SHRIMP FARMING IN THAILAND'S CHAO PHRAYA RIVER DELTA: BOOM, BUST AND ECHO

Brian W. Szuster, Ph.D.

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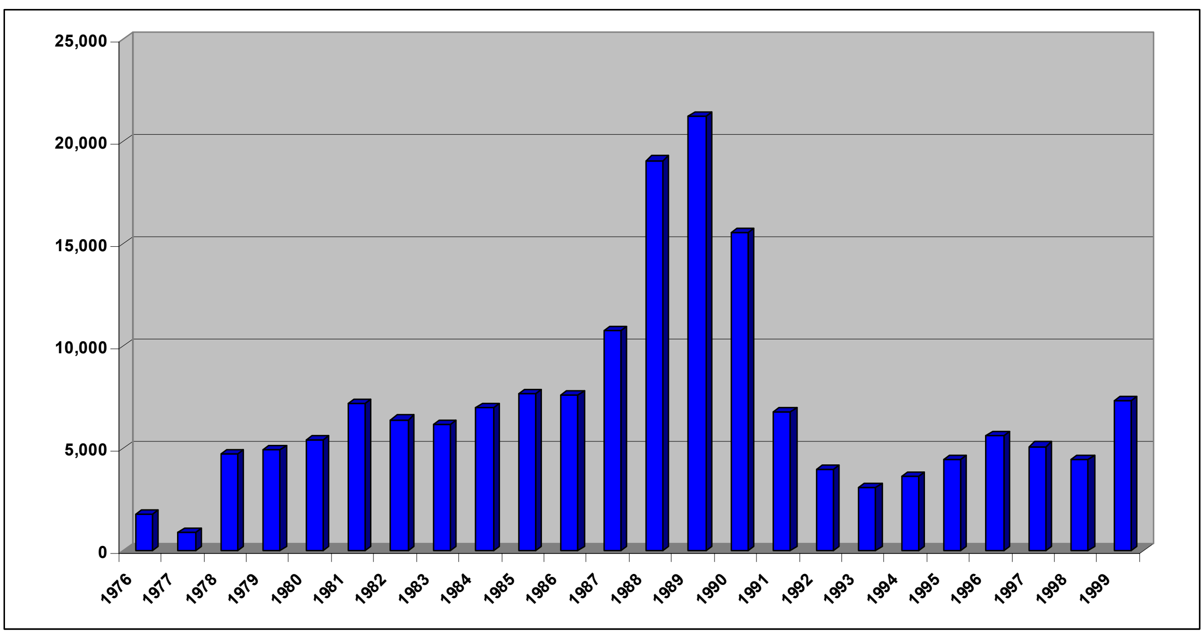
1.0 INTRODUCTION

Asians have been farming fish and crustaceans in coastal areas using traditional techniques for at least 3000 years (Stickney, 1979). New aquaculture technologies and a rising international demand for seafood products have, however, altered the basic character of aquaculture in coastal areas of Asia. Low intensity traditional forms of aquaculture that supported local food production are being replaced by resource intensive, high intensity systems that cater to international seafood markets (Stonich *et al*., 1997). Shrimp is by far the most valuable aquatic species currently being produced using high intensity aquaculture techniques, and the total value of global farmed shrimp production was approximately $7 billion USD in 2000 (FAO, 2002).

The Chao Phraya River Delta is one of most important agricultural regions in Thailand. This area also represents a major production area for farmed black tiger shrimp (*Penaeus monodon*). Shrimp farming created approximately $2 billion USD in export revenues for the Thai economy during 2000 (*ibid*.) but the history of this activity in the Chao Phraya Delta has been highly controversial. Traditional low production shrimp farms first emerged in the lower Chao Phraya Delta during the 1930s, and this culture system slowly expanded in coastal areas during the post-World War II period (Tookwinas, 1993). A dramatic shift occurred when Taiwanese intensive production techniques for black tiger shrimp were introduced to the Chao Phraya Delta during the mid 1980s. This capital and resource intensive production system was developed to supply a burgeoning international market for seafood products (Barraclough and Finger-Stich, 1996). The substantial profits associated with intensive shrimp farming initiated a frenzy of activity during the late 1980s as coastal land owners in the lower Chao Phraya Delta rushed to convert rice paddies, salt pans and mangrove into shrimp production. As quickly as the "shrimp boom" began in provinces such as Samut Prakarn and Samut Sakhon, production crashed as a result of viral disease pathogens, self-pollution and general environmental degradation. Annual farmed shrimp production in this area dropped to less than 15% of peak levels by 1992 (Figure 1) and substantial controversy emerged over the environmental and socio-economic impacts of this collapse.

"Boom and bust" cycles are characteristic of intensive shrimp production in the developing world and have affected shrimp farming areas throughout Southeast Asia. A unique set of circumstances arose in Thailand, however, that led to the continued expansion of intensive shrimp farming within the Chao Phraya Delta. Dry season salt water intrusion is a common characteristic of the low gradient river systems that flow into the Upper Gulf of Thailand, and the seasonal availability of brackish water encouraged the construction of a second generation of intensive shrimp farms some distance from the coast (Banpasirichote, 1993). These second generation farms were originally limited to one dry season crop per year because brackish water was unavailable when higher stream flows counteract tidal influences during the wet season. Low salinity shrimp farming techniques (Szuster, 2001) were developed to overcome this limitation, and utilize hyper-saline water trucked-in from the coast when natural supplies of brackish water are unavailable. Low salinity techniques provided the potential for producing two or even three shrimp crops per year, and facilitated the spread of black tiger shrimp farms into completely freshwater agricultural areas of the Chao Phraya Delta as far as 200 km from the Gulf of Thailand by 1998 (Committee on Inland Shrimp Farming, 1998).

Figure 1 Farmed Shrimp Production in the Lower Chao Phraya Delta[1] (tonnes)



[1]Samut Sakhon, Samut Prakarn and Bangkok provinces

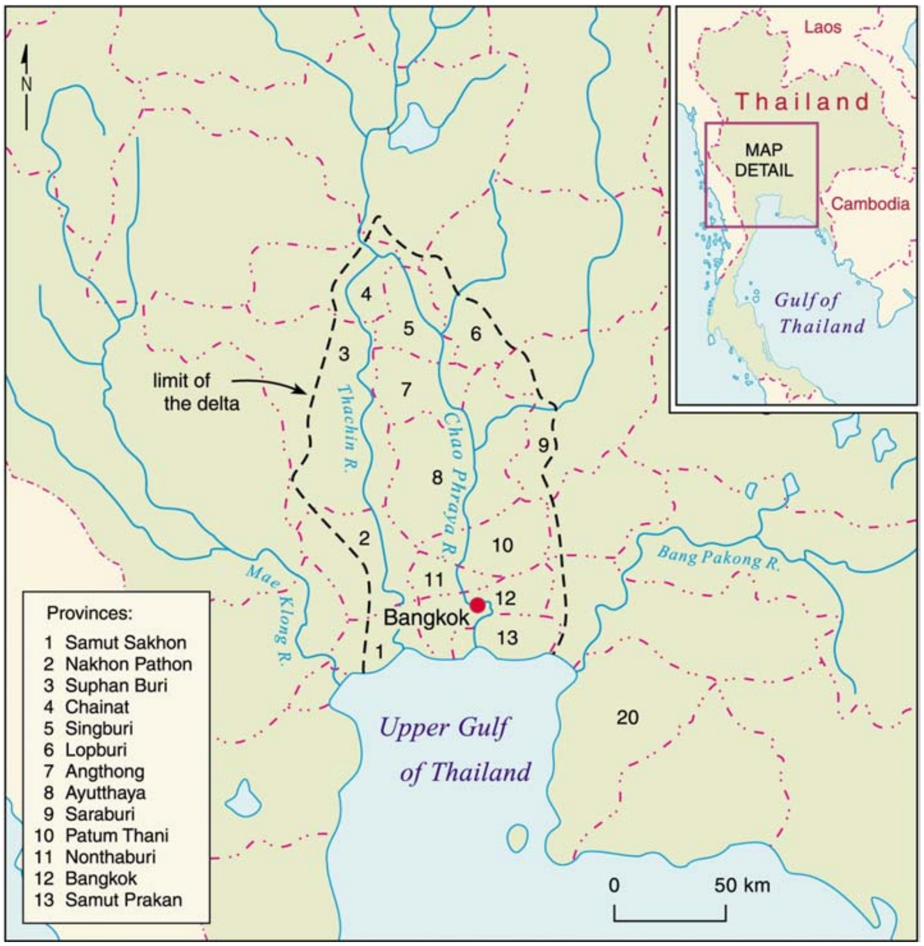
Data source: Department of Fisheries, 2002

Shrimp farming in the Chao Phraya Delta provides a fascinating example of how the global trade in commodities such as shrimp can cause extremely rapid shrifts in land use and resource allocation within tropical developing nations. These shifts can have profound implications for the long-term integrity of terrestrial and aquatic ecosystems, and represent a significant challenge to government agencies attempting to manage land and water resources within river basins. The following sections of this report provide a detailed account of shrimp farming in the Chao Phraya Delta. This includes a description of the Chao Phraya Delta study area and an outline the history of shrimp farming within this important agricultural region. Interactions between shrimp farming and the environment will also be identified and the river basin planning implications of shrimp aquaculture development within this tropical deltaic environment will be discussed.

2.0 STUDY AREA

The Chao Phraya Delta is one the largest deltas in Southeast Asia. It forms the lower portion of the Chao Phraya River Basin and is approximately 40,000 km^2 in area (Figure 2).

Figure 2. The Chao Phraya Delta



Tributary streams such as the Ping, Wang, Yom and Nan Rivers drain highland areas in the mid and upper Chao Phraya Basin, and these areas represent the source of sand, silt and clay sediments that have been deposited in thick sequences within the delta (Pendleton, 1962). Slope gradients can be as low as 1:10,000 and areas up to 150 kilometres inland of the Gulf of Thailand can be less than 20 meters above sea level. The delta is dominated by poorly drained sandy-clay soils of high to moderate fertility (Arbhabhirama *et al*., 1988). These soils are commonly associated with irrigated wet rice cultivation, and drainage is generally poor given the clay structure and low elevation. Surface soil horizons are generally black. This does not necessarily indicate high organic content or fertility, but is a characteristic of clay soils that undergo an alternating cycle of water saturation during the rainy season and intense drying and cracking during the hot season.

The Chao Phraya Delta possesses a tropical wet savannah climate produced by its location in peninsular Southeast Asia and the influence of oceanic and continental weather systems. The monsoon is the characteristic climatic feature and represents a seasonal shift in prevailing winds from the northeast (continental influence) to the southwest (oceanic influence). Temperatures and humidity are high and relatively consistent throughout the year (Sternstein, 1976) but the monsoon produces distinct wet and dry seasons. The "wet season" typically occurs between May and October in association with the oceanic influence of the southwest monsoon. Many areas of central Thailand receive over 1500 mm of precipitation during this period which can represent over 75% of the total annual rainfall. The development of an intense high pressure system each winter in continental Asia initiates the dry season in November. Temperatures are cooler during November and December, but increase steadily until April which is the hottest month of the year.

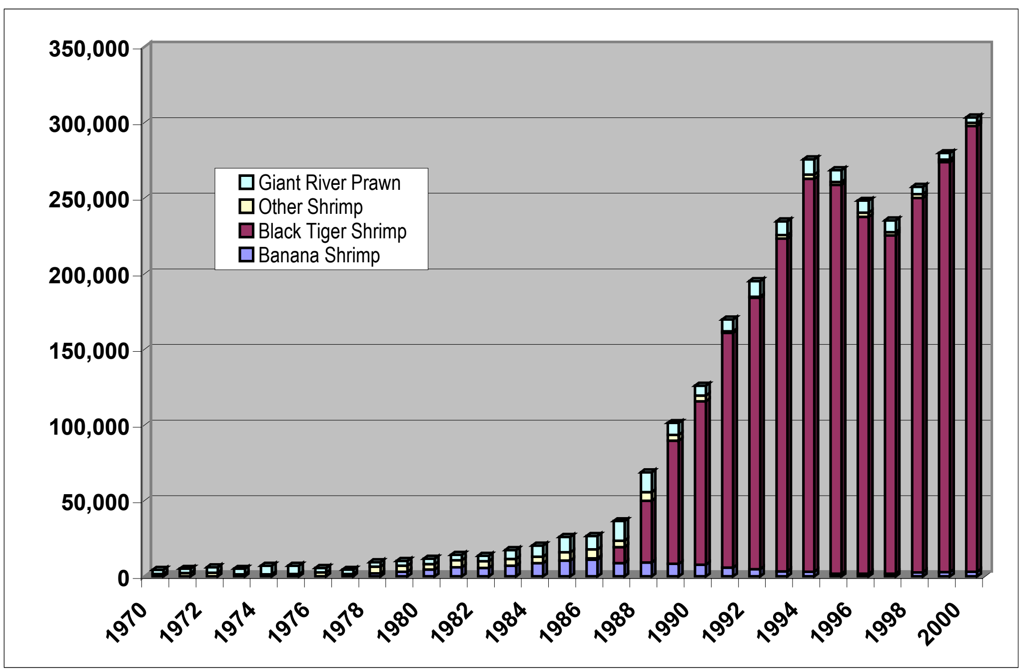
Stream flows in the Chao Phraya Delta are highly seasonal as a result of the monsoon (approximately 85% occurring between July and December). Variations in precipitation from year to year can lead to either flooding or drought (Pollution Control Department, 1997). The hydrological cycle starts in April when the streamflows are at a minimum (50 to 200 m^3/sec). Discharges gradually increase between May and August and then rise rapidly until reaching a peak in October (approximately 4,000 m^3/sec). Streamflows decrease fairly rapidly during November and December, and continue falling at a slower rate until minimum flow conditions are again reached during April. A combination of very low stream gradients and variable streamflows permits salt water intrusion to extend 175 km upstream of the coast during the dry season and 75 km upstream during the wet season. Given this extreme seasonality, it is not surprising that the Government of Thailand has constructed over 3,000 small and large water control structures in the Chao Phraya River Basin to meet dry season water needs and to decrease the intensity of flooding. The two largest facilities constructed in the upper basin are the Bhumibol and Sirikit Dams. These two dams control 22% of the runoff from the entire Chao Phraya River Basin and supply water for electric power, irrigation, domestic and industrial water uses. A number of barrages have also been constructed to divert water into a complex system of inter-connect canals serving agricultural production in the lower basin. Water is released from dams in the upper basin to support salinity control, irrigation, navigation, industry water needs and domestic water consumption.

Water quality is poor in many parts of the Chao Phraya Delta as this region contains several large population centers and is a major focus of industrial and agricultural activity within Thailand (Adeell *et al*., 2002). Land-based pollution sources include: agriculture, sewage, industrial discharges, urban storm water, and aquaculture. Major contaminants present in discharges from these sources are sediment, nutrients, toxic metals, pesticides, oxygen depleting substances, pathogenic organisms, larvae of exotic species, litter and toxic chemicals. Various non-point sources of pollution also exist in the Chao Phraya Delta and include surface runoff from agricultural land and diffuse effluent from intensive pig and chicken farms. Monitoring data collected by Thailand's Pollution Control Department indicates that water quality in the Chao Phraya Delta is below surface water quality standards for several parameters (Pollution Control Department, 1997). The major water quality problems in the Chao Phraya Delta include: low dissolved oxygen, high ammonia-nitrogen, high fecal coliform bacteria, high turbidity, and high organic matter. Fish kills have been recorded during the dry season are thought to be related to sudden reductions in dissolved oxygen (Simachaya *et al*., 2000).

3.0 HISTORY OF SHRIMP FARMING IN THE CHAO PHRYA RIVER DELTA

Thailand possesses over 2700 kilometers of coastline and a tropical climate that is ideal for farming lucrative marine species such as the black tiger shrimp. Basic biophysical factors are important, but the presence of appropriate aquaculture technologies, low agricultural wages, and the availability of tax and other incentives from the Thai government were also critical in supporting the development of the shrimp farming industry (Kongkeo, 1995). These factors converged during late 1980s to produce a boom in tiger shrimp farm development and Thailand becoming the world's largest producer of cultured shrimp in 1993 (Figure 3). The following information documents the history of shrimp farming in the Chao Phraya River Delta which is the home of modern intensive shrimp farming in Thailand. Several distinct development phases exist and each of these will be described to provide a comprehensive portrait of the shrimp farming industry in this important agricultural region.

Figure 3 Annual Production of Farmed Shrimp in Thailand (tonnes)



Data source: FAO, 2002

Pre-Expansion Phase (1930 – 1977)

Shrimp farming was likely introduced to the lower Chao Phraya Delta by Chinese immigrants during the 1930s (Tookwinas, 1993). These early farms (called *thammachaat* or "natural farms" by the Thai) used traditional techniques which involved flooding low-lying coastal paddy fields and capturing wild shrimp contained within the seawater. Enclosures were large (30 hectares or more) and a limited amount of daily water exchange was provided by natural tidal flows. Traditional techniques were inherently a polyculture because flood waters provide the entire supply of shrimp seed and the aquaculturalist exerted no control over species composition. Tidal flows also provided naturally occurring food organisms to sustain captured shrimp during the culture period. Traditional shrimp farming techniques required no special technical skills or infrastructure, and input costs were minimal due to the use of naturally occurring seed stock and food. Yields were low (approximately 200 kg/ha/year) due to an absence of stocking control and poor survival rates. Species cultured in this manner included banana shrimp (*P. merguiensis*), Indian white shrimp (*P. indicus*), school shrimps (*Metapeneaus monoceros*) and a small number of black tiger shrimp (*P. monodon*).

Coastal Salt Farm in Samut Prakan

Extensive farming techniques represented the first modest intensification of aquaculture practices during the pre-expansion phase. Shallow ponds were constructed within coastal mud flats and many salt farms were converted to shrimp production after World War II. This shift was motivated by depressed salt prices, and by the late 1960s, more than 50% of all salt farms in the lower Chao Phraya Delta were converted to shrimp production (Csavas, 1994). Pond enclosures are still large in extensive systems (5 hectares or more) but yields can increase to almost 400 kg/ha/year by exercising limited control over fry stocking, improving water management, and applying manure or chemical fertilizers to induce algae blooms. Although extensive techniques still provide low yields, these operation are not necessarily uneconomic if land and labour costs are modest (Pillay, 1997). The large, healthy shrimp produced in this system fetch high prices and this can compensate for low yields. Profits can be further enhanced by marketing these shrimp in a fresh state to specialty markets. Environmental damage associated with traditional and extensive shrimp farming systems is generally limited as a result of low production levels, but a large amount of intra-tidal coastal land is required for pond enclosures and this can impact coastal habitats such as mangrove.

Early Expansion (1972 – 1987)

Shrimp farming continued in a largely traditional form in Thailand until the early 1970s when the Thai Department of Fisheries began to experiment with semi-intensive monoculture techniques (Katesombun, 1992). This modified form of shrimp farming provides higher yields and was widely adopted in areas already supporting extensive operations. Black tiger shrimp were the focus of semi-intensive husbandry experiments. This species possesses a high export value, is able to grow quickly under artificial conditions, and is adaptable to a wide range of water temperature and salinity conditions (Pillay 1990). Another factor in the development of semi-intensive shrimp farming was the successful production of hatchery-raised tiger shrimp post-larvae by Thai personnel trained in Japan. This breakthrough, in conjunction with the development of improved feeds and husbandry techniques, set the stage for a dramatic expansion of shrimp farming in coastal Thailand (Liao, 1992).

Semi-intensive shrimp culture utilizes pond enclosures that are smaller than traditional farms (1-8 hectares), but this system provides significantly higher yields (1000 kg/ha/year). This increase in productivity is gained by the use of hatchery-raised fry, supplementary feeding, and a limited degree of mechanical water management provided by low-lift axial flow pumps to supplement the water exchange provided by tidal action (Tookwinas and Ruangpan, 1992). Construction costs are higher due to the need to construct levees or dykes, but the pond enclosures are more uniform in shape and contour to provides additional control over the grow-out environment (Pillay, 1993). The quality of effluent released to the surrounding environment is usually poorer than extensive farms (Miller, 1996) and overall environmental impacts are more pronounced due to the increased culture intensity. Coastal habitats such as mangrove are less affected by semi-intensive culture systems, however, because these operations are usually sited in supra-tidal areas that possess more appropriate soil properties (i.e., less acidic) and better drainage characteristics (Menasveta, 1997).

Shrimp Boom (1988 – 1995)

The introduction of the semi-intensive culture systems to Thailand was quickly followed by the development of intensive farming techniques (called *phattana* or "developed farms" by the Thai). This technology was introduced from Taiwan and created a boom in Thai cultured shrimp production. Farm yields increased from 0.45 to 2.13 metric tonnes per hectare between 1987 and 1999 and total annual farmed shrimp production also sky-rocketed (Figure 3).

Typical Intensive Black Tiger Shrimp Farm

In addition to favorable biophysical conditions and the availability of Taiwanese intensive farming technology, the Thai "shrimp boom" was supported by several institutional and socio-cultural factors (Flaherty and Vandergeest, 1998). The Thai government and international development agencies such as the Asian Development Bank provided significant assistance to the emerging shrimp aquaculture sector. This included direct financial support to potential aquaculturalists, aquaculture research and extension services, and infrastructure construction in coastal areas (e.g., roads and canals). In contrast to the significant corporate presence that exists within India and Latin America, the Thai shrimp farming industry is dominated by small independent operators (Flaherty e*t al.,* 2000). Approximately 80% of intensive shrimp farms in

Thailand are controlled by local residents who have constructed one or two small ponds (0.16 - 1.6 hectares) on their own land (Lin, 1992). Most of these operations are managed as family farms with little assistance from hired farm labor or professionals such as biologists or veterinarians. The economic risks associated with unresolved disease problems have led Thai multi-national companies to focus on feed manufacturing, shrimp processing, and marketing.

Intensive culture techniques were first adopted in the lower Chao Phraya Delta near Bangkok, but quickly expanded to cover large areas of coastal land throughout Thailand between the years 1987-1989. Intensive shrimp farms in the lower Chao Phraya Delta were constructed on existing extensive shrimp farms, salt pans or wetlands, but more than 80% were abandoned after only a few years in operation (Miller, 1996). Factors leading to the rapid demise of intensive shrimp farming in this area included self-pollution, insufficient water supplies, seasonal changes in water salinity, environmental degradation due to industrial encroachment, and a lack of experience with the new intensive husbandry techniques (Flaherty and Karnjanakesorn, 1995; Jenkins 1995; Briggs and Funge-Smith, 1995). Derelict shrimp ponds became a common sight in Samut Prakarn and Samut Sakhon at this time, and soils within the pond enclosures were often contaminated by salt and chemical residues (Miller, 1996). Although a small number of abandoned shrimp pond were used to grow lower value species such as fish or crab, many remained idle or were converted to non-agricultural land uses such as housing or manufacturing. After the collapse of production in the lower Chao Phraya Delta, the geographic focus of shrimp farming in Thailand moved to the eastern region (Chantaburi, Rayong, and Trat) and southern provinces (Surathani, Nakhon Si Thammarat and Ranong). These areas generally possess better soil and water supply characteristics than farm sites near Bangkok and a large number of new operations were constructed during the early 1990s (Jory, 1996).

Thai government agencies recognized the emergence of serious problems in the shrimp farming sector during the early 1990s, and responded by allocating resources to the development of more sustainable aquaculture techniques and management practices (Kongkeo, 1997). Initiatives supported by the Thai government and agencies such as the World Bank and the Food and Agriculture Organization of the United Nations include: training and extension services for small-scale aquaculturalists, the development of a Shrimp Farming Code of Conduct, shrimp aquaculture zoning, research into water recycling and zero-discharge farming techniques, mangrove reclamation in abandoned shrimp farming areas, and research into shrimp disease and the breeding of domesticated species. (MIDAS 1995; FAO and NACA, 1995). Seawater Circulation System Projects were also constructed to provide a secure salt water supply for coastal shrimp farms that is comparable to the freshwater irrigation systems supporting rice cultivation (Tookwinas and Yingcharoen, 1999). Treated effluent is pumped offshore in these systems to avoid contaminating the water intake site or coastal areas adjacent to shrimp farms. Seawater Circulation System Projects are very costly and it has been estimated that only 5% of Thai shrimp farms will have access to seawater circulation systems by 2002 (*ibid*.).

Constructing a Shrimp Pond

Although these management strategies, extension programs, and infrastructure projects were undeniably beneficial, their success in stabilizing the shrimp farming industry in Thailand is debatable. Total annual shrimp production continued to rise through 1995 as a result of new farms being brought on stream to replace operations in areas such as the lower Chao Phraya Delta which had collapsed. This strategy was successful for a time, but by 1995, most of the coastal land available for shrimp farming in Thailand was already in production or abandoned. Total annual harvests actually began to decline in 1996 for the first since the shrimp boom began. This led several observers to suggest that a crash in shrimp production similar to the Chinese and Taiwanese experience could be imminent (Dierberg and Kiattisimkul, 1996; Flaherty and Karnjanakesorn, 1995). Shrimp production in coastal areas of Thailand did in fact continue to fall during the latter half of the 1990s, but a significant innovation emerged during this period that would allow the shrimp boom to continue. Low salinity shrimp farming techniques were developed in Samut Sakhon and Chachoengsao provinces, and this innovation would allow intensive shrimp farming to make a dramatic return to the Chao Phraya River Delta.

Echo Boom – Low Salinity Shrimp Farming (1996 - 2002)

As environmental and husbandry problems associated with coastal shrimp farming increased and crop failures became commonplace in the lower Chao Phraya Delta, the shrimp farming industry began to search for alternatives to maintain production (Kaosa-ard and Pednekar, 1996). Crop failures in coastal areas had a serious economic impact on novice shrimp farmers who responded to this crisis in several ways. Many farmers decided to risk raising additional capital for new shrimp crops. Unfortunately, most farmers who adopted this strategy simply repeated or compounded the husbandry errors that led to the initial crop failures. Other farmers switched to freshwater fish or crab production which is less speculative, but provides smaller potential profits. Many individuals abandoned aquaculture completely and turned to off-farm employment in order to repay debts incurred from shrimp farming (Banpasirichote, 1993).

Loading Salt Water in Samut Prakarn

Relocating shrimp farms inland and away from disease prone areas also emerged as a response for farmers with larger financial resources. Low salinity shrimp farming techniques were first developed to support multiple crops in seasonally brackish zones located upstream of the failed coastal sites (Flaherty and Vandergeest, 1998). Shrimp farmers in Samut Prakarn and

Chachoengsao discovered that tiger shrimp post-larvae could be acclimatized to a low-salinity environment produced by mixing saline water trucked-in from the coast and freshwater drawn from irrigation canals or streams (Szuster, 2001). Although familiarity and availability were the primary reasons for utilizing black tiger shrimp in these experiments, this species is well known for its tolerance to significant variations in both temperature and salinity (Laubier, 1990).

Shrimp Farm in Suphanburi

Low salinity farming techniques are generally similar to those used in coastal operations which feature high stocking densities, aerated ponds, and the use of prepared feeds, fertilizers and chemotherapeutants. While coastal farms utilize naturally occurring brackish seawater (15-30 ppt) to fill and replenish pond enclosure, low salinity farms combine freshwater with saltwater purchased from coastal salt pans or saltwater concentrate operations (Miller *et al.,* 1999). This approach achieves an initial pond salinity level between 4 and 10 ppt. Additional freshwater inputs are used to offset evaporation and seepage losses over the grow-out period, and can reduce salinity levels to near zero by harvest unless supplementary saline water or bagged salt is applied. The standard grow-out period for low salinity culture systems is a relatively short 100-120 days; and harvest occurs earlier than coastal operations as a result of falling salinity levels and the negative effect this has on shrimp health and development (Ponza, 1999). Given the shorter culture period and sub-optimal growing environment, shrimp from low salinity farms tends to be smaller and of a poorer quality than those raised on brackish water coastal farms.

The combined use of hyper-saline water trucked from the coast and locally available freshwater from irrigation canals allowed two or even three shrimp crops to be raised within seasonally saline areas of the Chao Phraya Delta. Rice farmers in areas further upstream also soon realized that the high profits derived from shrimp production could easily offset costs associated with trucking salt water to their farms. Development opportunities were limited only by basic site suitability criteria (relatively flat land and a reliable source of water), salt water transportation expenses, and land leasing or purchase costs (Szuster *et al*., 2003). This facilitated a second shrimp boom within completely freshwater rice growing areas of the Chao Phraya Delta (e.g., Nakhon Pathom and Suphanburi) and farms could be found as far as 200 kilometers upstream from the Gulf of Thailand by 1998 (Committee on Inland Shrimp Farming, 1998).

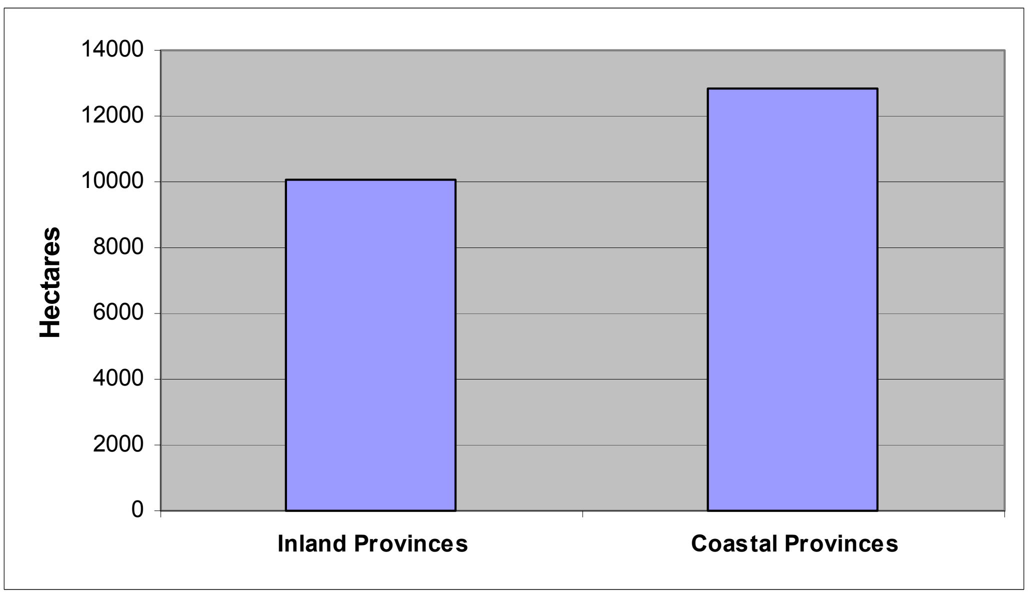
Low Salinity Shrimp Farms in the Chao Phraya Delta

In addition to water quality and disease concerns, a key force driving the expansion of low salinity shrimp farming was the high profitability of shrimp relative to wet rice production (Pongnak, 1999). Low returns for rice led a large numbers of farmers in the Chao Phraya Delta to convert irrigated paddy fields into shrimp ponds during the later half of the 1990s (Flaherty *et al.,* 1999). A recent survey of rice and shrimp farms in Nakhon Pathom province (Szuster *et. al.,* 2003) identified an average annual net income of $620 USD per hectare for rice farmers and $6030 USD per hectare for farmers who adopted tiger shrimp farming in the same area. The much higher net income available from shrimp farming does, however, require a greater level of investment. Both fixed costs (e.g., land preparation and equipment) and running costs (e.g., seed, feed, fuel and labor) were substantially higher in the case of shrimp farming. Fixed costs for rice production were estimated at $193 USD per hectare as opposed to $788 USD per hectare for shrimp. The difference was even more pronounced in the case of running expenses which were estimated at $172 USD per hectare for rice farming and approximately $14,000 USD per hectare for shrimp production. The very high running cost associated with tiger shrimp farming are largely a result of the need to stock shrimp ponds with hatchery-raised fry and maintain this crop using expensive factory-prepared pelletized feeds (Miller *et al*., 1999).

Given the much higher costs associated with shrimp culture, it is not surprising that the financial risks associated with this activity are also much greater than those associated with rice cultivation. Shrimp farms are susceptible to catastrophic crop failures as a result of the spread of viral or bacterial diseases, and numerous other factors such as poor water quality, cold weather, inappropriate soil characteristics, inexperienced farmers, and crop theft (Szuster, 2001). Disease and other husbandry-related problems can also reduce the size and quality of the shrimp crops which affects crop values and return on investment. A total of 62% of shrimp farmers surveyed in the Nakhon Pathom study reported experience with large or complete shrimp failures (Szuster *et at.,* 2003) and unsustainable levels of debt can quickly accumulate in cases where consecutive crop losses occur (Flaherty *et al*., 1999). Economic evaluations suggest that while a conversion from rice to shrimp crop in the Chao Phraya Delta can potentially produce much higher net incomes, the substantial running costs associated with each shrimp crop represent a serious on-going financial risk for aquaculturalists.

It is difficult to estimate the extent of shrimp farming within freshwater areas of the Chao Phraya River Delta because information collected by the Royal Department of Fisheries does not directly distinguish between freshwater and brackish production sources. Information is collected on the basis of provincial boundaries, however, and these data can be used to provide a rough estimate of the proportion of shrimp farms within freshwater and brackish environments. Surveys conducted by the Land Development Department (1999) and Department of Fisheries (2001) suggest that approximately 22,867 hectares of shrimp pond were located within the Chao Phraya River Basin in 1998. More than 44% of this total pond area was located within freshwater inland provinces, while the remaining 56% was located within coastal provinces such as Samut Prakarn and Samut Sakhon (Figure 4). This calculation closely matches earlier estimates by industry advocates who stated that low salinity farms operating within freshwater areas could have accounted for as much as 40% (or approximately 100,000 metric tones) of Thailand's total farmed shrimp output in 1998 (Limsuwan and Chanratchakool, 1998). If this overall estimate is accurate, it implies that the rapid the expansion of low salinity shrimp farming in the Chao Phraya Delta and other inland freshwater areas of central Thailand (e.g., Bangpakong River Basin) masked a very serious collapse of brackish water shrimp production in coastal areas throughout the country (Szuster, 2001).

Figure 4. Shrimp Farm Area in the Chao Phraya River Basin (1998)*



Data Source: Department of Fisheries, Department of Land Development

The expansion of low salinity shrimp farming into freshwater rice-growing areas of the Chao Phraya Delta initially proceeded with little overt government support or public controversy. This low profile disappeared, however, when the Thai print media became sharply critical of low salinity shrimp farming and the potential environmental damage this activity could produce within Thailand's most important agricultural region (Arunmart and Ridmontri, 1998). Academic researchers also suggested that low salinity shrimp farms could produce soil salinization, water pollution, and increased competition between agriculture and aquaculture for freshwater (Miller *et al*., 1999; Pongnak, 1999). After a vigorous public debate between pro and anti-shrimp farming groups and the completion of environmental impact studies, the Thai government banned shrimp farming in late 1998 within non-coastal provinces on the basis of a recommendation from the National Environment Board (Srivalo, 1998). Provincial governors in coastal provinces were then subsequently instructed to identify and map brackish water areas (where shrimp farming would be permitted) and freshwater zones (where shrimp farming would be restricted). In spite of the ban on low salinity shrimp farming, the practice continued relatively uninterrupted over the next 2 years. Harvests may have even increased between 1999 and 2001 as farmers were encouraged by the Thai government to increase production and take advantage of high prices stemming from a catastrophic collapse of shrimp farming in Latin American (Bangkok Post, 2000a). The Thai shrimp farming industry also lobbied strenuously for a reversal of the ban on shrimp farming in freshwater areas during this period (Bangkok Post, 1999). It appeared for a time that that the restriction on inland shrimp farming would be relaxed, but intense opposition from environmental groups and support from His Majesty King Bhumibol of Thailand finally convinced the National Environment Board to re-affirm its original decision and maintain the ban (Samabuddi, 2001). Progress on enforcing the ban has been slow, however, and a recent survey conducted by the Thai government suggests that many shrimp farms continue to operate within freshwater areas such as Nakhon Pathom (Samabuddhi, 2003).

The history of shrimp farming in the Chao Phraya Delta has been characterized by a constant struggle against environmental and economic factors. A combination of biophysical and socio-economic conditions encouraged the large-scale production of black tiger shrimp in coastal Thailand, but unsustainable intensive production techniques resulted in widespread crop failures. The industry responded to these problems by moving into freshwater areas that were perceived as less susceptible to disease and environmental problems, but this strategy was ultimately blocked by Thai government policies. More recent adaptations have included a conversion from marine shrimp to freshwater prawn culture in Nakhon Pathom and Suphanburi (Szuster *et al*., 2003) and the importation of Pacific white shrimp (*Penaeus vannamei*) for their disease resistance characteristics. The effectiveness of these most recent adaptations remains unclear, but the history of shrimp farming in the Chao Phraya Delta suggests that the aquaculture sector will continue to explore a wide range of alternatives in an effort to maintain or increase production levels in spite of systemic management problems and unresolved environmental concerns.

4.0 ENVIRONMENTAL IMPACTS OF SHRIMP FARMING

The economic success of shrimp farming in Thailand has not been attained without the creation of significant environmental impacts (Szuster *et al.,* 2003; Szuster and Flaherty, 2002a; Dierberg and Kiattisimkul, 1996; Phillips *et al.*, 1993; Pillay, 1992). A large and diverse body of research has investigated the relationship between shrimp aquaculture and the environment in Thailand, and individual impacts have been classified into five broad categories. These include: water use conflicts, water pollution, land use conflicts, disease transmission, and species interactions. Literature within these categories is reviewed in this section to evaluate recent research and document the environmental impacts of shrimp farming in the Chao Phraya Delta.

Water Use Conflicts

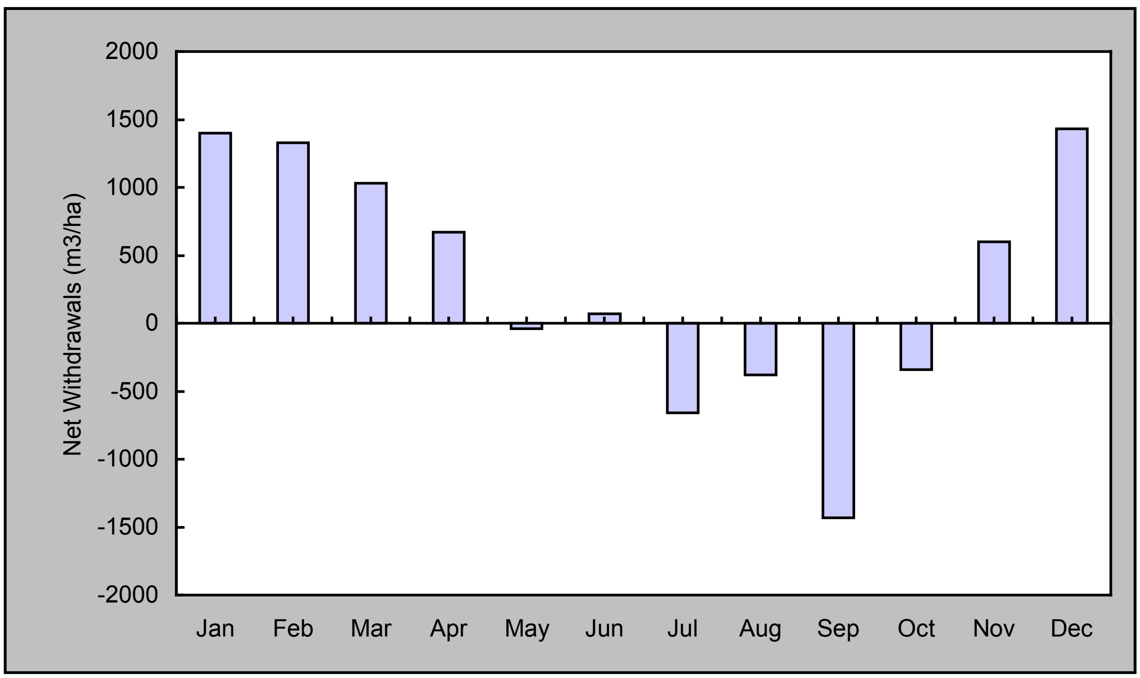
Shrimp farming requires substantial quantities of brackish or full strength seawater to fill the pond enclosures and to maintain environmental conditions during the grow-out period. A majority of existing aquaculture water use research has focused on freshwater fish species (e.g., Green and Boyd, 1995; Teichert-Coddington *et al.*, 1988). A small number of water use studies have, however, been conducted on shrimp farms. Braaten and Flaherty (2000) investigated low salinity shrimp farming in Chachoengsao; Briggs and Funge-Smith (1994) documented water use at a coastal brackish water farm as part of a nutrient study; and Primavera (1993) assessed shrimp farm water use in the Philippines. Given that water is the medium used to produce farmed shrimp, it is not surprising that aquaculture requires considerably more water than manufacturing or industrial production processes (Phillips *et al.*, 1991). Water use at any individual aquaculture operation can also increase well above average requirements under certain conditions. Poor husbandry practices such as high stocking densities or over-feeding can necessitate large daily water exchanges to maintain water quality (Chamberlain and Hopkins, 1994). Evaporation can also exceed 2.5 cm/day from open ponds in tropical regions (Jackson, 1989) and seepage through the pond walls and bottoms can rise as high as 0.66 cm/day depending on the porosity of building materials (Boyd, 1985). These factors produce a large degree of variability in water use between farms and among farming regions (Phillips *et al.*, 1993). A review of shrimp farm water use literature performed by Miller (1996) found that water withdrawal rates can vary between 44,000 - 233,000 m^3/ha/crop. Consumptive water use rates are much lower, however, and range between 7300 – 9050 m^3/ha/crop (Braaten and Flaherty, 2000). This analysis suggests that a significant percentage of water withdrawn by shrimp farms for use in grow-out operations is eventually returned to the supply source after being held within ponds for a relatively short period of time.

Lift Pump Adding Freshwater to a Low Salinity Shrimp Pond

Given that the supply of salt water in coastal areas is essentially unlimited, competition over this resource is rare. Water conflicts can develop in coastal areas, however, when surface freshwater or non-saline groundwater are used to reduce pond salinity to a level favorable for shrimp growth and development (Pillay, 1993). The over-extraction of groundwater by shrimp farmers has contributed to coastal land subsidence and associated flooding in several Asian countries (Primavera 1993). An example of this occurred in Taiwan where coastal areas were lowered by 0.3-2.0 m as a result of eel and shrimp culture operations during the 1980s (Chiang and Lee, 1986). Groundwater pumping for aquaculture purposes has also been implicated in the intrusion of saltwater into freshwater aquifers (Pillay, 1993). Based on this information, a ban on groundwater pumping for aquaculture purposes was imposed by the Thai government to prevent land subsidence and protect agricultural and domestic water supplies from saline intrusion (Phillips *et al.* 1993). The existing use groundwater as a water supply source for shrimp farming in Thailand is largely unknown, but no published or anecdotal reports confirming the illegal use of groundwater for shrimp farming have emerged to date.

Water use conflicts could also emerge as a result of low salinity shrimp culture because freshwater provides a significant proportion of the total water supply for these farms. Water supplies are abundant in Thailand during the rainy season and shrimp farm net withdrawals are often negative during this period as a result of direct inputs from precipitation and runoff (Figure 5). This suggests that water supply effects associated with rainy season shrimp production are negligible despite relatively large water losses associated with pond seepage and evaporation. Wet season water supplies in the Thailand are more than adequate to supply all existing water uses and flooding is a much more pressing concern during this period.

Figure 5 Shrimp Farm Net Water Withdrawals (Braaten and Flaherty, 2000)



Dry season natural water supplies are far more limited, however, and freshwater consumption for shrimp farming could potentially affect aquatic habitats and produce water conflicts with other agricultural, industrial or domestic water users. A combination of freshwater from irrigation canals and hyper-saline water transported to the farm-site by truck is the preferred water supply for most low salinity shrimp farms in the Chao Phraya Delta during the dry season (Table 1). This preference largely stems from concerns over water quality and the potential presence of marine shrimp pathogens in brackish water that is present within rivers and irrigation canals at this time (Ponza, 1999).

Table 1 Central Plains Region Shrimp Farm Water Supplies (Ponza, 1999)

WATER SOURCE	NUMBER OF FARMS	PERCENTAGE OF FARMS
Saline Water Supply		
1. Low salinity from irrigation canal	12	10%
2. Hyper-saline transfer by truck	64	53.3%
3. Bagged salt	20	16.7%
4. Brackish river water	2	1.7%
5. Combination of 1 and 2	2	1.7%
6. Combination of 1 and 3	12	10%
7. Combination of 2 and 3	8	6.7%
Freshwater Supply		
1. River or freshwater stream	2	1.7%
2. Irrigation canal	118	98.3%

Although the consumption of freshwater by shrimp farms in the Chao Phraya Delta during the dry season is of concern, the actual role of shrimp farming in exacerbating existing water use conflicts is far from clear. Most low salinity shrimp farms have been converted from irrigated rice production, and a recent comparison of shrimp and rice revealed no statistically significant differences in water consumption rates between these two crops (Braaten and Flaherty, 2000). Shrimp farm water consumption rates were also found to be marginally higher than those observed for cotton, beans, and corn; but less than bananas and sugar cane (Jackson, 1989). Given the similarity in consumptive water use patterns between shrimp and other agricultural crops typically grown in the Chao Phraya Delta, a significant alteration in regional water consumption is unlikely unless additional dry season shrimp crops are produced (Szuster and Flaherty, 2002a). Water demand and hydrology data at the watershed level are largely unavailable in Thailand, however, and this data gap precludes an analysis of local water supply conflicts that may exist as a result of aquaculture development in smaller tributaries.

Water Pollution

Intensive shrimp aquaculture practices in the Chao Phraya Delta are typified by high stocking densities (50-100 post larvae per square meter), high production rates (6-12 tonnes per hectare), high feeding rates (feed conversion rations between 1.8-2.0) and significant daily water exchanges (Funge-Smith and Briggs, 1998). This intensive approach can produce substantial quantities of nutrient-rich effluent that is highly polluting if released untreated into surface water bodies (Pollution Control Department, 1996). Waste produced by shrimp farms include solid matter (primarily eroded pond soils), organics (uneaten shrimp feed, faeces, shrimp mortalities, dead plankton) and dissolved metabolites such as ammonia, urea and carbon dioxide (Tookwinas, 1998, Briggs and Funge-Smith, 1994). Effluent production and water exchange are modest during the first 60 days of the grow-out cycle because the juvenile shrimp are small and require little supplemental feeding (Lee and Wickens, 1992). During the latter half of the culture cycle, however, the adult shrimp require increasingly large feed inputs and daily water exchanges are needed to maintain a suitable growing environment. Uneaten food pellets, faeces, and eroded pond soil tend to accumulate at the center of the pond enclosure due to the action of mechanical aerators. This "sludge" is enriched in nitrogen, phosphorus and carbon relative to surrounding sediments, and its accumulation is associated with anaerobic decomposition and the release of ammonia, organic sulphur and hydrogen sulfide (Philips *et al.,* 1993).

Feed wastage in black tiger shrimp culture is highly dependent on husbandry practices, but laboratory studies suggest that at least 11% of all feed goes uneaten (Wickins, 1985). Faecal production for tiger shrimp has been estimated at 26% of ingested feed (Beveridge *et al*., 1991). In their study detailed study of nutrient budgets on Thai shrimp farms, Funge-Smith and Briggs (1998) determined that shrimp feed and eroded pond soil are the primary sources of organics (22 tonnes per hectare per crop). Pond soil is the dominant contributor of solids (204 tonnes per hectare per crop) with shrimp feed providing a relatively inconsequential component (Table 2). The only other significant source of solid or organics is the inlet water used to fill pond enclosures and maintain water levels. Shrimp ponds are extremely efficient sedimentation sinks with a high percentage of both solids (93%) and organics (63%) entrained in pond sludge. Routine water exchanges and harvest draining represent important outputs of organic matter and solids (4.8 and 12.6 tonnes per hectare per crop respectively). Although both of these output sources contain nutrient loads that are far lower than pond sludge, the disposal of this wastewater can still have a negative impact on receiving waters (Hempel and Winther, 1998). Harvested shrimp were the only other notable output of organics (6.1%). Organic loads associated with shrimp farm effluent are dependent upon the quantity and rate of waste production, feed nutrient levels, feed conversion ratios, and site-specific conditions. Funge-Smith and Briggs (1998) estimated that 78-79% of all nitrogen and 92-95% of all phosphorus added to marine shrimp ponds during culture was lost to the environment. This research also confirmed the earlier findings of Civera and Guillaume (1989) who estimated a total nitrogen load of 57.3-118.1 kilograms and a total phosphorus load of 13.0-24.4 kilograms per tonne of shrimp production for feed conversion rations of 1.2:1 and 2.1:1 respectively. These loading figures suggest that 63-78% of all nitrogen and 76-86% of all phosphorus applied to a shrimp pond are lost to the pond ecosystem or subsequently released into the environment.

Table 2 Shrimp Pond Nutrient Budget (Funge-Smith and Briggs, 1998)

Inputs	Solids	Organics	Outputs	Solids	Organics
Inlet Water	2.8%	9.8	Water Exchange	3.6%	12.9%
Fertilizer	0.2%	1.2%	Harvest Drainage	2.6%	8.8%
Lime	1%	0%	Sludge	93%	63%
Feed	5%	40%	Shrimp Harvest	0.7%	6.1%
Pond Soils	91%	49%	Other*	0%	9.2

Impact of Liquid Wastes

Untreated liquid waste discharged by shrimp farms in Thailand during the early to mid grow-out period typically contains nutrient loads only slightly higher than many receiving waters (Ingthamjitr, 1999; Pollution Control Department, 1996). Early to mid grow-out shrimp pond effluent is also generally within a range acceptable to indigenous freshwater and marine organisms (Boyd, 1989) and complies with aquaculture effluent quality standards proposed by Thailand's Pollution Control Department (1996). The nature of effluent released during the late grow-out period and harvest is markedly different, however, and is characterized by significant concentrations of nutrients, solid organic matter, and salt (Funge-Smith and Briggs, 1998). Particulate matter entrained within shrimp farm harvest effluent can collect in drainage or irrigation canals below the discharge point (Phillips *et al.,* 1993) and impacts stemming from the accumulation of this material can include: smothering of benthic flora and fauna, reduced dissolved oxygen, hypernutrification and eutrophication (Pollution Control Department, 1996; FAO and NACA, 1995; Weston, 1991). The discharge of salt-laden shrimp pond effluent into freshwater bodies during water exchange or at harvest can also impact rice farmers or orchardists who access irrigation water during periods of elevated salinity (Braaten and Flaherty, 2000). Settling ponds or reservoirs are employed by an increasing number of shrimp farmers to treat liquid effluents, but most small-scale aquaculturalists in Thailand do not possess either adequate land or the experience to apply even this basic form of liquid waste management (Ponza, 1999).

Small Irrigation Canals Both Provide Water and Receive Effluent

Impact of Semi-Solid Wastes

The handling of semi-solid sludge that remains in grow-out ponds after harvest presents an even greater challenge than the management of liquid effluents. A process that involves drying, mechanically removing, and storing pond sludge in pits has been proven to be the most environmentally sound sludge disposal technique. Unfortunately, many shrimp farmers continue to simply flush pond sludge directly into adjacent water bodies that also serve as their water supply source (Department of Pollution Control, 1996: 148). Satapornvanit (1993) estimated that approximately 1650 m^2 per hectare of organic-rich effluent is produced by removing pond sediments from shrimp ponds floors using high pressure water sprays.

A second "wet flushing" technique involves simply allowing pond outlet structures to remain open over several tidal cycles (Braaten, 2000). The biological oxygen demand (BOD) of effluent produced by either of these sludge disposal techniques is extremely high and can reach 1500 mg/litre (Satapornvanit, 1993). Sludge disposal is problematic in all shrimp farming areas of Thailand, but this issue is particularly critical within freshwater regions. The Chao Phraya River Basin suffers significant dry season water quality problems, and shrimp farm effluent can represent a significant source of organic pollution during this period (Szuster, 2002). The small streams and irrigation canals that serve as both water source and waste disposal site for shrimp farms also possess relatively little assimilative capacity, and these water bodies can be significantly degraded by sludge dumping (*ibid*.). The disposal of pond sludge into any water body is illegal in Thailand, but this practice is not uncommon due to a lack of farmer awareness and regulatory enforcement (Braaten and Flaherty, 2000).

Wet Flushing Shrimp Pond Sludge Deposits

Chemotherapeutant Residues

A variety of chemicals, antibiotics, anesthetics, pesticides and disinfectants are used by shrimp farmers in Thailand throughout the culture cycle. Lime is commonly applied to pond bottoms between crops to neutralize acidity and sterilize sediments (Boyd, 1989). The amount used is highly dependent on site-specific conditions, but several tonnes per hectare may be required on acid sulfate soils that typically exist in former mangrove areas. Organic and inorganic fertilizers are also used to stimulate an initial algae bloom which serves as a food source for shrimp during the early post-larval development stages. The environmental impacts of liming is likely minimal, but fertilizer use may contribute to nutrient loading in receiving waters (*ibid.*). Piscicides and molluscicides are used to remove predators or competitors from grow-out ponds, and the potential effects of these substances is dependent upon their toxicity and persistence upon release into the environment. Biodegradable organic compounds such as rotenone, tea seed meal, or nicotine are also widely applied to remove predators (Baticados *et al.,* 1990) and are less persistent than chlorinated hydrocarbons such as DDT, endrin or aldrin (Philips *et al.,* 1993). Large-scale fish kills in mangrove areas have been associated with tea seed use in the Philippines (Primavera, 1993) and human skin diseases have been attributed to the presence of shrimp farm effluent in public waterways in Sri Lanka (Corea *et al.,* 1998). Anti-bacterial products are used to sterilize water and equipment in hatcheries, and zeolites can remove ammonia from grow-out ponds. Algicides include copper sulfate, while malachite green is used for fungal outbreaks and formalin is applied to suppress parasite infestations.

Antibiotics are applied in aquaculture to treat disease outbreaks and as a prophylactic (Austin, 1993). Antibiotic residues can enter the environment surrounding aquaculture facilities through the disposal of effluent, or after leaching from uneaten medicated food pellets. Products licensed in Thailand for use in shrimp farming include erythomycin, oxytetracycline, and furacin. The use of antibiotics can affect microbial communities within receiving waters by eliminating sensitive species (Samuelson *et al.* 1992). This process may eliminate aerobic bacteria that breakdown organic matter and favor more resistant strains such as *Vibrio spp.* which are associated with animal and human diseases (Nygaard *et al.* 1992). Drug resistance is a serious problem for shrimp farmers in Thailand, and several bacterial strains (*A. hydrophila, A. sobria and Vibrio sp.*) display resistance to antibiotics such as oxytetracycline, erythromycin and bactrim (Somsiri, 1995). The prevalence of drug resistant bacterial strains has forced shrimp farmers to seek out new antibacterial agents, but the presence of banned chloranphenicols and nitrofurans in Thai shrimp during 2002 led to a compete halt of shipments to the European Union (Somjetlertcharoen, 2002). Antibiotics residues can also be transferred to shellfish or other species raised in close proximity to shrimp farms, and this can produce concentrations above levels identified as safe for human consumption (Samuelson *et al.,* 1992). It is extremely difficult, however, to make any general statements regarding the significance of ecological or human health effects related to antibiotic usage in aquaculture. The persistence of antibiotic residues in the environment is influenced by a very complex set of variables, and the significance of potential impacts depends upon the compounds involved, dosages, frequency of use, and site-specific environmental conditions (Weston, 1996). The abuse of antibiotics and other chemicals by poorly trained shrimp farmers is unfortunately common in Thailand, and additional extension programs that focus on appropriate chemotherapeutant use are clearly needed to lessen human health concerns and eliminate the use of banned substances.

Land Use Conflicts

Site selection may represent the most critical decision in aquaculture development planning and management. It is a challenging procedure that incorporates a wide range of environmental and social variables, but appropriate site decisions can prevent many of the land use conflicts commonly associated with shrimp farm development (Pillay, 1993). Land use conflicts related to poor site selection include soil salinization in agricultural areas, the problem of abandoned shrimp ponds, and the loss of mangrove forests (Dierberg and Kiattisimkul 1996; Barraclough and Finger-Stich, 1996).

Soil Salinization

The growth of shrimp aquaculture within coastal and inland agricultural areas has been implicated in the salinization of agricultural lands (Flaherty *et al.,* 2000; Barraclough and Finger-Stich, 1996; Phillips *et al*., 1993). The effects of salinization on rice crop productivity is well established (Greenland, 1997) and water management strategies that assess rice yields in seasonally saline environments have also been investigated (Phonga *et al*., 2000). All rice varieties are sensitive to varying degrees of salinity which can inhibit the growth of rice seedlings, reduce yields, and increase vulnerability to insect pests (Salim *et al*., 1990). Shrimp farming produces direct salinization impacts through the deposition and accumulation in salts in pond bottom soils (Szuster, 2001). Indirect impacts can also occur as a result of lateral seepage from pond enclosures into adjacent fields, or if saline water is released into irrigation canals that represent a water source for rice paddies and orchards downstream. As aquaculture expanded rapidly in Thailand during the late 1980s and early 1990s, dense concentrations of shrimp farms emerged in many coastal areas. Agricultural yields in coastal areas tend to be rather poor due to marginal soil conditions, and this situation was aggravated by saline seepage from shrimp ponds or saltwater intrusion produced by groundwater withdrawals for aquaculture (Phillips *et al*., 1993). Although their economic importance is limited, the destruction of sugar palms originally planted in coastal rice fields is a highly visible reminder of aquaculture-induced soil salinization problems.

Sugar Palms Affected by Shrimp Farming

The issue of soil salinization is even more controversial within freshwater regions of central Thailand because many low salinity shrimp farms have been sited within highly productive rice growing areas. Recent research on direct land salinization impacts suggests that soil conductivity levels that negatively affect crop yields (greater than 4 mS/cm^{-1}) are likely to occur on all agricultural land converted to shrimp ponds (Committee on Inland Shrimp Farming, 1998). Most of this land was highly suitable for rice farming (Szuster, 2001) and soil productivity has almost certainly been negatively affected by a conversion to shrimp culture. The extent of indirect soil salinization impacts associated with low salinity shrimp farming are considerably more difficult to assess than direct impacts on pond bottom soils. Braaten and Flaherty (2001) determined that approximately 23 tonnes of salt per crop are lost to the surrounding environment through seepage, pond water discharge and pond sediments. Lateral seepage through pond walls (11.5 tonnes per crop) and the direct discharge of saline water to irrigation canals (9.7 tonnes per crop) were the most significant salt transfer pathways.

Zero discharge shrimp farming system was also investigated by Braaten and Flaherty (*ibid*.) because this approach may reduce salt transfers to surrounding areas. Although salt losses are reduced using a zero discharge system, approximately 12.4 tonnes of salt per crop were still lost to adjacent lands though lateral seepage. Studies conducted by the Thai government (Committee on Inland Shrimp Farming, 1998) determined that salt water seepage can increase salinity in paddy soils up to 100 meters from the edge of a low salinity shrimp pond, but other research has produced conflicting results (Land Development Department *et al.,* 2000). Caution must be exercised, therefore, in assessing the significance of indirect salinization impacts and the amount of land actually affected. Indirect salt transfer pathways are extremely complex, husbandry practices vary greatly, and a large amount of natural soil flushing is provided by monsoon rains. However, given the size and importance of agricultural areas potentially affected, the significance of direct and indirect soil salinization impacts should not be underestimated.

Abandoned Shrimp Ponds

A large number of shrimp farms have been sited in areas where production failed after a relatively short period of time (Chua, 1993). Factors contributing to farm failures include inappropriate soil conditions, poor husbandry practices, disease outbreaks stemming from infected water supplies and seedstock, and pollution from urban and industrial sources (Miller, 1996). The scale of farm failures was especially significant in the lower Chao Phraya Delta. Potaros (1995) estimated that approximately 19,900 hectares of shrimp farmland were abandoned in 1990-1991 along the upper Gulf of Thailand coastline, and as much as 45,000 hectares may have been abandoned in the entire central region of Thailand during this period (Briggs and Funge-Smith, 1995). Prior to its conversion into shrimp ponds, approximately half of the abandoned land in the lower delta was rice paddy. The remainder was equally divided between coconut plantation and salt farms (FAO and NACA, 1995). Pond bottom soils in abandoned shrimp ponds are commonly contaminated with high levels of salt, pesticides or antibiotics residues (Miller, 1996). Shrimp farming alters the physical and chemical properties of pond bottom deposits and former mangrove soils are particularly problematic. Exposed former mangrove soils are typically acid sulfate in nature and runoff from these deposits can destroy food resources, displace biota, release toxic levels of aluminum, and precipitate iron that smothers vegetation (Sammut *et al.,* 1996). Long-term changes to pH produced by acidic runoff can also change the biotic composition of an area by favoring acid tolerant plants and animals (Stevenson, 1997).

The return of abandoned shrimp ponds to productive use has met with mixed success (Stevenson *et al.,* 2000). Large areas of the lower delta near Bangkok were developed into housing or industrial estates, and a considerable number of abandoned shrimp farms have been converted in salt farms or crab fattening operations (Miller, 1996). Very few abandoned ponds in coastal Thailand were returned to coconut or rice production, however, and the relatively small profits generated by these traditional land uses make any significant re-conversion to agriculture unlikely (Stevenson, 1997). Mangrove or salt flat restoration may have more potential in coastal areas because this approach can produce numerous ecological, social and commercial benefits. Potential benefits include: shoreline protection, fisheries habitat enhancement, aqua-silvaculture, and community resource use (Lewis, 1999). Given the range and number of benefits associated with mangrove restoration, this option may represent an excellent opportunity address some of on-going problems associated with abandoned shrimp ponds in Thailand. Mangrove and agricultural restoration can only be expected to return a relatively small portion of the existing stock of degraded shrimp farmland. Economic considerations and recent experience suggests that a large proportion of abandoned shrimp ponds will ultimately be transformed into urban, industrial or manufacturing land uses. The potential for rehabilitating highly productive rice growing land converted to low salinity shrimp farms has also been investigated (Land Development Department, 1999). This research found that crops could be re-established in former shrimp ponds, but achieving previous levels of rice production is costly and can take several years.

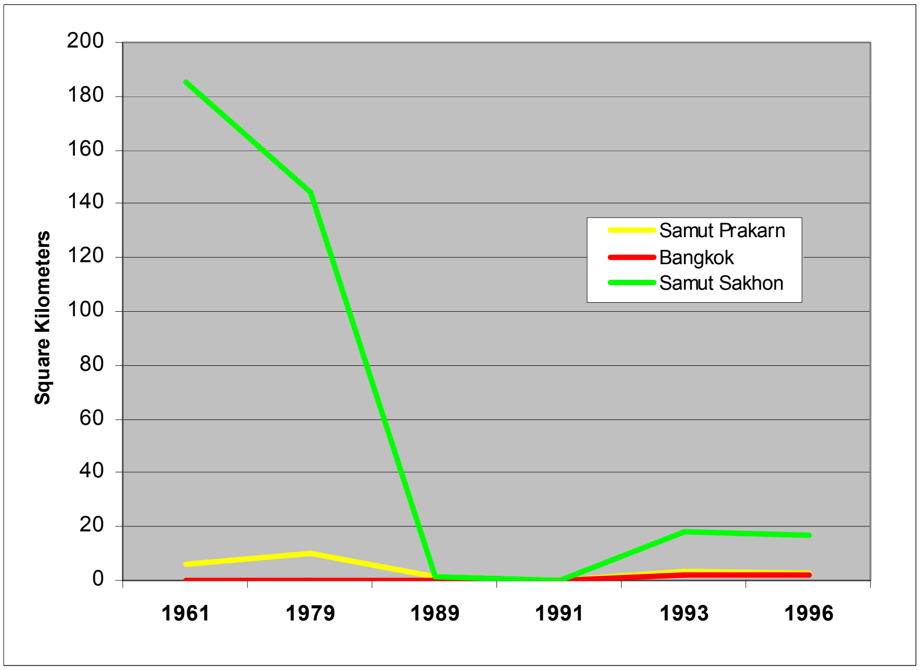
Mangrove Destruction

Mangrove forests represent an important component of Thailand's coastal ecosystem, even though a large amount of clearing has taken place since the 1960s (Flaherty and Karnjanakesorn, 1995). Mangrove ecosystems are uniquely adapted to coastal and estuarine conditions characterized by significant seasonal and diurnal changes in water quality conditions. Mangroves are extremely productive and serve a wide range of functions including: protecting coastal areas from wave and storm-induced erosion, filtering coastal runoff, supplying nutrients, and providing critical habitat for a wide range of plant and animal species (Pillay, 1992). A number of coastal communities still depend on mangroves for firewood, charcoal and construction materials (Barraclough and Finger-Stich, 1996), and the loss of these forests to shrimp farming has led to economic losses for these social groups (Ahmed, 1997; Yadfon Association, 1996).

Mangrove Rehabilitation Area – Kung Kraben Royal Project

The total area of mangrove forest within Thailand fell by approximately 50%. between the years 1960 and 1989 (Dierberg and Kiattisimkul, 1996). Aquaculture development played a significant role in this decline as many mangrove areas were directly converted into shrimp farms, degraded by shrimp farm effluent, or affected by aquaculture-related changes to coastal hydrology. The amount of mangrove forest lost to shrimp farming between 1960 and 1989 is a controversial topic, and recent estimates range between 17% and 38% of the total loss (Ahmed, 1997; Menasveta, 1997). This discrepancy reflects a disagreement over the original extent of mangrove forests in Thailand and a lack of information regarding the nature of the land conversions prior to the emergence of shrimp farming (Beveridge and Phillips, 1993). It appears that Samut Prakarn and Bangkok provinces were almost entirely devoid of mangrove by the early 1960s as a result of land conversion for salt farms, fish ponds, charcoal production, agriculture, port expansion and urban development (Tookwinas and Ruangpan, 1992). Samut Sakhon suffered significant mangrove forest losses during the early to mid 1980s which may have been partly attributable to semi-intensive shrimp farming, but most of these losses occurred prior to the boom in intensive shrimp aquaculture that began in 1988 (Figure 6).

Figure 6 Mangrove Forest Area in the Lower Chao Phraya Delta (1979-1996)*



Data Source: Thai Royal Forest Department

Mangroves possess several characteristics that are beneficial to shrimp farming (e.g., access to brackish water, subdued terrain), but these areas are also characterized by acid sulphate soils that form as a result of regular flooding (Boyd *et al*., 1994). Exposed acid sulphate soils produce significant amounts of sulphuric acid and require regular liming to become productive aquaculture sites. Recent studies suggest that supra-tidal areas located at a slightly higher elevation are much more suitable for shrimp farming (Boyd, 1995). Given these findings, and the substantial amount of criticism directed at Thailand for mangrove destruction by international environmental organizations, it is not surprising that the shrimp aquaculture industry has endorsed "sustainable" farming practices that discourage siting in mangroves (FAO and NACA, 2000; Rosenberry, 1998). The Government of Thailand has also sponsored mangrove replanting in areas surrounding Seawater Irrigation Projects and similar rehabilitation projects have been initiated in parts of the lower Chao Phraya Delta (e.g., Mahachai Mangrove Forest Study Centre in Samut Sakhon). The scale of these efforts is relatively small, however, and the effectiveness of many of these proposals is yet to be proven. Irrespective of existing and future mangrove reclamation efforts, greatly improved monitoring and enforcement is also required to prevent future losses of coastal mangrove forests in Thailand (Flaherty *et al*., 2000).

Disease Transmission

A large number of highly infectious viral and bacterial diseases affect both farmed and wild shrimp, and epidemics are the result of a complex interaction between host species, disease agents, and the environment (Iverson *et al.,* 1993). Disease outbreaks in shrimp farms stem from infected seedseed, broodstock or water supplies, and are exacerbated by elevated stress levels produced by artificial containment, high stocking densities, and poor water quality conditions (Beveridge and Phillips, 1993). Stress also plays an important role in the expression of disease in shrimp. The disease-causing pathogens affecting farmed shrimp are ubiquitous in marine and freshwater habitats, but mass mortalities in wild populations are rare unless poor water quality conditions create elevated levels of stress (Pillay, 1992). Global losses associated with disease outbreaks in farmed shrimp production exceed $1 billion USD and the economic impact on wild fisheries is unknown (Clay, 1996). Although viral pathogens represent the greatest source of concern for aquaculturalists, infectious bacteria such as *Vibrio spp.* and disease-causing protozoans such as *Zoothamnium spp.* have also produced substantial crop losses in shrimp farming regions (Flegel *et al.,* 1992). Although only a small number of the diverse range of known shrimp pathogens are discussed below, these viruses represent a substantial threat to farmed shrimp production in the Chao Phraya Delta and represent a serious concern in other shrimp farming areas.

Yellow-head virus (YHV) is one of the most common diseases affecting farmed shrimp production in Thailand. YHV typically strikes juveniles and sub-adults approximately one month after a pond has been stocked, and complete crop mortality can occur in as little as 3 days (Boonyaratpalin, 1992). Although the economic impact of a YHV outbreak on farmers can be significant, losses are somewhat reduced because prepared feeds are not used extensively during the first month of the grow-out cycle. YHV was originally restricted to *Penaeus monodon*, but transmission to *Penaeus stylirostris* and *Penaeus vannemei* is also possible (Lightner, 1996). YHV was first identified in Thailand and is now suspected to be present throughout Southeast Asia (Flegel and Sriurairatana, 1993). No effective treatment for YHV exists, although farmers often attempt an emergency harvest followed by cleaning and disinfection of the grow-out pond.

White spot syndrome baculovirus (WSBV) is a second common viral disease affecting farmed Thai shrimp. Mortalities in shrimp ponds can reach 100% within 3 to 10 days after the onset of symptoms (Chou *et al.,* 1995) and the virus can effect juvenile and adult shrimp up two-and-a-half months after stocking. A WSBV outbreak later in the grow-out cycle can be economically devastating. Farmers have made a substantial investment in prepared feeds by this point, but the shrimp are usually too small to be profitably harvested. Following its initial identification in Northeast Asia, WSBV is now believed to exist in India, Southeast Asia, and the mid-Pacific (Bower, 1996). WSBV has also been identified in the United States and Latin America where it may have been introduced via shrimp processing plants that imported infected species from Asia (*ibid*.). No known method of prevention or control of WSBV is available.

Black Tiger Shrimp Infected with White Spot Virus

Other significant viral pathogens affecting shrimp production in Thailand include the monodon baculovirus (MBV) and infectious hypodermal and hematopoietic necrosis virus (IHHNV). MBV was one of the first pathogens to have a substantial impact on intensive shrimp farming in Thailand, and outbreaks of this virus decimated both the Taiwanese and Chinese shrimp industries during the late 1980s and early 1990s (Chen *et al.,* 1992). IHHNV was transported to Hawaiian shrimp farms after *P. stylirostris* and *P. vannamei* were imported from Latin America. IHHNV affects a wide range of farmed shrimp species (*Penaeus stylirostris*, *Penaeus vannamei*, *Penaeus monodon*, *Penaeus chinensis*) and has spread to shrimp farming areas throughout the globe (Pillay, 1992).

Although the diseases that affect shrimp farming have their origins in wild stocks, the geographic range of these pathogens can be greatly extended by their transportation for aquaculture purposes (Arthington and Bluhdorn, 1996). The importation of exotic shrimp species can also provide a very effective pathway for new pathogens to infect native species and populations. Potential viral transmission pathways from farmed aquaculture to native shrimp include: the use of infected broodstock or seedstock, pond effluent disposal, pond flooding, shrimp escapes, transport to processing facilities, sediment or solid waste disposal, and birds (Lightner, 1996). The risk of pathogen transmission is also not limited to live transfers of infected shrimp. Packing plants that import frozen shrimp can discharge contaminated effluents into estuaries and imported frozen shrimp used as fishing bait poses a similar risk (Lightner and Redman, 1992). It has also been suggested that endemic viral pathogens may be amplified under farm conditions (Lightner, 1996). The disposal of shrimp farm waste products or escaped farmed shrimp can expose wild stocks to a much higher viral load if these pathogens are amplified under crowded farm conditions. Whether infected by an exotic or endemic pathogen stemming from aquaculture or seafood processing, wild shrimp populations can often appear visibly unaffected by viral diseases. These infected populations may not be "healthy", however, and any increased stress produced by changes in water temperature, salinity, or pollution loads can potentially lead to mass mortalities (de Graindorge, 2000).

Species Interactions

Exotic species have been used in aquaculture to increase the range of animals raised within a given geographic area, to improve the quality of aquatic products, and to enhance the profitability of production systems (Beveridge and Philips, 1993). Although characteristics such as high fecundity, rapid development, and wide environmental tolerances are attractive for aquacultural purposes, these traits are also commonly found in many invasive species. Examples of exotic species used in shrimp aquaculture includes: the eastern Pacific white shrimp (*P. vannamei*) and school shrimp (*P. stylirostris*) which were exported to countries such as India, Philippines and Taiwan. The common Indo-West Pacific species *P. monodon* was introduced to Latin America, and the sub-tropical karuma shrimp (*P. japonicus*) has been exported to Europe, Australia, Southeast Asia, Africa, and the United States (Pillay, 1992; Chou and Lam, 1989). Of particular concern in Thailand at the moment is the frequent appearance of Pacific white shrimp (*P. vannamei*) in local markets. The importation of this species is illegal, but it appears that many Thai shrimp farmers are now raising this product in the hope that its disease resistance characteristics make it less susceptible to local strains of the white-spot and yellow-head viruses.

Large-scale transfers of shrimp within their normal geographic range are also commonly used in aquaculture. Many nations that possess an intensive shrimp farming industry rely heavily upon the use of domesticated native shrimp that possess genotypes with desirable growth or disease resistance characteristics (Iverson *et al*., 1993). Specific hatchery-raised strains of *P. vannamei* have been widely dispersed throughout the southern United States, Central America, and Ecuador and now Thailand (as discussed above). Large transfers of *P. monodon* within Southeast Asia have also occurred (Liao and Lui, 1989). Potential environmental impacts resulting from species exports outside of their normal geographic range and species transfers include: alterations to the host environment, disruptions to the host community, and the genetic degradation of local stocks (Rosenthal, 1980). Exotic species may be introduced specifically for farming purposes, but escapes are inevitable and self-sustaining wild populations can affect local animal populations and habitats if suitable environmental conditions exist (Welcomme, 1988). A direct impact occurs when an exotic species preys upon native biotic communities. Indirect impacts can also emerge when an introduced species successfully competes against an ecological homologue for limited supplies of food and habitat (Lee and Wickens, 1992). Both direct and indirect impacts can reduce native species population numbers and diminish species diversity (Pillay, 1992). Exotic pond-raised shrimp have been accidentally lost or intentionally released to natural waters in many shrimp farming areas of the world. An unknown number of these shrimp are able to mature and survive in the wild, but the impact of these escapes on native shrimp populations and species diversity is difficult to assess and largely unexplored (Pullin, 1993).

The inter-breeding of escaped farmed and wild shrimp of the same species has the potential to degrade the genetic fitness of wild stocks (Pillay, 1992). Farm shrimp produced by domestic breeding programs are specifically adapted to aquaculture conditions. If domesticated shrimp escape and successfully mate with wild shrimp, domestic traits could enter the wild gene pool and reduce the fitness of these shrimp stocks (Jenkins, 1995). The extent of any impact on wild shrimp is dependent upon the extent of escapes, ecological or behavioral barriers to inter-breeding, and the relative size of the escaped farmed and wild shrimp populations (Weston, 1991). Very little research has assessed the divergence of farmed and wild shrimp populations in Thailand, but genetic differences are likely minimal due to the industry's heavy reliance on wild broodstock (Macintosh and Phillips, 1992). The long-term inter-breeding of farmed shrimp with wild populations and indirect selective pressures stemming from the competition for food and space could, however, induce genetic changes in unique shrimp populations (Noikorn, 2000).

5.0 RIVER BASIN MANAGEMENT IMPLICATIONS

The Chao Phraya River Basin represents a landscape under severe stress as a result of human development activities and associated landscape modifications. Agricultural, industrial and urban development have almost completely replaced natural vegetation in the lower basin, and habitats in middle and upper basin areas have been affected by agricultural activities, logging and erosion problems. Land conversion for agricultural or urban purposes has eliminated or substantially altered most terrestrial habitats, and many wildlife species are now restricted to relatively small parks or wildlife preserves. Aquatic systems in the delta are also highly stressed, and recent surveys have revealed a distinct temporal and a spatial pattern of environmental degradation (Pollution Control Department, 1996). Rivers and streams in the Chao Phraya Delta are currently used to dispose of a broad range of agricultural, urban and industrial wastes, and water quality is especially poor during the dry season when precipitation and streamflows are greatly reduced. Organic waste loads are particularly high in the lower delta areas that support large industrial complexes, intensive livestock rearing operations, and sizable urban populations.

It is within this environmental and development context that intensive shrimp aquaculture emerged and evolved in the Chao Phraya Delta. The first intensive shrimp farms were constructed in coastal areas of Samut Prakarn and Samut Sakhon as part of the shrimp boom that swept coastal Thailand during the late 1980s and early 1990s. These original farms suffered catastrophic crop failures relatively quickly, but were soon replaced by new operations that were gradually located into more distant upstream locations. This movement of shrimp farms from brackish water coastal sites, to seasonally saline areas, and finally to entirely freshwater zones allowed the overall production of farmed shrimp to remain fairy constant during late 1990s. It also masked a significant collapse in coastal shrimp production stemming from a combination of viral disease outbreaks and environmental management problems (Dierberg and Kiattisimkul, 1996). Shrimp farming has certainly produced significant short-term profits for small-scale landowners in rural areas of the Chao Phraya Delta, but these short-term gains appear to be subject to significant financial and environmental risks, and the long-term sustainability of intensive shrimp production remains in doubt (Szuster *et al*., 2003; Szuster and Flaherty, 2002a). Shrimp farming in both brackish and freshwater areas of the Chao Phraya Delta has been highly controversial, and the most contentious issues from a river basin management perspective include water use, liquid waste management, and land degradation as a result of soil salinization.

It appears unlikely that shrimp farming has produced any significant changes in the allocation of freshwater supplies within the Chao Phraya Delta because low salinity shrimp farming and wet rice paddy farming possess very similar water consumption profiles (Braaten and Flaherty, 2001). Given that most shrimp farms were converted from rice production, it is not surprising that regional consumption of freshwater would be largely unchanged as a result of shifting from rice to shrimp production. A conversion from agriculture to aquaculture could even reduce dry season freshwater consumption if naturally occurring saline water were used to a greater degree by low salinity shrimp farmers (Szuster, 2001). The existing use of naturally occurring brackish water by shrimp farmers is limited, however, as a result of concerns over the presence of contaminants such as pesticides and the occurrence of viral disease pathogens (Ponza, 1999, Pollution Control Department, 1996). Most shrimp farmers continue to use a mixture of imported salt (hyper-saline water delivered by truck or bagged salt) and freshwater drawn from irrigation systems, and this practice will likely continue until overall water quality conditions in the Chao Phraya Delta improve substantially.

The potential use of brackish water by shrimp farms in agricultural areas such as the Chao Phraya Delta raises several water management issues. Salt water intrusion is a common characteristic of many tropical deltas, and control structures such as dams, sluice gates, and weirs have been constructed to limit dry season saline intrusion in areas affected by tidal influences. The rational for constructing these structures is to control salinity, protect soils, increase the availability of fresh water, and improve agricultural crop diversity and intensity (Can Tho University and IRD, 2001). The construction of salt water exclusion structures has, however, resulted in a significant decrease of the estuarine character of many deltaic areas and serious environmental impacts have been produced by larger projects such as the Bangpakong River Dam (Bangkok Post, 2000b). Salt water exclusion structures can alter natural estuarine systems, prevent migratory fish from accessing upstream areas, and the lack of tidal flows can result in bank steepening and associated erosion problems (Van der Meulen, 2000). In addition to the ecological and hydrological effects associated with altering the hydrology of seasonally saline river systems, the potential economic benefits associated with rotating freshwater and brackish water crops within deltaic areas is an issue that is gaining increasing prominence (Can Tho University and IRD, 2001). Recent research in the Mekong River Delta has outlined a system where salt water exclusion structures are managed to meet the needs of both rice farmers and shrimp farmers (Fredenburg, 2002). This integrated approach to managing water resources within tropical river deltas may hold the potential for both improving rural income levels (brackish water aquaculture crops such as shrimp typically possess much higher profit margins than freshwater agricultural crops) and rehabilitating sensitive estuarine ecosystems damaged by the operation of saline control structures. The applicability of this approach in other seasonally saline river systems such as the Chao Phraya River is intriguing and should certainly be investigated further.

Existing water quality in many portions of the lower Chao Phraya River Basin cannot support aquatic life and is not suitable for contact activities such as fishing, swimming, or bathing (Pollution Control Department, 1997). The situation is particularly serious during the dry season when nutrient loading from agricultural, industrial and municipal sources produce algae blooms and very low dissolved oxygen levels (Kongrut, 2000). The management of liquid and semi-solid effluents produced by shrimp farms is a major concern because these waste flows are highly enriched with organic pollutants (Szuster and Flaherty, 2002b). Managing water quality impacts associated with shrimp farming is difficult, however, because environmental regulations are poorly enforced in Thailand and rural shrimp farmers are often unaware of the regional consequences of their activities. Eliminating the illegal disposal of pond sludge into freshwater streams or irrigation canals is critical because this material contains a large percentage of the total organic waste load produced by shrimp farms (Szuster, 2001). Strategies to reduce this practice could include providing additional extension programs for shrimp farmers that focus on waste management issues, and imposing a strict requirement that all shrimp farms utilize waste treatment ponds and sludge management techniques. Government staff at the local level could also be provided with additional resources and authority to enforce waste management regulations. Addressing waste management issues in the shrimp farming sector does not, however, guarantee regional water quality improvements because a large number of agricultural, industrial and domestic activities also produce organic pollutants in the Chao Phraya Delta. A multi-sectoral pollution reduction strategy is required, and in the absence of a broad-based approach within the entire Chao Phraya Delta, improved waste management practices introduced by shrimp farmers will have a limited impact on overall water quality.

With regard to soil salinization, aquaculture zoning strategies are being developed to mitigate the environmental impacts of shrimp faming on agricultural land use. A proposal by Thailand's Land Development Department (1999) would restrict shrimp farms in the Chao Phraya Delta to designated brackish-water zones within three coastal provinces (Samut Prakarn, Bangkok, and Samut Sakhon). Farm construction within these provinces would be limited to regions possessing soil parent materials with a conductivity of 2 mS/cm^{-1} or greater (measured at 1.5 m below the surface). This would restrict shrimp farms to less productive areas with saline sediments located relatively close to the surface. Shrimp farms within approved areas would also be required install perimeter ditches and/or pond liners to mitigate indirect salinization effects, and the disposal of saline pond effluent during periods when rice farmers are accessing irrigation water supplies would be controlled (Boyd, 2001). Shrimp farmers in restricted areas such as Nakhon Pathom and Suphanburi are being encouraged to raised freshwater crops, and the production of the freshwater prawn *Macrobrachium rosenbergii* appears to hold significant promise as a feasible alternative to farming marine species such as black tiger shrimp (Szuster *et al*., 2003). Enforcement of the ban has been slow and inconsistent, however, and it remains to be seen whether all shrimp farms within restricted areas will cease production or switch to alternative crops. Given the "boom and bust" history of aquaculture in coastal Thailand, restricting shrimp farming from freshwater zones represents the a prudent strategy for preserving agricultural land, and the implementation of this strategy in the Chao Phraya Delta should represent a high priority for the Government of Thailand.

6.0 CONCLUSIONS

Shrimp farming in the Chao Phraya Delta has undoubtedly produced significant foreign exchange earnings over the past two decades, but it will be very interesting to observe Thailand's farmed shrimp industry over the coming years. Coastal farming areas are fully exploited and will likely continue to experience problems with viral disease outbreaks and the degradation of land and water resources that support aquaculture production. These concerns have reduced farmed shrimp harvests in coastal areas during the past decade, and a trend toward stable or slightly lower harvests should continue. The ban on shrimp farming within inland freshwater provinces will also likely result in lower production in these regions. With reduced harvests from both inland and coastal production zones, and limited opportunities for expansion into undeveloped areas, the "shifting cultivation" strategy that has prevailed during the Thai shrimp boom appears to be at an end. Experience both in Thailand and abroad suggests that the long-term sustainability of existing intensive shrimp husbandry techniques remains questionable, and breaking the "boom and bust" cycles that characterize shrimp farming throughout the developing world will present a significant challenge to the Thai aquaculture industry.

The existence of suitable biophysical conditions, a well-developed irrigation system, and government support for export-based agricultural development fueled the expansion of shrimp farming in Chao Phraya Delta. These same conditions are also present in other deltaic regions of tropical Asia. Given the inter-connected nature of the global seafood industry, and ease that aquaculture technology can be transferred, it is conceivable that the controversies associated marine shrimp farming in Chao Phraya Delta may emerge in other regions. Basin level land use planning and environmental management techniques can certainly control this type of development, and the early implementation of strict zoning criteria can prevented the spread of brackish water shrimp farms into freshwater agricultural zones. Management procedures that adopt a systems perspective can also address environmental concerns related to water allocation and regional liquid waste management. It is very important to realize, however, that shrimp farming is only one of countless development activities that effect environmental conditions within deltaic regions. Multi-sectoral strategies are required to address regional environmental concerns, and in the absence of a broad-based management approach, improved practices introduced by individual sectors will have a limited effect on overall environmental quality.

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