto de Investigación Agropecuaria de Panamá (IDIAP) and McGill University's laboratories.

Soil Analysis	Method used by IDIAP	Method used by McGill	Reference
Particle size analysis	Bouyoucus hydrometer method	Bouyoucus hydrometer method	Ashworth *et al.*, 2001; Bouyoucus, 1951
pH	Water-pH	$CaCl_2$-pH	Hendershot *et al.*, 1993b
Nutrient extraction	Mehlich 1	Mehlich 1 and Mehlich 3	Mehlich, 1978; Mehlich, 1984; Tran and Simard, 1993
Organic matter content	Walkley-Black method	-	Walkley, 1935; Walkley and Black, 1934
Cation exchange capacity	-	$BaCl_2$-CEC	Hendershot *et al.*, 1993a
Percent base saturation	-	Based on CEC	Hendershot *et al.*, 1993a

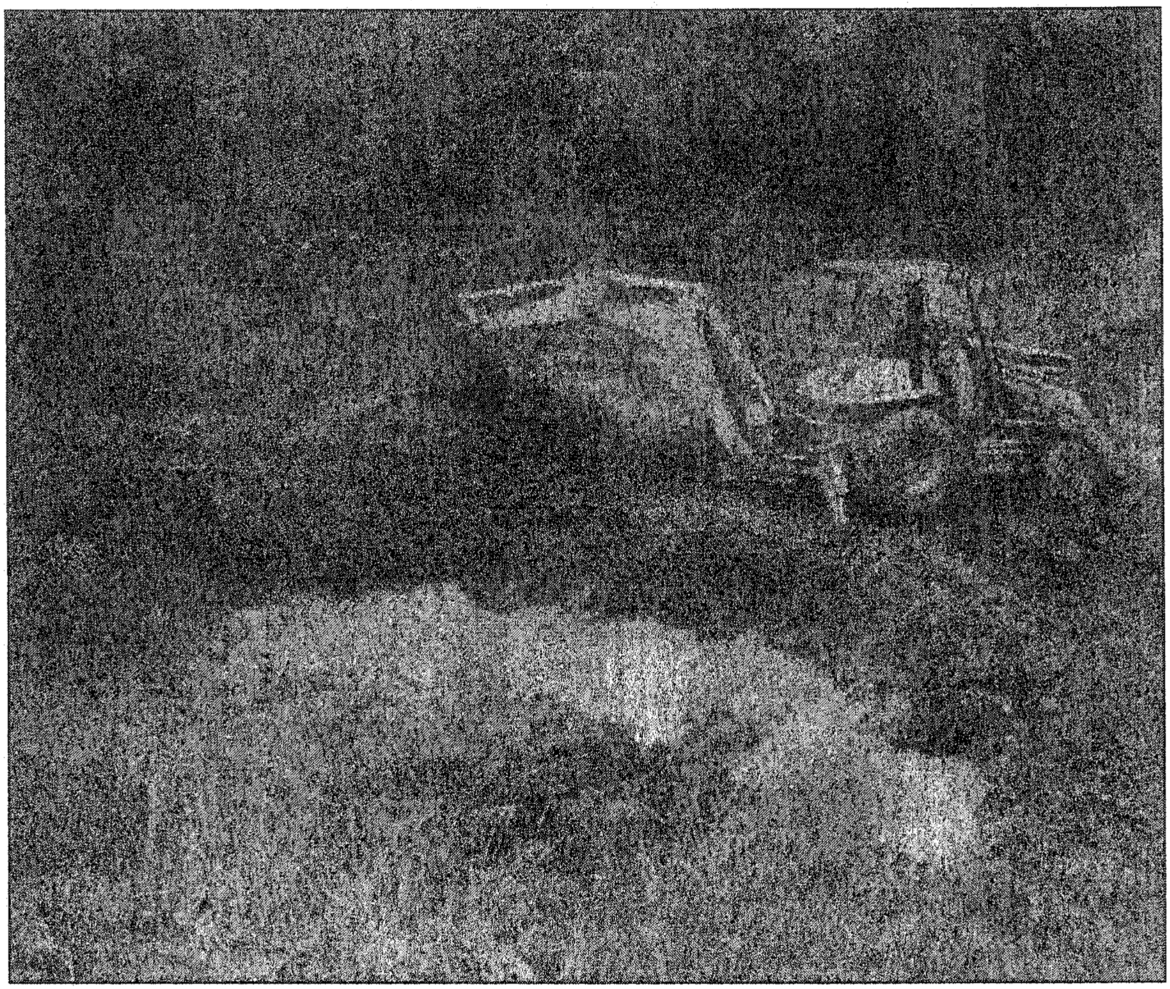
3.3 Estimation of storage capacity of pond

Before pond construction began, pond storage capacity was estimated using the combination of two methods: the Graphical Method and the Mass Curve Method. The combination of these methods is referred to as the Graphical Mass Curve Method (Kuiper, 1999). Cumulative runoff was plotted on a bar graph, and water consumption was represented using a diagonal line. For this method, assumption had to be made that water demand was constant throughout the year. The average monthly runoff was estimated based on the Rational Method. Average monthly rainfall was estimated using data from meteorological station La Mesa de Macaracas, which is the closest station from the pond construction site.

3.4 Pond construction

The municipal works of Chitré (Ministerio de Obras Públicas) graciously helped with the soil excavation for the construction of the water-harvesting scheme. A team and machinery were already working in the area of El Cedro at the time the pond project began. A tractor was first brought into the site for soil removal, but had difficulty reaching the construction site since the terrain is fairly sloped. Therefore, a backhoe loader was brought into the site and was able to remove most of the soil, as shown in Photo 3.1. While excavating the pond a surface spring was encountered and was therefore included within the water-harvesting scheme. However, this made the task even more difficult for the backhoe loader, since water accumulated and wetted the clay soil. Finally, men from El Cedro helped to excavate with shovels the remaining soil within the pond. No sealer was used since soil texture was fine clay and compaction of the soil with machinery during soil excavation was sufficient to reduce water seepage. When excavation work was completed, *Vetiveria zizanioides* (Linn.) was planted on top and on the outer sides of the ponds' walls in order to stabilize the soil as rapidly as possible. Finally, the pond and adjacent area was fenced with barbwire to restrict livestock from entering the area.

A seasonal stream passed through the area that was designated for the pond, so this stream was diverted with the help of the backhoe loader.



Photograph 3.1 Pond excavation using a backhoe loader.

3.5 Implementation of irrigation system

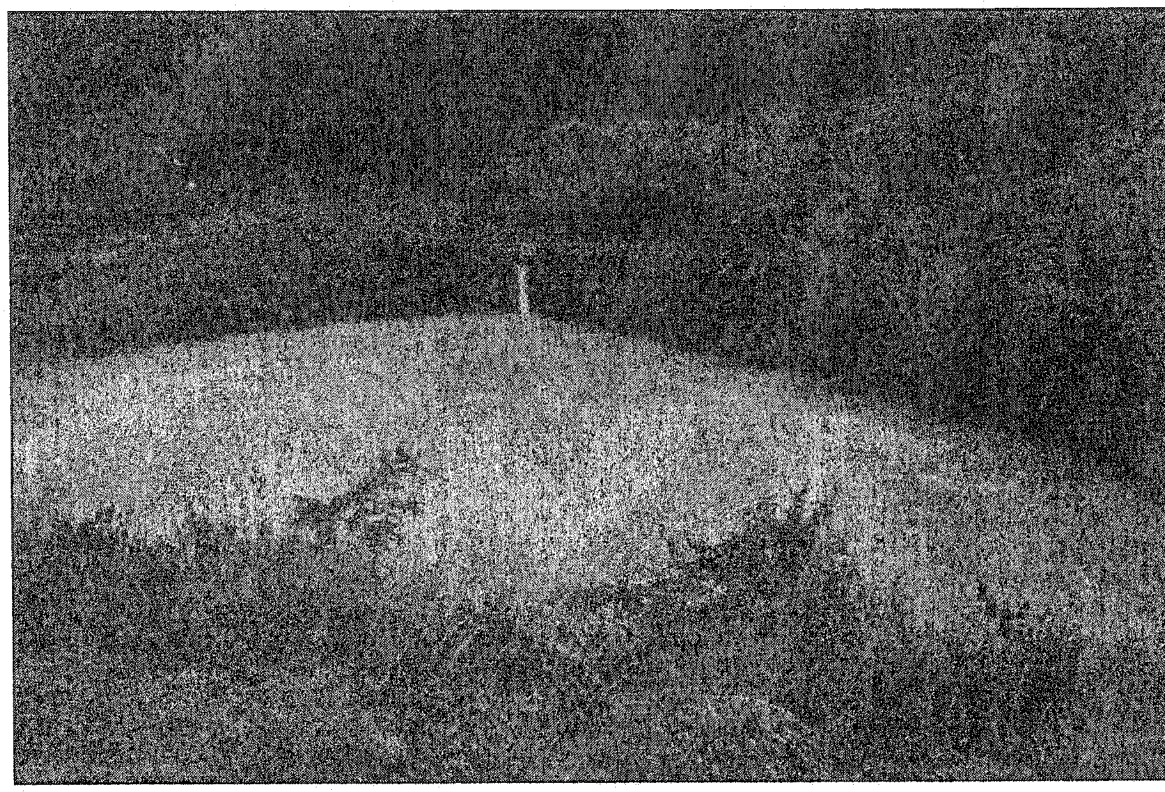
3.5.1 Choosing appropriate system

When choosing an irrigation system to convey water from the pond to the field, it was essential to consult and discuss with Señor González, the landowner. Generally, irrigation systems are seen as large-scale and costly (Adams and Hughes, 1990). Therefore, the notion of small-scale irrigation was explained and irrigation techniques practiced in the area were explored. The irrigation system had to be designed in a way to allow for full participation of the farmer in its planning and development. Past experience has proven that farmer participation in irrigation scheme design leads to improved system design, reduced construction costs, and increased willingness of producers to maintain the system (Adams and Hughes, 1990).

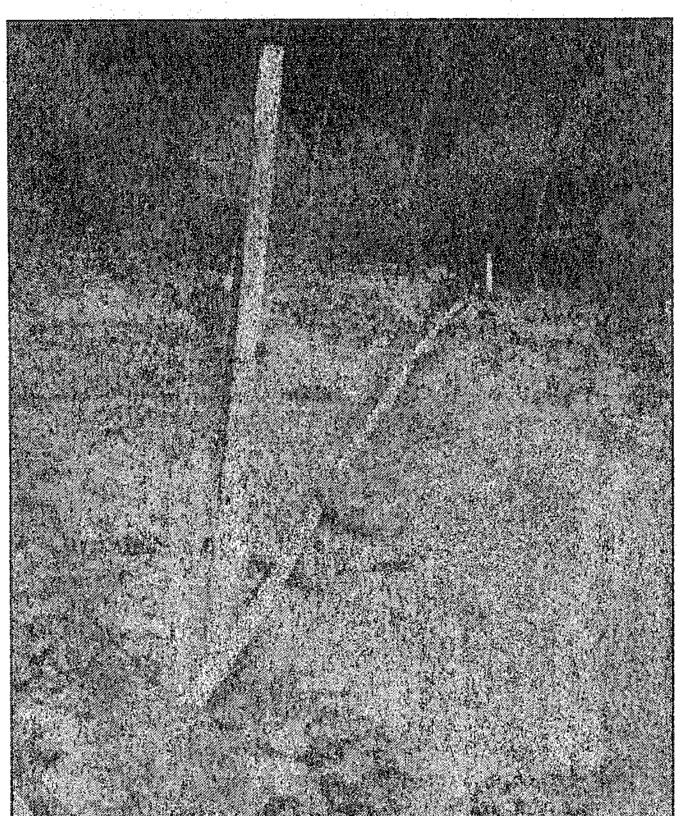
Small-scale or subsistence farmers are often reluctant to adopt projects which require input-intensive technology, or significant amounts of money or labour if they are not guaranteed increases in income (Jazairy *et al.*, 1992). Therefore, the development and selection of the irrigation system that was implemented had to reflect the farming conditions of the producer.

3.5.2 Conveying water to the field

In order to convey water collected within the pond to the field to be irrigated, a system of PVC pipes was implemented, where water was conveyed by gravity to the field. A simple pivoting riser pipe inlet system was implemented within the pond to draw water out. When irrigation was complete the pipe was turned upward to a vertical position, as identified by the circle in Photo 3.2. A screen was placed at the pipe inlet to avoid pipe obstruction. Three-inch diameter PVC pipes were used to initially draw water out of the pond, and two-inch diameter PVC pipes were subsequently used to convey water to the field. It was found that the installation of an air riser just downstream of the pond berm was necessary in order for gravity flow to occur along the irrigation supply line (Photo 3.3). Thereafter, the farmer and members of his family buried the irrigation supply line from the pond to the field, which covers a distance of 215 meters. The pipes were covered with soil in order to prevent damage due to cattle trampling.



Photograph 3.2 Pivoting riser pipe inlet system after irrigation is completed.



Photograph 3.3 Irrigation air riser installed just downstream of the pond berm.

3.5.3 Conveying water to the crop

Water flows by gravity from the pond to the field through PVC pipes, but a system needed to be put into place in order to convey water to the crops within the field. Water needed to be delivered to the crops, keeping in mind that the system had to be simple to use at low costs. In addition, the system had to consider water conservation, to minimize water lost through evaporation and seepage. Determination of the system was obtained through participatory discussion with local producers. The simple-to-use and low-cost system of hand constructed contour ditches was chosen (Faustino, 1986; Santana and Vargas, 1984). The contour lines were measured using a triangular "A" level (Faustino, 1986). The contour ditches were approximately 10 to 15 centimetres deep, 15 centimetres wide, and spaced by approximately 40 to 50 centimetres, as shown by Photograph 3.4.

Photograph 3.4 Hand constructed contour ditches to convey water to crops.

3.6 Crop selection

The crop selection for the irrigated field was entirely the farmers' decision, since he and his family were going to consume the harvest. The majority of the field was planted with beans (*Phaseolus vulgaris* L.), and the lower areas with tomatoes (*Lycopersicon esculentum* M.) and peppers (*Capsicum annuum* L.). In addition, small sections of the field were planted with watermelon (*Citrullus vulgaris* L.), carrots (*Daucus carota* L.), passion fruit (*Passiflora edulis f. flavicarpa*), and cantaloupe (*Cucumis melo* L.). Since this was the first year that the field was in cultivation, the farmer was experimenting with certain crops in order to plan for next years' harvest. He was already planning for the following year to incorporate sugar cane (*Saccharum officinarum* L.) and pineapple (*Ananas comosus* L.) in the sloping areas in order to reduce erosion, and papaya (*Carica papaya* L.) on the edge of the field.

3.7 Decision Support System

There are a variety of factors influencing the size of a pond, which include: local climatic conditions, rainfall patterns, presence of other water sources, size of catchment area, conditions of the site (topography, vegetation, soil texture), water usage rates, and residual water requirement. A Decision Support System (DSS) was developed in order to facilitate the evaluation of pond size for agricultural purposes. The DSS was developed with the help of Microsoft Excel Visual Basic Editor. Included in the DSS are four different programs that were designed to estimate pond volume for a variety of case scenarios and site conditions. Three of the programs are based on a water budget, where water supply and demand determine pond size. The fourth program is based on the Graphical Mass Curve Method.

Water budgets are used to estimate water requirements, by determining water inflows and outflows of a system. In addition, water budgets are useful for the assessment of whether an existing water source supply is sufficient to meet the water needs of a specific scheme (Nath, 1996). The general concept for the development of this specific water budget was based on the one developed for the computer simulation model POND (Nath, 1996; Nath *et al.*, 1995; Nath and Bolte, 1998). PONDS' water budget focuses on aquaculture ponds, and so the water budget developed for this current study incorporated irrigation and livestock watering purposes. Water budgets were determined annually for two of the programs and seasonally for the other one. The basis of the water budget is based on the following equation, where water demand is subtracted from water supply:

$$PS = \left[Q + Sp + St + A\left(\frac{P}{1000}\right)\right] - \left[O + Irr + AW + A\left(\frac{ET + S}{1000}\right)\right] \quad (4)$$

where PS is pond size in m^3, Q is runoff in m^3, Sp is surface spring in m^3, St is stream in m^3, A is surface area of pond in m^2, P is precipitation in mm, O is drainage overflow in m^3, Irr is water used for irrigation in m^3, AW is water used for animal watering in m^3, ET is evapotranspiration in mm, and S is seepage in mm.

To evaluate the DSS, the Tierras Blancas case scenario and site conditions are given as an example and inputted into the four programs. For the example given for the Tierras Blancas, precipitation was determined from meteorological station La Mesa de Macaracas (Appendix 1). Given that field vegetation is short, potential evapotranspiration was assumed to be equal to pan evaporation (Linsley *et al.*, 1982; Brutsaert, 1982), and was determined from meteorological station Los Santos. Runoff values were estimated using the Rational Method. Water supply by surface spring and stream were calculated directly in the field at Tierras Blancas, during the months of September (wet season) and February (dry season) as water levels varied. To measure spring water contribution, a ruler was inserted directly in a cylinder placed to collect the spring water. As for the water contributed by seasonal stream, a PVC pipe (2 inches diameter) was installed to convey water from the stream to the pond. Water flow was measured by placing a bucket to collect the pipe outflow and a ruler was used to monitor the rise of water in the bucket. To facilitate the pond size estimation, pond overflow was assumed to be negligible for the first year of implementation, since the pond had to fill up. It is difficult to estimate the amount of overflow, before having estimated the pond volume. The method to evaluate the volume of water used for irrigation purposes consisted in measuring the decrease in pond water height after a day of irrigation and multiplying this depth by pond surface area (for this example, the total volume and surface area of Tierras Blancas pond was used). This amount was then summed with daily volume of water entering the pond from other sources (water inflows) and extrapolated for the duration of the dry period, since water is used for irrigation only during this period. Water used for animal watering was not calculated for this particular example, since water was used only for irrigation purposes. However, if animal water requirements needed to be estimated, Table 3.4 could be used.

Table 3.4 Daily water requirements for various farm animals (Frasier and Myers, 1983).

Animal	Daily water requirement (l/day)
Beef cattle	
Mature animals	30-45
Cows with calves	38-57
Calves	19-30
Dairy cattle	
Mature animals	38-57
Cows with calves	45-68
Sheep	
Mature animals	4-8
Ewes with lambs	6-9
Horses	38-45
Swine	15
Chickens (per 100 head)	15
Turkeys (per 100 head)	26

Chapter 4. RESULTS AND DISCUSSION

4.1 Final scheme for Tierras Blancas pond and field areas

A scheme for the study area of Tierras Blancas was designed, based on a topographical survey of the site (Figure 4.1). The final dimensions of the pond constructed are 13 by 11 metres, and 3 metres deep. Therefore the pond has a surface area of 143 m^2 and a total volume of 429 m^3. The total size of the area irrigated with the water collected within the pond is 0.3 ha. The total distance between the pond area and the cultivated field is 215 m. Buried PVC pipes convey water over the entire distance, following the path of a seasonal stream that runs near the pond down to the field (Figure 4.1). This project is considered small-scale due to the size of the pond and the field irrigated. Small-scale projects are needed in the region since families cultivate their land independently as opposed to organizing cooperatives and owning communal land. Small-scale projects also meet the demand of regional farmers since their practices serve to meet their daily needs. Farmers practice subsistence agriculture as opposed to producing for commercial purposes.

The pond was constructed on uneven terrain, where an elevation difference of approximately 2.5 m was measured, as indicated in Figure 4.1. Water was drawn out of the pond with the pivoting riser pipe inlet at an elevation of 319 m above sea level, and reaches the field outlet at an elevation of 337.5 m. Therefore, a difference in elevation of 18.5 m was recorded between the pond and the field, which is more than sufficient to convey water by gravity flow. The difference in elevation was measured using surveying equipment, and the actual elevation above sea level was measured using a Geographical Positioning System (GPS) having a horizontal precision of three meters.

Figure 4.1 also illustrates the PVC water inlet from the seasonal stream to the pond (located on the Northwest corner of the pond), and the surface spring (Northeast corner). In addition, the PVC water outlet for overflow (Southeast corner), and the PVC water inlet for irrigation (Southwest corner of the pond) are represented. Finally, the original and modified courses of the seasonal stream are illustrated in Figure 4.1.

4.2 Field analysis

Soil profile results show that all horizons are characterized by blocky soil structure, and soil texture for the O horizon is Loam, and Clay Loam for the A, B and C horizons (Table 4.1). Although soil texture was determined within the field, particle size analysis had to be done in order to determine the actual, precise soil texture. As for the presence of roots, there are few in the O, A and B horizons and none in the C horizon (Table 4.1). Finally, there are no rocks found within the soil profile.

Results for the terrain description show that gentle slopes characterize the terrain, site position is located in a depression, soil drainage is very poor, and there is common abundance of fine mottles (Table 4.2). As for the water infiltration tests, results show hardly any water is lost through seepage at the pond site (Figure 4.2).

It is always good to know the conditions of the soil and terrain before implementing a project in order to avoid unexpected surprises. Based on these results, the selected site would be appropriate for pond implementation.

4.3 Laboratory analysis

Particle size analysis

Particle size for the samples taken from the soil profile decrease from the surface (O horizon) to the bottom of the profile (C horizon) (Figure 4.3). This indicates that clay content increases with depth. Textural analysis done at McGill show that horizons O, A and B are composed primarily of silt particles while horizon C of clay. Soil texture for the O horizon is Loam, and A, B and C horizons are Clay Loam (Table 4.3). These results agree with the ones obtained from the IDIAP soil laboratory, with the exception of horizon C where soil texture was determined to be Clay as opposed to Clay Loam. Nevertheless, results from IDIAP follow a trend of increasing clay content with profile depth. Since the soil profile was dug in the centre of the area designated for the pond construction, as shown in Figure 4.1, these results give a good idea of how the water will be retained within the pond, given that soil texture directly influences soil water retention. Thus, water will be well retained within the pond in view of the fact that fine textured soil predominate the lower soil layers.

As for the samples taken from the pond area, Sample 1 is primarily sand, while Samples 2 and 3 are silt (Figure 4.4). The samples for the pond area were analyzed only at the McGill University soil laboratory. By interpreting the results of the particle size analysis for these samples, soil texture for Sample 1 is Loam, and Samples 2 and 3 are Clay Loam (Table 4.3). These results give an idea of whether water will be lost around the pond area through seepage. Since most of the samples contain a majority of silt and clay (including the soil profile analysis), there should not be many problems related to water loss near the pond, as shown by infiltration rate results (Figure 4.2).

Finally, particle size analysis was performed on samples taken from the field area to be irrigated. Soil water retention is important in order to plan the location of crops since some plants require well-drained soil and others require wetter conditions. Samples 1, 2 and 3 are composed primarily of silt particles, while Sample 4 is composed of clay and silt particles in equal amounts (Figure 4.5). By interpreting the results of the particle size analysis performed at the McGill University soil laboratory for the samples taken from the field area, soil texture for Samples 1 and 3 is Loam, and Samples 2 and 4 are Clay Loam (Table 4.3). Results obtained from IDIAP for the field area agree with those obtained from McGill since it was determined that Clay Loam predominate the field area. For the analysis performed at the IDIAP soil laboratory, the four samples taken from the field area were mixed together so as to obtain a general result for the entire field. On the other hand, at the McGill laboratory each field sample was analyzed individually in order to evaluate the existing variance within the field so as to better plan crop location.

pH

A flocculating solution of $CaCl_2$ was used at the McGill soil laboratory to avoid suspended soil particles in order to measure the pH of the samples. On the other hand, the IDIAP laboratory used only distilled water for pH measurement. Therefore, in order to compare results obtained from both laboratories, a value of 0.5 was added to pH-$CaCl_2$ results, which gives the equivalent pH-H_2O (Lalande, 2003). Results obtained for samples taken from the soil profile indicate that the soil is acidic, varying from 5.39 to 6.20 (Table 4.4). Figure 4.6 shows that pH increases with soil depth. Results obtained from both laboratories are comparable since they do not differ greatly and follow the same trend.

The pHs obtained from the pond area samples vary from 5.36 to 6.01 (Table 4.4). Analysis for pH of the pond samples was performed only at the McGill laboratory. Figure 4.6 shows that pH is not completely uniform throughout the pond area and that it varies slightly.

Finally, pHs for the field area samples vary from 4.92 to 6.03, which is again an indication of an acidic soil (Table 4.4). The IDIAP laboratory had mixed the four samples together in order to estimate a mean pH for the entire field, and obtained a result of 5.1. This result is comparable to the ones obtained at the McGill lab.

Nutrient extraction

Extractants used for nutrient extraction vary from one laboratory to another. However, Mehlich 3 is by far the most commonly used extractant (Alva, 1993). Yet, most Panamanian soil laboratories use Mehlich 1. Mehlich 1 is used particularly for highly weathered soils, whereas Mehlich 3 is used under a wider range of soil types including highly weathered soils (Cox and Taylor, 1993; Mamo *et al.*, 1996). Mehlich 1 extractions were performed in both laboratories, and extractions were repeated using Mehlich 3 at the McGill laboratory.

Available potassium

<u>*Soil profile*</u>

For samples taken from the soil profile, results obtained from the extraction of potassium with Mehlich 1 are much greater for the IDIAP than McGill laboratory; 10 times greater for the O horizon (39 versus 389 $mgkg^{-1}$), 16.6 times greater for the A horizon (21 versus 349 $mgkg^{-1}$), 6.5 times greater for the B horizon (48 versus 310 $mg.kg^{-1}$), and 5.5 times greater for the C horizon (51 versus 279 $mgkg^{-1}$), as indicated in Table 4.5. Similarly, amounts of potassium obtained from Mehlich 1 by IDIAP are much greater than the ones estimated with Mehlich 3 by McGill. However, K extractions obtained with Mehlich 1 and 3 from the McGill laboratory are very similar and therefore comparable (Table 4.5). Potassium amounts seem to decrease from the surface O horizon to the bottom C horizon based on the results obtained by IDIAP (Figure 4.7). However, the trend is different for the results obtained by McGill where potassium amounts do not seem to vary greatly from one horizon to the next, with the exception of Mehlich 1 from the O horizon to the A where potassium amounts decrease and increase again in the B horizon.

Pond area

Since the pond area samples were analyzed only by McGill, Mehlich 1 and Mehlich 3 results are compared. Amounts of potassium are similar and follow the same trend for Samples 1 and 2 (Figure 4.7). However, amounts seem slightly higher for Sample 3 when analyzed with Mehlich 1 compared with Mehlich 3.

Field area

Amounts of potassium obtained for the field area are very similar when extracted with Mehlich 1 and Mehlich 3 at the McGill laboratory, however the amounts obtained at IDIAP differ by a factor 20 from the ones obtained by McGill.

Finally, average amounts of K for a tropical soil are of 120-160 $mgkg^{-1}$ (ILACO B.V., 1981). Compared to other tropical soils, amounts of potassium for the samples analyzed at the McGill laboratory are considered low and the ones obtained at IDIAP excessively high. Low amounts of potassium can have a negative impact on crop yield.

Available phosphorus

Amounts of phosphorus obtained for the soil profile, pond area, and field area are in general very low and levels do not vary greatly (Table 4.5). Levels of phosphorus extracted with Mehlich 3 were slightly higher than the ones obtained with Mehlich 1 and follow the same trend (Figure 4.8). Mamo *et al.* (1996) and Kraske *et al.* (1989) agree with the fact that levels of P obtained with Mehlich 3 are generally higher than the ones obtained with Mehlich 1. Extraction results obtained for Sample 3 of the field area does not follow the same trend for both extractants.

Average amounts of P for a tropical soil extracted with Mehlich 1 are between 18 to 54 $mgkg^{-1}$ (Name and Cordero, 1987). Compared to other tropical soils, amounts of P for the samples analyzed at both laboratories are considered very low. Low amounts of phosphorus can have a negative impact on crop yield.

Available magnesium

Soil profile

For the samples taken from the soil profile, results obtained from the extraction of Magnesium with Mehlich 1 for both laboratories and Mehlich 3 for McGill are all of the same order and generally follow a similar trend (see Table 4.5 and Figure 4.9). Results show that only one point does not follow the same trend; amounts of Mg obtained from Mehlich 1 by IDIAP for horizon A are higher than the ones for horizon C, which differs from the results obtained by McGill where amounts of Mg increase gradually with soil depth (Figure 4.9). For all samples, results obtained from Mehlich 1 by McGill are lower, Mehlich 1 by IDIAP are higher, and those from Mehlich 3 by McGill represent the average of the two sets obtained with Mehlich 1.

Pond area

Since the pond area samples were analyzed only by McGill, Mehlich 1 and Mehlich 3 results are compared. Amounts of Mg are similar and follow the same trend for Samples 1, 2 and 3 (Figure 4.9). However, all results are higher with Mehlich 3 as compared with Mehlich 1.

Field area

Amounts of Mg obtained for the field area are similar and follow the same trend when extracted with Mehlich 1 and Mehlich 3 at the McGill laboratory (Figure 4.9). Only one result is obtained at IDIAP since they have mixed the four field samples together in order to get an average value for the entire field. This value is within the same range as the results obtained at McGill. The amounts of Mg estimated for Sample 2 however seem higher than the other samples.

Finally, results obtained for Mg extractions with Mehlich 1 from both laboratories and Mehlich 3 from McGill are similar and therefore comparable. Average amounts of

Mg for a tropical soil extracted with Mehlich 1 are between 720 to 2160 $mgkg^{-1}$ (Name and Cordero, 1987). Compared to other tropical soils, amounts of Mg for the soil profile samples analyzed at both laboratories are considered average. However, amounts of Mg for the field and pond area are considered low. Mg deficiencies in plants have repercussions on growth (California Fertilizer Association, 2001).

Available calcium

Soil profile

For the samples taken from the soil profile, results obtained from the extraction of Calcium with Mehlich 1 at both laboratories and Mehlich 3 at McGill are all of the same order and generally follow a similar trend (Table 4.5 and Figure 4.10). For all samples, results obtained from Mehlich 1 at McGill are lower, the ones from Mehlich 1 at IDIAP are higher, and those from Mehlich 3 at McGill represent the average of the two sets obtained with Mehlich 1. The trend shows that amounts of Ca gradually increase from horizon O to horizon B and then decrease in horizon C (Figure 4.10).

Pond area

Since the pond area samples were analyzed only by McGill, Mehlich 1 and Mehlich 3 results are compared. Amounts of Ca are similar and follow the same trend for Samples 1, 2 and 3 (Figure 4.10). However, results for Samples 2 and 3 are higher with Mehlich 3 compared with Mehlich 1.

Field area

Amounts of Ca obtained for the field area are similar and follow the same trend when extracted with Mehlich 1 and Mehlich 3 at the McGill laboratory (Figure 4.10). Only one result is obtained at IDIAP since the four field samples were mixed together in order to get an average value for the entire field. This value is within the same range as the results obtained at McGill. However, amounts of Ca estimated for Sample 2 seem slightly higher than the other samples and Sample 4 lower.

Finally, results obtained for Ca extractions with Mehlich 1 by both laboratories and Mehlich 3 by McGill are similar and therefore comparable. Average amounts of Ca for a tropical soil extracted with Mehlich 1 are between 4000 to10,000 $mgkg^{-1}$ (Name and Cordero, 1987). Compared to other tropical soils, amounts of Ca for the samples analyzed at both laboratories are considered low. Ca deficiencies in plants have repercussions on growth (California Fertilizer Association, 2001).

Available aluminium

Samples were analyzed with Mehlich 1 only at IDIAP and Mehlich 3 at McGill.

Soil profile

For the samples taken from the soil profile, results obtained from the extraction of Al with Mehlich 1 by IDIAP are much lower than the ones extracted with Mehlich 3 by McGill; 2.9 times lower for the O and A horizons (748 versus 259 $mgkg^{-1}$), 2.5 times lower for the B horizon (639 versus 260 $mgkg^{-1}$), and 2.3 times lower for the C horizon (597 versus 259 $mgkg^{-1}$), as indicated in Table 4.5. Al amounts seem to be constant throughout the soil profile based on results obtained by IDIAP (Figure 4.11). On the other hand, Al amounts seem to be constant for horizon O and A and then gradually decrease down to horizon C based on results obtained by McGill (Figure 4.11).

Pond area

The pond area samples were analyzed only with Mehlich 3. Amounts of Al are similar for Samples 2 and 3, but are lower for Sample 1 (Figure 4.11).

Field area

Again, results obtained from the extraction of Al with Mehlich 1 at IDIAP are much lower than the ones extracted with Mehlich 3 at McGill. Only one result was obtained for IDIAP since the four field samples were mixed together in order to get an average value for the entire field. This value is much lower than the results obtained by McGill (Figure 4.11). Al amounts are similar for Samples 1, 3 and 4 and lower for Sample 2 when extracted at McGill (Figure 4.11).

Average amounts of Al for a tropical soil extracted with Mehlich 1 are between 1620 to 2700 $mgkg^{-1}$ (Instituto de Investigación Agropecuaria de Panamá, 2002). Compared to other tropical soils, amounts of Al for the samples analyzed at the McGill laboratory are considered low and the ones obtained at IDIAP are very low. Tropical soils are usually characterized by high amounts of Al, which can cause toxicity to plants (Blamey *et al.*, 1991).

Available manganese

Samples were analyzed with Mehlich 1 only by IDIAP and Mehlich 3 by McGill.

Soil profile

For the samples taken from the soil profile, results obtained from the extraction of Mn with Mehlich 1 at IDIAP are much higher than the ones extracted with Mehlich 3 at McGill; 3.2 times higher for horizon O (449 versus 140 $mgkg^{-1}$), 2.3 times higher for horizon A (319 versus 139 $mgkg^{-1}$), 2.6 times higher for horizon B (130 versus 50 $mgkg^{-1}$), and 5.9 times higher for horizon (129 versus 22 $mgkg^{-1}$), as indicated in Table 4.5. Mn amounts seem to decrease sharply from horizon O to horizon B, and then stay constant down to horizon C, based on results obtained at IDIAP (Figure 4.12). On the other hand, Al amounts seem to be constant from horizon O to horizon A, then decrease sharply to horizon B and finally gradually decrease down to horizon C, based on results obtained at McGill (Figure 4.12).

Pond area

The pond area samples were analyzed only with Mehlich 3. Amounts of Mn are relatively similar for Samples 1, 2 and 3 (Figure 4.12).

Field area

Results obtained from the extraction of Mn with Mehlich 1 at IDIAP are lower than the ones extracted with Mehlich 3 at McGill, with the exception of Sample 2, which is higher than the results obtained at McGill. Only one result is obtained for IDIAP since the four field samples were mixed together in order to get an average value for the entire field. This value is lower than the results obtained at McGill (Figure 4.12). On the other hand, Mn amounts are similar for Samples 3 and 4 and lower for Samples 1 and 2 extracted at McGill (Figure 4.12).

Average amounts of Mn for a tropical soil extracted with Mehlich 1 are between 141 to 490 $mgkg^{-1}$ (Instituto de Investigación Agropecuaria de Panamá, 2002). Compared to other tropical soils, amounts of Mn for the samples analyzed at both laboratories are considered average to low. Mn deficiencies in plants can have negative repercussions on growth.

Organic matter content

The soils' organic matter content was analyzed solely in the IDIAP laboratory. Results show that organic matter content decreases from the O to the A horizon and then increases into the B horizon and finally decreases again into the C horizon, as shown in Figure 4.13. Organic matter content varies from 0.94 to 2.95 %. As for the field area, it was estimated that there is 2.95 % organic matter content overall. Average organic matter content for a tropical soil varies between 2 to 6 % (Instituto de Investigación Agropecuaria de Panamá, 2002). Compared to other tropical soils, organic matter content for the A and C horizons are considered low, and O and B horizons as well as the field area are considered average. Organic matter content is an important factor for soil fertility and ultimately crop yield. It is therefore important to conserve organic matter. Techniques used to preserve organic matter content include: reduced tillage or no-till, leaving plant residues on soil surface (or incorporated), crop rotations, and mulching.

Cation exchange capacity (CEC) and base saturation percentage (BSP)

The soils' CEC was analyzed solely at the McGill laboratory. Results show that CEC is relatively constant in the O and A horizons, and then increases sharply into the B horizon and gradually into the C horizon, as shown in Figure 4.14. CEC varies from 8.65 to 25.90 $cmol(+)kg^{-1}$. As for the pond area, CEC levels vary from 14.71 to 24.72 $cmol(+)kg^{-1}$. Finally, CEC levels vary from 14.92 to 24.10 $cmol(+)kg^{-1}$ for the field area. Average CEC for a tropical soil is of 13-25 $cmol(+)kg^{-1}$ (ILACO B.V., 1981). Compared to other tropical soils, CEC for the O and A horizons are considered low, and all other samples average. CEC will mostly have effects on the field area, since recommended liming and fertilization practices will vary with soil CEC. The soils' CEC corresponds to its ability to interact with and hold on to nutrients needed for plant growth. For example, soils having high CEC generally do not need to be limed as often as soils with low CEC.

The soils' BSP results show that levels are relatively constant in the O and A horizons, then increase sharply into the B horizon and stay constant throughout the C horizon (Figure 4.15). As for the pond area, BSP results do not vary greatly (Figure 4.15). Finally, BSP results obtained for the field area show that Samples 1 and 3 vary considerably from Samples 2 and 4 (Figure 4.15). BSP results for all samples vary between 90.00 and 99.54%. Average amounts of BSP for other tropical soils are of 41-60% (ILACO B.V., 1981). Compared to other tropical soils, BSP for the samples taken are considered as very high.

In conclusion, the Tierras Blancas site can be characterized as having a Clay Loam soil texture, acidic pH, with very low levels of P, low levels of K, Ca, and Al, average to low levels of Mn, and average levels of Mg (based on results obtained by the McGill laboratory) (Table 4.6). Results obtained at McGill from extracting solutions Mehlich 1 and 3 for K, P, Mg, and Ca follow the same trend. However, more samples would need to be analyzed in order to establish a certain correlation between the two solutions. The organic matter content is considered average, and levels of CEC are average to low (Table 4.6). As for the comparison of results obtained by the IDIAP laboratory in Panama and the McGill laboratory in Canada, the differences are mostly in the nutrient extraction analysis. Only one nutrient, P, obtained by the IDIAP is comparable and follows the same trend as the one obtained at McGill. Results for Ca follow the same trend for both laboratories but amounts estimated are not at the same scale. All other nutrients, K, Mg, Al and Mn do not follow the same trend and amounts estimated are not at the same scale. It is difficult to establish the reasons for such differences in results for both laboratories, especially due to the fact that control results from the IDIAP laboratory were not provided. Thus, there could have been a handling error and/or contamination of the samples and/or of the extracting solution and would not have been noted.

4.4 Pond storage capacity

Estimation of the pond storage capacity for the Tierras Blancas site was done using the Graphical Mass Curve Method. The only input needed for this method is cumulative runoff. Runoff was calculated using the Rational Method. First, a runoff coefficient C was estimated using Table 2.2, where a value of 0.36 was chosen (pasture vegetation, rolling topography, and Clay Loam soil texture). Then, precipitation data from La Mesa de Macaracas was put into the Rational Method formula, as well as a size of the catchment area of 2911 m^2 (established through site survey). Average monthly precipitation, estimated runoff and cumulative runoff are presented in Table 4.7. As indicated, runoff produced by the catchment area varies from 3 m^3 during February to 358 m^3 during October. Results obtained for the Tierras Blancas site from the Graphical Mass Curve Method are presented in Figure 4.16. Letters A and B indicate residual storage at the beginning of the wet season, and residual storage at the end of the dry season, respectively. These amounts are identical, and correspond to the 200 m^3 needed to maintain piscicultural activities in the pond. This amount was determined by consulting with local agricultural extension agents. The letter C in Figure 4.16 indicates pond storage requirement. This amount is estimated by first establishing cumulative water use by drawing a straight diagonal line from the point of origin (0,0) to the point corresponding to the amount of residual storage (letter B) on the cumulative runoff graph. Then, the largest area between cumulative runoff (bar graph) and water demand (straight line) is determined and represents pond storage requirement (Gould and Nissen-Petersen, 1999). For the Tierras Blancas site, the pond storage volume was estimated to be 822 m^3, based on the Graphical Mass Curve Method (Figure 4.16). Based upon topographic reality at the pond site, the pond was built to a volume of 429 m^3. There are several important factors affecting water demand for the site that were not considered in the Graphical Mass Curve Method estimate; First, the Graphical Mass Curve Method assumes that water demand is regular and continuous all year round. On the contrary, water demand is not continuous all year round for the Tierras Blancas site since water collected during the wet season is used only during the dry season. Second, the Graphical Mass Curve Method assumes that runoff is the only water source for the system.

However, there is more than one water source for the pond at the Tierras Blancas site (precipitation, runoff, a surface spring, and a seasonal stream).

In order to offer other alternatives to estimate pond storage requirement for water-harvesting systems similar to Tierras Blancas, other methods are examined in the following section.

4.5 Alternative methods for pond storage requirement

Three different pond storage requirement estimation methods are evaluated and compared with the Graphical Mass Curve Method. These methods were developed in order to compare pond sizes under the same site conditions but for different case scenarios. An evaluation was done to determine which method would be best for specific circumstances.

Annual water budget, average rainfall scenario

Pond storage requirement was estimated based on an annual water budget for an average rainfall scenario. For the Tierras Blancas site, average yearly precipitation was calculated using 19 years of daily precipitation data from the La Mesa de Macaracas meteorological station and average yearly evapotranpiration was calculated using 31 years of daily pan evaporation data from the Los Santos meteorological station. For the Tierras Blancas site, potential evapotranspiration was assumed to be equal to average annual pan evaporation, given that vegetation within the field is short (Linsley *et al.*, 1982; Brutsaert, 1982). As results indicate, water supply estimated using this method is 3,149 m^3 (Table 4.8), where runoff was calculated using the Rational Method and all other variables were calculated as described in section 3.7. As for water demand, it was estimated at 984 m^3 (Table 4.8). Pond storage requirement is obtained by subtracting water demand from supply, giving a value of 2,165 m^3. See Appendix 3 for calculation details. For design purposes, drainage overflow is usually assumed to be zero for the first year after pond implementation (Table 4.8).. Clearly, the amount of overflow depends on pond size, and this is what we are estimating. The assumption is based on an iterative approach, where you cannot estimate overflow before estimating pond size, and vice versa.

Annual water budget, 1 in 15 dry-year scenario

Pond storage requirement was then estimated based on an annual water budget for a 1 in 15 dry-year scenario. This allows farmers to balance risk of having a drier year (compared to a more common event such as a 1 in 10 or 1 in 5 dry-year) against costs and benefits. To calculate a 1 in 15 year case scenario, the 'standard normal transformation' was used (Viessman and Lewis, 1996). For Tierras Blancas site, this transformation was based on the 19 years of precipitation data from La Mesa de Macaracas, and the 31 years of pan evaporation data from Los Santos. Again, it was assumed that potential evapotranspiration was equal to pan evaporation. There was not enough long-term data to perform a 'standard normal transformation' to estimate the surface spring and stream yield for a 1 in 15 dry-year, but given that yield varies with precipitation it was assumed that they would differ from the average year yield as much as the difference between average rainfall and 1 in 15 dry-year rainfall (Appendix 3). As results indicate, water supply estimated using this method is 2,357 m^3 and water demand is 1,045 m^3 (Table 4.8). As generally is the case for a drier year, water supply is less and water demand is more than an average rainfall year. Pond storage requirement is obtained by subtracting water demand from supply, giving a value of 1,312 m^3 (Table 4.8). See Appendix 3 for detailed calculations. Again, overflow estimation was based on the same iterative approach as stated in the previous method.

Dry season demand versus supply, average year scenario

Pond storage requirement was also estimated based on dry season water demand versus supply for an average year scenario. For this approach, the pond is designed based on dry season water outflows and inflows. As water supply is relatively low during this period, pond size relies almost entirely on dry season water demand. For Tierras Blancas site, results show that water supply is 97 m^3 and 816 m^3 for water demand (Table 4.8). With this method, the pond is designed to meet the dry season supply and therefore is empty at the end of this period. However, if the producer needs to have a residual storage of water within the pond, then the residual storage requirement should be added to the total pond volume. In the example calculation, the pond size needed is 919 m^3 (Table 4.8). This method is easily understandable and gives an estimate of minimum pond storage requirement to irrigate throughout the dry season. See detailed calculations in Appendix 3.

The three previous methods give a good estimate of what is actually happening within the field, assuming that the estimation of each variable was calculated to reflect reality. Compared to the Graphical Mass Curve Method, these three methods take into consideration variations in water demand for different times of the year as opposed to continuous, and also allow the input of other water sources. However, estimation of pond storage varies a lot from one method to the other. The largest estimation of pond volume requirement was obtained with the average rainfall water budget (2,165 m^3), followed by the 1 in 15 dry-year water budget (1,312 m^3), the dry season demand versus supply (919 m^3), and finally the Graphical Mass Curve Method (822 m^3) (Table 4.8). The actual pond constructed at Tierras Blancas is 429 m^3. Therefore, if the pond had been designed to catch all the water entering the system for an average rainfall year, it would have had to be much larger in size. Therefore, determination of pond size depends on the farmers' needs, preferences, economic ability, and topography of the site. For example, the average rainfall water budget should be used when there is high water demand and no topographic restrictions as to the size of the area designated for the pond. As for the 1 in 15 dry-year water budget, it should be used in situations where water demand is higher than usual, farmer wants a medium size pond if topography permits, and also farmer wants to use the pond water as a backup during drier years when water supply is lower than average rainfall years. Finally, the dry season demand versus supply method should be used when the farmer is not interested in having a large pond, or topography of the site restricts the size, and water demand is low.

For the particular example of Tierras Blancas, the farmer was interested in collecting water for irrigation of a small field only during the dry season, and for small-scale pisciculture. Therefore, since water demand was low and to be used only during the dry season, and topography restricted pond size, the dry season demand versus supply method would have been best for pond size estimation. The pond would have been approximately 900 m^3 compared to the actual 429 m^3.

4.6 Length of time needed to fill pond

Water collected at the Tierras Blancas site is used only during the dry season. Therefore, an estimation to determine how long it would take to fill the remainder of the pond after the end of the dry season (end of April) was applied to each pond size. Firstly, the volume of water left in the pond at the end of the dry season had to be determined. To do so, it was assumed that the pond was full at the beginning of the dry season. The volume of water left inside the pond was determined by adding dry season inflows and subtracting outflows from the total pond volume. Then, monthly inflows were added until total pond volume was full. As results indicate, it would take a total of 1.97 months to fill a 2,165 m^3 pond, 2.18 months for 1,312 m^3, 1.43 months for 919 m^3, and 1.97 months for 822 m^3 (Table 4.9). As for the actual pond constructed, it would take 1.20 months to fill the 429 m^3 pond. See Appendix 4 for detailed calculations. The actual pond constructed at Tierras Blancas would be too small to meet water demand for the duration of the dry season. Since the Tierras Blancas pond has already been constructed, then attention should be given on management of the harvested water. For example, crops should be carefully selected based on their water requirements and avoid high-demanding crops (ex: tomato, maize, sugar cane). In addition, implementation of a more effective irrigation system could help reduce water demand (ex: drip irrigation).

At the beginning of the wet season, the pond will start to fill up again. When the pond will have attained its full capacity, all further water entering it will be lost through drainage overflow. Amount of overflow can cause erosion if spillway is not properly vegetated. These amounts can be important in volume, depending on the size of the pond and the amount of water remaining at the end of the dry season. If producers wish to take advantage of this water, some drainage overflow management techniques exist and include: building other ponds adjacent to the main pond to collect overflow, and managing a plot adjacent to the pond to produce crops that rely on overflow during the wet season.

4.7 Decision support system

Four different programs have been developed in order to facilitate the estimation of pond storage requirement for a variety of case scenarios. The programs were designed in Microsoft Office 2000 Excel, using the Visual Basic tools. The programs are specifically designed for the Arco Seco region of Panama, since data from local meteorological stations was inputted into the programs. However, it is possible to manually input data from other stations than the ones listed. With minor modifications, the DSS is applicable to other regions. The programs are user-friendly and straightforward. For more specific details regarding the use of the programs, consult the Instruction Manual included in the Compact Disc in Appendix 5. To try the actual programs, they are located within the Compact Disc in Appendix 5.

As demonstrated in section sections 4.4 and 4.5 (see Table 4.8), required pond size for the same site may differ greatly depending on the estimation method. The selection of which program to use for a particular site will depend on the sites' characteristics, and water demand and supply. For example, if a ponds' only water source is runoff, and water demand is constant throughout the year, then the Graphical Mass Curve Method program should give a good estimate on the pond size required. On the other hand, if a pond has various water sources, and water demand is not constant throughout the year, then one of the three other programs should be selected. Moreover, if water demand is high and topography does not restrict pond size, then the Water Budget, Average Year Scenario program should be selected. Conversely, if water demand is even higher, topography does not restrict pond size, and farmer wants to use the pond water as a backup during drier years, then the Water Budget, 1 in 15 Dry-Year Scenario program should be selected. Alternatively, if water demand is low and topography restricts pond size, then the Dry Season Demand versus Supply program should be selected.

Each of the programs is write-protected so that information written within cells, and formulas associated are not changed mistakenly. Only certain cells can be filled in manually: the ones highlighted in yellow. Therefore, if someone wants to change or add an element to the programs, they will have to contact the program developer in order to obtain the permission and protection password.

Now that the Decision Support System has been developed, the next phase consists in its distribution to agricultural extension agents in the Arco Seco region of Panama. The first group that will be approached with the system will be the Ministry of Agriculture (Ministerio de Desarrollo Agropecuario; MIDA) in Santiago. Some of the directors and extension agents working at this branch had a general interest in constructing more ponds in the area, and also had a specific interest in the Tierras Blancas project since it's beginning. These extension agents usually work directly with small-scale farmers in the area of the Arco Seco. After distributing the DSS, there will be a trial period in order to make sure that the extension agents understand the functioning of the programs well, and to see if they have any suggestions.

The programs were designed in English for the purpose of this thesis, however a Spanish version of the programs will be available for extension agents working in Panama and in Latin America.

Table 4.1
Results for the soil profile description for the Tierras Blancas site.

Characteristic	O horizon	A horizon	B horizon	C horizon
Soil structure	Blocky	Blocky	Blocky	Blocky
Soil texture	Moist cast test: easy to squeeze Ribbon test: short Feel test: Stickiness: slight Graininess: smooth Dry feel: less than 50 % sand Taste test: somewhat gritty Shine test: moderately shiny **Soil texture: Loam**	Moist cast test: somewhat hard to squeeze Ribbon test: medium Feel test: Stickiness: somewhat Graininess: smooth Dry feel: less than 50 % sand Taste test: smooth with no grit Shine test: very shiny **Soil texture: Clay Loam**	Moist cast test: somewhat hard to squeeze Ribbon test: medium Feel test: Stickiness: somewhat Graininess: smooth Dry feel: less than 50 % sand Taste test: smooth with no grit Shine test: very shiny **Soil texture: Clay Loam**	Moist cast test: somewhat hard to squeeze Ribbon test: medium Feel test: Stickiness: somewhat Graininess: smooth Dry feel: less than 50 % sand Taste test: smooth with no grit Shine test: very shiny **Soil texture: Clay Loam**
Presence of roots	Few	Few	Few	None
Presence of rocks	None	None	None	None

Table 4.2 Results for the terrain description for the pond area of the Tierras Blancas site.

Slope	Site position	Soil drainage	Presence of mottles
Gentle slope	Depression	Very poor	a) Abundance - common (2-20%) b) Dimension - fine (< 5mm)

Table 4.3
Soil texture obtained from particle size analysis for soil samples taken from Tierras Blancas site. Results from both McGill and IDIAP laboratories are compared.

Sample	Soil Texture	
	McGill	IDIAP
Soil profile		
O horizon	Loam	Loam
A horizon	Clay Loam	Clay Loam
B horizon	Clay Loam	Clay Loam
C horizon	Clay Loam	Clay
Pond area		
Sample 1	Loam	*
Sample 2	Clay Loam	*
Sample 3	Clay Loam	*
Field area		
Sample 1	Loam	Clay Loam
Sample 2	Clay Loam	
Sample 3	Loam	
Sample 4	Clay Loam	

* Result not available

Table 4.4
pH obtained for soil samples taken from Tierras Blancas site. Results from both McGill and IDIAP laboratories are compared.

Sample	pH		
	McGill		IDIAP
	pH ($CaCl_2$)	Equivalent pH (H_2O)	pH (H_2O)
Soil Profile			
O horizon	4.89	5.39	5.7
A horizon	4.97	5.47	5.9
B horizon	5.41	5.91	6.0
C horizon	5.52	6.02	6.2
Pond area			
Sample 1	4.86	5.36	*
Sample 2	5.11	5.61	*
Sample 3	5.51	6.01	*
Field area			
Sample 1	5.36	5.86	
Sample 2	4.42	4.92	5.1
Sample 3	5.22	5.72	
Sample 4	5.53	6.03	

* Result not available

Table 4.5
Results obtained from the extraction of nutrients K, P, Mg, Ca, Al and Mn ($mgkg^{-1}$) using extracting solutions Mehlich 1 and Mehlich 3. Results from both laboratories are compared.

Samples	Mehlich 1		Mehlich 3	Mehlich 1		Mehlich 3	Mehlich 1		Mehlich 3	Mehlich 1		Mehlich 3
	McGill	IDIAP	McGill	McGill	IDIAP	McGill	McGill	IDIAP	McGill	McGill	IDIAP	McGill
	K ($mgkg^{-1}$)			P ($mgkg^{-1}$)			Mg ($mgkg^{-1}$)			Ca ($mgkg^{-1}$)		
Soil profile												
O	39	389	45	0.751	Traces	0.1794	738	1124	867	1455	1575	1665
A	21	349	43	0.298	Traces	0.1096	956	1817	1215	1514	2291	1952
B	48	310	43	0.435	Traces	0.0899	1079	1678	1428	1608	2397	2058
C	51	279	45	0.315	Traces	0.1593	1225	1685	1603	1354	2031	1872
Pond area												
Sample1	35	*	24	2.385	*	1.1377	659	*	739	1856	*	1816
Sample2	29	*	20	0.525	*	-0.1498	609	*	729	1198	*	1318
Sample3	48	*	10	0.362	*	-0.0198	625	*	708	1230	*	1369
Field area												
Sample1	17		16	1.425		0.3571	228		268	933		992
Sample2	14	278	10	0.266	Traces	-0.0400	569	322	709	1119	972	1378
Sample3	16		12	1.654		-0.0496	218		258	1082		1102
Sample4	14		16	0.328		-0.0599	269		314	492		529

* Result not available

Table 4.5 (con't)

Samples	Extractants			
	Mehlich 1	Mehlich 3	Mehlich 1	Mehlich 3
	IDIAP	McGill	IDIAP	McGill
	Al ($mgkg^{-1}$)		Mn ($mgkg^{-1}$)	
Soil profile				
O	259	748	449	140
A	259	757	319	139
B	260	639	130	50
C	259	597	129	22
Pond area				
Sample1	*	798	*	53
Sample2	*	938	*	98
Sample3	*	933	*	127
Field area				
Sample1		793		238
Sample2	387	999	198	160
Sample3		844		316
Sample4		858		319

* Result not available

Table 4.6
Summary of soil analysis results

Soil texture	pH	Nutrient Extraction (based on results obtained at McGill)						O.M.	CEC
		P	K	Ca	Al	Mn	Mg		
Loam to Clay Loam	acidic	Very low	Low	Low	Low	Average to Low	Average	Average	Average to Low

Table 4.7
Monthly average precipitation for meteorological station of La Mesa de Macaracas for 19 years of data (1980-1998), and monthly and cumulative runoff produced by the pond catchment area. Estimates were done using the Rational Method.

Months	Average Precipitation (mm)	Runoff (m^3)	Cumulative Runoff (m^3)
May	224.0	235	235
June	237.5	249	484
July	171.4	180	664
August	211.3	221	885
September	279.5	293	1178
October	341.5	358	1536
November	219.7	230	1766
December	58.1	61	1827
January	14.0	15	1842
February	2.6	3	1845
March	6.2	7	1852
April	68.5	72	1924

Table 4.8
Pond storage requirement based on four different methods of estimation. Methods are compared to actual pond constructed.

	Methods				
Water supply (inputs)	**Water budget (average year)**	**Water budget (1 in 15 dry year)**	**Dry season demand versus supply (average year)**	**Graphical Mass Curve**	**Actual pond constructed**
Precipitation (mm)	1831.2	1369.0	91.3	-	-
Runoff (m^3)	1919.0	1435.0	0	-	-
Surface spring (m^3)	873.5	655.1	66.0	-	-
Seasonal stream (m^3)	14.4	10.8	14.4	-	-
Total (m^3)	**3149**	**2357**	**97**	Cum. runoff: **1766**	-
Water demand (outputs)					
Irrigation (m^3)	649.0	649.0	649.0	-	-
Animal watering (m^3)	0	0	0	-	-
Evapotranpiration (mm)	1791.5	2117.0	892.0	-	-
Seepage (mm)	0	0	0	-	-
Drainage overflow (m^3)	0	0	0	-	-
Total (m^3)	**984**	**1045**	**816**	Cum. water use: **944**	-
Residual storage (m^3)	No need	No need	200	200	-
Pond storage requirement (m^3)	**2165**	**1312**	**919**	**822**	**429**

Table 4.9

Length of time needed to fill pond based on storage requirements determined by the four estimation methods.

	Water budget (average year)	Water budget (1 in 15 driest year)	Dry season demand versus supply	Graphical Mass Curve	Actual pond constructed
Pond surface area (m^2)	187	187	187	187	143
Pond storage requirement (m^3)	2165	1312	919	822	429
Dry season demand (m^3)	816	843	816	816	777
Dry season supply (m^3)	97	51	97	97	93
Amount left at end of dry season (m^3)	1446	520	200	103	EMPTY
Amount to fill (m^3)	719	792	519	719	429
May					
Water input					
Precipitation (mm)	224	224	224	224	224
Runoff (m^3)	235	235	235	235	235
Surface spring (m^3)	109	109	109	109	109
Water output					
Evapotranspiration (mm)	157	157	157	157	157
Total (m^3)	357	357	357	357	354
Amount left to fill (m^3)	**362**	**435**	**162**	**362**	**75**
June					
Water input					
Precipitation (mm)	238	238	238	238	238
Runoff (m^3)	249	249	249	249	249
Surface spring (m^3)	106	106	106	106	106
Water output					
Evapotranspiration (mm)	106	106	106	106	106
Total (m^3)	380	380	380	380	380
Amount left to fill (m^3)	**FULL**	**55**	**FULL**	**FULL**	**FULL**

Table 4.9 (con't)

July					
Water input					
Precipitation (mm)	-	171	-	-	-
Runoff (m^3)	-	179	-	-	-
Surface spring (m^3)	-	109	-	-	-
Water output					
Evapotranspiration (mm)	-	110	-	-	-
Total (m^3)	-	299	-	-	-
Amount left to fill (m^3)	-	**FULL**	-	-	-
Total time to fill pond (month)	**1.97**	**2.18**	**1.43**	**1.97**	**1.20**

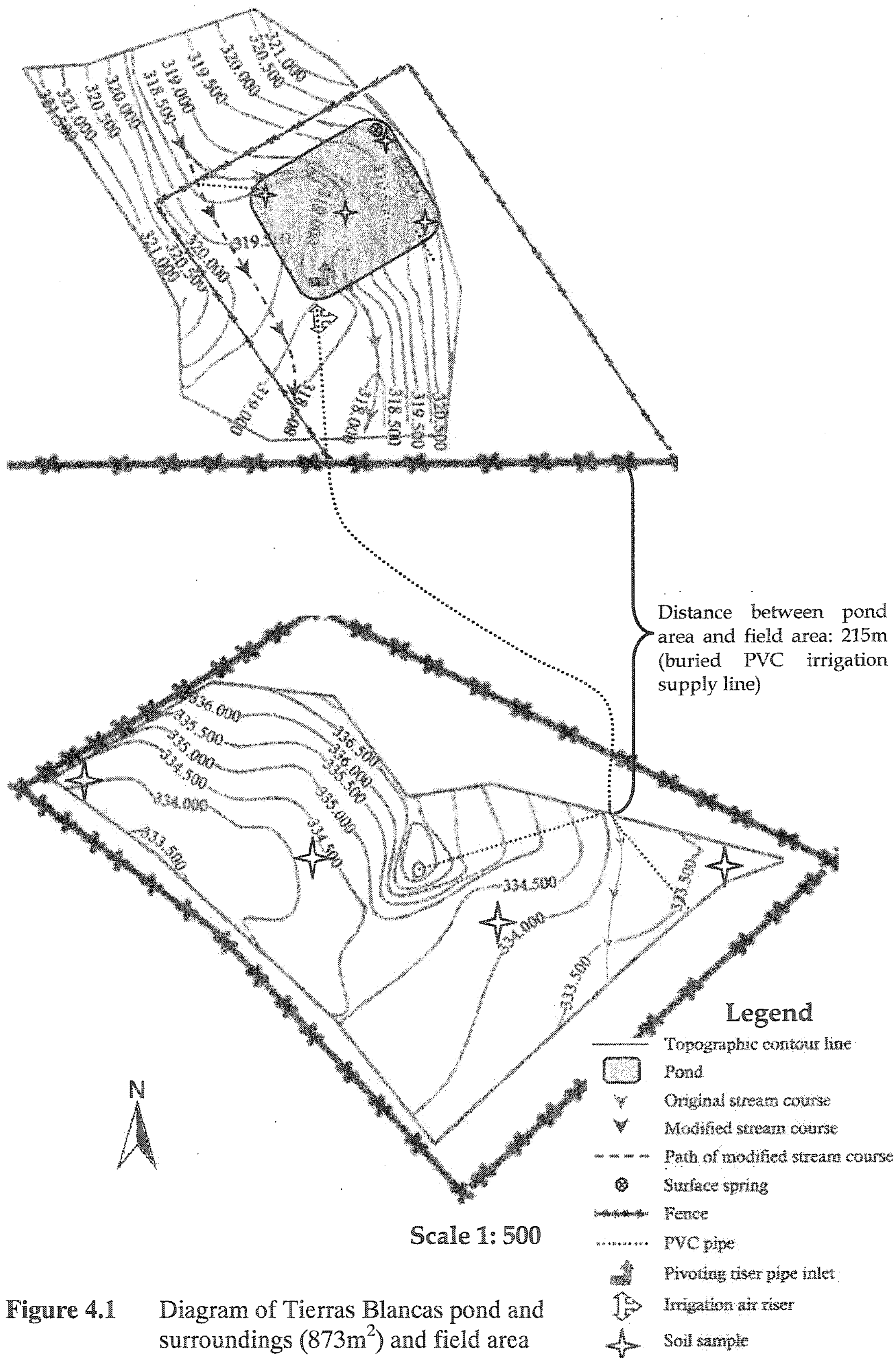


Figure 4.1 Diagram of Tierras Blancas pond and surroundings (873m^2) and field area (0.3 ha)

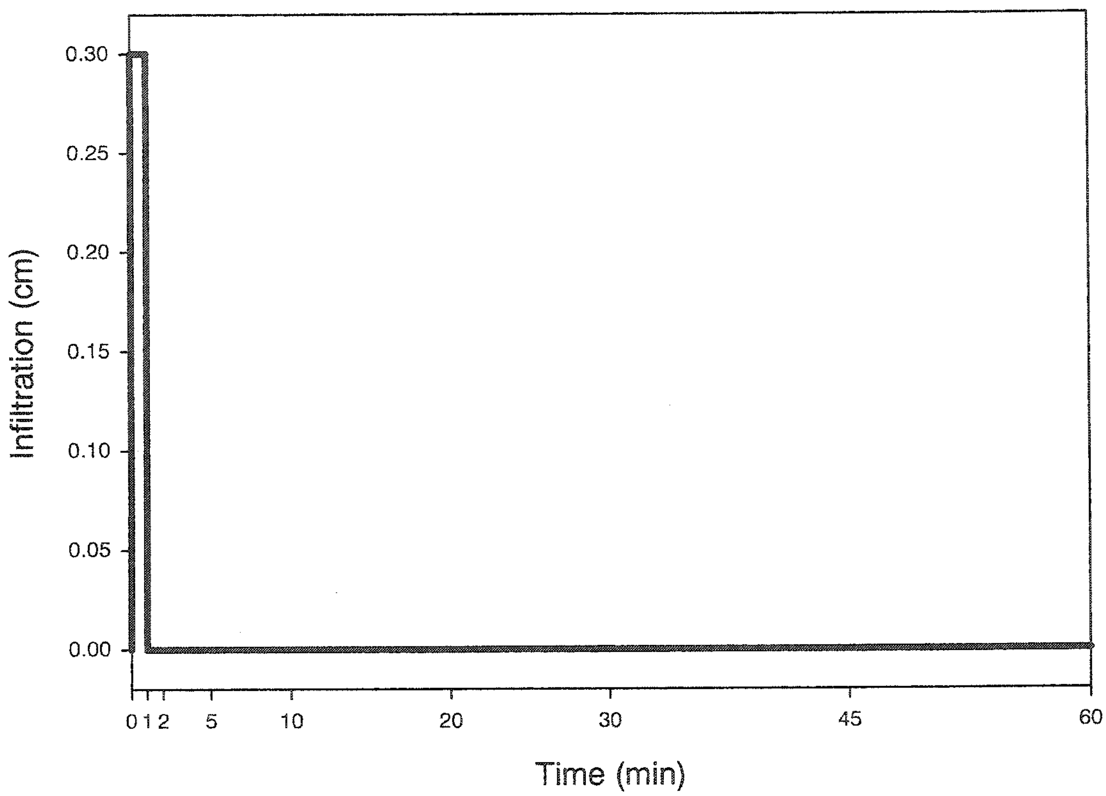
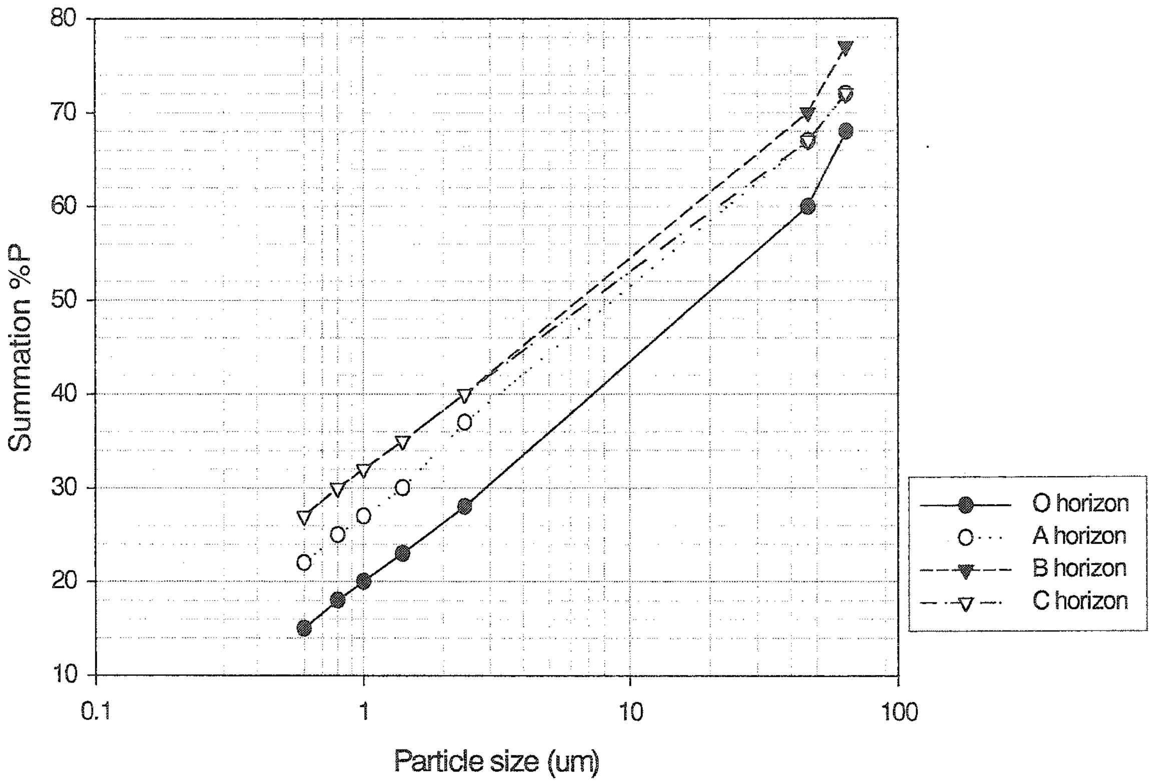
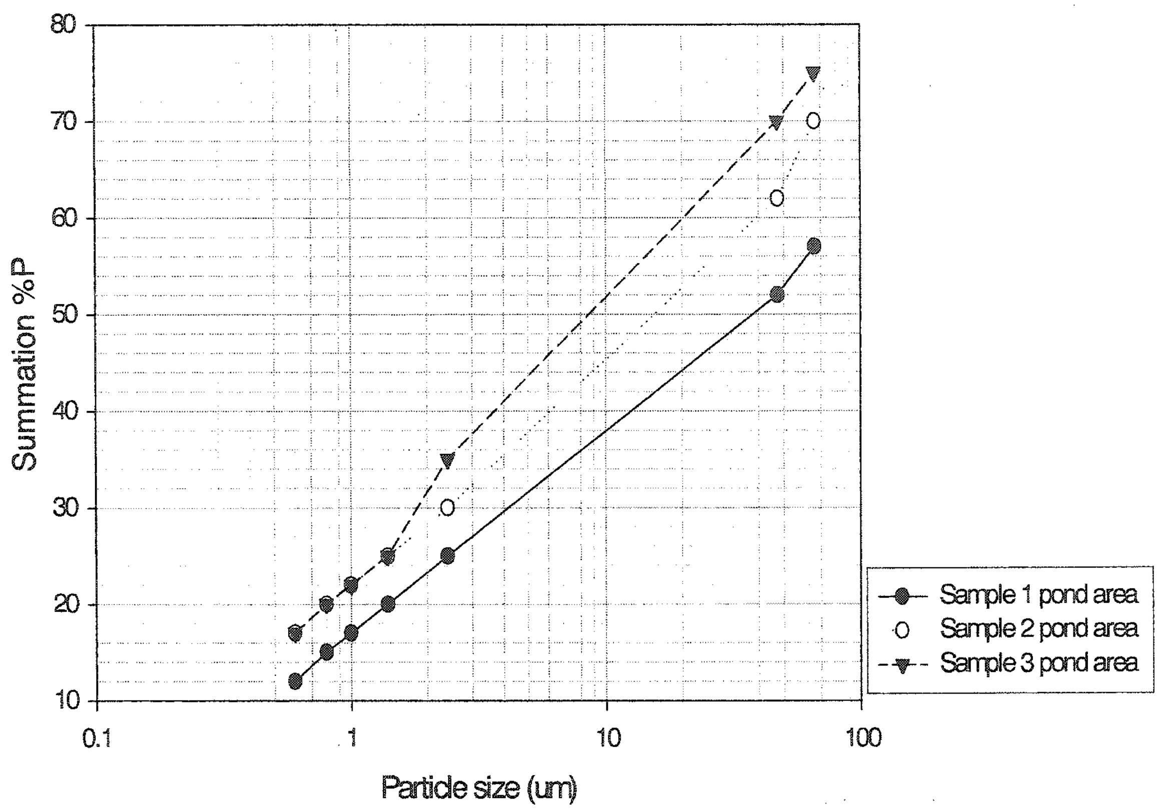


Figure 4.2 Water infiltration results for the pond site.



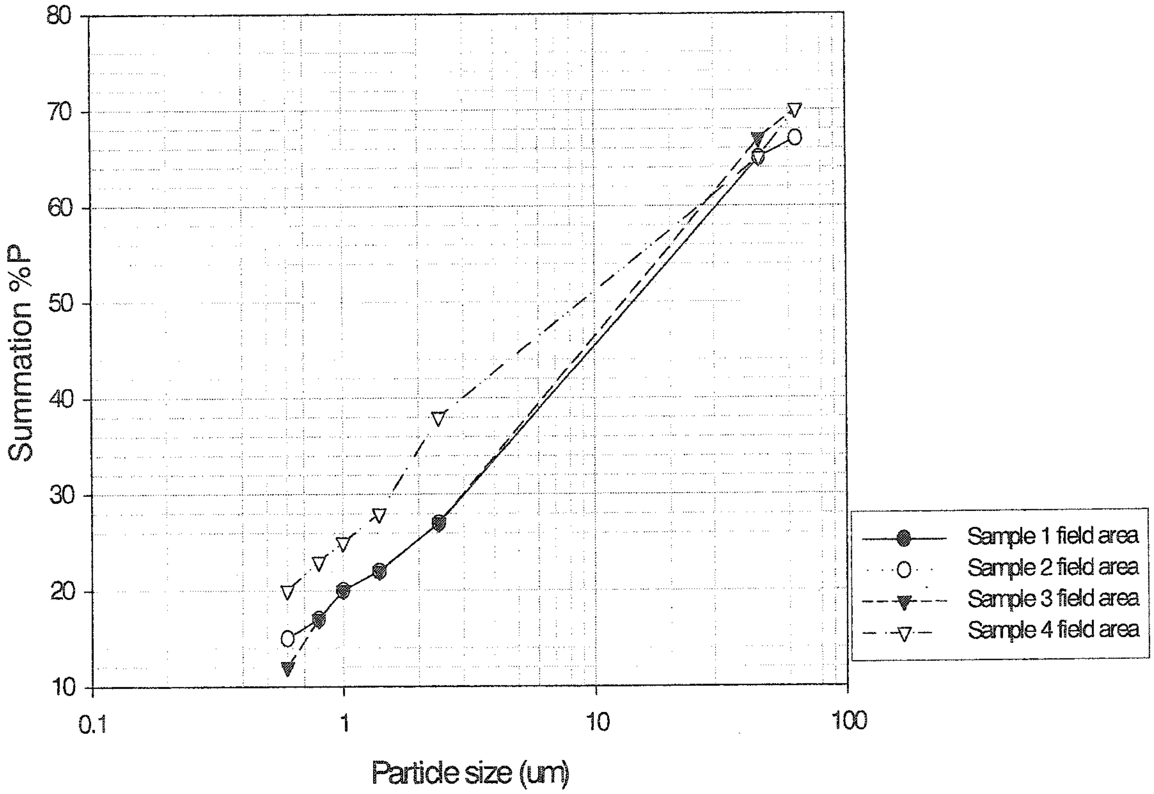
O horizon: 26% Clay, 41.5% Silt, 32.5% Sand; Loam
A horizon: 35% Clay, 37.5% Silt, 27.5% Sand; Clay Loam
B horizon: 38.5% Clay, 39% Silt, 22.5% Sand; Clay Loam
C horizon: 38.5% Clay, 33.9% Silt, 27.6% Sand; Clay Loam

Figure 4.3 Particle size analysis performed at the McGill University soil laboratory for samples taken from soil profile.



Sample 1: 23.5% Clay, 34% Silt, 42.5% Sand; <u>**Loam**</u>
Sample 2: 28.5% Clay, 41.4% Silt, 30.1% Sand; <u>**Clay Loam**</u>
Sample 3: 32% Clay, 43% Silt, 25% Sand; <u>**Clay Loam**</u>

Figure 4.4 Particle size analysis performed at the McGill University soil laboratory for samples taken from pond area. Sample 1 was taken adjacent to the surface spring located on the Northeast corner of the pond, Sample 2 was taken from the Northwest corner of the pond, and Sample 3 was taken from the Southeast corner.



Sample 1: 25% Clay, 42.4% Silt, 32.6% Sand; Loam

Sample 2: 30.5% Clay, 41.9% Silt, 27.6% Sand; Clay Loam

Sample 3: 25% Clay, 45% Silt, 30% Sand; Loam

Sample 4: 35% Clay, 35% Silt, 30% Sand; Clay Loam

Figure 4.5 Particle size analysis performed at the McGill University soil laboratory for samples taken from field area. The samples were taken 20m apart throughout the field, where Sample 1 was taken from the furthest point West of the field, and Sample 4 from the furthest point East.

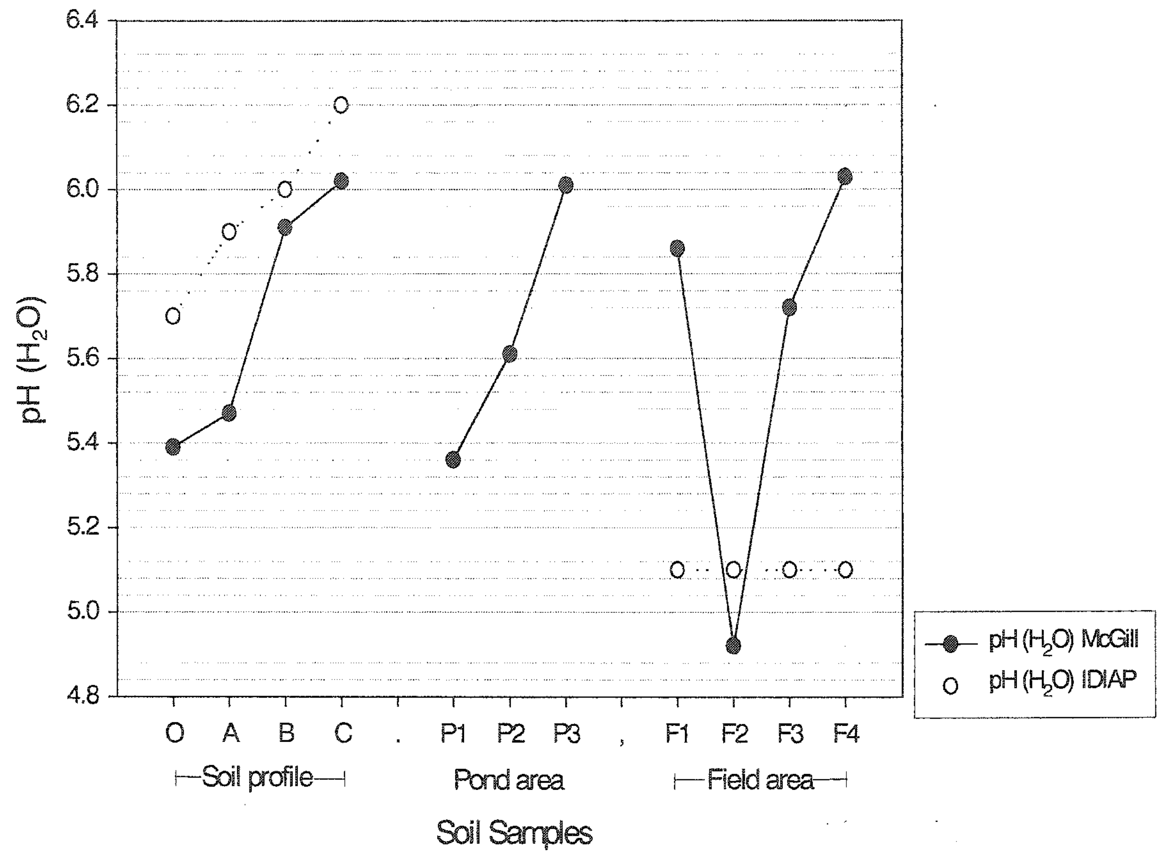


Figure 4.6 pH of soil samples taken from soil profile, pond area and field area. Results from both McGill and IDIAP laboratories are compared.

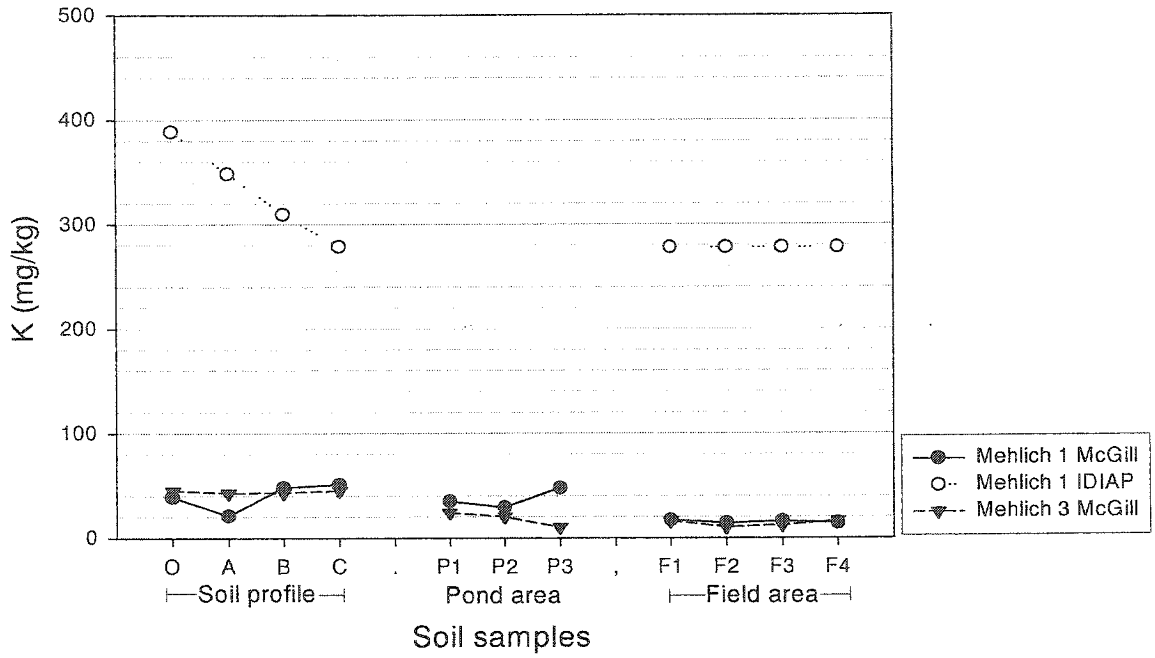


Figure 4.7 Potassium extractions of soil samples taken from soil profile, pond area and field area. Results for Mehlich 1 extractions from both McGill and IDIAP laboratories are compared and results for Mehlich 3 extractions from McGill laboratory are illustrated.

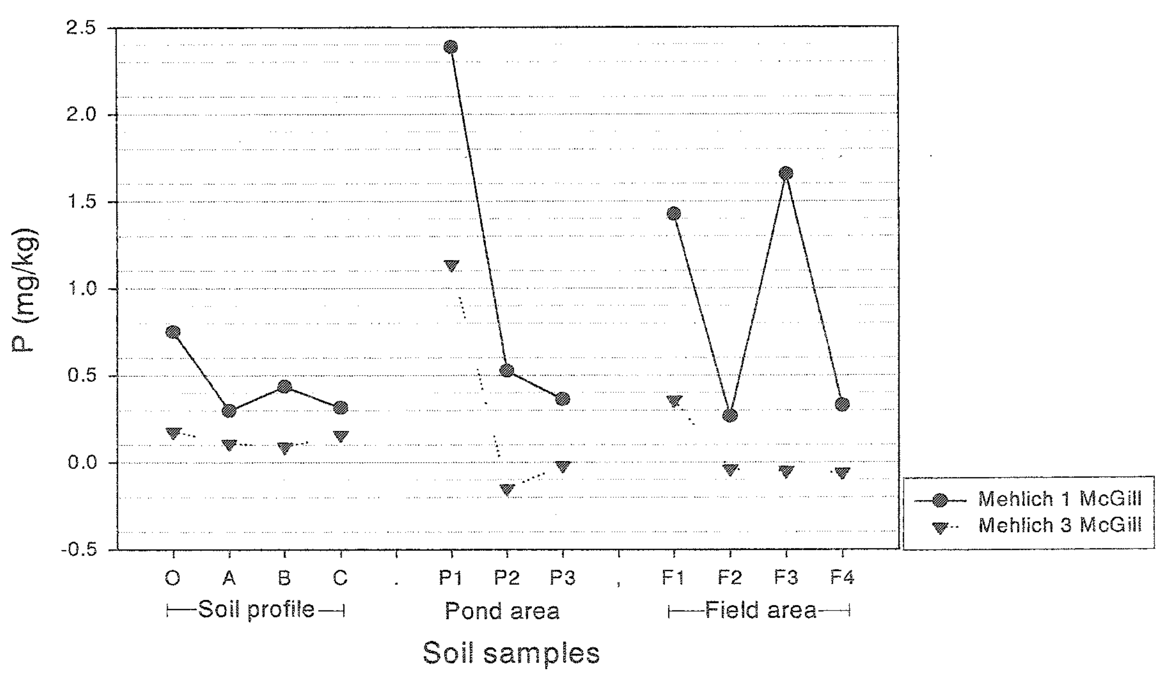


Figure 4.8 Phosphorus extractions of soil samples taken from soil profile, pond area and field area. Results for Mehlich 1 and Mehlich 3 extractions from McGill laboratory are compared.

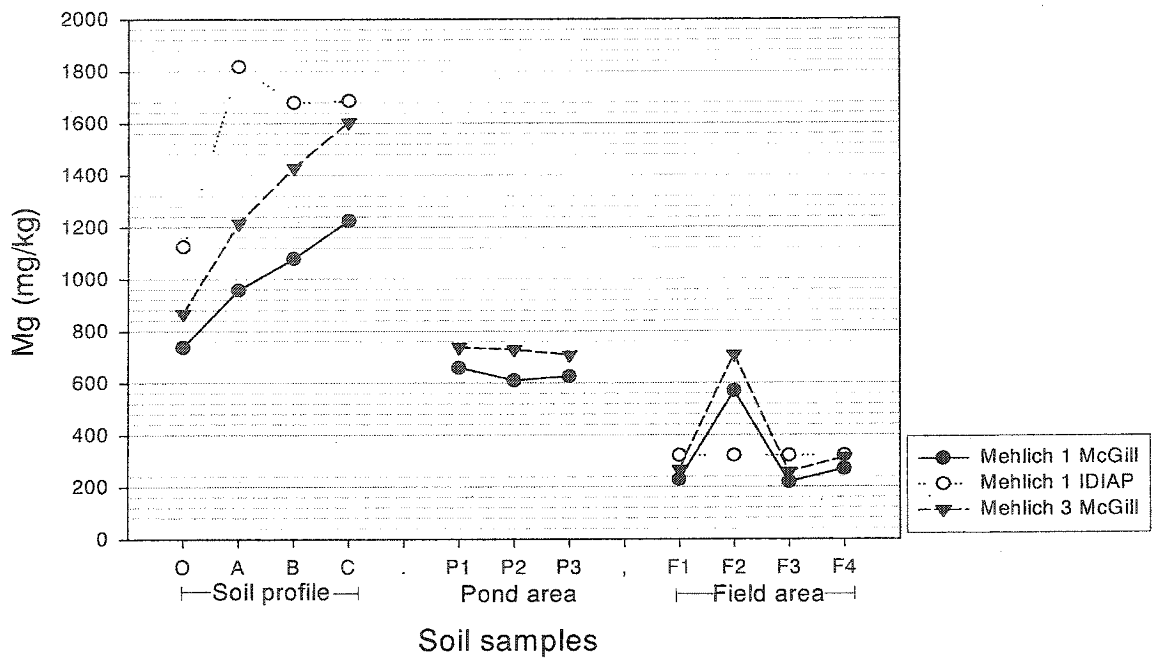


Figure 4.9 Magnesium extractions of soil samples taken from soil profile, pond area and field area. Results for Mehlich 1 extractions from both McGill and IDIAP laboratories are compared and results for Mehlich 3 extractions from McGill laboratory are illustrated.

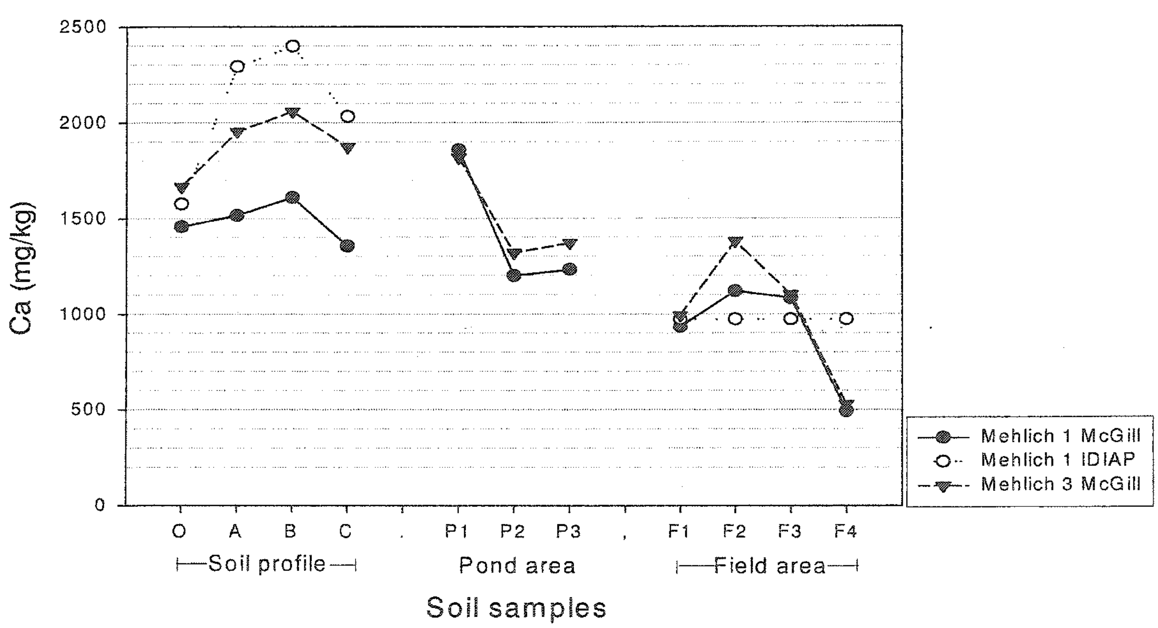


Figure 4.10 Calcium extractions of soil samples taken from soil profile, pond area and field area. Results for Mehlich 1 extractions from both McGill and IDIAP laboratories are compared and results for Mehlich 3 extractions from McGill laboratory are illustrated.

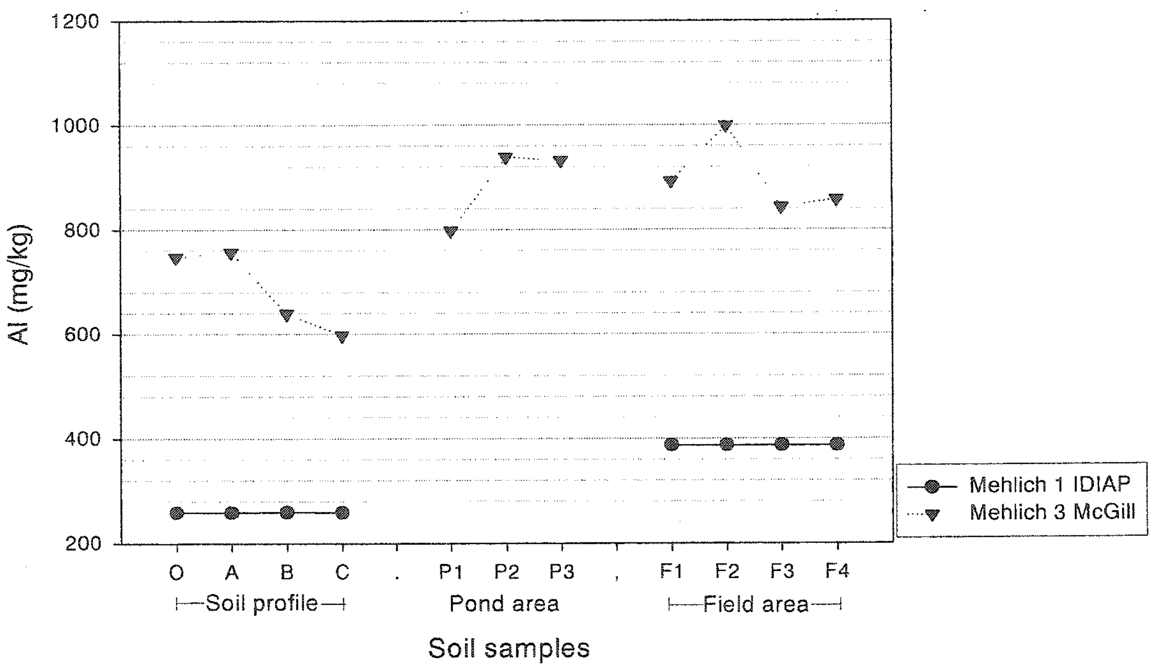


Figure 4.11 Aluminium extractions of soil samples taken from soil profile, pond area and field area. Results for Mehlich 1 from IDIAP laboratory and Mehlich 3 extractions from McGill laboratory are compared.

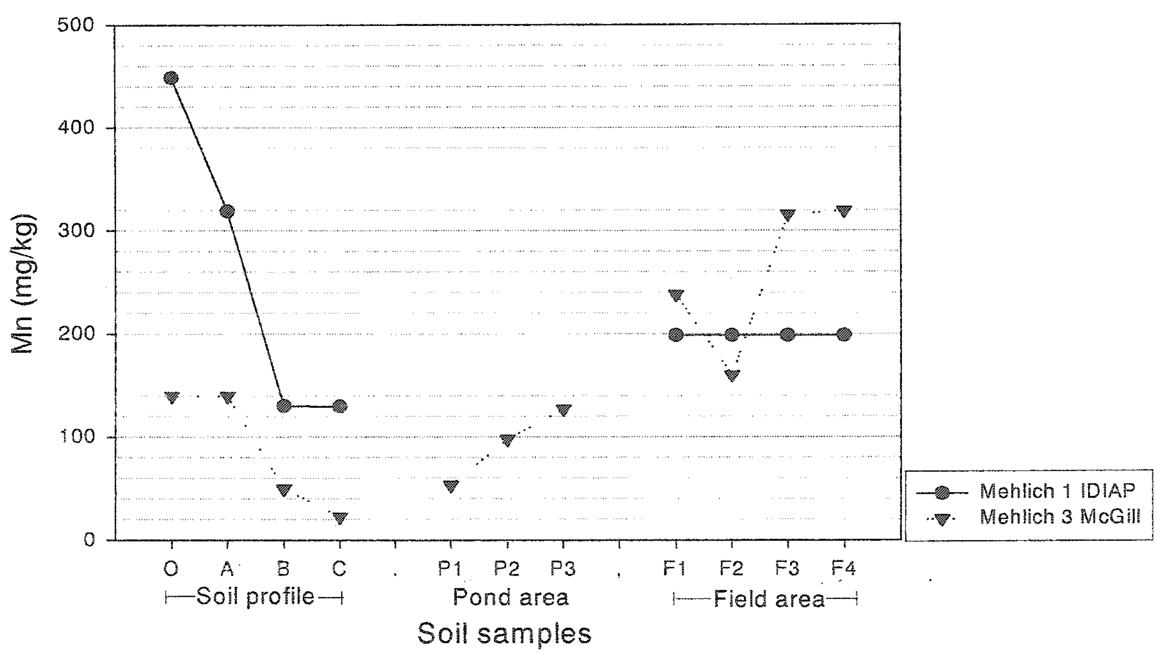


Figure 4.12 Manganese extractions of soil samples taken from soil profile, pond area and field area. Results for Mehlich 1 from IDIAP laboratory and Mehlich 3 extractions from McGill laboratory are compared.

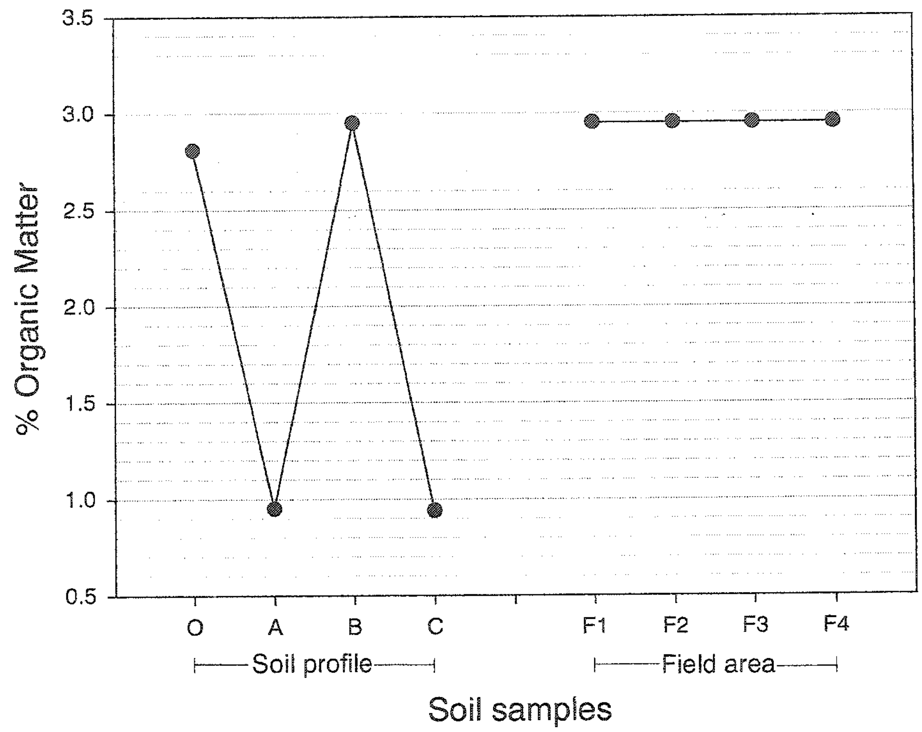


Figure 4.13 Percent organic matter content of soil samples taken from soil profile and field area analyzed by the IDIAP laboratory.

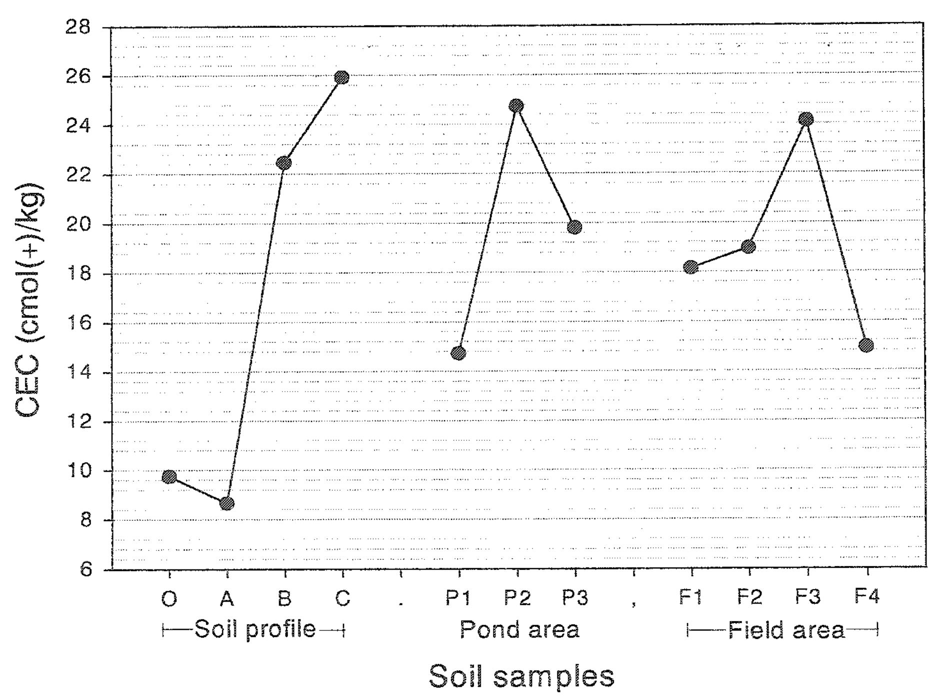


Figure 4.14 Cation exchange capacity of soil samples taken from soil profile, pond area, and field area analyzed by the McGill laboratory.

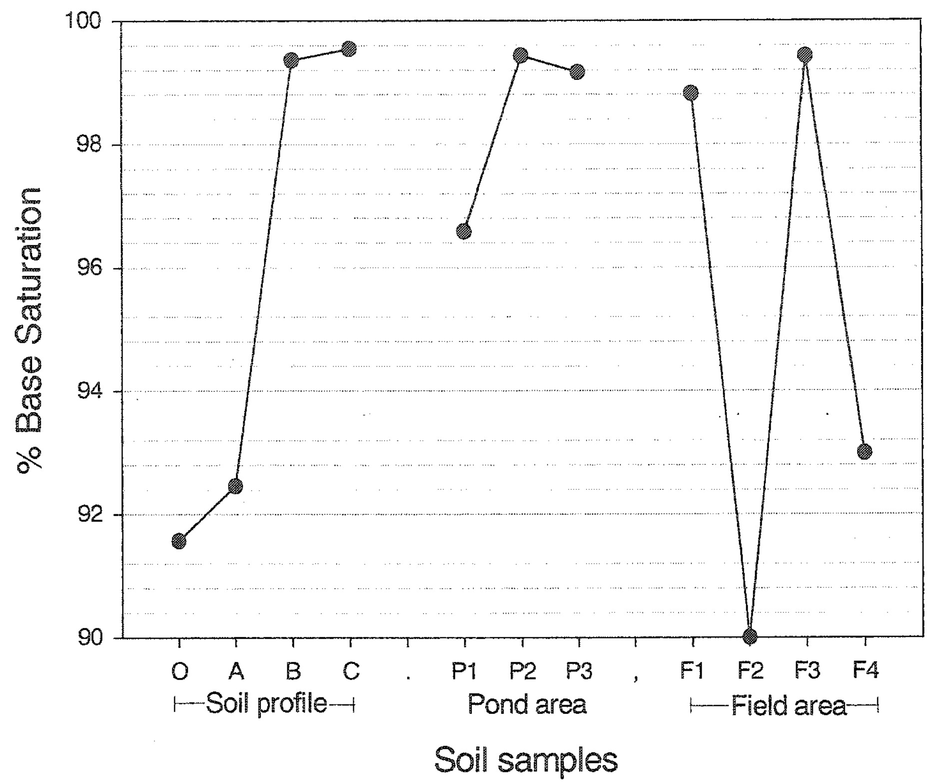


Figure 4.15 Percent base saturation of soil samples taken from soil profile, pond area, and field area analyzed by the McGill laboratory.

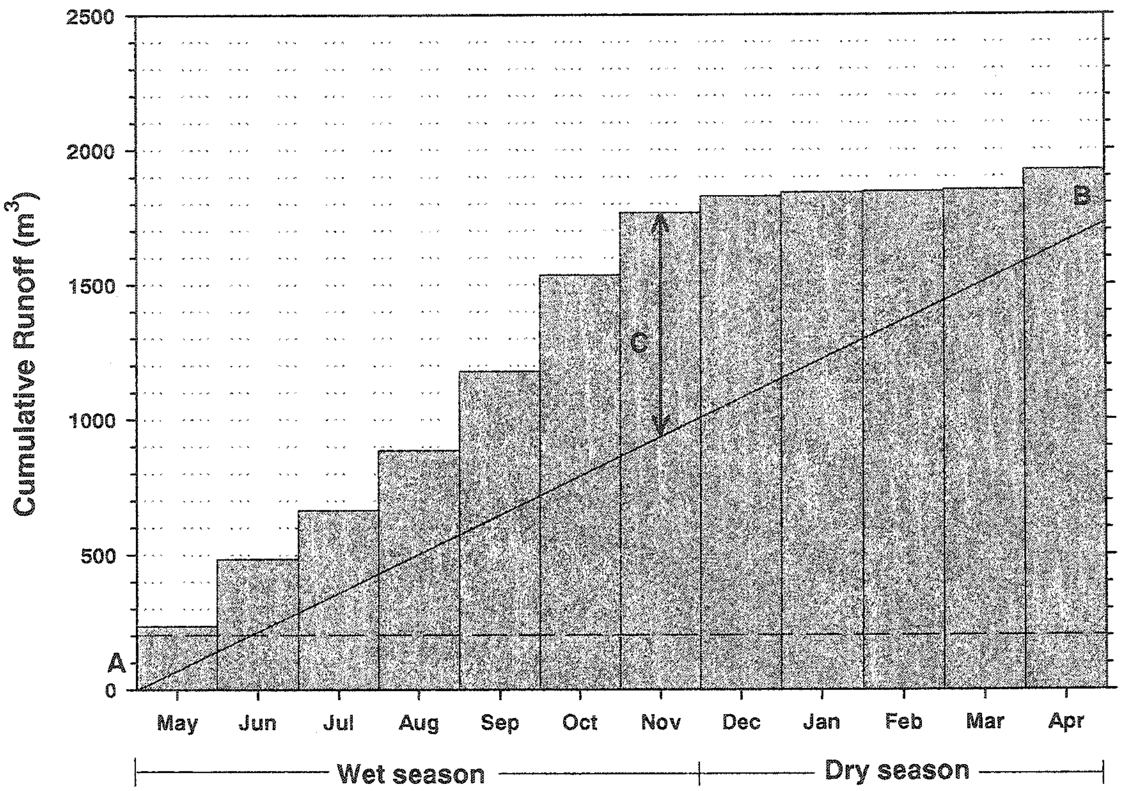


Figure 4.16 Approximate pond storage requirement estimated using the Graphical Mass Curve Method.

A Residual storage (200m^3): amount of water remaining in pond at beginning of the wet season.

B Residual storage (200m^3): amount of water remaining in pond at end of the dry season.

C Pond storage requirement: 822m^3

Chapter 5. SUMMARY, CONCLUSIONS AND LIMITATIONS

The Arco Seco region of the Republic of Panama is characterized by high temperatures, low rainfall, falling watertables, and high evapotranspiration. The area is also known for its severe deforestation, extensive cattle ranching activities, water scarcity, and as the heartland of small-scale farming. Most research carried out in the area has focused on the improvement of large-scale farms with high-tech machinery and the drilling of wells to provide water. Not much attention has been given to 'campesinos interioranos' (small-scale farmers of the Azuero Peninsula). This current research has attempted to focus entirely on the latter group with regards to sustainable water harvesting through ponds for agricultural use during the dry season. Most agricultural extension agents of the area are inexperienced in this field of research, and therefore are unable to advise farmers on this topic.

As part of the current research, a systems approach to study the sustainability of water harvesting through ponds for agricultural purposes is proposed. This required a thorough analysis of the components to be integrated into the scheme. To implement such a system, there needs to be detailed field analysis of the pond construction site and laboratory analysis of the soil properties. Particle size analysis should be given most attention, since results will present an idea of the amount of seepage likely to occur at the site. Water demand and supply should be thoroughly analyzed prior to pond construction. These elements will determine pond storage capacity requirement. If harvested water is to be used for irrigation, then field properties should be examined (drainage, fertility, pH, CEC). Ponds need to be well constructed and adequately located. When selecting a site for pond implementation, consideration should be given to the physical properties of the site, as well as the socio-economic situation of the area. Once constructed, it should be well protected and maintained to allow for long-term use.

In order to have sufficient water stored to meet demand a pond needs to be adequately sized. As pond construction takes time, effort and monetary investment, the design should be done with care to avoid unnecessary cost. A Decision Support System has been developed specifically for the region of the Arco Seco (yet with minor modifications is applicable to other regions) to facilitate pond storage capacity estimation. As part of the DSS, four computer programs have been designed for four different case scenarios: the first is for sites that have high water demand and no topographical restrictions for pond size (Water Budget; Average Rainfall Scenario program), the second is for sites having even higher water demand, no topographical restrictions for pond size, and for farmers who wish to have a backup of water to use mostly during drier years (Water Budget; 1 in 15 Dry-Year Scenario program), the third is for low water demand, usage during the dry season only, and topographical restrictions for pond size (Dry Season Demand versus Supply program), and finally the fourth is for constant water demand throughout the year, and for sites where runoff is the only water source (Graphical Mass Curve Method program).

To illustrate the DSS approach, emphasis was placed on a pond that was designed by the author in the community of Tierras Blancas. The site was carefully selected and field and laboratory analysis properly done. Laboratory analysis of soil properties was performed both at the Instituto de Investigaciones Agropecuaria de Panamá (IDIAP) and at the McGill University soil-testing laboratory. Results for particle size analysis (Clay Loam) and pH (slightly acidic) are similar and comparable from one laboratory to the other. However, most nutrient extraction results obtained at the IDIAP laboratory are very different from the ones from McGill. Based on results obtained at McGill, levels of available P are considered very low, available K, Ca, and Al are considered low, available Mn are average to low, and Mg are considered average. In addition, results obtained at McGill from extracting solutions Mehlich 1 and 3 for K, P, Mg, and Ca follow the same trend. Soil fertility analysis was important to be done for the Tierras Blancas site since collected water was used for irrigation purposes, and it had to be ensured that the land was appropriate to put into cultivation and therefore be irrigated.

Based on Tierras Blancas site conditions, results obtained from the DSS show that if the pond had been designed with the Water Budget; Average Rainfall Scenario program, it would have required a volume of 2,165 m^3 and taken 1.97 months to fill up. On the other hand, with the Water Budget; 1 in 15 Dry-Year Scenario program, the pond would have required a volume of 1,312 m^3 and taken 2.18 months to fill up. In contrast, with the Dry Season Demand versus Supply program, the pond would have required a volume of 919 m^3 and taken 1.43 months to be full. Finally, with the Graphical Mass

Curve Method program, the pond would have required a volume of 822 m^3 and taken 1.97 months fill. In reality, the pond at Tierras Blancas was built during the middle of the wet season, at the end of the month of July, and was full soon after. Therefore, a lot of overflow occurred. When the dry season started, the pond was full. The author was at the site at the beginning of the first dry season, but was not present until the end of the season. However, the producer informed her that enough water was supplied to the pond to meet his needs during the dry season, and even had residual water storage to maintain pisciculture. Based on the calculations of the amount of water needed and supplied, there should not have been enough water within the pond to meet all the needs during the dry season. The producer said that he was also surprised that so much water was supplied to the pond, and said that he attributes this to the unusually high amount of water supplied by the surface spring during that precise dry season. He said that the surface spring yielded much more water during that period than any other previous dry season. The producer was so satisfied with the system that he built another pond the following year in order to provide water for other agricultural purposes! Finally, based on farmers' interests and topographic realities of the Tierras Blancas site, the Dry Season Demand versus Supply program was evaluated to be the best program for pond size estimation.

The main limitations that this study encountered were basically financial and time restrictions; only one pond was implemented and no on-site station to measure long-term meteorological conditions was installed. Therefore, analysis had to rely on data from meteorological stations located a few kilometres from the study site. Another limitation was the fact that there was no communal land on which to implement the water-harvesting scheme where it would benefit the entire community. Since the pond was built on privately owned land rather than on a communal plot, the project had to be adapted to the farmers' preferences and suggestions, which can sometimes be a difficult task. Furthermore, the study site was located in a mountainous rural area where access was very difficult and scarce, especially during the wet season when the road was impracticable. Finally, the difficulty of obtaining data and reports in third world countries is well known; it was difficult for the author to obtain government documentation concerning similar previous studies.

Chapter 6. RECOMMENDATIONS FOR FURTHER RESEARCH

To expand on the current work reported in this thesis, the following research should be conducted:

1. The Decision Support System needs to be tested over time and space:
    a. More ponds should be constructed in the Arco Seco region under different case scenarios and the performance of the DSS should be tested:
        - Test for sites requiring different water demands (high, medium, and low).

    b. More ponds should be constructed in the Arco Seco region under various field conditions and the performance of the DSS should be tested:
        - Test for different topographical features, vegetation type and soil texture (runoff C coefficient).

    c. More ponds should be constructed in low rainfall areas of Latin America and the performance of the DSS should be tested.

2. Additional meteorological stations should be incorporated into the programs for it to be applicable to other areas of the Arco Seco and Azuero Peninsula.

3. An economics section should be added to the DSS in order to estimate the costs of implementing a water harvesting system through ponds based on available resources of the region.

APPENDIX 1

Total annual precipitation and pan evaporation data from meteorological stations

	Meteorological stations				
	Los Santos		La Mesa	Los Pozos	La Pitaloza
Year	Total Precipitation (mm)	Total Pan Evaporation (mm)	Total Precipitation (mm)	Total Precipitation (mm)	Total Precipitation (mm)
1972	833.8	1683.4	-	-	-
1973	1524.2	1295.9	-	-	3320.8
1974	1050.7	1676.7	-	-	1975.9
1975	1063.1	1656.7	-	-	2513.6
1976	688.7	1872.7	-	-	1389.2
1977	945.4	2256.5	-	-	1966.5
1978	945.8	2061.3	-	-	1958.2
1979	1170.2	1741.3	-	-	2388.8
1980	918.8	1910.3	1890.0	1579.0	1732.3
1981	1405.0	1681.0	2283.6	2288.9	2627.0
1982	875.4	1898.1	1855.8	1462.1	1823.6
1983	826.1	1848.7	1492.6	1510.8	1568.6
1984	1084.0	1721.8	2304.7	2025.2	2456.3
1985	815.9	1934.3	1521.6	1940.7	1813.4
1986	921.4	2082.5	1664.9	1374.6	2127.8
1987	816.4	1968.9	1346.1	1269.1	1748.8
1988	1403.2	1883.1	2221.1	2221.2	2658.4
1989	959.4	1800.7	1695.0	1732.1	2007.0
1990	1141.8	1871.8	1864.3	1744.9	2312.1
1991	818.9	1914.3	1312.9	1518.8	1551.1
1992	688.2	1960.1	1976.3	1358.6	1932.2
1993	1021.3	1672.5	1642.0	1530.2	1981.7
1994	1084.5	1241.1	2057.3	1449.5	2092.9
1995	1219.2	1763.8	2069.8	1623.5	3076.1
1996	1304.9	1621.9	2038.1	1522.5	2642.4
1997	644.8	2029	1506.1	1435.5	1860.0
1998	1191.8	1752.6	2051.2	1644.0	2301.2
1999	1684.9	1434.3	-	-	2736.8
2000	1140.5	1709.0	-	-	-
2001	734.3	1801.3	-	-	-
Average	**1030.8**	**1791.5**	**1831.2**	**1643.7**	**2169.0**
St. Dev.	**255.6**	**217.1**	**308.1**	**286.3**	**469.8**

APPENDIX 2

Total annual precipitation and pan evaporation data from meteorological stations La Mesa de Macaracas and Los Santos.

Year	Mesa	Santos	Mesa	Santos	Mesa	Santos	Mesa	Santos	Mesa	Santos	Mesa	Santos	Mesa	Santos
	P* (mm)	E** (mm)	P* (mm)	E** (mm)	P* (mm)	E** (mm)	P* (mm)	E** (mm)	P* (mm)	E** (mm)	P* (mm)	E** (mm)	P* (mm)	E** (mm)
	January		February		March		April		May		June		July	
1972	-	143.6	-	204.2	-	240.2	-	203.9	-	127.1	-	90.2	-	105.6
1973	-	192.4	-	201.6	-	211.4	-	-	-	156.0	-	86.5	-	85.7
1974	-	152.4	-	202.8	-	232.5	-	238.0	-	143.5	-	96.0	-	110.0
1975	-	166.0	-	205.7	-	248.8	-	229.3	-	168.4	-	101.4	-	90.8
1976	-	188.7	-	193.5	-	231.3	-	193.2	-	178.1	-	104.8	-	118.6
1977	-	223.8	-	225.0	-	245.8	-	232.2	-	167.7	-	100.8	-	148.4
1978	-	256.6	-	164.9	-	234.4	-	219.1	-	138.0	-	161.4	-	187.6
1979	-	215.3	-	220.7	-	263.1	-	195.0	-	192.1	-	-	-	102.5
1980	1.1	197.3	10.9	240.6	0.0	276.4	6.0	232.0	346.2	162.3	222.1	112.7	128.9	108.9
1981	32.4	216.1	0.0	182.9	3.4	229.8	245.6	188.3	282.6	102.6	377.4	88.5	119.6	114.4
1982	113.0	189.0	14.1	221.0	0.0	270.6	136.6	195.6	391.9	125.7	294.5	108.5	163.2	127.1
1983	0.0	230.2	0.0	220.8	20.5	217.6	36.0	226.3	151.7	172.5	207.5	109.1	124.0	120.2
1984	5.6	204.2	2.4	195.4	35.0	236.9	27.7	208.9	318.4	154.5	270.2	78.3	219.9	87.1
1985	0.0	210.4	0.0	232.6	0.0	250.4	55.3	225.0	131.9	158.5	176.3	115.9	180.4	114.3
1986	0.0	245.2	0.0	228.1	0.0	269.8	8.4	240.4	298.5	169.6	99.5	115.1	69.2	136.0
1987	0.0	229.3	0.0	229.8	7.5	260.8	46.1	235.9	198.9	178.8	109.4	128.2	116.6	82.9
1988	0.0	254.5	0.0	261.4	11.1	278.1	42.6	258.3	232.3	169.0	412.1	115.5	161.6	100.0
1989	0.5	186.5	0.0	219.3	0.0	246.9	0.6	259.1	109.8	205.8	230.1	93.9	151.0	105.3
1990	2.1	215.2	0.0	235.5	0.0	259.8	104.0	230.8	290.8	165.1	199.2	118.0	196.4	110.5
1991	0.0	200.5	0.0	224.8	31.0	265.8	15.6	239.9	152.4	134.5	155.0	111.3	161.6	97.9
1992	0.0	237.3	0.0	238.8	0.0	286.1	29.6	238.3	207.6	203.4	290.5	100.4	286.4	107.7
1993	70.4	178.2	0.0	219.2	7.9	236.1	223.4	218.0	152.0	137.1	291.0	110.6	85.0	102.8
1994	0.0	-	0.0	169.8	0.0	275.6	43.9	269.0	243.4	170.4	261.9	106.8	138.2	67.8
1995	0.0	250.6	0.0	251.9	2.1	255.7	161.3	228.5	181.6	116.4	212.6	96.5	245.7	100.3
1996	39.4	161.2	0.2	205.8	0.0	242.8	38.2	209.9	333.6	124.4	299.1	75.9	199.8	90.5

APPENDIX 2 (Con't)

1997	1.0	196.9	0.0	209.0	0.0	269.6	58.3	214.1	66.3	218.9	226.3	119.5	145.5	143.7
1998	0.0	238.5	22.2	202.3	0.0	274.1	22.5	241.1	165.7	131.1	177.3	112.6	362.8	114.7
1999	-	141.1	-	184.0	-	224.7	-	189.8	-	113.0	-	77.0	-	100.4
2000	-	173.6	-	217.4	-	232.8	-	220.2	-	139.2	-	106.5	-	98.0
2001	-	198.9	-	236.4	-	237.1	-	241.0	-	163.8	-	131.7	-	117.6
2002	-	180.2	-	220.3	-	261.2	-	211.7	-	169.1	-	102.8	-	99.0
Average:	14.0	**202.5**	2.6	**215.0**	6.2	**250.5**	68.5	**224.4**	**224.0**	**156.7**	**237.5**	**105.9**	**171.4**	**109.6**
Median:	**0.0**	(199.7)	**0.0**	(219.3)	**0.0**	(248.8)	**42.6**	-	-	-	-	-	-	-

* P = precipitation
** E = pan evaporation

APPENDIX 3

Detailed calculations for pond size estimations for Tierras Blancas using the three alternative methods (see Table 4.7). Calculations are done using annual precipitation data from station La Mesa and pan evaporation data from station Los Santos (Appendix 1).

1) Water budget, average rainfall scenario

Water supply:

- **Precipitation (mm):** average annual precipitation for 19 years of data.

$$\frac{\begin{array}{l}1890.0+2283.6+1855.8+1492.6+2304.7+1521.6+1664.9+1346.1+2221.1+\\1695.0+1864.3+1312.9+1976.3+1642.0+2057.3+2069.8+2038.1+1506.1+2051.2\,mm\end{array}}{19\,yrs}=\underline{1831.2mm}$$

- **Runoff (Q) (m^3):** calculated using the Rational Method, based on conditions at Tierras Blancas:

  Runoff coefficient (C) = *0.36*

  Catchment area (A) = $2911m^2$

  Rainfall (i) = *1831.2 mm*

$$Q=CiA=0.36*1.83m*2911m^2=\underline{1919.0m^3}$$

- **Surface spring (m^3):** estimated directly from the surface spring at Tierras Blancas during September (second wettest month of the year), and February (driest month of the year). Discussing with Señor Gustavo, the landowner, he said that from his life-long experience of living on the land, the surface spring yield varies depending on precipitation. He said that compared with the driest month of the year, the spring usually yields 2 times more water during the second driest months of the year, 8 times more during the second wettest months of the year, and 9 times more during the wettest months of the year. A cement cylinder of 36 cm diameter was put into the spring so that water yielded goes directly into the pond. Based on these comments, water supply from surface spring was established as follows:
  - *Driest months*: January, February, March (Table 7.1)

    Measured water rise in spring: *0.005 cm/sec*

Volume of water yield:

$$\pi r^2 h = \pi (0.18m)^2 4.32mday^{-1} = 0.44m^3 day^{-1}$$

Total for this period: *39.6 m^3*

- 2^{nd} *driest months*: April, December (Table 7.1)

  Spring yield: *0.005 * 2 = 0.001 cm/sec*

  Total for this period: *53.7 m^3*

- 2^{nd} *wettest months*: May, June, July, August, November (Table 7.1)

  Spring yield: *0.005 * 8 = 0.04 cm/sec*

  Total for this period: *538.6 m^3*

- *Wettest months*: September, October (Table 7.1)

  Spring yield: *0.005 * 9 = 0.045 cm/sec*

  Total for this period: *241.6 m^3*

Total water supplied by surface spring for an average year:

$$39.6 + 53.7 + 538.6 + 241.6 = \underline{873.5m^3}$$

Table 7.1
Average monthly precipitation for meteorological station La Mesa de Macaracas, based on 19 years of daily data, and pan evaporation for Los Santos, based on 31 years of daily data.

Months	Meteorological station	
	La Mesa Average Precipitation (mm)	Los Santos Average Pan Evaporation (mm)
January	14.0	202.5
February	2.6	215.0
March	6.2	250.5
April	68.5	224.4
May	224.0	156.7
June	237.5	105.9
July	171.4	109.6
August	211.3	108.3
September	279.5	99.7
October	341.5	99.9
November	219.7	103.9
December	58.1	145.9

- **Stream (m^3):** estimated directly from the stream. A PVC pipe was installed to convey water from the stream to the pond. The PVC is put in only during the 4 months of the dry season. Water flow was measured by placing a bucket to collect the pipe outflow and a ruler was used to monitor the rise of water in the bucket. The bucket was cylindrical, with a diameter of 30 cm.

  Measured water rise in bucket: *0.12 cm/min*

  Volume of water yield:

  $\pi r^2 h = \pi(0.15m)^2 1.728mday^{-1} = 0.12m^3 day^{-1}$

  Total for the 4 months: $\underline{14.4\ m^3}$

Total water supply, average rainfall year, for Tierras Blancas pond (for this estimation, a pond surface area had to be specified based on the conditions of the site. For this particular site, the maximum surface area that the pond could have is 11 m by 17 m, 187m²):

$$\left(\frac{1831.2mm}{1000} * 187m^2\right) + 1919m^3 + 873.5m^3 + 14.4m^3 = \underline{3149m^3}$$

Water demand:

- **Irrigation (m^3):** Estimated directly in the field by measuring the decrease in pond water height after a day of irrigation. Since there is water being contributed to the pond during this period of time through surface spring (all year) and stream (dry season only), and water lost through pond evaporation (Table 7.1), the related height measured does not represent only the water used for irrigation. Therefore, volume of water entering the pond was added and evaporated was subtracted from the total daily decrease in pond volume. It was assumed that there was no precipitation during the days of irrigation. On average, the pond water height decreased 8 cm after one day of irrigation (the pond constructed has a surface area of 143 m^2), where the producer irrigated every 2 days during the dry season.

  Measured water decrease: *8 cm/day*

  Related volume of water in pond: $0.008mday^{-1} * 143m^2 = 11.44m^3 day^{-1}$

Monthly usage of water for irrigation:

$$\underline{January}:\ 15days\left(\frac{11{,}44m^3}{day}+\frac{0.44m^3}{day}+\frac{0.12m^3}{day}\right)-\left(0.1013m*143m^2\right)=\underline{163.8m^3}$$

$$\underline{February}:\ 14days\left(\frac{11.44m^3}{day}+\frac{0.44m^3}{day}+\frac{0.12m^3}{day}\right)-\left(0.1075m*143m^2\right)=\underline{152.6m^3}$$

$$\underline{March}:\ 15days\left(\frac{11.44m^3}{day}+\frac{0.44m^3}{day}+\frac{0.12m^3}{day}\right)-(0.1253m*143m^2)=\underline{162.1m^3}$$

$$\underline{April}:\ 15days\left(\frac{11.44m^3}{day}+\frac{0.88m^3}{day}+\frac{0.12m^3}{day}\right)-(0.1122m*143m^3)=\underline{170.6m^3}$$

Total of water needed for irrigation during the dry season: $\underline{649\ m^3}$

- **Evapotranspiration (mm):** For the Tierras Blancas site, potential evapotranspiration was assumed to be equal to average annual pan evaporation, given that vegetation within the field is short (Linsley *et al.*, 1982; Brutsaert, 1982). Average annual evaporation was calculated from 30 years of data from station Los Santos (Appendix 1):

$$\frac{53{,}745.6mm}{30years}=\underline{1791.5mmyear^{-1}}$$

- **Seepage (mm):** was calculated directly on the site using a double-ring infiltrometer. There was essentially no seepage occurring on the site.
- **Drainage overflow (m^3):** for design purposes, it was assumed that there was no drainage overflow for the first year so that the pond fills up completely. Obviously, this highly depends on the period when the pond was constructed. However, this assumption was based on an iterative approach, where overflow can be estimated only once the pond size has been chosen.

<u>Total water demand, average rainfall year, for Tierras Blancas pond (the maximum surface area that the pond could have for this site is 11 m by 17 m, 187 m²):</u>

$$649m^3+(1.7915m*187m^2)=\underline{984m^3}$$

Pond storage requirement based on the water budget, average rainfall scenario:

$$\textit{Water supply} - \textit{water demand} = 3149\ m^3 - 984\ m^3 = \underline{2165\ m^3}$$

2) **Water budget, 1 in 15 dry-year scenario**

Water supply:

- **Precipitation (mm):** to calculate a 1 in 15 year case scenario, the 'standard normal transformation' was used, assuming the yearly precipitation follows a normal distribution (Viessman and Lewis, 1996). The mean ($\bar{x}$) and standard deviation (s) were estimated based on data from station La Mesa de Macaracas (Appendix 1). Equation used to estimate precipitation for 1 in 15 dry year:

  $x = \bar{x} - z(s)$

  $\bar{x} = 1831.2\ mm$

  $s = 308.1\ mm$

  $P(z) = 1/T_r = 1/15 = 0.0667$ (exceedence probability)

  $F(z) = 0.5 - P(z) = 0.4333$

  $z = 1.5$ (by interpolating tables of established z values (see Table B.1 in Appendix B of Viessman and Lewis, 1996)).

  $$x = 1831.2 - 1.5(308.1) = \underline{1369 mm}$$

- **Runoff (m^3):** calculated using the Rational Method, based on conditions at Tierras Blancas:

  Runoff coefficient (C) = *0.36*

  Catchment area (A) = $2911 m^2$

  Rainfall (i) = *1369 mm*

  $$Q = CiA = 0.36 * 1.369 m * 2911 m^2 = \underline{1435 m^3}$$

- **Surface spring (m^3):** calculations could not be done based on the 'standard normal transformation' method since there was no long-term data for surface spring yield (no mean or standard deviation). However, given that spring yield varies with precipitation, it was assumed that the yield would differ from the average year yield as much as the difference between average rainfall and 1 in 15 dry-year rainfall:

Average rainfall: *1831.2 mm*

1 in 15 dry-year rainfall: *1369 mm (25 % less than average)*

Average spring yield: *873.5* m^3

1 in 15 dry-year spring yield: $0.75 * 873.5 = \underline{655.1\ m^3}$

- **Stream (m^3):** again, calculations could not be done based on the 'standard normal transformation' method since there is no long-term data for stream yield (no mean or standard deviation). Therefore, the same method as the one used to estimate spring yield for the 1 in 15 dry-year was used:

  Average stream yield: *14.4* m^3

  1 in 15 dry-year stream yield: $0.75 * 14.4 = \underline{10.8\ m^3}$

Total water supply, 1 in 15 dry-year, for Tierras Blancas pond (same maximum pond surface area: 187 m^2):

$$(1.369m * 187m^2) + 1435m^3 + 655.1m^3 + 10.8m^3 = \underline{2357m^3}$$

Water demand:

- **Irrigation (m^3):** same as previously calculated (*649* m^3)
- **Evapotranspiration (mm):** Again, potential evapotranspiration was assumed to be equal to average annual pan evaporation. To calculate a 1 in 15 year case scenario, the 'standard normal transformation' was used (Viessman and Lewis, 1996). The mean ($\bar{x}$) and standard deviation (*s*) were estimated based on data from station Los Santos (Appendix 1). Equation used to estimate evaporation for 1 in 15 dry year: $x = \bar{x} + z(s)$

  $\bar{x} = 1791.5\ mm$

$s = 217.1\ mm$

$P(z) = 1/T_r = 1/15 = 0.0667$ (exceedence probability)

$F(z) = 0.5 - P(z) = 0.4333$

$z = 1.5$ (by interpolating tables of established z values (see Table B.1 in Appendix B of Viessman and Lewis, 1996)).

$$x = 1791.5 + 1.5(217.1) = \underline{2117 mm}$$

- **Seepage (mm):** it was assumed that there was no seepage, similar as an average rainfall year.
- **Drainage overflow (m^3):** for design purposes, it was assumed that there was no drainage overflow for the first year so that the pond fills up completely. Clearly, this depends on when the pond was constructed. Assumption is based on the same iterative approach as mentioned in previous method.

<u>Total water demand, 1 in 15 dry-year, for Tierras Blancas pond (same maximum pond surface area: 187 m^2):</u>

$$649m^3 + (2.117m * 187m^2) = \underline{1045m^3}$$

Pond storage requirement based on the water budget, 1 in 15 dry-year scenario:

$$\textit{Water supply} - \textit{water demand} = 2357\ m^3 - 1045\ m^3 = \underline{1312\ m^3}$$

3) <u>Dry season demand versus supply:</u>

<u>Water supply:</u>

- **Precipitation (mm):** average monthly precipitation for the dry season (January-April) from 19 years of data from station La Mesa de Macaracas (Table 7.1):

$$14.0 + 2.6 + 6.2 + 68.5 = \underline{91.3mm}$$

- **Runoff (m^3):** it was assumed that runoff was negligible since precipitation during the dry season is very low and sporadic. The soil is so dry during this period that most of the rainfall is seeped through the soil very fast.
- **Surface spring (m^3):** estimated based on monthly amounts determined in the water budget, average rainfall scenario (see section 1 of this Appendix):

  January, February, March: *39.6* m^3

  April: $0.88\ m^3 day^{-1} * 30\ days = 26.4\ m^3$

  Total for the dry season: $39.6 + 26.4 = \underline{66\ m^3}$

- **Stream (m^3):** volume contributed for the 4 months of the dry season was estimated in the water budget, average rainfall scenario (see section 1 of this Appendix): $\underline{14.4\ m^3}$

<u>Total water supply for the dry season, for Tierras Blancas pond (same maximum pond surface area: 187 m^2):</u>

$$\left(0.0914m * 187m^2\right) + 66m^3 + 14.4m^3 = \underline{97m^3}$$

<u>Water demand:</u>

- **Irrigation (m^3):** same as calculated in the water budget, average rainfall year (*649* m^3)
- **Evapotranspiration (mm):** again, potential evapotranspiration was assumed to be equal to average annual pan evaporation. Average monthly pan evaporation for the dry season (January-April) calculated from Los Santos data (Table 7.1):

$$202.5 + 215.0 + 250.5 + 224.4 = \underline{892mm}$$

- **Seepage (mm):** it was assumed that there was no seepage, similar as an average rainfall year.
- **Drainage overflow (m^3):** for design purposes, it was assumed that there was no drainage overflow for the first year so that the pond fills up completely. Clearly, this depends on when the pond was constructed.

Total water demand for the dry season, for Tierras Blancas pond (same maximum pond surface area: 187 m^2):

$$649m^3 + (0.892m * 187m^2) = \underline{816m^3}$$

Pond storage requirement based on the dry season demand versus supply for a pond needing 200 m^3 of residual storage:

$$\textit{water demand - water supply + res. sto.} = 816\ m^3 - 97\ m^3 + 200m^3 = \underline{\mathbf{919\ m^3}}$$

APPENDIX 4

Detailed calculations for the length of time needed to fill pond based on storage requirements determined by the four estimation methods (see Table 4.8).

1) Water budget, average rainfall scenario

Firstly, an estimate of water remaining in pond at the end of the dry season is necessary. In order to do so, it was assumed that the pond was full at the beginning of the dry season. Then, dry season water demand was subtracted and water supply added to the total pond volume. Then, monthly water budgets were estimated until the pond was full. See section 3 in Appendix 3 (dry season demand versus supply) for detailed calculations of dry season water demand and water supply. See Table 7.1 for monthly precipitation and pond evaporation.

Water remaining at end of dry season = total pond volume + dry season supply – dry season demand

Water remaining at end of dry season = $2165\ m^3 + 97\ m^3 - 816\ m^3 = \underline{1446\ m^3}$

Amount of water to fill pond = total pond volume – water remaining at end of dry season

Amount of water to fill pond = $2165\ m^3 - 1446\ m^3 = \underline{719\ m^3}$

May: *monthly water contribution to pond = inflows – outflows*

monthly water contribution to pond =(precipitation + runoff + spring) – pond evaporation

Stream yield is not considered in the inflows, since PVC piping is put only during the dry season when water demand is at its' highest.

monthly water contribution to pond =

$$((0.224m*187m^2)+(0.36*0.224m*2911m^2)+\left(\frac{3.52m^3}{day}*31days\right)) - (0.157m*187m^2)$$

$$= \underline{357m^3}$$

Amount of water left to fill pond = $719\ m^3 - 357m^3 = \underline{362\ m^3}$

June: the same procedure was followed; the pond was full at the end of June.

2) Water budget, 1 in 15 dry-year scenario

In order to estimate the amount of water remaining in the pond at the end of the dry season, it was assumed that the pond was full at the beginning of the dry season.

Then, dry season water demand was subtracted and water supply added to the total pond volume:

Water remaining at end of dry season = 1312 m^3 + dry season supply – dry season demand

Dry season water supply:

- **Precipitation**: the 'standard normal transformation' could not be used to calculate the 1 in 15 dry-season total precipitation, since monthly precipitation during this period does follow a normal distribution (Appendix 2). Therefore, the median for each month was calculated and then summed for the four months. When data is not normally distributed and skewed to the left, the median gives a value that is smaller than the average. However, when data follows a normal distribution the median should be close to the average. For the dry season, the median is 0 for the months of January, February and March, which could not be less for a 1 in 15 dry-season scenario:

  Total precipitation for dry season: *0.0 + 0.0 + 0.0 + 42.6* = ***42.6 mm***

- **Runoff**: it was assumed that runoff was negligible since precipitation during the dry season is very low and sporadic.

- **Surface spring**: to calculate surface spring yield for the dry season, the same method as the one established in section 2 of Appendix 3 was used (see water budget, 1 in 15 dry-year scenario; surface spring):

  Average rainfall for dry season period: *91 mm*

  Dry-season rainfall: *42.6 mm (53 % less than average)*

  Average spring yield for dry season: 66 m^3

  Dry-season spring yield: 0.53 * 66 = ***35 m^3***

- **Stream**: to calculate stream yield for the dry season, the same method as the one established in section 2 of Appendix 3 was used (see water budget, 1 in 15 dry-year scenario; stream):

  Average stream yield: *14.4 m^3*

  Dry-season stream yield: *0.53 * 14.4* = ***7.6 m^3***

Total water supply for the dry season: *(0.0426m*187m^2)+35m^3+7.6m^3*= ***51 m^3***

Dry season water demand:

- **Irrigation:** the same amount of water needed for irrigation as the amount previously estimated: *649m³*.
- **Evapotranspiration:** potential evapotranspiration is assumed to be equal to pan evaporation. The 'standard normal transformation' was used to calculate 1 in 15 dry-season evaporation, since the data follow a normal distribution (as seen in Appendix 2, average and median are similar, which is typical of a normal distribution).

January: $x = \bar{x} + z(s)$

$\bar{x} = 202.5\ mm$
$s = 32.3\ mm$

$P(z) = 1/T_r = 1/15 = 0.0667$

$F(z) = 0.5 - P(z) = 0.4333$

$z = 1.5$
$x = 202.5 + 1.5(32.3) = 251.0mm$

February: $x = 248.5mm$

March: $x = 279.9mm$

April: $x = 255.6mm$

Total evaporation for the 1 in 15 dry season: *1035 mm*

Total water demand for dry season: $649m^3 + (1.035\ m*187m^2) = \mathbf{843\ m^3}$

Water remaining at end of dry season $= 1312\ m^3 + 51\ m^3 - 843m^2) = 520\ m^3$

Amount of water to fill pond $= 1312\ m^3 - 1169\ m^3 = \underline{792\ m^3}$

May: Since the pond was designed for a 1 in 15 dry-year, then the second wet season should normally be an average rainfall year. Therefore, monthly water contributions to pond are equal to the average rainfall year starting in May, until the pond is full (see previous section of this Appendix). The pond will be at its fullest at the beginning of the month of July. See Appendix 2 for details on precipitation and pan evaporation data for the months of June and July.

3) **Dry-season demand versus supply:** Same as method used in the water budget, average rainfall scenario (see section 1 of this Appendix).

4) **Graphical Mass Curve Method:** Dry season water supply and demand were calculated based on an average year (see section 1 of this Appendix).

5) **Actual pond:** Dry season water supply and demand were calculated based on an average year (see section 1 of this Appendix). Based on these estimations, pond storage is too small to meet the water demand for the whole dry season and therefore should be empty at the end of the season.

APPENDIX 5

Decision Support System for estimation of pond storage requirement. Compact Disc includes the four programs developed and instruction manual, both in English and Spanish:

- 'Water Budget: Average Rainfall Scenario' or 'Balance Hídrico: Situación de Precipitación Promedia'
- 'Water Budget: 1 in 15 Dry-Year Scenario' or 'Balance Hídrico: Situación en la que 1 de cada 15 Años es Seco'
- 'Dry Season Demand versus Supply' or 'Demanda de Agua versus Contribución de Agua Durante el Periodo Seco'
- 'Graphical Mass Curve Method' or 'Método de la Curva Gráfica de Masa'
- 'Instruction Manual' or 'Manual de Instrucción'

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