Hydrology of inland brackishwater shrimp ponds in Chachoengsao, Thailand

Robert O. Braaten a,*, Mark Flaherty b

a Land and Water Sciences Division, Bureau of Rural Sciences, Agriculture, Fisheries and Forestry — Australia, PO Box E11, Kingston, ACT 2604, Australia
b Department of Geography, University of Victoria, PO Box 3050, Victoria, BC, Canada V8W 3P5

Received 9 December 1999; accepted 30 May 2000

Abstract

This study focuses on a new trend in shrimp aquaculture, the development of brackishwater ponds for Penaeus monodon culture in inland freshwater areas of Thailand’s Central Plain. Water balances were calculated for ponds and reservoirs at an inland shrimp farm in Chachoengsao, Thailand, between May and July 1999. Regulated inflow and outflow were the largest water fluxes, averaging 0.94 and 0.70 cm/day. Other daily average water gains were rainfall (0.52 cm/day) and runoff (1.7 cm/day), and other water losses were evaporation (0.31 cm/day) and seepage (0.52 cm/day). Over an entire crop cycle, of average length 109 days, average water inputs were: initial pond filling (84 cm); regulated inflow (103 cm); rainfall (57 cm); and runoff (3 cm). Average outputs were: regulated outflow (76 cm); seepage (57 cm); evaporation (34 cm); and draining at harvest (87 cm). The main feature of note in the water balance is the large volume of regulated outflow. All regulated outflow and most (82%) of the pondwater drained at harvest went directly to the irrigation canal system. Such large volumes of discharge could have serious environmental implications because small inland waterways have low assimilative capacity and pond effluent is saline. Consumptive water use for 14 inland shrimp ponds and reservoirs averaged 0.83 ± 0.14 cm/day. Consumptive water use was also measured for 11 nearby rice fields, the main land use in the regions where inland shrimp farming is proliferating. Rice paddy water use averaged 0.91 ± 0.17 cm/day. There was no significant difference in the daily consumptive water use of shrimp ponds and rice fields, suggesting that conversion from rice farming to shrimp farming would have little net impact on water availability for irrigation. © 2000 Elsevier Science B.V. All rights reserved.

* Corresponding author. Tel.: +61-2-62724798; fax: +61-2-62725827.
E-mail address: robert.braaten@brs.gov.au (R.O. Braaten).

0144-8609/00/$ - see front matter © 2000 Elsevier Science B.V. All rights reserved.
PH: S0144-8609(00)00059-5
1. Introduction

Thailand is the world’s largest producer of cultured shrimp, earning an estimated USD 1.6 billion in 1998 from exports (Bangkok Post, 1998). Historically, the development of shrimp farming has been concentrated in a narrow band of land along Thailand’s coast. Newly developed low-salinity methods for farming black tiger shrimp (*Penaeus monodon*), however, have facilitated the rapid expansion of marine shrimp farming away from the coast into the freshwater areas of Thailand’s Central Plain. By 1998, it was estimated that as much as 40% of Thailand’s cultured shrimp production came from 22,455 ha of inland shrimp farms (Department of Fisheries, 1998; Limsuwam and Chanratchakool, 1998). The emergence of this new form of shrimp farming has raised concerns about the potential impacts on agricultural land and rural water resources (Flaherty and Vandergeest, 1998; Musig and Boonom, 1998; Fegan, 1999; Miller et al., 1999). The main concerns relate to the dynamics of water flows on the shrimp farms. Unlike coastal shrimp farms, inland farms withdraw large volumes of freshwater from rice irrigation canals. In the absence of restrictions on water use, the high consumptive rates of shrimp farms could stress the freshwater irrigation system. It is also feared that seepage and discharge of pondwater could carry salt and waste products into irrigation water and onto neighboring agricultural land. While crude estimates of inland shrimp farm water consumption rates and possible environmental impacts are available (Tookwinas, 1997; Flaherty et al., 1999), detailed assessments are lacking.

The hydrology of aquaculture ponds generally, and shrimp ponds in particular, has received limited attention in the literature. Most previous studies have focused on species other than shrimp, and have been undertaken in areas of the world with different geographical conditions from Thailand. Examples include catfish ponds in Alabama (Boyd, 1982), embankment fish ponds in Honduras (Green and Boyd, 1995) and tilapia ponds in Panama (Teichert-Coddington et al., 1988). Although Briggs and Funge-Smith (1994) examined the hydrology of shrimp ponds in Thailand, this investigation was undertaken within the context of a nutrient budget study. As few primary data were collected, their assessment of pond hydrology is based on regional averages and published typical rates for many of the water fluxes.

Shrimp culture now represents the largest component of global aquaculture in terms of market value, and is believed to have strong potential for further growth (Lucien-Brun, 1997). Some of the anticipated increase in production will be achieved through the development and adoption of more intensive forms of production. It is likely, however, that there will also be a large increase in pond area as established farmers expand their operations and/or new operators enter the industry. Given the potential for pond proliferation, it is essential that a better understanding of water dynamics be obtained in order to assess the impacts of these farming systems on local water supplies and agricultural land. This information will
be useful both for assessing the need for greater regulation of the industry, as well as for identifying ways of making intensive shrimp culture techniques more environmentally friendly. This paper presents insights from a case study of the hydrology of an inland shrimp farm in Chachoengsao Province, in Thailand’s Central Plain region.

2. Site description

Thailand’s Central Plain (Fig. 1) is the richest and most extensive rice-producing area in the country. The plain is located in the tropical savannah climatic zone, with a distinct dry season from November to April and a wet or monsoon season from May to November. High temperatures and high humidity persist year round. The region is agriculturally fertile with rich clay soils and an extensive man-made irrigation network dating back over 100 years. Historically free access to irrigation

Fig. 1. Map of Thailand’s Central Region showing the Central Plain and the location of the study site.
water has favored the development of water-intensive agriculture in the area (Poapongsakorn et al., 1998). Irrigated rice is the most widespread crop, followed by fruit orchards and field crops such as tomatoes and corn. The development of low salinity shrimp culture techniques, coupled with the high farm gate price of shrimp relative to rice, however, have provided strong incentives for rice farmers to convert paddy land to shrimp ponds.

The province of Chachoengsao has experienced some of the most extensive development of inland shrimp farms in the Central Plain. Thailand’s Department of Fisheries (1998) estimates that Chachoengsao Province contains 5000 shrimp farms, covering 8400 ha. During the dry season saline water intrudes up the Bang Pakong River from the Gulf of Thailand, which makes the irrigation canal water progressively brackish. The ephemeral brackishwater supply has encouraged the concentrated development of intensive shrimp farming along the river in excess of 100 km from the coast. Most shrimp farms stock brackishwater in reservoirs during the dry season. During the wet season, brackishwater from the reservoirs is mixed in the shrimp ponds with freshwater from irrigation canals to grow shrimp at salinity levels ranging from about half seawater (15 ppt) to as low as 1 ppt. If necessary, growout pond salinity may also be augmented using bagged salt or trucked in hypersaline water.

The study site is located about 45 km from the coast and 1 km from the Bang Pakong River (Fig. 1). It is very typical of the small-scale shrimp farming operations that dominate Thailand’s shrimp farming industry. It consists of ten culture ponds ranging in area from 2010 to 4263 m² and six reservoirs with areas from 493 to 4263 m² (Table 1). Total pond area is 2.6 ha and total reservoir area is 0.9 ha. The study farm is one of the older ones in the area, having been in operation for about ten years. The ponds and reservoirs were constructed using heavy machinery and consist of packed earthen banks and bottoms. Ponds and reservoirs are about 1.3 m in depth, but are rarely filled higher than 1 m to avoid overflow during heavy rainfall. The banks of the ponds and reservoirs are angled an average of 40° from vertical. Most ponds contain underwater gates connecting them to adjacent reservoirs and the canal. Shrimp growout cycles are staggered so that no more than three ponds are at the same crop stage (Table 1). Water input to the ponds is accomplished using screw pumps driven by diesel motors. Water output is done either with the same pumps or by opening gates in the pond banks and allowing the water to flow out into a canal or reservoir under gravity flow.

3. Methods

Site visits took place about every second day over a 66-day period from May 17, 1999 to July 21, 1999, corresponding to the beginning of the wet season. Because the growout cycles were staggered on the farm, the 10-week field season allowed the observation of all stages of the growout cycle in at least two ponds. The objective of field data collection was to quantify the terms of the water balance for each pond and reservoir, given by the following equation:
Table 1
Characteristics of the shrimp ponds and reservoirs at the study site

<table>
<thead>
<tr>
<th>Pond or reservoir</th>
<th>Area (m²)</th>
<th>Watershed Area (m²)</th>
<th>Crop cycle</th>
<th>Crop length (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Stocked</td>
<td>Harvested³</td>
</tr>
<tr>
<td>Pond 1</td>
<td>2601</td>
<td>390</td>
<td>Apr. 1</td>
<td>May 29²</td>
</tr>
<tr>
<td>Pond 2</td>
<td>2474</td>
<td>390</td>
<td>Feb. 1</td>
<td>May 27</td>
</tr>
<tr>
<td>Pond 3</td>
<td>3525</td>
<td>317</td>
<td>Feb. 1, July 10</td>
<td>June 2</td>
</tr>
<tr>
<td>Pond 4</td>
<td>4005</td>
<td>491</td>
<td>Feb. 1, July 7</td>
<td>June 2</td>
</tr>
<tr>
<td>Pond 5</td>
<td>2450</td>
<td>299</td>
<td>Apr. 1</td>
<td>July 20</td>
</tr>
<tr>
<td>Pond 6</td>
<td>2138</td>
<td>282</td>
<td>Apr. 1</td>
<td>July 20</td>
</tr>
<tr>
<td>Pond 7</td>
<td>3375</td>
<td>408</td>
<td>May 29²</td>
<td>July 14</td>
</tr>
<tr>
<td>Pond 8</td>
<td>3765</td>
<td>301</td>
<td>June 13</td>
<td></td>
</tr>
<tr>
<td>Pond 9</td>
<td>3398</td>
<td>629</td>
<td>June 24</td>
<td></td>
</tr>
<tr>
<td>Pond 10</td>
<td>2010</td>
<td>241</td>
<td>Idle</td>
<td></td>
</tr>
<tr>
<td>Mean ± S.D.</td>
<td>2974 ± 680</td>
<td>375 ± 110</td>
<td></td>
<td>109 ± 3</td>
</tr>
<tr>
<td>Reservoir 1</td>
<td>4263</td>
<td>638</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir 2</td>
<td>924</td>
<td>408</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir 3</td>
<td>493</td>
<td>266</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir 4</td>
<td>510</td>
<td>325</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir 5</td>
<td>1539</td>
<td>477</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir 6</td>
<td>910</td>
<td>503</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir 7</td>
<td>628</td>
<td>427</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± S.D.</td>
<td>1324 ± 1245</td>
<td>435 ± 113</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

³ Where no harvest date is shown, harvest occurred after the end of the field season.
² On May 29th, the shrimp from Pond 1 were shifted to Pond 7.

\[ \text{ΔDepth} = \text{Rainfall} + \text{Runoff} + \text{Inflow} - \text{Evaporation} - \text{Outflow} - \text{Seepage} - \text{Overflow} \]  (1)

where ΔDepth is the change in pond depth, inflow and outflow are the farmer-controlled water exchange fluxes and all fluxes are expressed in depth units (cm).

On the first visit, pond and reservoir lengths and widths were measured using a tape measure and bank angles were measured using a hand-held level. Watershed areas around each pond and reservoir were measured using a measuring tape (Table 1). Also on this visit, staff gauges were installed in each pond and reservoir. Because rice farming is the most widespread land use in the study area, and most shrimp ponds are constructed in former rice paddies, staff gauges were also installed in 11 nearby rice fields so as to facilitate a comparison of water consumption rates between rice fields and shrimp ponds. A class A evaporation pan filled with brackish pond water and a standard inverted funnel rain gauge were placed on a bund between two ponds in the open sun.

On each visit, pond and reservoir water levels were read off the staff gauges to a precision of ± 1 mm. Rainfall depth was measured from the rain gauge giving a precision of ± 0.1 mm. The change in evaporation pan water level was measured to
a precision of ±0.5 mm. Pan evaporation was converted to pond evaporation using a pan coefficient of 0.81. This coefficient is the annual average of a series of monthly pan coefficients developed by Boyd (1985) in a study comparing pan evaporation to directly measured evaporation from an aquaculture pond in Alabama.

Regulated inflow and outflow, because they occurred intermittently and through a variety of methods (i.e. different pumps, draining through different sized gates), were difficult to measure directly. Instead, these water exchange fluxes were estimated from several other information sources. These included direct observation of water being pumped or drained through pond gates, changes in pond depth not explained by other water fluxes, changes in pond salinity not explained by other water fluxes, placement of water pumps, placement of barriers used to open and close pond pond/reservoir gates, and communication with the farmer. The accuracy of the regulated water exchange data is estimated to be in the range of ±1 to ±5 cm per water exchange event.

Runoff was estimated using the approach developed by the United States Soil Conservation Society (1982). This approach assigns the watershed a runoff curve based on the watershed soil type and land cover. The runoff curve relates the depth of a rainfall event to a corresponding depth of runoff from the watershed. The study site had packed clay soils with sparse vegetative cover. A runoff curve of 90, corresponding to soil group D (clay soils with low infiltration) and poor vegetation-pasture land cover, was used to estimate the depth of runoff. Depth of runoff was combined with watershed and pond water surface area to compute the change in pond depth due to runoff for each rainfall event. Pond watersheds consisted mainly of the bunds between ponds and reservoirs and the area of the pond banks that was not submerged. Because the pond banks were angled, this area was dependent on the depth of the ponds. For ponds and reservoirs whose water depth varied by more than 25% over the field season, watershed areas were adjusted using basic geometry to reflect changes in depth. Where depths varied by less than 25%, changes in watershed area were not sufficient to substantially alter runoff.

Seepage was computed from the other fluxes in Eq. (1) through the process of elimination (Boyd, 1984). Because of the relatively low accuracy of regulated water exchange estimates (±5 cm), seepage was computed only for visits with no water exchange, i.e.:

\[
\text{Seepage} = \Delta\text{Depth} - \text{Rainfall} - \text{Runoff} + \text{Evaporation} \quad \text{(Inflow = Outflow = 0)}
\]

Seepage was then interpolated to days with water exchange. Although this reduced the number of seepage data points for the shrimp ponds, several reservoirs had long periods with no water exchange, which provided accurate seepage data.

During the field season, the ponds and reservoirs had no overflow. Water levels were always kept at least 20–30 cm beneath the tops of the banks, and rainfall never exceeded 8 cm in a single event. Overflow was actively avoided by the shrimp farmer because it meant a loss of valuable saltwater and the possibility of shrimp being lost over the pond banks.
4. Results

Regulated inflow and outflow refer to the amount of water that is added to or discharged from a shrimp pond through the direct actions of the farmer. Water exchange observations in the nine culture ponds in operation during the field season revealed a consistent pattern in water exchange over the crop cycle, summarized in Table 2. The flux values shown are the averages of all ponds observed at the given crop stage. During the 2 weeks prior to stocking, water was pumped into the ponds to fill them. This filling continued until about 40 days after stocking when water depth reached about 1 m. Over this period there was no regulated water outflow. From about day 40 to day 60 after stocking, no water outflow occurred as waste products had not yet built up to a point where water quality was affected. In the ponds observed at this stage, high rainfall compensated for losses due to seepage and evaporation and regulated water inflow was not needed. Had rainfall not been sufficient to maintain pond levels, small amounts of regulated inflow would have been used at this stage to compensate for seepage and evaporation losses. Around day 60, water quality in the ponds began to deteriorate due to the build up of shrimp waste and uneaten feed. Between this time and harvest, water was exchanged at an increasingly rapid rate to improve water quality. At harvest, on about day 110, the entire volume of the ponds was discharged.

All regulated inflow to the shrimp ponds came from adjacent reservoirs. Reservoir water was preferable to canal water as a pond input because suspended sediment had been allowed to settle out and because there was less chance of disease being imported to the ponds from other nearby farms. All regulated water outputs during shrimp growout were discharged directly into the local canal system. Because the main reason for discharging water during the crop was to improve water quality, the effluent was considered of poor quality and not worth saving for future use. At harvest, all the water remaining in five of the seven ponds observed at harvest was discharged entirely to the canal. All the water from one pond and one third of the water in another was pumped into adjacent reservoirs to retain for future use. The amount of water recycled for future use corresponded to about 18% of the total amount discharged at harvest and 10% of the total amount of water discharged over the field season.

After regulated water inflow, rainfall was the next largest contributor of water to shrimp ponds and reservoirs (Fig. 2). Over the 66 day field season, ponds and reservoirs received a total of 33.6 cm of rain, averaging 0.52 cm/day. This is very close to the normal daily rainfall for Chachoengsao in May–July of 0.54 cm/day (Van der Kevie and Yenmanas, 1972). Fig. 2 shows, however, that rainfall was not evenly distributed over time. Up to day 36, rainfall was frequent and received in large amounts, averaging 0.83 cm/day. Between day 36 and 61, however, there was a total of only 0.85 cm over the entire 25 day period. After day 61, the rain returned and averaged 0.60 cm/day until the end of the field season. The period of very low rainfall in the middle of the field season was locally referred to as a monsoon break and was similar in climate to the dry season, with very high temperatures and dry conditions.
Table 2
Water exchange observed in eight inland shrimp ponds shrimp pond summarized by crop stage (average ± standard deviation)a

<table>
<thead>
<tr>
<th>Days after stocking</th>
<th>Crop stage</th>
<th>Water exchange activity</th>
<th>Water in (cm)</th>
<th>Water out (cm)</th>
<th>Observed in ponds</th>
</tr>
</thead>
<tbody>
<tr>
<td>−15-40</td>
<td>Preparation and early growout</td>
<td>Pond filling; no discharge</td>
<td>84 ± 8</td>
<td>0</td>
<td>3, 4, 8, 9</td>
</tr>
<tr>
<td>40-60</td>
<td>Mid growout</td>
<td>Pond full and water quality acceptable; no water exchange required</td>
<td>0</td>
<td>0</td>
<td>5, 6, 7</td>
</tr>
<tr>
<td>60-110</td>
<td>Late growout</td>
<td>Water quality deteriorates; water exchange to improve water quality</td>
<td>103 ± 12</td>
<td>76 ± 20</td>
<td>2, 3, 4, 5, 6, 7</td>
</tr>
<tr>
<td>~110</td>
<td>Harvest</td>
<td>Entire pond discharged</td>
<td>0</td>
<td>87 ± 9</td>
<td>1, 2, 3, 4, 5, 6, 7</td>
</tr>
</tbody>
</table>

a The difference between total water in and out is explained by evaporation and seepage losses outweighing rainfall and runoff gains.
Runoff was a relatively insignificant flux for the nine shrimp ponds, with total water input from runoff over the field season ranging from just 1.1 to 2.5 cm with an average of 1.7 cm (S.D. = 0.4). Average daily runoff for the nine ponds was only 0.03 cm (S.D. = 0.1). For the six reservoirs, however, runoff was more significant, resulting in a total field season water input as high as 10.1 cm, an average field season runoff of 6.3 cm (S.D. = 3.0) and average daily water gain of 0.1 cm (S.D. = 0.05). The higher reservoir runoff was caused by the reservoirs being on average smaller than shrimp ponds, but having watersheds of similar size (Table 1).

Total field season pond and reservoir evaporation was 20.2 cm. Daily evaporation ranged from 0.16 to 0.51 cm/day and averaged of 0.31 cm/day (S.D. = 0.10). This is similar to published normal values for May–July potential evaporation in the Central Plain of 0.28–0.32 cm/day (Van der Kevie and Yenmanas, 1972). Fig. 2 shows that evaporation increased over the field season, from around 0.3 cm/day in May, to as high as 0.4 or 0.5 cm/day in July. The increase in evaporation was likely related to the reduction in rainfall and hotter and dryer conditions near the end of the field season. Penman’s (Penman, 1956) equation relating potential evaporation to aerodynamic and heat budget information was also used to estimate pond evaporation based on published May–July climatic normals for the Central Plain (Van der Kevie and Yenmanas, 1972; Oldeman and Frere, 1982; Land Development Department, 1993). The Penman Equation produced a slightly higher evaporation estimate of 0.45 cm/day.

Daily seepage rates were computed for eight ponds and six reservoirs. An average of 12 data points per pond and reservoir were unaffected by water exchange, representing 19 days of data per pond and reservoir which could be used to calculate seepage. Average daily pond seepage ranged from 0.23 to 0.69 cm/day, with an overall average of 0.50 cm/day (S.D. = 0.18). Reservoir seepage was similar to pond seepage, ranging from 0.20 to 0.90 cm/day, with an overall average of 0.55 cm/day.
Fig. 3. Estimated water budget for an inland shrimp pond over one crop cycle. Total gains were 247 cm and total losses 254 cm. The difference between total gains and losses was likely caused by using different combinations of ponds to compute each of the regulated water exchange fluxes (Table 2).

(S.D. = 0.21). The simple arithmetic mean of seepage values for all ponds and reservoirs was 0.52 cm/day with a standard deviation of 0.21 cm/day. The mean weighted by the number of days of data for each pond/reservoir was also 0.52 cm/day. These seepage values are consistent with the published range for ponds constructed in clay soils of 0.125–1 cm/day (Coche and Van der Wal, 1981).

5. Discussion

5.1. Water balance

The hydrology data for all observed ponds were combined to produce a composite water budget for a typical growout cycle based on Eq. (1). The average values of regulated water exchange shown in Table 2 were used for regulated inflow and outflow. Average observed daily values of rainfall, runoff, evaporation and seepage from all ponds were extrapolated to the average crop length of 109 days. The resulting water budget is illustrated in Fig. 3. This figure shows that the farmer-controlled water fluxes dominated the water budget. Regulated inflow, regulated outflow, pond filling and pond draining represented 76% of the total water inputs and 64% of the total water outputs respectively. The difference between these two figures is explained by rainfall and runoff additions being outweighed by seepage and evaporative losses. Of the fluxes not controlled by the farmer, rainfall was the main water gain at 57 cm and runoff was a relatively insignificant water gain at only 3 cm. Seepage was higher than evaporation but both were important losses representing 57 and 34 cm of water loss, respectively.

5.2. Representativeness

In order to assess whether the water balance shown in Fig. 3 can be applied to other shrimp farms in the region, it is necessary to examine its representativeness, both spatially and temporally. Evaporation, rainfall, runoff, are mainly a product...
of climatic conditions, and when averaged over time should be spatially representative of other farms in the area. Seepage has a climatic component but also varies with soil type and compaction and pond depth. Soil types are relatively homogeneous in Chachoengsao (Land Development Department, 1993). Pond depths were observed to be similar for other farms in the area and soil compaction should also be similar since most ponds in the area were constructed using heavy equipment. The frequency and volume of pond water exchange depend on the actions of individual shrimp farmers and could vary to a large degree among farms. However, during the site visits, several other farms were observed discharging water from their ponds both during growout and at harvest, suggesting that large amounts of water exchange are common for shrimp farms in the area. Therefore the water balance observed at the study site is likely reasonably representative of other farms in the region.

Because of the distinct seasonality in the tropical savannah climate zone, fluxes that are dependent on climatic conditions would be expected to show some temporal variation. Published pan evaporation data for Bangkok, the closest available station to Chachoengsao, show that average monthly evaporation for the dry season was 9.3 cm compared to 8.3 cm in the wet season (Oldeman and Frere, 1982). These figures suggest that seasonal variation in the shrimp pond evaporative water flux would likely be in the order of only about 10%. Teichert-Coddington et al. (1988) found similar results in their wet and dry season study of fish ponds in Panama where wet season evaporation rates were 86% of those in the dry season.

Seepage also has a climatic component due to its dependence on soil moisture and water table levels. It is influenced by the hydraulic gradient and by water temperature, which affects water’s viscosity. Other studies have found that the range of temperatures in aquaculture ponds is insufficient to have a substantial effect on seepage (Boyd, 1982; Green and Boyd, 1995). However, soil moisture and groundwater level fluctuations could cause substantial seasonal influence on seepage rates, especially in the wet season when the soils in the low-lying Central Plain can become saturated and flooding often occurs (Land Development Department, 1993).

Seasonal effects on farmer-regulated water exchange would likely be most pronounced for regulated water inflow, since similar volumes of discharge would be required in any season to remove the build-up of waste products that degrade water quality. Regulated inflow would be strongly influenced by rainfall, the most seasonably variable flux, and, to a lesser degree, runoff. In Chachoengsao, normal monthly rainfall ranges from 0.7 cm in December to 28 cm in July (Van der Kevie and Yennmanas, 1972). During the field season, monthly rainfall averaged 16.2 mm, near the centre of this range. During high rainfall periods, the rainfall flux would dominate as the water source to the ponds, and regulated water inflow would be less significant. During dry periods, the opposite would be true. Runoff would vary in the same manner as rainfall. Therefore, while rainfall, runoff and regulated inflow would be expected to show substantial seasonal variation, evaporation, seepage and regulated outflow observed at the study site should be reasonably representative of other times of the year.
5.3. Comparison with other studies

The composite water balance for an inland shrimp pond estimated here is compared to other published studies of pond hydrology in Table 3. Water fluxes shown in this table were computed from the mean flux totals for all ponds reported in the studies divided by the number of days of measurement. Data were converted to the common unit of mm/day to facilitate comparison between studies with different periods of measurement. Inflow and outflow shown in this table do not include initial pond filling or draining at harvest because these activities occur only at the beginning and end of the growout cycle and are not meaningful on a per day basis.

Table 3 shows rainfall to be reasonably similar for all studies, ranging from 2.8 to 9.0 mm/day. Rainfall at the inland shrimp farm was 5.2 mm, near the middle of the range and similar to the other studies in Thailand. Evaporative losses in all studies were similar, ranging from 3.1 to 5.9 mm/day with the value observed in this study at the low end of the range. The lower evaporation observed for the inland shrimp farm may be due to exceptionally high humidity in Thailand’s water-abundant inland agricultural areas, a bias in the evaporation pan data used, seasonal differences in the timing of the studies or higher salinity levels retarding evaporation.

Runoff is low in five of the six studies, ranging from 0.1 to 0.4 mm/day, and similar to the 0.3 mm/day observed at the inland shrimp farm. Teichert-Coddington et al. (1988), however, report a much higher runoff figure of 13.0 mm/day for tilapia ponds in Panama. One reason for the large difference in their study is that the observed much larger watershed areas relative to pond water surface area. Another factor could be the methods used to estimate runoff. The studies that reported low runoff rates used the United States Soil Conservation Society’s (United States Soil Conservation Society, 1982) approach while Teichert-Coddington et al. (1988) used a different method. In their method, the net combination of monthly runoff gains and seepage losses, termed ‘apparent seepage’, was regressed against monthly rainfall. The $y$-intercept of the regression equation (i.e. when rainfall is 0) was assumed to represent actual seepage for all months, and the difference between actual seepage and apparent seepage during months with rain was assumed to represent runoff. It is possible that the United States Soil Conservation Society (1982) method, which was developed for larger watersheds and rainfall events than those typically found in aquaculture ponds, underestimates runoff. Alternatively, the Teichert-Coddington et al. (1988) method could overestimate runoff by assuming that seepage rates in period of zero rainfall also apply in periods of high rainfall, when increases in soil moisture and groundwater levels could reduce seepage rates.

Seepage rates reported in the six studies are highly variable, ranging from 1.2 to 31.0 mm/day. The wide range in seepage rates is related to differences in soil type and water table conditions. The highest seepage rate of 31.0 mm/day, reported by Teichert-Coddington et al. (1988), was observed in ponds built in soils with unusually high iron and aluminum content which resulted in a granular soil
Table 3
Mean daily water balances observed, estimated and modeled in selected studies of aquaculture ponds, shown with the water balance for the observed inland shrimp ponds (in italics)

<table>
<thead>
<tr>
<th>Pond type, location</th>
<th>Method</th>
<th>Water inputs (mm/day)</th>
<th>Water outputs (mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rainfall</td>
<td>Runoff</td>
</tr>
<tr>
<td>Inland Shrimp, Thailand</td>
<td>Observed</td>
<td>5.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Coastal Shrimp, Thailand</td>
<td>Estimated</td>
<td>5.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Inland Fish, Thailand</td>
<td>Modelled</td>
<td>6.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Inland Fish, Honduras</td>
<td>Modelled</td>
<td>3.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Inland Tilapia, Panama</td>
<td>Observed</td>
<td>9.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Inland Catfish, Alabama</td>
<td>Observed</td>
<td>2.8</td>
<td>0.1</td>
</tr>
<tr>
<td>Inland Fish, Honduras</td>
<td>Observed</td>
<td>2.7</td>
<td>0.1</td>
</tr>
</tbody>
</table>

*a Source: this study.
*b Source: Briggs and Funge-Smith (1994).
*d Source: Teichert-Coddington et al. (1988).
*e Source: Boyd (1982).
*f Source: Green and Boyd (1995).
structure and high permeability. These seepage rates were also measured in the dry season when seepage is likely to be at its highest. The very low seepage rate of 1.2 mm/day in the Briggs and Funge-Smith (1994) study was estimated assuming that no seepage occurred from the pond bottoms. Because the pond bottoms were resting on the water table, seepage was calculated for the pond banks only, based on published typical seepage rates. In the remaining five studies, seepage ranged from 2.7 to 7.8 mm/day with the 5.2 mm/day observed in this study lying near in the middle. Overflow water loss was negligible for all studies.

The most remarkable difference between the study site water budget and the other published water budgets in Table 3 is the regulated water exchange. While all ponds required some inflow to make up for a net water loss from the other fluxes, only two of the six studies reported any discharge. The four studies that did not require water discharge focused on inland fish ponds. The lack of water exchange observed in these studies may be related to less-intensive growout systems generally used for fish ponds. In contrast, the two studies in Table 3 that reported discharge focused on shrimp farms. The Briggs and Funge-Smith (1994) study looked at coastal shrimp farms in Thailand and found water inflow and outflow to be around 40 mm/day. This was much higher than at the inland shrimp farm where water exchange averaged about 7 mm/day. Farms on the coast can better afford to have high exchange rates because of the abundant supply of ocean water. In addition, the impacts of high water discharge rates are less serious in coastal areas because of the high assimilative capacity of coastal waters.

The effluent discharge rate observed at the inland shrimp farm, however, has important implications for waste management. Pond effluent not only contains waste products, but is also brackish which is in contrast to the water supply that is fresh for most of the year. Many other users including orchardists and rice farmers, depend on freshwater from the irrigation system for their livelihoods. Measurements of salinity in the local canal and neighbouring rice fields and orchards revealed elevated salinity levels related to water exchange during growout. During pond harvests, canal salinity routinely rose above levels which reduce yields of rice and orchard crops for short periods of 1 or 2 days (Braaten, 2000). The substantial seepage term in the inland shrimp pond water budget could also lead to soil and groundwater salinization caused by seepage of saline pondwater.

5.4. Water use

Consumptive water use is water that is converted by a human activity to another part of the hydrologic cycle making it unavailable for other human uses. Consumptive water use for an aquaculture pond consists of water losses due to evaporation and seepage, and can be calculated from the change in pond depth after all other fluxes in Eq. (1) have been taken into account. That is:

$$\text{Consumptive Water Use} = \Delta \text{Depth} - \text{Rainfall} - \text{Runoff (Inflow} = \text{Outflow} = 0)$$

(3)
Note that like seepage, consumptive water use was only estimated for days with no water exchange because of the lower accuracy of water exchange estimates.

Consumptive water use was computed for eight ponds and six reservoirs. For ponds, average daily water use ranged from 0.63 to 0.95 cm/day with an overall average of 0.82 cm/day (S.D. = 0.12). For reservoirs, the results were similar, ranging from 0.58 to 1.16 cm/day and averaging 0.86 cm (S.D. = 0.19). The simple arithmetic mean for all ponds and reservoirs was 0.83 cm/day (S.D. = 0.14) and the mean weighted by the number of days of data was similar at 0.82 cm/day. These water use rates are comparable to the 1.16 and 0.87 cm/day observed in catfish ponds in Alabama and fish ponds in Honduras (computed from mean evaporation and seepage rates in Boyd, 1985 and Green and Boyd, 1995), and the 0.71 cm/day estimated for coastal shrimp ponds in Thailand (Briggs and Funge-Smith, 1994). Using the simple arithmetic mean figure of 0.83 cm/day, the total consumptive water use for an average inland shrimp crop, of length 109 days, is 90.5 cm.

Fig. 4 shows daily consumptive water use over the field season, computed as the average of all ponds and reservoirs. Evaporative fluxes are superimposed on this chart to show the relative proportions of water consumption due to evaporation and seepage. It is clear that the majority of consumptive water use occurs through seepage. There does not appear to be any obvious trend in consumptive water use over the field season although there was significant day-to-day variability closely emulating daily changes in evaporation. This short-term variability is expected as evaporation is highly dependent on weather conditions which also fluctuate on a day-to-day basis. Seepage, which is dependent to a large degree on hydraulic head and soil properties, does not show such a large degree of variability, although there is a slight downward trend over the field season. This could be caused by lower average pond depths, and resulting reduced hydraulic head, toward the end of the field season when a greater proportion of the ponds were in the early stages of the growout cycle. It could also be related to the onset of the rainy season and a rising water table, which would also reduce hydraulic head.

The most widespread land use in Chachoengsao and much of the Central Plain area is rice-farming and speculation regarding the freshwater consumption of inland shrimp farms has focused mainly on the impacts on rice paddies (Flaherty et al.,

Fig. 4. Average daily consumptive water use for all inland shrimp ponds and reservoirs partitioned into seepage and evaporative losses.
Water level measurements taken in 11 rice fields in this study can be used to directly compare the water requirements of inland shrimp farms and rice farms. Consumptive water use for rice fields was calculated using the same methods as for the shrimp ponds in Eq. (3). Runoff for the rice fields was assumed to be negligible because watershed areas were less than 1% of field areas.

Consumptive water use for rice fields ranged from 0.54 to 1.16 cm/day, almost exactly the same span as for ponds and reservoirs (0.58–1.16 cm/day). The simple arithmetic mean was 0.91 cm/day (S.D. = 0.17), only 0.08 cm higher than the equivalent figure for the shrimp ponds and reservoirs. The average weighted by the number of days with data was slightly higher at 0.95 cm/day. Since the average irrigated rice crop in Thailand is 110–130 days in length (Greenland, 1998), water use per crop for rice fields would range from about 100.1 to 118.0 cm. This figure is similar to other published figures for consumptive water use of irrigated tropical rice which range from 80 to 125 cm/crop (Jackson, 1989).

A t-test revealed no significant difference between the mean daily consumptive water use of the 11 rice fields and 14 shrimp ponds/reservoirs (P = 0.250). Although ponds likely have higher seepage rates due to their greater depth (~100 cm versus ~30 cm) and consequent higher hydraulic head, rice fields probably have higher evaporation rates related to higher water temperatures. Measurements of shrimp pond and rice field water temperatures on several representative farm visits revealed consistently higher rice field temperatures in both sunny and overcast conditions. Mean shrimp pond temperature at noon was 31.6°C (S.D. = 0.9, n = 32), while mean rice field temperature at noon was 34.7°C (S.D. = 1.8, n = 30). A t-test showed a significant difference in the mean temperature of shrimp ponds and rice fields (P < 0.001). The lack of difference in the daily consumptive water use of shrimp and rice suggests that converting from one land use to the other is likely to have little effect on water supply.

In addition to daily comparisons, the seasonal dimension of water use can be explored by calculating a shrimp farm’s monthly water requirements, or the amount of water which must be withdrawn from the irrigation system on a monthly basis. Assuming no overflow, the net water requirement of a shrimp pond is:

\[
\text{Net Water Requirement} = \text{Consumptive Water Use} - \text{Rainfall} - \text{Runoff}
\]

Inland shrimp farms in Thailand typically grow two crops of shrimp per year (Miller et al., 1999). Assuming that the consumptive water use figures computed above apply year round, annual consumptive use is about 181 cm. Since growout periods are staggered year round, this water consumption would be distributed throughout the year at about 15.1 cm/month. Using normal monthly rainfall data for Chachoengsao, and assuming that the proportion of rainfall received as runoff observed in this study (5%) applies year round, net monthly water requirements for inland shrimp farms were plotted in Fig. 5. In this figure, a positive requirement refers to water that must be withdrawn from the irrigation system.

Fig. 5 shows that, in the wet season, the net water requirements are negative as more water is received from rainfall and runoff than is needed by the shrimp farm.
During the dry season water requirements are positive and high, peaking at 14.4 cm/month in December. In the field area, most rice and fruit farmers only withdraw water in the wet season because the canal salinity is too high in the dry season. By contrast, most of the water extraction for shrimp farming falls in the dry season and shrimp farmers actually prefer the salty water. This suggests that little conflict between shrimp and agriculture should occur over water supplies in areas with ephemerally brackish irrigation systems. If water use conflict does occur in these areas in the future, it will likely be among shrimp farmers themselves due to the rapid expansion of shrimp farming in the region. Many farmers also grow shrimp in areas with year round freshwater irrigation, relying exclusively on bagged salt or trucked in hypersaline water for their salt requirements. In these areas, where rice and fruit farmers also use irrigation water in the dry season, there is some potential for conflict between the water-intensive shrimp farms and other forms of water-intensive agriculture. However, this study suggests that shrimp farming would be no greater a contributor to water conflict than rice farming.

6. Conclusion

The hydrology observed in the inland shrimp ponds was similar to previously reported water balances for other types of aquaculture ponds with one exception. While most other studies of aquaculture ponds observed near zero regulated outflow, large amounts of discharge were observed for the inland shrimp ponds. After discharge, seepage was the next largest water outflux from the ponds. Discharge and seepage of saline water into the freshwater inland environment could lead to salinization impacts, which could pose a threat to surrounding agricultural lands, particularly if the number of inland ponds continues to increase. Waste products in effluent could also have serious impacts on small inland waterways that have low assimilative capacity. Efforts to abate the environmental impacts of inland shrimp culture should focus on reducing waste and salt outputs through lowering water exchange and pond seepage.
While the impacts of inland shrimp farming on water quality could be serious, the impacts on water quantity are likely to be negligible. Consumptive water use for the inland shrimp ponds was similar to other types of tropical aquaculture ponds. Observations in nearby rice fields found no significant difference in the daily water use of shrimp ponds and rice fields, the main land use in the areas where inland shrimp farming has proliferated, suggesting that conversion from rice farming to shrimp farming would have little impact on irrigation water availability. On a seasonal basis, most of shrimp farming’s water requirements fall in the dry season, when, in areas of brackishwater intrusion, irrigation water is too salty for other users. In these seasonally brackish areas, inland shrimp farming may actually be an efficient use for irrigation water otherwise neglected in the dry season. In year round freshwater areas, shrimp farming would be similar to rice farming in its water requirements and its potential to contribute to water use conflict.

Acknowledgements

Financial support for this study was provided by the Natural Sciences and Engineering Research Council of Canada, the Asia-Pacific Foundation of Canada, and the Centre for Asia-Pacific Initiatives of the University of Victoria. Logistical support was provided by the Department of Aquatic Sciences at Burapha University in Bangsaen, Chonburi, Thailand. Sincere thanks are also due to the shrimp farmer and his family who allowed us access to their farm for the duration of the study.

References