Characterization of effluent from an inland, low-salinity shrimp farm: what contribution could this water make if used for irrigation

Dennis McIntosh *, Kevin Fitzsimmons

Environmental Research Lab, University of Arizona, 2601 East Airport Drive, Tucson, AZ 85706, USA

Received 7 July 2002; accepted 7 October 2002

Abstract

Coastal aquaculture can contribute to eutrophication of receiving waters. New technologies and improved management practices allow the aquaculture industry to be more sustainable and economically viable. Current practices, however, do not provide an additional use for effluent water. Nitrogen, phosphorus and other effluent compounds could be valuable plant nutrients. Inflow and effluent water from an inland, low-salinity shrimp farm, were monitored. Bi-weekly analysis included total nitrogen, ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen, total phosphorus, reactive phosphorus, alkalinity, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS) and volatile suspended solids (VSS), as well as temperature, salinity, dissolved oxygen and pH. Alkalinity and total nitrogen decreased during the in-pond residency. The other parameters increased while in the ponds. The potential benefit of having nutrient enriched wastewater to irrigate field crops was substantial, supplying between 20 and 31% of the necessary nitrogen fertilizer for wheat production.

© 2002 Elsevier Science B.V. All rights reserved.

Keywords: Inland aquaculture; Integration; Arizona; Marine shrimp
1. Introduction

Coastal shrimp farming with brackish water effluents often contributes to the eutrophication of receiving waters (Dierberg and Kiattisimkul, 1996; Paez-Osuna et al., 1998). Stringent government regulations and increased awareness of the impacts of effluents on receiving waters have encouraged the development of new technologies and innovations, helping to make the aquaculture industry more sustainable and economically viable (Boyd et al., 1998). In February 2000, the United States Environmental Protection Agency (EPA) began the process of gathering data from the aquaculture industry to develop technology-based effluent limitation guidelines. A proposed ruling concerning aquaculture effluents was released in September 2002 (EPA, 2002).

Some of the innovations that have been explored to help clean up aquaculture effluents include pond based recirculating systems (Rosati and Respicio, 1999), constructed wetlands (LaSalle et al., 1999), decreased water discharge (Hopkins et al., 1993), particulate removal via sedimentation and bivalves (Wang, 1990; Jones et al., 2001; Kinne et al., 2001) and better feeds and feeding practices (Cho and Bureau, 1997). Each of these innovations can reduce the load of organics and metabolites in the discharge water. None of these solutions, however, provide an additional use for the water. One best management practice (BMP) that is expected to be included in the new technology-based effluent limitation guidelines handed down from the EPA is land application of effluent water. This under-explored opportunity could become especially important in arid and semi-arid regions around the world where water is an already limited resource.

Numerous marine species including: red drum, *Sciaenops ocellatus* (Forsberg et al., 1996; Forsberg and Neill, 1997), white shrimp, *Litopenaeus vannamei* (Samocha et al., 1998) and tiger prawns, *Penaeus monodon* (Cawthorne et al., 1983; Flaherty and Vandergeest, 1998) have been commercially reared in moderately saline inland groundwater. Low-salinity groundwater is an abundant resource of many arid regions. Achieving a more efficient use of this water could make an important contribution to agricultural industries in arid regions by maximizing farm production without increasing water consumption.

Integrating aquaculture production into traditional agriculture may be one solution. The impact of farming on already limited water resources (Prinsloo and Schoonbee, 1993; Ingram et al., 2000) and the reliance on chemical fertilizers can be reduced (Fernando and Halwart, 2000), thereby, providing a greater economic return per unit of water. In land-based, freshwater aquaculture, effluents can be applied to any number of agricultural products (Prinsloo and Schoonbee, 1987). Inland, low-salinity aquacultural effluents will require a more salt-tolerant field crop.

The research reported here focused on the characterization of inland, low-salinity shrimp farm effluent water and its potential contribution to meeting the fertilizer requirements of field crops when used as an irrigation source in Arizona. Inland shrimp farming in Arizona began as niche production of specific pathogen free (SPF) *L. vannamei* broodstock. While producing animals in this capacity, growth rates of up to 1.7 g/week were realized (Samocha et al., 1998). Promising results led to the
expansion and subsequent commercialization of shrimp farming in Arizona. Today, there are four commercial producers of *L. vannamei* in Arizona. As of 2000, annual production of marine shrimp from Arizona’s farms was close to 100 metric tons (mt), with a farm gate value of over one million dollars (Fig. 1; Toba and Chew, 2001).

Shrimp operations in Arizona are commonly incorporated into existing farms that are already using moderately saline groundwater for the irrigation of cotton, sorghum and wheat (Fitzsimmons, 1988). Typically, wheat production requires the application of nitrogen (N) fertilizer at a rate of between 168 and 258 kg N/ha to optimize production (Doerge et al., 1991) and approximately 144 ha-cm of irrigation water over the 6 months growing season (Erie et al., 1968). Olive trees are commonly fertilized with 0.45–0.90 kg N per tree per year (Freeman et al., 1994) and will need approximately 320 ha-cm of water (Beede and Goldhamer, 1994). Yields of both wheat and olives have been shown to increase with increasing N fertilization (Doerge et al., 1991; Freeman et al., 1994) however, the economics of N fertilization often limit the final yield (Doerge et al., 1991).

The commercial scale integration of inland, low-salinity shrimp farming with traditional agriculture in Arizona provides a unique opportunity to explore the possibility of using low-salinity shrimp farm effluents as an irrigation water source. In undertaking this study, there were two specific objectives:

1) Quantify chemically the effluent generated at an inland, low-salinity shrimp farm.
2) Evaluate the potential contribution that low-salinity shrimp farm effluent could make toward meeting the fertilizer requirements of field crops when used as an irrigation source in Arizona.

Fig. 1. Quantity and value of aquaculture products grown in Arizona from 1994 to 2000 (adapted from Toba and Chew, 2001).
2. Materials and methods

This effluent characterization study was conducted at Wood Brothers’ Farm in Gila Bend, Arizona between 1 June 2000 and 11 October 2000. In addition to growing marine shrimp (*L. vannamei*), the 1000 ha farm regularly plants sorghum and wheat, and it has recently planted 162 ha in olives (*Olea europaea* var. Manzanillo). For the 2000 shrimp season, Wood Brothers’ shrimp farm had 18 ponds in production (15 production and three nursery) ranging in size from 0.2 to 1.0 ha each, for a total of 12 ha of surface area (Fig. 2). On average, ponds were stocked at 65 shrimp per m². During the 2000 season, 73.4 mt of feed were used and 37.5 mt of shrimp were harvested, resulting in an average farm feed conversion ratio of 2.2. The estimated average daily water exchange was approximately 1%, with all effluents generated on the shrimp farm being collected and used to irrigate the wheat, sorghum and olive trees.

Samples of incoming well water and shrimp pond effluent were collected bi-weekly at approximately 09:00. Triplicate 1-l samples were collected from each location. Sampling locations are plotted on the farm map (Fig. 2), with a ‘W’ indicating the well water collection site and an ‘E’ indicating the effluent collection site. Following the example of Ziemann et al. (1992), sample collection locations and frequency were chosen to quantify the ‘average’ effluent quality of a low-salinity, inland shrimp farm, rather than quantify changes in pond water quality as a result of daily management practices. During sample collection, temperature, dissolved oxygen, salinity (as EC) and pH were also measured for each sample location. Water samples were transported on ice to the University of Arizona’s Environmental Research Lab for chemical analysis.

Laboratory analysis included total nitrogen (TN), ammonia-nitrogen (NH₃-N), nitrite-nitrogen (NO₂-N), nitrate-nitrogen (NO₃-N), total phosphorus (TP), reactive phosphorus (RP), alkalinity (ALK), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS) and volatile suspended solids (VSS). Ammonia-nitrogen was measured with the salicylate method (HACH Co., Loveland, CO). All other analyses were conducted in accordance with American...
Public Health Association (1995) (Table 1). With the exception of TSS and VSS, water quality was monitored with a HACH DR-890 spectrophotometer (HACH Co).

Samples (six per sample date) were analyzed separately and results were grouped by location (effluent and well) for statistical analysis. Data were analyzed using the statistical software package JMP IN v4 (SAS Institute Inc., Pacific Grove, CA). A one-way ANOVA was applied to the water quality data.

3. Results

3.1. Environmental data

Salinity, dissolved oxygen and pH increased between the well water and the effluent, while temperature decreased (Table 2). Average effluent salinity was 2.2 ppt, 0.2 ppt higher than the well water salinity ($F_{1,46} = 1.8766, P = 0.1774$).

Table 2
Differences in environmental data between the incoming water and effluent water at an inland low-salinity shrimp farm in Gila Bend, AZ.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Well water</th>
<th>Effluent water</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (S.E.M.)</td>
<td>Range</td>
<td>Mean (S.E.M.)</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>28.7 (0.39)</td>
<td>25.5–29.8</td>
<td>27.9 (0.39)</td>
</tr>
<tr>
<td>Dissolved oxygen (mg/l)</td>
<td>6.40 (0.199)</td>
<td>5.44–7.90</td>
<td>6.70 (0.199)</td>
</tr>
<tr>
<td>Salinity (ppt)</td>
<td>2.0 (0.07)</td>
<td>1.6–2.5</td>
<td>2.2 (0.07)</td>
</tr>
<tr>
<td>pH (SI unit)</td>
<td>7.69 (0.068)</td>
<td>7.18–7.95</td>
<td>8.84 (0.068)</td>
</tr>
</tbody>
</table>

* Negative numbers indicate a decrease while in the ponds.
Dissolved oxygen averaged 6.70 mg/l in the effluent and 6.40 mg/l in the well water \((F_{1,58} = 1.1592, P = 0.2861)\). Effluent pH was 8.84 on average, 1.15 points higher than the incoming well water \((F_{1,58} = 141.9601, P < 0.0001)\). Unlike salinity, dissolved oxygen and pH, temperature was lower in the effluent than the well water, averaging 27.9 versus 28.7 °C \((F_{1,58} = 1.9769, P = 0.1651)\).

3.2. Water quality

Increases were observed in many of the tested parameters between the incoming water and the shrimp farm effluent. Concentrations of NH₃-N, NO₂-N, NO₃-N, TP, RP, COD, BOD, TSS and VSS increased during in-pond residency. Alkalinity and TN decreased during this same time. At \(z = 0.05\), concentration differences between incoming well water and effluent water were statistically significant for TN, NH₃-N, NO₂-N, NO₃-N, TP, RP, ALK, BOD, TSS and VSS \((P < 0.05\) for all). The difference between well water and effluent COD was not statistically significant \((F_{1,52} = 2.5331, P = 0.1175\) from a one-way ANOVA; Table 3).

Mean NH₃-N concentrations increased from 0.02 to 0.17 mg/l \((F_{1,58} = 24.4022, P < 0.0001)\) between the incoming well water and the shrimp farm effluent. Nitrite-nitrogen increased by 0.256 mg/l and NO₃-N increased by 3.20 mg/l while in the ponds \((F_{1,58} = 360.8860, P < 0.0001\) and \(F_{1,58} = 9.4448, P = 0.0032\), respectively). The concentration of TP increased by 0.34 mg/l, from 0.40 mg/l in the well water to 0.74 mg/l in the effluent \((F_{1,58} = 25.1915, P < 0.0001)\).

4. Discussion

Nutrient level increases between the incoming well water and the inland low-salinity shrimp farm effluents are not unexpected. Similar increases have been

Table 3
Levels of selected water quality parameters measured from both incoming and effluent waters at an inland, low-salinity shrimp farm

<table>
<thead>
<tr>
<th>Parameter (mg/l)</th>
<th>Well water</th>
<th>Effluent</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (S.E.M.)</td>
<td>Range</td>
<td>Mean (S.E.M.)</td>
</tr>
<tr>
<td>Total nitrogen</td>
<td>11 (0.5)</td>
<td>3–17</td>
<td>9 (0.5)</td>
</tr>
<tr>
<td>Ammonia-Nitrogen</td>
<td>0.02 (0.022)</td>
<td>0.00–0.07</td>
<td>0.17 (0.022)</td>
</tr>
<tr>
<td>Nitrite-Nitrogen</td>
<td>0.005 (0.0095)</td>
<td>0.000–0.110</td>
<td>0.261 (0.0095)</td>
</tr>
<tr>
<td>Nitrate-Nitrogen</td>
<td>6.7 (0.73)</td>
<td>3.7–19.1</td>
<td>9.8 (0.73)</td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>0.40 (0.047)</td>
<td>0.00–0.81</td>
<td>0.74 (0.047)</td>
</tr>
<tr>
<td>Reactive phosphorus</td>
<td>0.14 (0.033)</td>
<td>0.00–0.60</td>
<td>0.33 (0.033)</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>134 (4.8)</td>
<td>102–187</td>
<td>96 (4.8)</td>
</tr>
<tr>
<td>COD</td>
<td>13 (4.2)</td>
<td>0–68</td>
<td>23 (4.2)</td>
</tr>
<tr>
<td>BOD</td>
<td>1.09 (0.475)</td>
<td>0.16–4.40</td>
<td>6.40 (0.475)</td>
</tr>
<tr>
<td>TSS</td>
<td>4.6 (5.89)</td>
<td>0.0–10.0</td>
<td>46.8 (5.89)</td>
</tr>
<tr>
<td>VSS</td>
<td>2.4 (1.89)</td>
<td>0.0–5.0</td>
<td>24.1 (1.89)</td>
</tr>
</tbody>
</table>

* Negative numbers indicate a decrease while in the ponds.
documented for more traditional shrimp farms by Ziemann et al. (1992), Kinne et al. (2001). The magnitude of the increases observed between effluent water and well water in the current study were generally on par with those reported by Ziemann et al. (1992), with a few notable exceptions. In the present study, NH$_3$-N concentrations increased by 88.2%, from an average of 0.02 mg/l NH$_3$-N in the well water to 0.17 mg/l in the effluent, versus the 36.1% increase in concentrations reported by Ziemann et al. (1992).

Even more interesting were changes observed in NO$_2$-N and NO$_3$-N concentrations. Ziemann et al. (1992) reported a decrease of 364.2% for NO$_2$-N and NO$_3$-N combined. We observed increases of 31.6 and 98.1%, for NO$_2$-N and NO$_3$-N, respectively, similar to the 100.0% increase in NO$_2$-N and 90.8% increase in NO$_3$-N observed by Kinne et al. (2001). In the current study, it is likely that shrimp metabolism, coupled with the use of groundwater are responsible for the observed increases in NO$_2$-N and NO$_3$-N. While Ziemann et al. (1992) report decreases in NO$_2$-N and NO$_3$-N, they provided little information on the source of the incoming water, making a more detailed comparison impossible.

4.1. Contributions to irrigation

While the observed increase in nutrient concentrations is promising from an irrigation point of view, this is only one piece of the necessary information. The remaining information comes from the volumes of effluent water generated. As mentioned above, the average water exchange rate was estimated to be 1% per day. No direct measurements were taken of the water exchange rate. Therefore, based on the number and size the ponds in production, we estimated that approximately 2725 m$^3$ of effluent were generated per day, from late-May until mid-October. Combining these two pieces of information reveals that substantial amounts of nutrients were made available for use as fertilizer.

Between May and October 2000, 0.41 kg of NH$_3$-N, 0.698 kg of NO$_2$-N, 8.7 kg of NO$_3$-N and 0.93 kg of TP were made available as fertilizer each day. According to Doerge et al. (1991), Erie et al. (1968)a 1-ha field planted to wheat will require between 168 and 258 kg N and 144 cm of water, respectively, during its 6 months growing season. When a 1-ha field is irrigated with this volume of effluent, an additional 46.1 kg NO$_3$-N is added to the field. Ammonia-nitrogen and NO$_2$-N supply an additional 2.2 and 3.7 kg N, respectively. Combined, we see that the inland, low-salinity shrimp farm effluent in this study can supply up to 51.9 kg N/ha, effectively supplying between 20 and 31% of the necessary N fertilizer for wheat. Clark and Carpenter (2000) report that the cost of nitrogen fertilization alone can reduce the value of the grain produced by 20%. Therefore, it is clear that the integration of aquaculture with agriculture can provide significant benefits to the farmer, both economical and environmental.

Current farm management strategies utilize the nutrient rich ‘wastewater’ generated from the production of marine shrimp as an irrigation source. Efficient water utilization is fundamental for the sustainability of shrimp farming in arid, inland locales. In these regions, where water is already a precious commodity,
irrigating with aquacultural effluents can potentially eliminate some of the pressure placed on this resource and help reduce the reliance on chemical fertilizers.

While using effluent generated on the shrimp farm to irrigate field crops eliminates effluent disposal problems and/or treatment concerns, the concentrated load of dissolved solids makes this water a two-edged sword. With the dissolved solids, also come concerns of soil salinization. Water analysis results suggest that the water being used in this region is not well suited for irrigation. A prior analysis of pond water indicates that the sodium adsorption ratio (SAR) of this water is high (15.82). A slightly lower value can be expected for the well water, as salinity increased by 0.2 ppt on average between the two sources. No SAR data, however, are currently available for the well water.

The high SAR reported would suggest that these waters would lead to poor productivity (FAO, 1988) when applied to field crops. Despite this fact, there is a long history of agriculture in this area. One likely explanation is the soil. Hendricks (1985) has classified the soils in this area (Gila Bend, AZ) as a Torrifluvent association, which has a low clay content (~7.7%). The low soil clay content means that with sufficient irrigation, (that is any amount in excess of the combined needs of the crops being grown and the surface evaporation) the negative effects of using irrigation water with high SAR values can be minimized, if not altogether eliminated (FAO, 1984) by flushing salts from the root zone. Under different soil conditions, the high SAR could become a major problem.

Anecdotal evidence from farm personnel indicates that fields irrigated with shrimp pond effluent are more productive than those irrigated with groundwater. To date, however, this apparent increase in productivity has not been quantified. Research is currently being conducted to investigate the growth enhancing effects of low-salinity shrimp farm effluent and the potentially negative effects that irrigating with slightly saline water has on the soil.

Acknowledgements

We wish to thank Gary Wood (owner) and Craig Collins (manager) of Wood Brothers’ Shrimp Farm; Wood for granting us access to both the farm for sampling and to the farm production data and to Collins for his help and time with sampling and answering my many questions. Financial support for this project research was provided, in part, by grant numbers 01R-08 from the International Arid Lands Consortium and USDA Grant No. 00-38500-911 CFDA No. 10.200, awarded to Dr Kevin Fitzsimmons of the University of Arizona’s Environmental Research Lab.

References

American Water Works Association, Water Environment Federation, and American Public Health Association, Washington, DC, USA.


