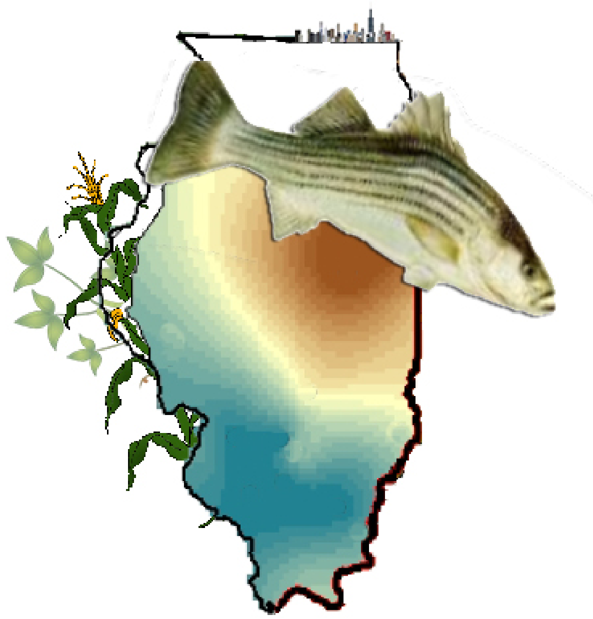
Feasibility Study: Establishing a Saline Aquaculture Industry in Illinois

Prepared for
Illinois Indiana Sea Grant
August 28th, 2013

Srirupa Ganguly
Kwamena Quagrainie
Nandakishore Rajagopalan
Brian Small



ILLINOIS SUSTAINABLE TECHNOLOGY CENTER
PRAIRIE RESEARCH INSTITUTE

Southern Illinois University

Illinois Sustainable Technology Center
One Hazelwood Drive
Champaign, IL 61820

Executive Summary

Objectives

The goal of this project was to conduct a preliminary study on the viability of establishing a saline aquaculture industry in Illinois. Striped bass was chosen as a model species because it is currently marketed in the region and is a euryhaline species. The following three tasks were undertaken:

1. Determine the existing and near-term (5-10 years) market for ***striped bass*** species in the Midwest region of the US for food consumption.
2. Analyze the competitive advantages of rearing a euthyhaline species (Striped Bass) in Illinois/Midwest using regional saline water resources.
3. Locate appropriate saline water resources in Illinois and examine water quality for compatibility with striped bass production.

Rationale

The United States is the third largest consumer of seafood in the world with a per capita consumption of approximately 16 pounds per year[6]. Currently, the United States imports 86 percent of its seafood accounting for a trade deficit of approximately $10.4 billion[5]. About half of those imports (both fresh water and marine production) are from aquaculture[5]. The U.S. demand for seafood is slated to rise as a result of population growth and rising consumer awareness of seafood's health benefits. Recent dietary guidelines, for example, recommend that Americans increase seafood consumption from 3 to 6 ounces per week and pregnant or breastfeeding women consume 8 to12 ounces of seafood per week from a variety of seafood products[7]. As wild stocks are not projected to meet the increased demand even with rebuilding efforts, the increased demand is likely to be met by a combination of imports and increased domestic production.

It is, therefore, not surprising that interest in commercial aquaculture production in the marine environment has increased in the US. US marine aquaculture is estimated to be only 20% of total US aquaculture production[5]. It is largely accounted for by production of mollusks (clams, oysters, and mussels), salmon and shrimp.

There are a number of barriers facing the expansion of the saline aquaculture industry. Among these are the high cost and limited availability of coastal land and water resources; environmental impact concerns; high production costs; and lack of sufficient quality fish seedstock[3].

A number of these concerns can be overcome if saline aquaculture can be practiced inland. The suitability of inland sites for culture of euryhaline and marine species is governed by the availability and quality of saline water. It is in this context that we chose to investigate the feasibility of inland saline aquaculture in the state of Illinois.

Why Illinois?

Agricultural Powerhouse: Illinois ranks first in the nation in soybean production, second in corn, and fourth in hogs and also ranks within the top ten states for winter wheat, oats, and grain sorghum[10]. Illinois also boasts an extensive infrastructure which includes transportation networks, processing facilities, and storage. Illinois also has the technical expertise to support agriculture-related economic activity. In short, Illinois is a global agricultural powerhouse. Leveraging this economic advantage can potentially give Illinois aquaculture producers a competitive edge. This edge is already being recognized by agricultural organizations. The American Soybean Association, the Illinois Soybean Association and the Illinois Corn Growers Association are taking an active interest in the state's developing aquaculture industry[1].

Developing Aquaculture Industry: Aquaculture in Illinois has grown substantially since the initiation of the Illinois Fish Farmers Cooperative in 2000. The Cooperative provides technical services, processing, and marketing assistance. Illinois growers produce an array of species marketed throughout the U.S. and Canada, including hybrid striped bass, largemouth bass, channel catfish, tilapia, and carp. In 2011, total production of all species sold exceeded 360,000 pounds, worth over $1.5 million[2].

Access to Markets: The Chicago seafood market is the fifth largest in the U.S. and imports 99% of the product consumed in the Midwest. The majority of aquaculture species currently produced in the Illinois is sold in Chicago, as well as in the St. Louis and Toronto seafood markets.

Enormous Room for Growth: Currently, less than one percent of the farm-raised seafood consumed in the U.S. is produced in the Midwest. Indications are that Midwestern aquaculture will continue to grow because: (1) per capita consumption of farm-raised products is increasing; (2) the Midwest provides a ready supply of raw materials for low cost fish feed (corn and soybeans); (3) the Midwest supports a large consumer base and Chicago is one of the five largest U. S. seafood markets; and (4) the Midwest has a large number of potential producers who are receptive to incorporating aquaculture into their existing farming operations.

Proximity to the Sea: The sea is closer to Illinois than most residents realize. In fact, Illinois sits on top an underground "sea". The salinity of water in the northern portions of the state are slightly brackish, in the central portions moderately brackish, and in the bottom portions varying from brackish to marine to hypersaline. This vast resource is currently underutilized.

Major Findings

Consumers Attitudes Encouraging Towards Locally Grown Striped Bass (See Chapter 1)

At present, the Midwest region imports seafood products from the US coasts which makes them relatively expensive. A previous study suggested that purchase of saltwater finfish, shellfish, quality assurance, and high incomes were significant factors that influenced higher seafood expenditure patterns on live seafood by Midwestern shoppers[9]. Previous studies have also reported the importance of regional sourcing, freshness, and the high value consumers place on such seafood products[8].

Therefore, this study focused on identifying demographic and other attributes that influence seafood purchase preferences and the willingness to pay (WTP) a certain price. A total of 581 consumers participated in the survey and included 88 from Illinois, 40 from Indiana, 33 from Iowa, 77 from Michigan, 46 from Minnesota, 41 from Missouri, 91 from Ohio, 106 from Pennsylvania, and 58 from Wisconsin.

- Of the respondents, 69% were female, 62% married, 91% Caucasian (white), 63% were 50 years and older, and 47% had college degrees.
- Freshness was ranked very high as the preferred form of seafood for purchase. On a scale of 1 to 3 where 3 is the more preferred, the average ranking for freshness by respondents was 2.5 while the average rank for frozen indicated by respondents was 2.1.
- About 31% of respondents indicated they would be willing to pay up to $3.99/lb; 23% would pay $4.00 to $4.99/lb; 18% would pay $5.00 to $5.99/lb; and 28% would be willing to pay $6.00 and more for striped bass produced in the Midwest.
- 34% of respondents prefer seafood that is harvested from the wild; 16% prefer seafood produced from farms; and 42% were indifferent to whether fish was wild-harvested or farm-raised.
- 30% of respondents consumed seafood less than once per month; 49% consumed seafood one to three times within a month; and 15% consumed seafood once per week.
- Respondents spent $14/visit on seafood purchases for home consumption.
- Males relative to females as well as consumers who are 29 years of age and younger, were more likely to pay higher amounts for Midwest striped bass.
- Customers with preference for farmed seafood and preference for fresh seafood were willing to pay higher amounts for Midwest striped bass.
- Customers who currently bought seafood with a frequency of one to three times a month for home consumption and those who ate seafood 26-50% of the time when eating out and those who ate shrimp or salmon while eating out were willing to pay a higher amount for Midwest striped bass.

Saline Water Resources Are Vast (See Chapter 2)

Illinois has a vast supply of saline water. Sources include saline aquifers; saline springs; produced water from oil extraction; effluents from coal beneficiation; waters produced from coal bed methane production; and other industrial effluents resulting from water treatment, waste volume concentration, and food processing.

The Mt. Simon and the St. Peter formations represent the deeper saline aquifers in the state. In many locations, the salinity in these aquifers increases with depth and can greatly exceed that of seawater (Figure 1). Currently, these aquifers are being investigated for storage of CO_2 captured from power plants. The first million ton CO_2 injection project into the Mt. Simon formation began operation at the ADM Decatur, IL, plant in fall, 2011. Full-scale deployment of this technology will lead to the need for pressure relief of the water within the aquifer. It is estimated that CO_2 emissions from one 1 GW coal-powered plant will displace 7.5 million m^3 of brine annually (~6 MGD).

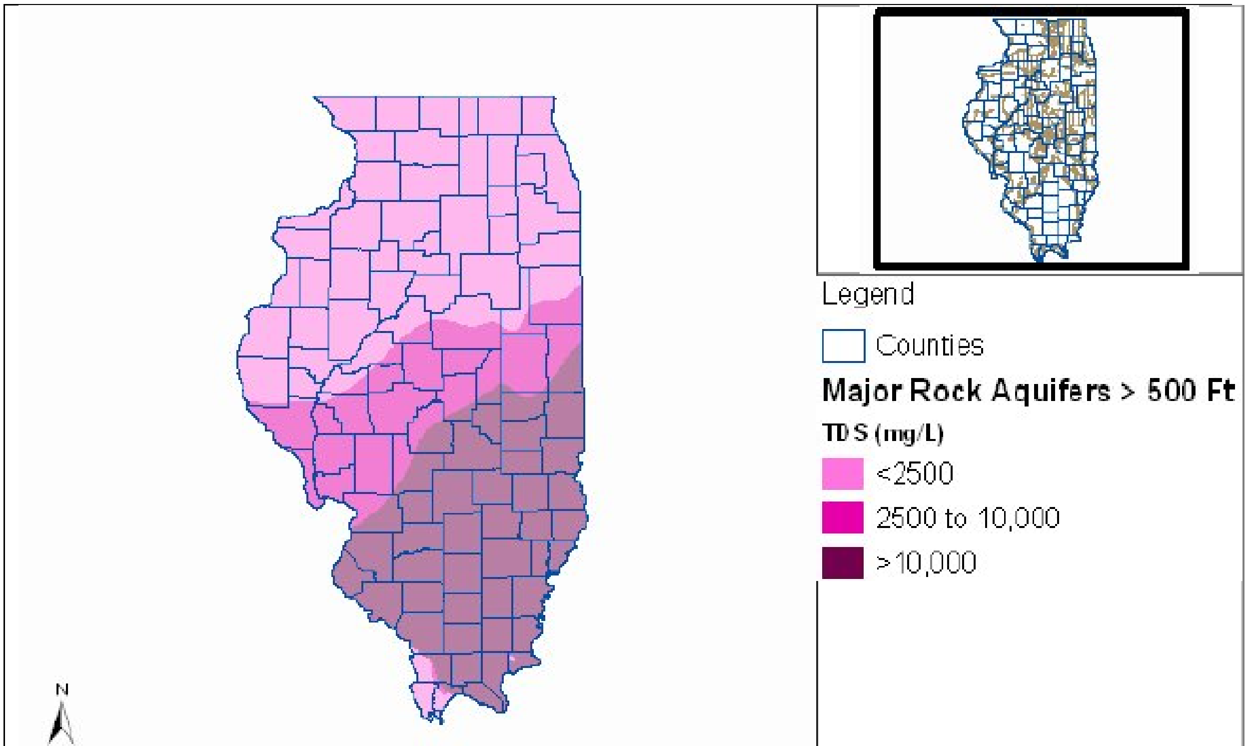


Figure 1: Location-based variation in salinity of rock aquifers in Illinois

Illinois continues to produce oil from the Illinois basin. It produced nine million barrels of oil in 2008. Along with the oil, the process also generates brines – termed produced water. In new wells, the ratio of water to oil produced is of the order of 5:1 to 8:1. In older wells, the ratio may be greater than 50:1. A recent estimate calculates that about 10.8 billion gallons/year (29 MGD) of produced water (brackish/saline) currently disposed into injection wells in Illinois may be potentially available for other uses[4].

Carbon bed methane (CBM) is a form of natural gas that is found in coal seams. CBM extraction requires the removal of groundwater to facilitate flow to the surface. The associated water can be saline and can potentially be used for marine aquaculture. The quantity of water available from this source is about 0.3 MGD according to one estimate[11].

Other sources of available saline water include industrial operations and brine generated during treatment of drinking water, such as ion exchange regenerant solution and reverse osmosis (RO) concentrate. The available quantity is difficult to quantify without a more extensive survey.

It is clear that the state has a considerable quantity of saline water available to support the needs of a marine aquaculture industry. The cost of obtaining these waters will depend on their accessibility. Deeper waters are likely to be more difficult and expensive to extract unless produced through secondary operations such as CO_2 sequestration. Waters from existing coal beneficiation and other industrial operations can be easily accessed provided that transportation costs are low. Produced waters that are currently transported for disposal are also likely to be accessible at low cost.

These saline waters vary significantly in composition. The waters from deep aquifers are often contaminated with trace elements; those of produced water with hydrocarbons, nitrogen, and trace elements; and industrial effluents with organic matter. Analytical information on these sources of saline waters is limited and often incomplete. It is, therefore, safe to assume that a degree of pretreatment would be required prior to use for aquaculture.

In conclusion, the feasibility of utilizing these saline waters for aquaculture is likely to be highly location dependent and will hinge on both accessibility and water treatment cost.

Striped Bass Grow Well in Aquifer Water (See Chapter 3)

Striped bass were grown in saline water mimicking the major constituents of the Ironton-Galesville formation after dilution to a TDS of 10,000 mg/L. Water of similar salinity made with Instant Ocean was used as control.

Percent weight gain was not statistically different ($P>0.05$) between systems at any time throughout the 24 week growth study. Percent weight gain over 24 weeks averaged 1094.1 and 1094.2% (pSEM = 44.7%) for the Aquifer and Control treatments, respectively. There were also no statistical differences ($P>0.05$) for feed efficiency or feed consumption between the systems. Final proximate composition of the carcass produced from fish in both treatments was not significantly different ($P>0.05$).

Mean 24-week water quality indicate that the total ammonia nitrogen (TAN) concentrations increased over the duration of the study. TAN concentrations averaged lower ($P<0.0001$) in the Control (1.18 ppm) than in the Aquifer treatment (4.56 ppm) throughout the study. Total hardness was also higher ($P<0.0001$) in the Aquifer treatment relative to the Control treatment, but did not change with time.

Although qualitative, there were clear differences in observed fish behavior between the two treatments. Fish in the Control treatment appeared relatively calm during feeding and handling during sampling. On the other hand, fish in the Aquifer treatment were excitable during feeding and appear agitated during sampling. To determine whether fish in the Aquifer treatment were experiencing a chronic stress, plasma cortisol levels were measured in fish from both treatments before and after an acute low-water stress event. No differences ($P>0.05$) in plasma cortisol were observed between fish in the two treatments either pre- or post-stress.

The results to date show similar fish growth performance between treatments. However, increasing TAN concentrations in the Aquifer system are indicative of inefficient biological filtration. One possible explanation may be a lack of essential trace elements for the bacteria colonizing the biofilter. This may also explain the apparent excitability and agitation of fish held in the Aquifer system. For this study, the concentrations of trace elements in the Ironton-Galesville formation were unavailable. Another possibility is the higher total hardness in the Aquifer treatment water (459 ppm); however, this is unlikely to have affected the fish given seawater has a total hardness of approximately 6630 ppm. Therefore, modification of the Aquifer salt composition to add trace minerals may be necessary to improve biological filtration.

These results indicate that the major constituents of regional saline water aquifers are acceptable for the production of striped bass during the early growth phase and suggest suitability for the culture of other euryhaline or saline fishes.

The Availability of Saline Water Confers a Material Economic Advantage (See Chapter 4)

The cost of saltwater in a typical or baseline recirculating aquaculture system (RAS) is significant, and savings from utilization of saline aquifer water provides an economic advantage (Table 1). The composition of the saline aquifer water needs to be carefully determined in order to ascertain the level of pretreatment it may require before use in a marine land-based RAS.

Environmental and Economic Impacts of Effluent Handling Can be Managed (See Chapter 4)

Saline wastewater and solids from land-based RAS need to be carefully managed before being discarded (see Figure 2). Saline wastewater from marine RAS systems will be high in salinity, nitrate, suspended solids, COD, and BOD. The larger the volume of saline wastewater, the greater the disposal cost. To minimize the environmental impacts and economic costs, it is recommended that the saline liquid effluent be treated to allow maximum recycling within the recirculating system, thereby minimizing disposal volume of saline wastewater. The denitrification of the liquid effluent using sludge particles as a carbon substrate allows reduction of both solid and liquid effluents. The economic impacts of various operational scenarios on a facility with an annual fish production of 100,000 lbs, growing juvenile fish from an initial size of 50g to market size of 750g are highlighted in Table 1.

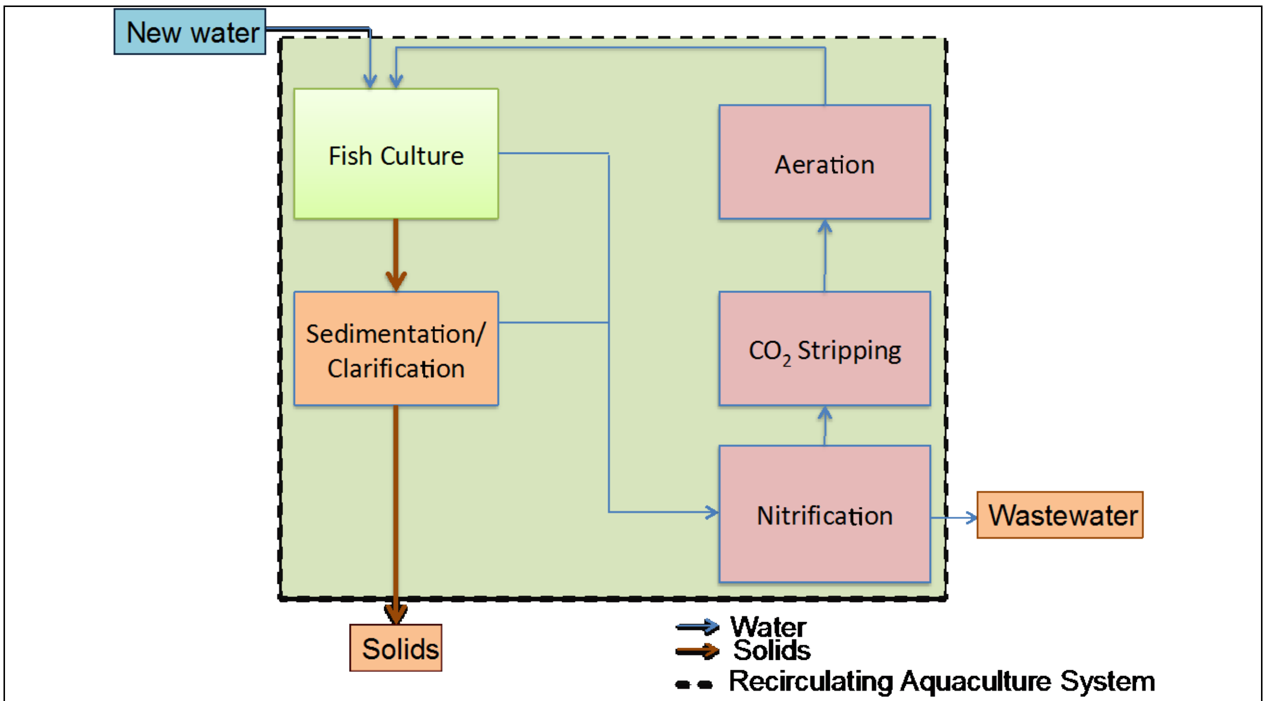


Figure 2: Layout of a typical RAS system

Table 1: Comparison of the annual cost of wastewater and solids disposal, and saline make-up water in a RAS with 10% water exchange rate. The annual costs avoided are in comparison to the baseline cost scenario.GW indicates groundwater.

Baseline	Saline Groundwater(GW)	Exogenous Denitrification (Acetate)	Endogenous Denitrification (Sludge)
Makeup water: Saltwater Disposal of wastewater and solids by subsurface injection	Makeup water: Saline aquifer GW diluted with municipal water Disposal of wastewater and solids by subsurface injection	Makeup water: Saline aquifer GW diluted with municipal water Recycled water: 99% after denitrification Disposal of solids only by subsurface injection	Makeup water: Saline aquifer GW diluted with municipal water Recycled water: 99% after denitrification Disposal of solids only by subsurface injection
Saline water: $216,975 WW disposal: $48,660 Solids disposal: $5,230 Cost avoidance: $0	Saline water: $4,087 WW disposal: $48,660 Solids disposal: $5,230 Cost avoidance: $212,888	Saline water: $409 WW disposal: $0 Solids disposal: $8,344 Cost avoidance: $262,112	Saline water: $409 WW disposal: $0 Solids disposal: $4,736 Cost avoidance: $265,721

Figure 4.4: Comparison of the annual cost of wastewater and solids disposal, and saline make-up water in a RAS with 10% water exchange rate. The annual costs avoided are in comparison to the baseline cost scenario.

Conclusions

Although the results of this study are preliminary, they do indicate that it may be worthwhile to further examine the economic viability of saline aquaculture in Illinois, particularly given the market preference for locally grown fish and the paucity of locally grown *marine* fish, and the willingness of consumers to pay prices ranging from $3.99/lb to >$6/lb.

Furthermore, the availability of a saline water source will confer a material benefit in improving the economic viability of the operation. It also appears that the use of salt water compositions derived from aquifer-type water may be suitable for rearing euryhaline species, provided some pretreatment is performed. The type, degree, and cost of such pretreatment will be location-specific and species-dependent. Finally, the environmental impacts and associated treatment costs of effluents generated can be minimized using currently available technology.

In conjunction with the above and ongoing work on reducing fish feed costs through incorporation of protein from plant sources such as soybean and corn, it appears that states like Illinois can indeed benefit from conducting a more detailed examination of the viability of saline aquaculture. Additional work on market analysis, production, mitigation of environmental impact, and outreach to entrepreneurs will be necessary in order to fully realize this opportunity.

References

1. *Corn and Soybean Digest*, http://cornandsoybeandigest.com/ddgs-viable-alternative-fishmeal-rations-aquaculture.
2. Fisheries and Illinois Aquaculture Center, unpublished. Personal communication with Dr. Brian Small, 2012.
3. *Florida Oceans and Coastal Resources Council's report. Current status and opportunitiesfor marine stock enhancement and aquaculture in Florida, February, 200.* http://www.floridaoceanscouncil.org/reports/FOCC_Aquaculture_Report.pdf, accessed 8/2/2013.
4. Knutson, C., Dastgheib, S., Yang, Y., Ashraf, A., Duckworth, C., Sinata, P., Sugiyono, I., Shannon, M.A., and Werth, C.J. Reuse of produced water from CO2 enhanced oil recovery, coal-bed methane, and mine pool water by coal-based power plants. Report to NETL, 2012.
5. *National Marine Fisheries Service*, http://www.nmfs.noaa.gov/aquaculture/aquaculture_in_us.html, accessed 8/2/2013.
6. *National Marine Fisheries Service*, http://www.st.nmfs.noaa.gov/st1/fus/fus09/08_perita2009.pdf, accessed 8/2/2013.
7. *National Marine Fisheries Service*, http://www.nmfs.noaa.gov/aquaculture/faqs/faq_seafood_health.html, accessed 8/2/2013.
8. Kumar, G., Quagrainie, K.K., and Engle, C. "Factors that Influence Frequency of Purchase of Catfish by U.S. Households in Selected Cities." *Aquaculture Economics and Management*, 12(4) 2008: 252-267.
9. Quagrainie, K.K., A. Xing, and K.G. Hughes. Factors influencing the purchase of live seafood in the north central region of the United States. *Marine Resource Economics*, 26 (1) 2011.
10. *Union of Concerned Citizens*, http://www.ucsusa.org/greatlakes/glregionill_agr.html, accessed 8/2/2013.
11. USEPA, Coalbed Methane Extraction: Detailed Study Report, *U.S. Environmental Protection Agency*, EPA-820-R-10-022, 2010.

Table of Contents

Chapter 1

A Study of the Potential Market for Striped Bass in the Midwest

Dr. Kwamena Quagrainie

Introduction

A study of shoppers' attitudes regarding seafood expenditure patterns on live seafood in the Midwest suggested that purchase of saltwater finfish, shellfish, quality assurance, and high incomes were significant factors that influenced higher seafood expenditures by Midwestern seafood shoppers[7]. This suggests a potential market for saltwater finfish in the Midwest. Quagrainie et al. [8] also studied consumers' interest in Indiana farm-raised aquaculture products and reported that there was 58% probability that consumers would be "interested" and 24% probability that consumers would be "strongly interested" and would buy Indiana farm-raised aquaculture products. The study reported that consumers who expressed willingness to buy Indiana aquaculture products were those who had previously bought farm-raised aquaculture products and who frequently consumed seafood at home.

Previous studies have reported the importance of regional sourcing and freshness and the high value consumers place on such seafood products [3,6,9]. Midwest seafood consumers, might view seafood products from the Midwest as being local and fresh and be willing to pay more for such products.

The Midwest region has traditionally not been viewed as having marine or saltwater resources. Therefore, seafood products produced from saline sources are currently shipped over long distances from the coasts making them relatively expensive. Striped bass is an example of a marine species that has been successfully adapted to freshwater habitat and is currently farmed in the Midwest. It was chosen as a model species to explore the potential of growing a marine species in an inland saline environment in states such as Illinois. In order to develop an effective marketing strategy, it is necessary to examine the willingness of consumers to pay for this product among seafood products offered in the marketplace. Midwestern aquaculture producers can become competitive in raising marine species inland if they understand the factors that influence consumers' willingness to pay. Such an understanding will enable them to make strategic and economically sound production and marketing decisions.

When eliciting willingness to pay from consumers, demographic factors and product attributes have often been found to be significant factors[3,4,5,9,10] . The main objective for this study is to determine the existing and near-term (5-10 years) market for striped bass species in the Midwest region of the US for food consumption using willingness to pay information from consumers in the Midwest.

Data

A randomly generated sample of seafood consumers in the Midwest was surveyed for the study by a market research company, Decipher, Inc., in Fresno, CA. The online survey solicited interests and willingness to purchase striped bass, a marine species to be grown in the Midwest. The survey collected information on how much respondents are willing to pay for Midwestern saltwater seafood, Midwestern striped bass, general seafood preferences, seafood purchasing attitudes, and demographic factors about the respondents and their households. A total of 581 consumers participated in the surveyed and included 88 from Illinois, 40 from Indiana, 33 from

Iowa, 77 from Michigan, 46 from Minnesota, 41 from Missouri, 91 from Ohio, 106 from Pennsylvania, and 58 from Wisconsin.
For striped bass species to be grown in the Midwest, respondents were provided with various price categories to choose from, representing how much they are willing to pay for the product. A statistical summary of the selected factors and attributes used in this study is provided in Table 1.1. About 31% of respondents indicated they would be willing to pay up to $3.99/lb; 23% would pay $4.00 to $4.99/lb; 18% would pay $5.00 to $5.99/lb; and 28% would be willing to pay $6.00 and more.

Other information collected related to general fish preferences of respondents and included seafood production methods, frequency of seafood purchases for home consumption, expenditures on seafood consumed at home, forms of seafood preferred, frequency of eating out, preferred seafood products when eating out, and how often seafood is consumed when eating out (Table 1.1). The responses obtained indicate that 34% of respondents prefer seafood that is harvested from the wild; 16% prefer seafood produced from farms; and 42% were indifferent to whether fish was wild-harvested or farm-raised. Information gathered on how frequently seafood was consumed at home suggests that 30% of respondents consumed seafood less than once per month; 49% consumed seafood one to three times within a month; and 15% consumed seafood once per week. On average, respondents spent $14/visit on seafood purchases for home consumption, and freshness was ranked very high as the most preferred form of seafood for purchase. On a scale of 1 to 3 where 3 is the most preferred, the average ranking for freshness by respondents was 2.5 while the average rank for frozen indicated by respondents was 2.1. (Table 1.1) Of the respondents, 69% was female, 62% was married, 91% was Caucasian (white), 63% were 50 years and older, and 47% had college degree.

Methodology

The analytical framework used to determine the market for striped bass species in the Midwest is in the form of a consumer's willingness to pay (WTP) for striped bass species. Following economic theory of consumer choice, a consumer is assumed to obtain utility, U from obtaining a product or service, and in this case, the purchase of striped bass fillets. If a consumer's utility increases with a purchase, it suggests they may be willing to pay more for the product provided an increase in the product price does not lower utility beyond some base level. The theory of consumer choice also assumes that a consumer's WTP is influenced by their individual tastes, preferences, attitudes and perceptions towards seafood products, as well as demographic factors. In this context, a consumer's WTP can be expressed as a function of the change in utility arising from the choice of a product among alternative products. The choice of one product over another is discrete and modeling WTP is usually specified with limited dependent variable or latent variable approaches[1,2,7,8]. Specifically, a consumer's WTP is a function of the change in utility expressed as:

(1) $$WTP = f\,(\Delta U), \text{ where } \Delta U \text{ is the change in utility and } f' > 0$$

The utility obtained from choosing an i^{th} alternative (U_i) among a set of alternatives, is composed of a deterministic component, which are observable factors and attributes (X_i) that influence the level of utility realized by choosing the i^{th} alternative; and a random component representing unobservable factors, such as unobservable variations in preferences, random individual behavior and measurement error (ε_i), i.e., $U_i = X'_i\beta + \varepsilon_i$. In this context, the i^{th} alternative is chosen if and only if the change in utility is positive, i.e., $\Delta U = U_i - U_j > 0$ or $U_i > U_j$ for all $j \neq i$. Thus, assuming WTP reflects the extent to which utility changes with a choice of an alternative, willingness to pay – WTP can be written as

$$\text{(2)} \qquad \text{WTP} = X'\beta + \varepsilon, \qquad \text{where } X = X_i - X_j \text{ and } \varepsilon = \varepsilon_i - \varepsilon_j$$

The expression in (2) suggests that a larger increase in utility is a reflection of consumers' willingness to pay more. This relationship between WTP and factors / attributes can be used to predict the probability (Pr) of a consumer's WTP being greater than a specified lower bound willingness to pay ($\underline{WTP}$) and less than a specified upper bound ($\overline{WTP}$). The probability that a consumer's WTP falls between the defined levels of willingness to pay can be expressed as:

$$\text{(3)} \qquad \Pr\left(\underline{WTP} < WTP \leq \overline{WTP}\right) = \Pr(X'\beta + \varepsilon \leq \overline{\gamma}) - \Pr\left(X'\beta + \varepsilon \leq \underline{\gamma}\right);$$

where ($\overline{\gamma}$) and ($\underline{\gamma}$) are threshold changes and β is a vector of regression coefficients associated with the observable factors.

Respondents were provided with various price categories to choose from, representing how much they are willing to pay for striped bass grown in the Midwest, i.e., up to \$3.99/lb, \$4.00 to \$4.99/lb, \$5.00 to \$5.99/lb, and \$6.00 and more. Since WTP takes the form of ordered multiple qualitative responses, the ordered probit model is adopted to determine the effects of selected factors on the probability of a consumer's WTP. Willingness to pay for striped bass grown in the Midwest is modeled to be affected by seafood production methods, frequency of seafood purchases for home consumption, expenditures on seafood consumed at home, forms of seafood preferred, frequency of eating out, preferred seafood products when eating out, how often seafood is consumed when eating out, and demographic factors about the respondents and their households.

The use of an ordered probit model allows for an estimation of predicted probabilities for each WTP category and marginal effects. The modeling approach also allows simulation to predict probabilities for a factor or attribute of interest at selected levels. These predictions provide valuable insights and interpretations into consumers' willingness to pay, which helps to determine potential market for striped bass species produced in the Midwest region.

Results

The threshold parameters ($\underline{\gamma}, \overline{\gamma}$) estimated from the model were 1.14 and 2.14; both are positive and highly significant indicating that the four categories of WTP amounts are indeed ordered. Though there are four alternatives of WTP amounts, only two threshold parameters were estimated because J - 2 = 4 – 2, with the first normalized to 0.

The predicted probabilities for each WTP category evaluated at the means of the variables were calculated as 30% for WTP up to \$3.99/lb (y = 0); 22% for WTP \$4.00 to \$4.99/lb (y = 1); 19%

for WTP \$5.00 to \$5.99/lb ($y = 2$); and 28% for WTP \$6.00 and more ($y = 3$). The calculated predicted probabilities suggest that there is a strong willingness of the average seafood consumer to pay for striped bass grown in the Midwest.

The model involved 32 variables with corresponding estimated coefficients; 16 coefficients are found to be statistically significant. The estimated coefficients are not reported; instead the marginal effects of the explanatory factors on the probability of consumers' WTP falling into the various categories are reported in Table 1.2. The sign and magnitude of estimated coefficients in ordered choice models do not provide clear indications of the direction and effects of the explanatory variables on the various levels of WTP. The marginal effects do provide a more meaningful measure of the effect of an explanatory variable and the distribution of predicted probabilities for the various levels of WTP. For continuous variables, the marginal effect represents the change in the predicted probability of WTP levels as a result of a unit change in the explanatory variable, all other factors held constant. For the binary variables, the marginal effects are the differences of the two predicted probabilities, with and without the variable.

Marginal effects are calculated at the mean values of all explanatory variables. Thus, the marginal effects show the change in the predicted probability for each WTP category for an average consumer. The marginal effects for each explanatory variable across the four WTP categories sum to zero by default because the predicted probabilities for the four WTP categories sum to one. All the explanatory variables are binary except 'average seafood expenditure' and 'WTP more for Midwest saltwater seafood [1].

From Table 1.2, the demographic variables that appear significant have positive marginal effects for the lower two WTP categories, i.e., WTP up to \$3.99/lb and WTP \$4.00 - \$4.99/lb, but a negative effect on the other WTP categories, i.e., WTP \$5.00 - \$5.99/lb and WTP at least \$6.00/lb. Moreover, these marginal effects tend to be stronger for the first and last WTP categories ($y = 0$ and $y = 3$). For example, the marginal effects for females indicate that they are 13% more likely to be willing to pay up to \$3.99/lb for Midwest striped bass relative to males and 14% less likely to be willing to pay at least \$6.00/lb relative to males. It suggests that males are more likely to pay higher amounts for Midwest striped bass than females. Similarly, relative to consumers who are 29 years of age and younger, older consumers are more likely to pay at most \$4.99/lb for Midwest striped bass. The marginal effects for the age groups are positive for WTP up to \$4.00/b ($y = 0$) and \$4.00 - \$4.99/lb ($y = 1$) for Midwest striped bass. It also suggests that consumers who are 29 years of age and younger are more likely to pay higher amounts for Midwest striped bass than older consumers.

From Table 1.2, a number of variables positively affect the probability of consumers' willingness to pay higher amounts (y=2 and/or y=3). An alternative interpretation is that these variables significantly reduce the probability of willingness to pay lesser amounts for Midwest striped bass (y=0 and y=1). The variables include preference for farmed seafood; preference for fresh seafood; seafood purchase frequency of 1 to 3 times per month; seafood purchase frequency of once per week; eating out 1 to 3 times per month; eating seafood 26 – 50% of the

[1] WTP more for Midwest saltwater seafood was incorporated as a continuous variable as follows: not WTP more = 0; WTP 2% more = 0.02, WTP 4% more = 0.04, WTP 6% more = 0.06, WTP 8% more = 0.08 and WTP 10% more = 0.1.

time when eating out; and eating mostly shrimp and salmon when eating out. From Table 1.2, consumers who prefer farm-raised seafood are 10% less likely to pay up to $4.00/lb but 10% more likely to pay at least $6.00/lb relative to consumers who do not know the source of their seafood. The likelihood is the same for consumers who buy seafood 1 to 3 times per month for home consumption relative to consumers who buy seafood for home consumption less than once per month. For consumers who buy seafood once a week, they are 16% less likely to pay up to $3.99 but 20% more likely to pay at least $6.00 relative to consumers who buy seafood for home consumption less than once a month (Table 1.2). Freshness is found to positively affect willingness to pay at least $6.00/lb for striped bass.

The results from Table 1.2 also show that consumers who indicated their willingness to pay more for Midwest seafood and those who purchase seafood once per week have a very strong probability of paying at least $5.00 for Midwest saltwater striped bass. Consumers who eat seafood 26 – 50% of the time when eating out are 9% less likely to pay $3.99 and less for Midwest saltwater striped bass but 10% more likely to pay $6.00/lb and more relative to consumers who eat seafood at most 25% of the time they eat out. Consumers who purchase mostly shrimp when eating out have similar and opposite probabilities for the first WTP (-8%) and last WTP (8%) amounts and also for the two middle WTP categories (2%) compared to consumers who purchased other species than shrimp.

In addition to the interpretations from the marginal effects of variables that would increase the likelihood of consumers' willingness to pay higher amounts for Midwest saltwater striped bass, we also simulated predicted probabilities at each level of three relevant variables, i.e., 'buys seafood about 1 to 3 times per month for home consumption;' 'buys seafood once per week for home consumption;' and 'eats seafood 26 – 50% of the time when eating out' (Table 1.3). These variables represent frequency of purchase and consumption of seafood products. The results reported in Table 1.3 show the probability distribution at particular levels of each variable. It is evident that frequent seafood consumers have a higher likelihood to pay more for Midwest striped bass; the magnitude of predicted probability increases from lower to larger categories of WTP. For example, the predicted probability increases from 27% for WTP up to $4.00/lb to 31% for WTP at least $6.00/lb. The predicted probability for consumers who do not buy seafood about 1 to 3 times per month for home consumption have the opposite effect; it reduces from 34% for paying up to $3.99 for Midwest striped bass to 26% for WTP at least $6.00.

For consumers who buy seafood once per week for home consumption, the predicted probability significantly increases from 18% for WTP up to $4.00/lb to 41% for WTP at least $6.00/lb. The predicted probability for consumers who do not buy seafood once a week for home consumption reduces from 33% for paying up to $3.99 for Midwest saltwater striped bass to 26% for WTP at least $6.00. For consumers who eat seafood 26 - 50% of the time when they eat out, the predicted probability increases from 21% for WTP up to $4.00/lb to 39% for WTP at least $6.00/lb (Table 1.3).

An indication of willingness to pay more for Midwestern saltwater seafood is one of the variables that significantly increase the probability of consumers' WTP higher amounts for Midwest striped bass. Therefore, we also performed a simulation of the predicted probability of

WTP the highest category for Midwest striped bass (y = 3) at each level of willingness to pay more for Midwest saltwater seafood, i.e., 2%, 4%, 6%, 8% and 10% more against the factors of purchasing seafood about 1 to 3 times per month for home consumption and eating seafood 26 – 50% of the time when eating out. The results are reported in Table 1.4. Note that this simulation examined the effect of two variables on the predicted probability of the highest outcome (y = 3). The results suggest that consumers who buy seafood one to three times per month and willing to pay 2% more for Midwestern saltwater seafood are 27% likely to pay at least $6.00/lb for Midwest striped bass. The likelihood increases with willingness to pay more than 2%, i.e., 36% likelihood for consumers willing to pay 4% more; 46% likelihood for consumers willing to pay 6% more; 56% likelihood for consumers willing to pay 8% more; and 66% likelihood for consumers willing to pay 10% more (Table 1.4). Even consumers who do not buy seafood one to three times per month but are willing to pay more for Midwest saltwater seafood also show increasing probability; e.g., consumers willing to pay 2% more for Midwest saltwater seafood are 22% likely to pay the highest amount for Midwest striped bass (y = 3). The likelihood increases to 30% for consumers willing to pay 4% more, 39% for consumers willing to pay 6% more, 49% for consumers willing to pay 8% more, and 59% for consumers willing to pay 10% more.

Similar trends can be observed for consumers who, whether or not, eat seafood 26 – 50% of the time when eating out but indicated they are willing to pay more for Midwest saltwater seafood. From Table 1.4, consumers who eat seafood 26 – 50% of the time when eating out and willing to pay 2% more for Midwest saltwater seafood are 34% likely to pay WTP at least $6.00/lb. The predicted probability significantly increases with consumers willing to pay more, up to 73% for consumers willing to pay 10% more (Table 1.4).

It is obvious that certain factors contribute significantly to the probability of consumers paying more for Midwest striped bass. The challenge for prospective farmers would be adopting cost-effective production methods to enable them become competitive in the marketplace. Marketing strategies could also be adopted targeted at consumer segments that are willing to pay higher premiums.

Summary and Conclusions

The study examined the potential market for a model marine species, striped bass, to be grown in the Midwest region of the US for food consumption using willingness to pay information from consumers in the Midwest. We found that males relative to females, and consumers who are 29 years of age and younger relative to older consumers, are more likely to pay higher amounts for Midwest striped bass.

Other variables found to increase the probability of paying higher amounts for Midwest striped bass include preference for farmed seafood; preference for fresh seafood; seafood purchase frequency of 1 to 3 times per month for home consumption; seafood purchase frequency of once per week for home consumption; eating out 1 to 3 times per month; eating seafood 26 – 50% of the time when eating out; and eating mostly shrimp when eating out.
Simulated results from selected variables show that frequent seafood consumers have a higher likelihood to pay more for Midwest striped bass with the magnitude of predicted probability

increasing from lower to larger categories of WTP for striped bass. This includes consumers who buy seafood 1 to 3 times per month for home consumption, consumers who buy seafood once per month for home consumption, and consumers who eat seafood 26 - 50% of the time when they eat out.

For the highest WTP category, i.e., at least $6.00/lb for Midwest striped bass, simulation results at each level of consumers' willing to pay more for Midwest saltwater seafood, i.e., 2%, 4%, 6%, 8% and 10% more against whether or not a consumer buys seafood 1 to 3 times per month for home consumption and whether or not a consumer eats seafood 26 – 50% of the time when eating out show that predicted probabilities increase significantly as the level of willingness to pay more for Midwest saltwater seafood increases.

References

1. Cranfield, J.A.L. and E. Magnusson. Canadian Consumer‟s Willingness-To-Pay For Pesticide Free Food Products: An Ordered Probit Analysis. *International Food and Agribusiness Management Review*, 6(4) 2003: 13-30.
2. Kaneko, Naoya and W. Chern. Willingness to Pay for Genetically Modified Oil, Cornflakes, and Salmon: Evidence from a U.S. Telephone Survey. *Journal of Agricultural and Applied Economics*, 37(3) 2005.:701-718.
3. Kumar, G., Quagrainie, K.K., and Engle, C. "Factors that Influence Frequency of Purchase of Catfish by U.S. Households in Selected Cities." *Aquaculture Economics and Management*, 12(4) 2008: 252-267.
4. Loureiro, Maria L. and S. Hine. Discovering Niche Markets: A Comparison of Consumer Willingness to Pay for Local (Colorado Grown), Organic, and GMO-Free Products. *Journal of Agricultural and Applied Economics*, 34(3) 2002: 477-487.
5. McCluskey, Jill J., K. Grimsrud, H. Ouchi, and T.I. Wahl. Bovine Spongiform Encephalopathy in Japan: Consumers' Food Safety Perceptions and Willingness to Pay for Tested Beef. *The Australian Journal of Agricultural and Resource Economics*, Vol. 49, 2005: 197-209.
6. Puduri, Venkata, R. Govindasamy, J.J. Myers, and L.J. O'Dierno. Demand for Live Aquatic Products in the Mid-Atlantic States: An Ordered Probit Analysis towards Consumers' Preferences. *Aquaculture Economics and Management*, Vol. 14, 2010:30-42.
7. Quagrainie, K.K., A. Xing, and K.G. Hughes. "Factors Influencing the Purchase of Live Seafood in the North Central Region of the United States." *Marine Resource Economics*, 26 (1) 2011: 59-74
8. Quagrainie, K.K., Hart, S.D., Brown, P.B. "Consumer Acceptance of Locally Grown Food: The Case of Indiana Aquaculture Products" *Aquaculture Economics and Management*, 12(1) 2008:54–70
9. Quagrainie, Kwamena. IQF Catfish Retail Pack: A Study of Consumers' Willingness to Pay. *International Food and Agribusiness Management Review*, 9(2) 2006: 75-87.
10. Umberger, Wendy J., D.M. Feuz, C.R. Calkins, K. Killinger-Mann. U. S. Consumer Preference and Willingness-to-Pay for Domestic Corn-Fed Beef Versus International Grass-Fed Beef Measured Through an Experimental Auction. *Agribusiness*, 18(4) 2002: 491-504.

Appendix

Table 1.1: Statistical Summary of Model Variables.

Variable	Mean	Std. Dev.	Min	Max
Willing to pay up to $3.99/lb (y = 0)	0.312	0.464	0	1
Willing to pay $4.00 to $4.99/lb (y = 1)	0.229	0.421	0	1
Willing to pay $5.00 to $5.99/lb (y = 2)	0.180	0.385	0	1
Willing to pay $6.00 and more (y = 3)	0.278	0.449	0	1
Prefer wild-harvest seafood	0.338	0.474	0	1
Prefer farm-raised seafood	0.158	0.365	0	1
Indifferent to seafood source	0.423	0.494	0	1
Buys seafood 1-3x / month	0.487	0.500	0	1
Buys seafood 1x / week	0.150	0.358	0	1
Buys seafood more than 1x / week	0.068	0.251	0	1
Average seafood expenditure / shopping visit	13.985	11.910	0	60
Prefers fresh seafood	2.457	0.769	1	3
Prefers frozen seafood	2.107	0.621	1	3
WTP more for Midwest saltwater seafood	0.021	0.027	0	0.1
Eats out 1-3x / month	0.372	0.484	0	1
Eats out 1x / week	0.184	0.388	0	1
Eats out more than 1x / week	0.115	0.319	0	1
Eats seafood 26-50% when eating out	0.226	0.418	0	1
Eats seafood more than 50% when eating out	0.118	0.323	0	1
Shrimp mostly eaten out	0.380	0.486	0	1
Salmon mostly eaten out	0.122	0.328	0	1
Lobster mostly eaten out	0.075	0.264	0	1
Female	0.692	0.462	0	1
Age – 30 to 39 years	0.120	0.326	0	1
Age – 40 to 49 years	0.154	0.361	0	1
Age – 50 to 59 years	0.244	0.430	0	1
Age – 60 years and above	0.393	0.489	0	1
Married	0.622	0.485	0	1
Caucasian / White	0.906	0.292	0	1
High School	0.229	0.421	0	1
College Degree	0.472	0.500	0	1
Income - $20,000 to $39,999	0.233	0.423	0	1
Income - $40,000 to $59,999	0.248	0.432	0	1
Income - $60,000 to $79,999	0.148	0.356	0	1
Income - $80,000 to $99,999	0.092	0.289	0	1
Income - $100,000 and above	0.105	0.307	0	1

Table 1.2: Estimated marginal effects of explanatory variables on the probability of willingness to pay for saltwater striped bass fillets.

	≤\$3.99 $y = 0$	\$4.00-4.99 $y = 1$	\$5.00-5.99 $y = 2$	≥\$6.00 $y = 3$
Prefer wild-harvest seafood	0.036	0.010	-0.012	-0.034
Prefer farm-raised seafood	-0.084^{**}	-0.033	0.022^{**}	0.094^{*}
Indifferent to seafood source	-0.029	-0.009	0.009	0.028
Buys seafood 1-3x / month	-0.093^{**}	-0.027^{**}	0.030^{**}	0.091^{**}
Buys seafood 1x / week	-0.155^{***}	-0.077^{***}	0.028^{***}	0.204^{***}
Buys seafood more than 1x / week	0.065	0.013	-0.023	-0.055
Average seafood expenditure / shopping visit	-0.000	-0.000	0.000	0.000
Prefers fresh seafood	-0.051^{**}	-0.015^{*}	0.017^{**}	0.050^{**}
Prefers frozen seafood	0.004	0.001	-0.001	-0.004
WTP more for Midwest saltwater seafood	-3.945^{***}	-1.136^{***}	1.277^{***}	3.804^{***}
Eats out 1-3x / month	-0.067^{*}	-0.021	0.021^{*}	0.067^{*}
Eats out 1x / week	0.009	0.002	-0.003	-0.008
Eats out more than 1x / week	-0.066	-0.026	0.018	0.074
Eats seafood 26-50% when eating out	-0.087^{**}	-0.032^{*}	0.024^{***}	0.095^{**}
Eats seafood more than 50% when eating out	-0.039	-0.013	0.012	0.040
Shrimp mostly eaten out	-0.078^{**}	-0.025^{**}	0.024^{**}	0.079^{**}
Salmon mostly eaten out	-0.085^{*}	-0.035	0.022^{**}	0.097
Lobster mostly eaten out	-0.073	-0.029	0.019^{*}	0.083
Female	0.129^{***}	0.048^{***}	-0.035^{***}	-0.141^{***}
Age – 30 to 39 years	0.166^{*}	0.016	-0.060^{*}	-0.122^{**}
Age – 40 to 49 years	0.163^{*}	0.019^{**}	-0.059^{*}	-0.123^{**}
Age – 50 to 59 years	0.269^{***}	0.021	-0.095^{***}	-0.195^{***}
Age – 60 years and above	0.242^{***}	0.045^{***}	-0.079^{***}	-0.208^{***}
Married	0.039	0.012	-0.012	-0.038
Caucasian / White	-0.126^{*}	-0.016^{***}	0.045	0.096^{**}
High School	0.025	0.007	-0.008	-0.023
College Degree	0.005	0.001	-0.002	-0.005
Income - \$20,000 to \$39,999	0.011	0.003	-0.004	-0.010
Income - \$40,000 to \$59,999	0.039	0.010	-0.013	-0.036
Income - \$60,000 to \$79,999	0.159^{**}	0.018^{**}	-0.057^{**}	-0.120^{***}
Income - \$80,000 to \$99,999	0.043	0.010	-0.015	-0.038
Income - \$100,000 and above	-0.036	-0.012	0.011	0.037

'***', '**', '*' signify statistical significance of estimate at the 1%, 5% and 10% levels respectively.

Table 1.3: Simulated probabilities of the effects of selected variables on willingness to pay for saltwater striped bass[1].

	<\$3.99 Prob(y=0)	\$4.00 - \$4.99 Prob(y=1)	\$5.00 - \$5.99 Prob(y=2)	≥ \$6.00 Prob(y=3)
Buys seafood for home consumption 1 - 3x / month = 1	0.266	0.227	0.201	0.307
Buys seafood for home consumption 1 - 3x / month = 0	0.338	0.222	0.177	0.262
Buys seafood for home consumption 1x / week = 1	0.178	0.197	0.212	0.413
Buys seafood for home consumption 1x / week = 0	0.325	0.229	0.184	0.261
Eats seafood 26-50% when eating out = 1	0.212	0.199	0.201	0.388
Eats seafood 26-50% when eating out = 0	0.330	0.232	0.185	0.254

[1] Other variables are valued at their means.

Table 1.4: Simulated probabilities of WTP more for Midwest saltwater seafood with selected frequency of seafood consumption on the highest willingness to pay at least $ 6/lb (y = 3)[1]

	WTP 2% more	WTP 4% more	WTP 6% more	WTP 8% more	WTP 10% more
Buys seafood for home consumption 1-3x / month= 1	0.274	0.362	0.460	0.562	0.658
Buys seafood for home consumption 1-3x / month= 0	0.222	0.300	0.392	0.492	0.593
Eats seafood 26-50% when eating out = 1	0.344	0.440	0.542	0.640	0.728
Eats seafood 26-50% when eating out = 0	0.222	0.300	0.392	0.492	0.593

[1] Other variables are valued at their means.

Chapter 2

Potential Saline Water Resources in Illinois for Aquaculture

N. Rajagopalan/ S. Ganguly

Introduction

Illinois has a vast supply of saline water. Sources include saline aquifers, saline springs, produced water from oil extraction, effluents from coal beneficiation, waters produced from coal bed methane production, and industrial effluents resulting from water treatment, waste volume concentration, and food processing.

Saline Aquifers

Figure 2.1 shows the major rock aquifers of the state at depths greater than 500 feet classified by the total dissolved solids (TDS) content[4]. At depths greater than 500 feet the TDS content in the underlying formations increase going south. In general, waters of less than 10,000 mg/L TDS are considered potential sources of drinking water. Waters of TDS greater than 10,000 mg/L have not been historically viewed as drinking water sources and should be accessible for marine aquaculture.

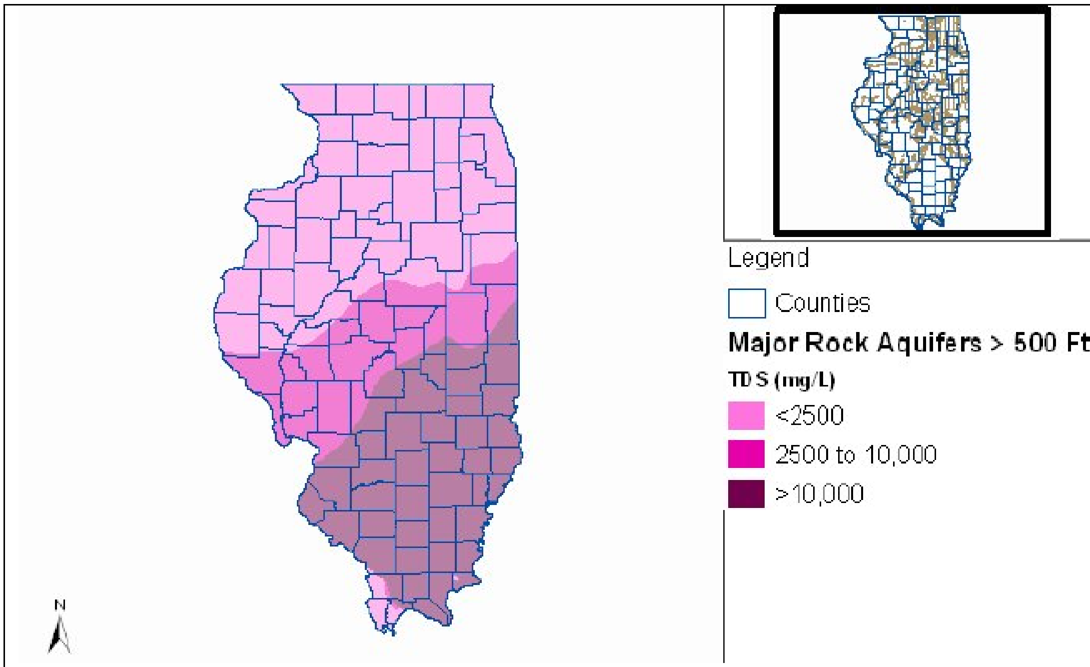


Figure 2.1: Variation of salinity as classified by TDS (in mg/L) in the state of Illinois

Figure 2.2 provides data on the distribution of salinity and the depths of various formations within the state[1]. Shaded areas in the map represent water of TDS <5,000 mg/L. The Mt. Simon and the St. Peter formations represent the deeper saline aquifers of the state. The salinity in these aquifers greatly exceeds that of seawater at many locations as shown in Figure 2.2.

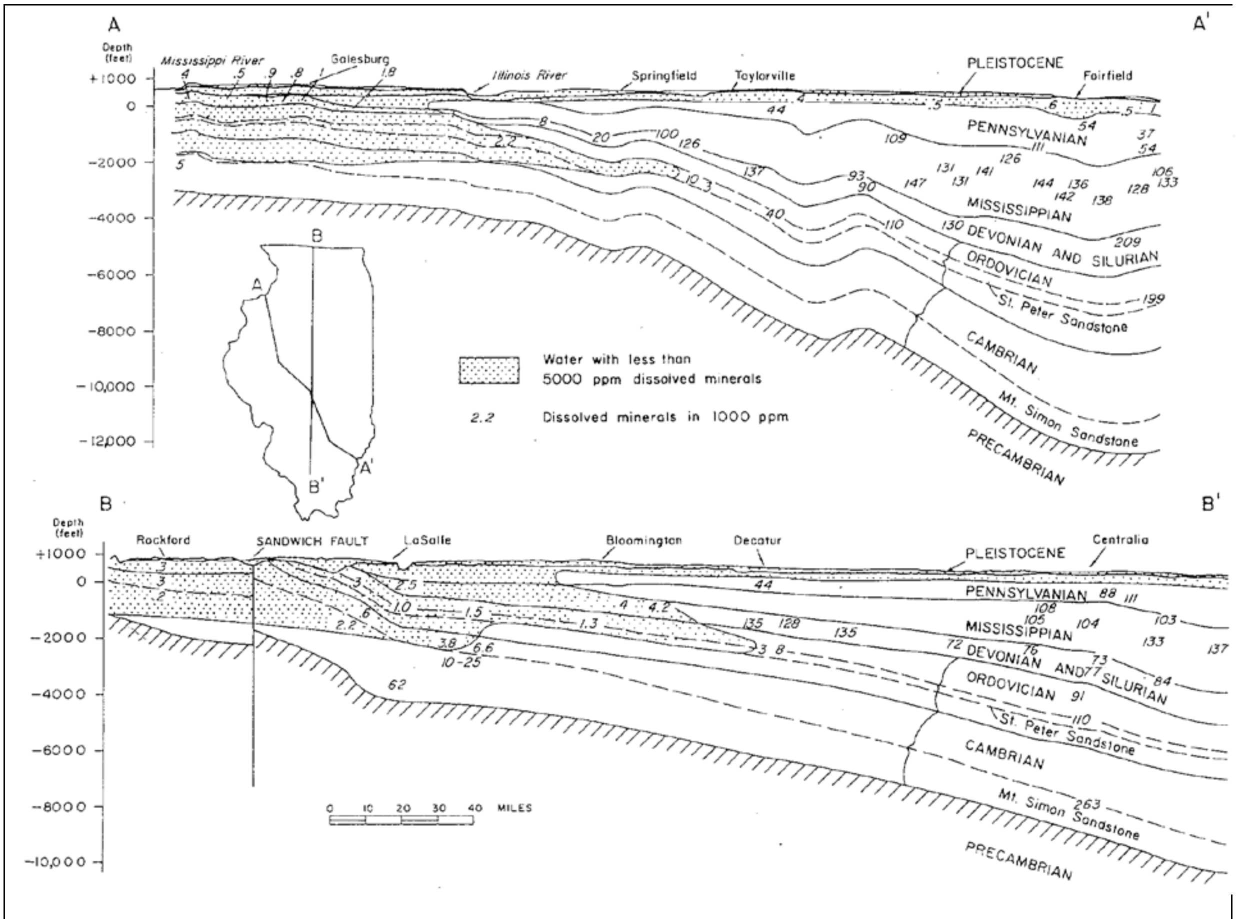


Figure 2.2: Statewide cross-sectional view of salinity of groundwater in rock aquifers

Figure 2.3 is an updated version of the salinity of the Mt. Simon aquifer as reported by the Midwest Geological Sequestration Consortium[8].

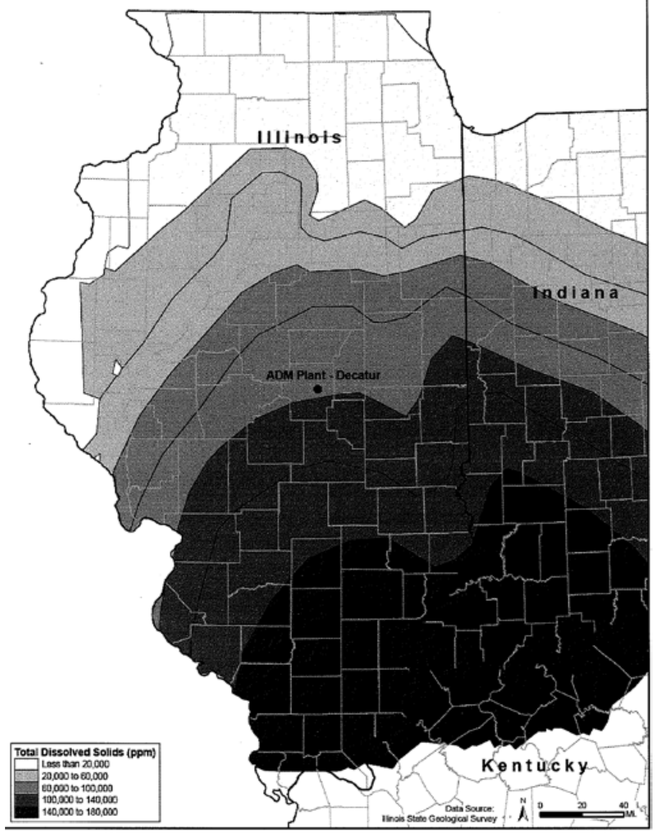


Figure 2.3: Salinity of the Mt. Simon sandstone in the Illinois Basin

Geologic Carbon Sequestration and Saline Water Production

Currently, the overwhelming scientific consensus advocates the minimization of emissions of carbon dioxide (CO_2), a global greenhouse gas. CO_2 emissions in Illinois increased from 94.6 million tons in 2000 to 107 million tons in 2010. Coal-based electricity generation in Illinois is one of the major CO_2 emitters. Other large emission sources include cement manufacturers, auto manufacturers, glass manufacturers, refineries, ammonia producers, iron and steel producers, and corn-to-ethanol facilities. One approach towards mitigation of CO_2 emissions is based on geological sequestration. Carbon Storage and Sequestration (CSS) technologies are designed to store CO_2 captured from power plants in deep saline aquifers such as the Mt. Simon and St. Peter formations. The first million ton CO_2 injection project into the Mt. Simon formation began operations at the ADM Decatur in fall, 2011.

At scale deployment of geologic sequestration is expected to lead to increased pressure in the trapped water. The increases in pressure can decrease CO_2 holding capacity, risk breaching the capping layer, lead to potential for water seepage and increase seismic risk. It is likely that pressure relief of the water within the aquifer will be provided leading to discharge of a highly saline effluent. CO_2 emissions from one 1 GW coal-powered plant are estimated to displace 7.5 million m^3 of brine annually (~6 MGD)[12]. This highly saline effluent could be potentially useful as a resource for marine aquaculture.

Tables A.1 and A.2 in Appendix A provide water quality information at select locations as available from the Mt. Simon and St. Peter formations, respectively.

Oil Field Associated Brines

The Illinois basin reservoir is reported to have held 14 Billion barrels of oil[3]. Four billion barrels of oil from the basin is estimated to have been extracted. Along with the oil, the process also generates brines termed produced water. In new wells, the ratio of water to oil produced is on the order of 5:1 to 8:1. In older wells, the ratio may be greater than 50:1[9]. A large fraction of this water is recycled back to the oil well. The remainder is disposed into injection wells. A recent estimate calculates that about 10.8 billion gallons/year (29 MGD) of produced water currently disposed into injection wells in Illinois may be potentially available for other uses[5]. Marine aquaculture could benefit from this effluent.
Appendix B provides water quality information for the St. Genevive and Aux Vases formation waters as reported by Demir and Seyler[2]. A more comprehensive compilation is that of Meents[7]. A more recent survey has been completed by Dr. Sam Panno at ISGS and was being vetted before release[10].

Coal Bed Methane (CBM) Produced Water

Coal bed methane (CBM) is a form of natural gas that is found in coal seams. CBM extraction requires the removal of groundwater to facilitate flow to the surface. The associated water can be saline and can potentially be used for marine aquaculture. EPA reports[11] water discharges associated with coal bed methane production in Illinois were 113.4 million gallons in 2008 (0.3 MGD). The quality of water associated with this water is given in Appendix C.

Water From Coal Mining

Two types of water are discharged from coal mining and coal cleaning operations. One is the water that is pumped from mines so as to maintain dry conditions. The second results from coal cleaning operations. Typically, coal cleaning waters are concentrated due to recycling and are moderately saline. Approximately 0.5 MGD may be available from a coal mine (American Company) at Galatia and another 0.5 MGD from White County Coal Company, IL. Water quality information from a couple of locations is given in Appendix D.

Industrial Effluents

Many industrial plants including power plants use ion exchange or reverse osmosis to treat water to make it fit for industrial use. The regeneration of ion exchange beds and the desalination of water by reverse osmosis frequently generate effluents with TDS in excess of 10,000 mg/L. These streams can be a source of saline water if segregated. An example of one such source is an ethanol plant in Illinois that produces 20 tons of salt per day from water treatment operations.

Summary

A considerable quantity of saline water is available to support the needs of a marine aquaculture industry in Illinois. The sources vary from isolated, deep rock aquifers to industrial effluents. The cost of obtaining these waters will depend on their accessibility. Deeper waters are likely to be more difficult and expensive to extract unless produced through secondary operations such as CO_2 sequestration. Waters from existing coal beneficiation and other industrial plants can be easily accessed provided transportation costs are low. Produced waters that are currently transported for disposal are also likely to be accessible at low cost.

These saline waters vary significantly in composition. The waters from deep aquifers are often contaminated with trace elements; those of produced water with hydrocarbons, nitrogen, and trace elements; and industrial effluents with organic matter. Analytical information on these sources of saline waters is limited and often incomplete. It is, therefore, safe to assume that a degree of pretreatment would be required prior to use for aquaculture.

In conclusion, the feasibility of utilizing the above sources of saline waters for aquaculture is likely to be highly location dependent and will hinge on both accessibility and water treatment cost.

Description of Water Used in This Study

The water used in this study is representative of the waters of the Ironton-Galesville formation. The Ironton-Galesville aquifer formation overlies the Mt. Simon formation. It represents saline water accessible at moderate depths free of hydrocarbon contaminants. In an ongoing CO_2 injection study at the ADM plant site at Decatur, the Ironton-Galesville formation is being monitored for evidence of salt water migration from the Mt. Simon zone. At the outset of this project, it was believed that several hundred gallons of this water might be available from the Illinois State Geological Survey (ISGS) as part of a planned flushing process. However, this did not materialize. The ISGS did however share information on the composition of the water that is presented in Table 2.1.

Assuming that the water would be diluted to a 1% concentration (10,000 mg/L TDS) for rearing striped bass, a dilution factor of 6.5 would be required. It is likely that trace metals such as copper and zinc might be present in these waters at levels that would necessitate treatment. Nitrogen, phosphorus, radionuclides, and various gases may also be present in these waters. In summary, while the Ironton-Galesville formation water provides all of the required major ions and has an advantageous high hardness level, it may need to be treated to remove some trace metals, aerated to increase DO content, and supplemented with alkalinity to render it suitable.

Table 2.1: Ironton-Galesville Formation Water Quality[6].

Constituent	mg/L
pH	6.9
Total Dissolved Solids	65,600
Na^+	17,200
Ca^{2+}	5,200
K^+	520
Mg^{2+}	950
Cl^-	36,900
Br^-	180
Alkalinity as $CaCO_3$	130
SO_4^{2-}	1200

References

1. Bergstrom, R. E. Feasibility of subsurface disposal of industrial wastes in Illinois, *Illinois State Geological Survey*, Champaign, IL, 426, 1968.
2. Demir, I., Seyler, B. Chemical composition and geologic history of saline waters in Aux Vases and Cypress formations, Illinois Basin. *Aquatic Geochemistry*. 5, 1999: 281-311.
3. Frailey, S.M. Carbon dioxide enhanced oil recovery in the Illinois basin. http://www.purdue.edu/discoverypark/energy/assets/pdfs/cctr/cctr-meetings/april_2012/CCTR_April5-2012_Frailey.pdf. Accessed March 28, 2013.
4. ISGS, http://isgs-ablation.isgs.uiuc.edu/website/ilwater/viewer.htm
5. Knutson, C., Dastgheib, S., Yang, Y., Ashraf, A., Duckworth, C., Sinata, P., Sugiyono, I., Shannon, M.A., and Werth, C.J. Reuse of produced water from CO2 enhanced oil recovery, coal-bed methane, and mine pool water by coal-based power plants. Report to NETL, 2012.
6. Locke, R. Deep brine characterization for the Illinois Basin Decatur project. http://sequestration.org/resources/PAGNov2011Presentations/07-IBDPBrineCharacterization_Locke_Final.pdf. Accessed March 28, 2013.
7. Meents, W.F., Bell, A.H., Rees, O.W., and Tilbury, W.G. Illinois oil field brines: Their geologic occurrence and chemical composition, *Illinois State Geological Survey*, Champaign, IL, IP # 66 1952.
8. MGCS, http://sequestration.org/resources/publish/saline_salinity_map_dec05.pdf
9. NETL, Produced water management information systems. Introduction to produced water. http://www.netl.doe.gov/technologies/pwmis/intropw/index.html. Accessed March 28, 2013.
10. Panno, S. Personal Communication, 2012.
11. USEPA, Coalbed Methane Extraction: Detailed Study Report, *U.S. Environmental Protection Agency*, EPA-820-R-10-022, 2010.
12. Wolery, T.J., Aines, R.D., Hao, Y., Bourcier, W., Wolfe, T., and Haussman, C. Fresh water generation from aquifer-pressured carbon storage. LLNL Report- TR-420857, 2009.

Appendix

Appendix A

Table A.1: Mt. Simon brine composition at select locations[7] (values in mg/L)

Formation	Mt. Simon	Mt. Simon
County	Douglas	Decatur
Depth (ft)	4046-4090	-
pH	7.3	5.9
TDS	128,312	190,000
Na	34,567	50,000
Ca	10,590	19,000
Mg	1,916	1,800
SiO_2	13	na
Fe Filtered	13	na
Fe Unfiltered	20	na
Al_2O_3	77	na
Mn	9.4	na
SO_4^{2-}	1,292	na
Cl^-	76,570	120,000
NO_3^-	11	na
CO_3^{2-}		
HCO_3^-	174	97.6
NH_4^+	13	na

Table A.2: St. Peter brine composition at select locations[7] (values in mg/L)

Formation	St. Peter	St. Peter	St. Peter	St. Peter	St. Peter	St. Peter
County	Adams	Adams	Bond	Clark	Clark	Crawford
Depth (ft)	344-971	666-675	2505-3154	3945-3960	2923-3009	4650-4654
pH	7.4	7.2	-	-	-	6.3
TDS	8210	12258	12201	124550	24114	160730
Na	2443	3715	3563	37346	6941	44295
Ca	319	456	583	6778	1551	11260
Mg	157	266	260	2418	494	2306
SiO_2	36	22	6	5	33	32
Fe Filtered	0.4	0.8	0	40	0.8	0
Fe Unfiltered	1	0.8		128		0.4
Al_2O_3	11	6	332	81	0.9	37
Mn	0	1.3	0	3	0	1.2
SO_4^{2-}	992	987	1614	121	2618	945
Cl^-	3876	6398	5973	76000	12563	94257
NO_3^-	9.6	8.1	32	13		21
CO_3^{2-}	10					
HCO_3^-	292	328	217	7	678	110
NH_4^+	3.6	5.2	13	142		41

Appendix B

Table B.1 Brines Associated with Oil Production[2] (values in mg/L)

Formation	Aux Vases	Cypress
	Mean (std. deviation)	Mean (std. deviation)
pH	6.61 (0.51)	6.60 (0.57)
TDS	126212 (20763)	101577 (28434)
Na	43792 (7210)	35863 (9714)
Ca	4816 (1148)	3317 (1586)
Mg	1602 (482)	1103 (367)
K	200 (56)	111 (34)
Sr	279 (183)	150 (76)
Ba	3.16 (4.42)	21.32 (51.89)
Li	8.22 (3.04)	4.96 (2.36)
Fe	5.84 (10.34)	8.20 (12.5)
Mn	0.88 (0.59)	1.52 (1.19)
B	3.9 (1.39)	2.58 (0.57)
Si	4.5 (1.60)	5 (2.80)
Al	0.2 (0.1)	0.2 (0.1)
Cl	74654 (12558)	60383 (17018)
Br	156 (47)	120 (48)
I	8.8 (2.8)	6 (4)
SO_4^{2-}	690 (584)	392 (374)
NO_3^-	0.27 (0.24)	0.62 (0.87)
CO_3^-	0.18 (0.27)	0.20 (0.21)
HCO_3^-	127 (70)	177 (125)
$NH4^+N$	29 (8)	24 (8)

Appendix C

Table C.1 Coal Bed Methane Waters[5] (values in mg/L)

Project	Delta	Shelby	Macoupin	Pioneer
pH	8.1	7	7.69	7.3
TDS	2,532	83,920	12,611	32,291
Na	552	27,911	4,304	10,105
Ca	9.07	2,271	241	1,307
Mg	3.79	970	194	646
Fe	1.66	3.27	2	
K	2	62		
Ba	0.5	37	3	35
Sr	0.32	182.6		
Mn	0.08	0.58		
Cl^-	500	52,300	7,300	19,506
HCO_3^-	1,464	244	560	705
SO_4^{2-}	1	1	6	

Appendix D

Table D.1 Coal Mine Associated Waters (values in mg/L)

Company	American Coal Company	White County Coal Company
Sample	Thickener underflow	Mine water
TDS	9,010	21,000
Na	3,100	6,900
K	31	28
Ca	150	450
Mg	53	150
Cl^-	3,400	9,400
SO_4^{2-}	1,780	2,700
Br-	7.6	16
F-	0.86	1.1
NO_2^-	0.42	1.4
NO_3^-	0.78	3.5
Alkalinity (meq/L)	2.9	8.2

Chapter 3

Rearing a Euryhaline Species (Striped Bass) in Illinois/Midwest Using Regional Saline Water Resources

Dr. B. C. Small

Introduction

Growth of domestic aquaculture would support fishing and agricultural communities and new aquaculture-based industries in the United States. There are a number of barriers facing the expansion of a domestic saline aquaculture industry. Among these are the high cost and limited availability of coastal land, water resources, environmental impact concerns, high production costs, and lack of sufficient quality fish seedstock. A number of these concerns can be overcome if saline aquaculture can be practiced inland. The suitability of inland sites for culture of euryhaline and marine species is governed by the availability and quality of saline water. It is in this context that we propose that the feasibility of inland saline aquaculture be examined in the state of Illinois. The sea is closer to most residents of the state than realized. In fact, Illinois sits on top an underground sea of saline pore water in rock aquifers. *Aquaculture of euryhaline or marine species offers the potential to beneficially use this saline water.* In conjunction with other techniques based on biological serial concentration, saline aquaculture can be an important cog in a comprehensive sustainable technosystem that fully utilizes this resource with minimal adverse impacts on the environment.

Methods

Water quality information from the Ironton-Galesville formation was used to develop a synthetic mixture to replicate the salt content on this water source. A stock synthetic mixture was made and diluted to yield a 2 ppt salinity solution using municipal water treated with sodium thiosulfate ($Na_2S_2O_3$, 0.035g per 10 L) and sodium bicarbonate ($NaHCO_3$) for dechlorination and maintenance of alkalinity, respectively. This solution was added to a recirculating culture system containing 4 replicate tanks, a sump, and bead filter for solids and bio-filtration, with a total system volume of 745 L. A second system, identical to the first, was filled with 2 ppt salinity water using a commercial synthetic salt solution (Instant Ocean, Spectrum Brands, Madison, WI) as a control treatment. Channel catfish were then stocked into both systems at a density of approximately 5.5 g/L (5 fish/tank) for system cycling. A concentrated bacterial additive (Nutrafin Cycle, Hagen, West Yorkshire, UK) was then added to boost the nitrogen cycle, following manufacturers recommended dosing of 25 mL/38 L on Day 1, and 10 mL/38L on Days 2 and 3. Water temperature was maintained around 22^{o}C and dissolved oxygen (DO) was maintained above 6 mg/L. Both were monitored using a YSI Model 550A Oxygen Meter (Yellow Springs, OH). Total alkalinity, total hardness, total ammonia nitrogen (TAN), nitrite, and pH were monitored weekly using a LaMotte Smart3© Colorimeter (La Motte Co., Chestertown, MD) and a S20 SevenEasy pH meter (Mettler Toledo, Columbus, OH). All fish were maintained on a 12-h light:dark cycle. Completion of the nitrogen cycle took 2 months. After which, the catfish were removed and 20 striped bass fingerlings were weighed (mean ± SEM = 8.5 ± 0.2 g) and stocked into each tank in both systems for grow-out. Salinity was increased incrementally to approximately 10 ppt over a 3 week period. Water quality analysis was done on a weekly basis for both systems.

Striped bass was reared for a total of 24 weeks with continued monitoring of water quality and 4-week incremental fish growth. At the conclusion of the 24 week growth phase, all fish were weighed and 5 fish per tank were euthanized for determination of proximate carcass composition (moisture, protein, lipid, and ash). The remaining fish were allowed to recover from sampling for 3 weeks at which time two fish per tank were rapidly netted and sedated. Blood was collected from the caudal vasculature, plasma separated by centrifugation, and stored until plasma cortisol concentration could be determined. Cortisol is the primary stress hormone in fish. Thus, the purpose was to determine if fish in the Aquifer system were experiencing greater stress. The remaining fish were then subjected to an acute low-water stressor by draining the tanks until the water level was at the height of the fishes' back. After 15 minutes of stress, two fish per tank were netted, sedated and bled as described for cortisol analysis. Cortisol was measured by ELISA (DRG International, Inc, NJ). The purpose of the acute stressor was to determine if there were differences in stress response related to treatment.

Results

Percent weight gain was not statistically different ($P>0.05$) between systems at any time throughout the 24 week growth study (Figure 3.1). Percent weight gain over 24 weeks averaged 1094.1 and 1094.2% (pSEM = 44.7%) for the Aquifer and Control treatments, respectively. There were also no statistical differences ($P>0.05$) for feed efficiency (Figure 3.2) or feed consumption (Figure 3.3) between systems. Final proximate composition of the carcass produced from fish in both treatments was not significantly different ($P>0.05$). Treatment means are presented in Figure 3.4.

Mean 24-week water quality is presented in Table 3.1. Total ammonia nitrogen (TAN) concentrations increased over the duration of the study (Figure 5). TAN concentrations averaged lower ($P<0.0001$) in the Control (1.18 ppm) than in the Aquifer treatment (4.56 ppm) throughout the study. Total hardness was also higher ($P<0.0001$) in the Aquifer treatment relative to the Control treatment, but did not change with time.

Although qualitative, there were observed differences in behavior between the two treatments. Fish in the Control treatment appeared relatively calm during feeding and handling during sampling. On the other hand, fish in the Aquifer treatment were excitable during feeding and appeared agitated during sampling. To determine whether fish in the Aquifer treatment were experiencing a chronic stress, plasma cortisol levels were measured in fish from both treatments before and after an acute low-water stress event. No differences ($P>0.05$) in plasma cortisol were observed between fish in the two treatments either pre- or post-stress (Figure 3.5).

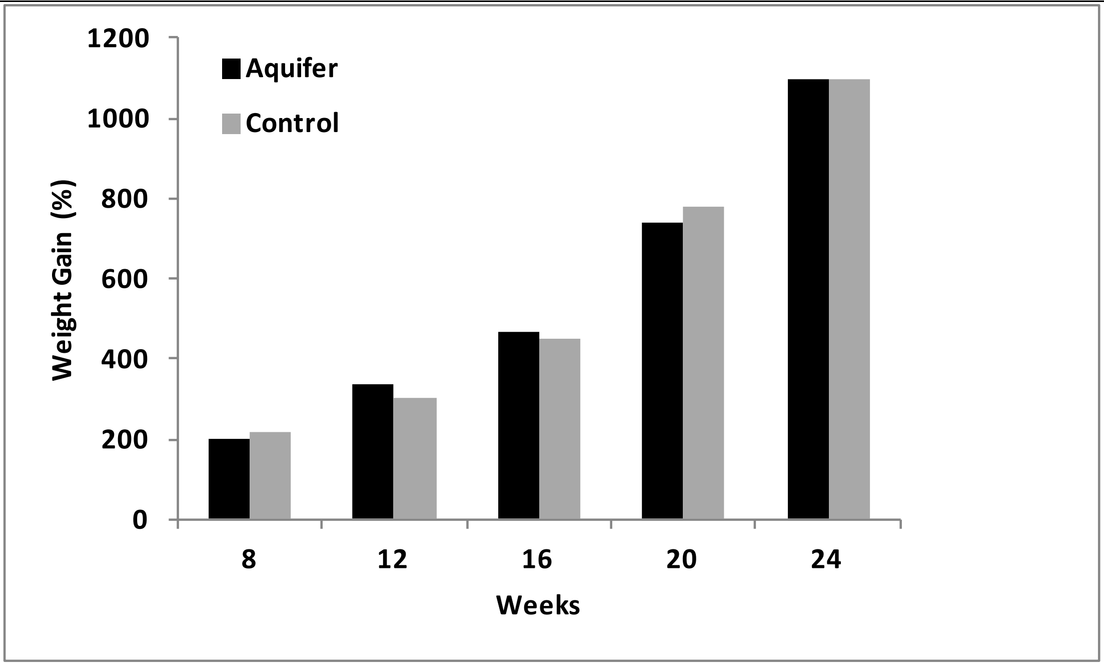


Figure 3.1: Cumulative weight gain of striped bass reared in synthetic Aquifer water compared to fish reared in Control water prepared from Instant Ocean sea salt. No statistical differences were observed (P>0.05)

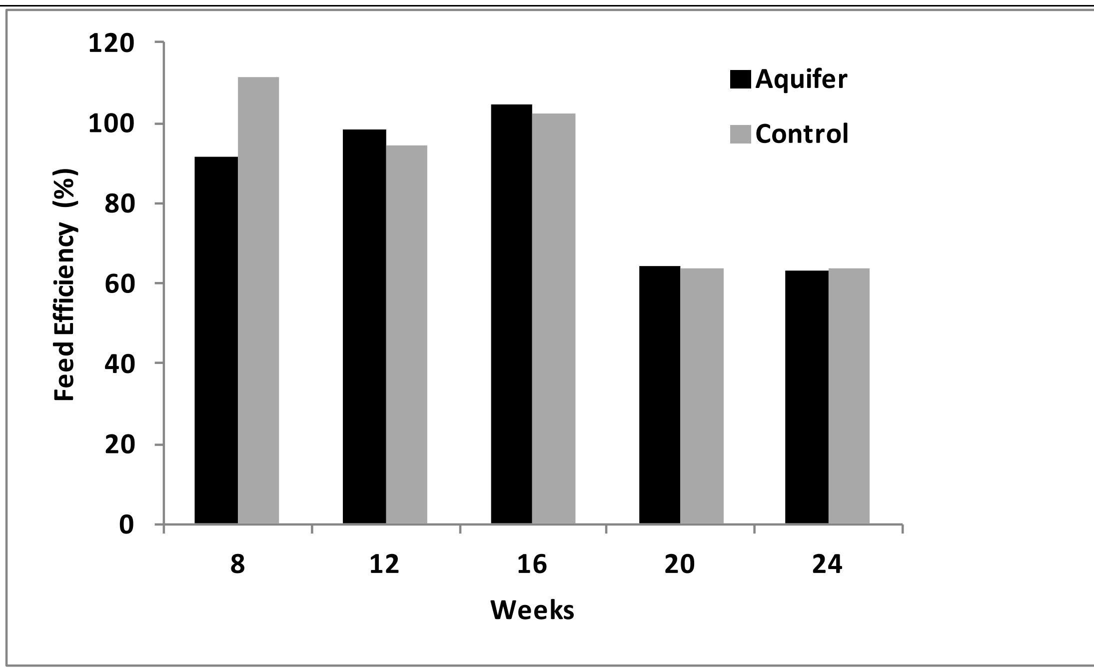


Figure 3.2: Cumulative feed efficiency (FE = weight gain (g)/feed consumed (g) x 100) of striped bass reared in synthetic Aquifer water compared to fish reared in Control water prepared from Instant Ocean sea salt. No statistical differences were observed (P>0.05)

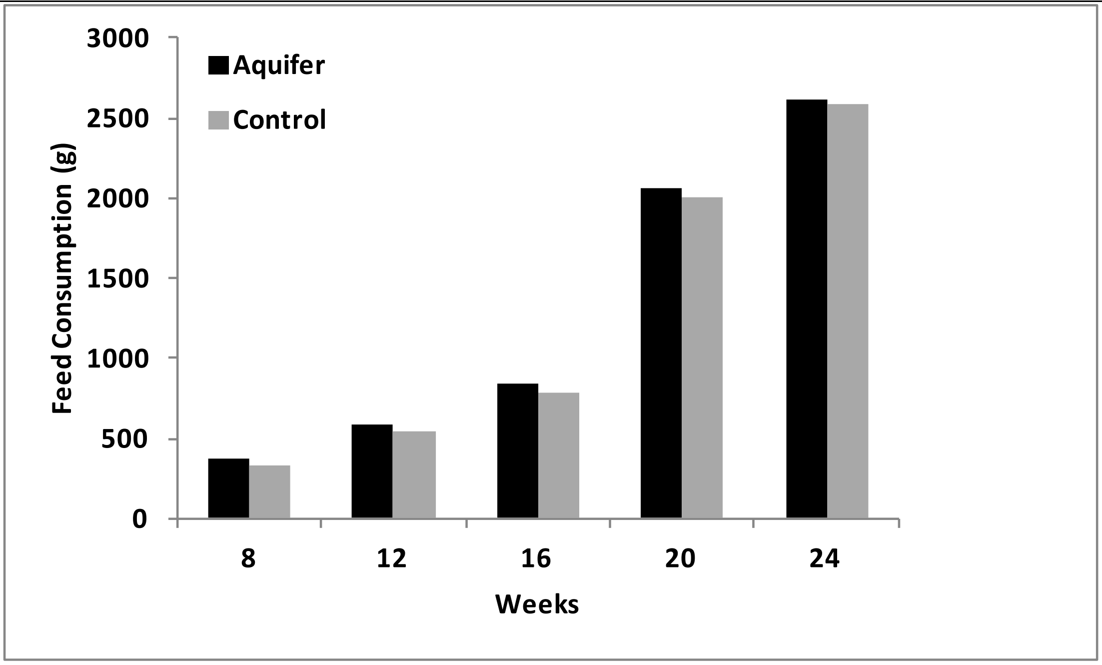


Figure 3.3: Cumulative feed consumption of striped bass reared in synthetic Aquifer water compared to fish reared in Control water prepared from Instant Ocean sea salt. No statistical differences were observed (P>0.05)

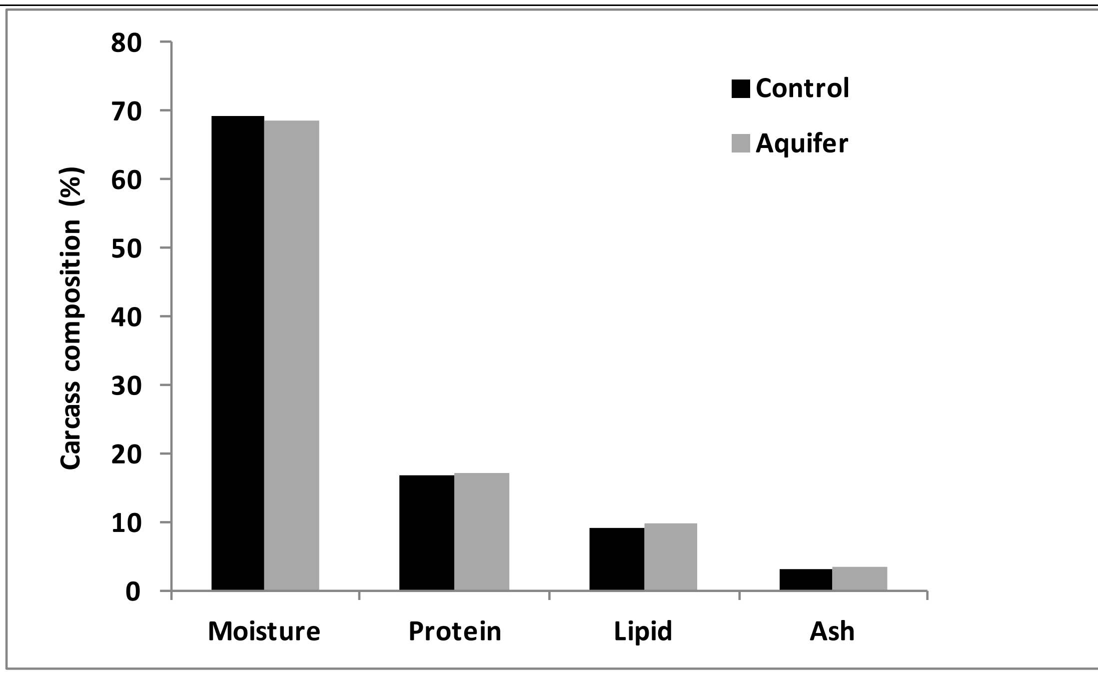


Figure 3.4: Proximate carcass composition of striped bass reared in synthetic Aquifer water compared to fish reared in Control water prepared from Instant Ocean sea salt. No statistical differences were observed (P>0.05)

Table 3.1: Mean water quality over 24 weeks.

Treatment	Salinity (ppt)	Temp (^oC)	pH	TAN (ppm)	Nitrite (ppm)	Alkalinity (ppm)	Hardness (ppm)
Aquifer	9.5	21.9	8.1	4.56	0.16	90.6	480.5
Control	9.1	21.5	8.1	1.18	0.15	89.9	297.0
pSEM	0.5	0.2	0.1	0.42	0.02	7.9	18.4
P-value	0.57	0.22	0.92	<0.0001	0.80	0.94	<0.0001

For this study, the concentrations of trace elements in the Ironton-Galesville formation were unavailable. Although the results to date demonstrate similar fish growth performance between treatments, increasing TAN concentrations in the Aquifer system are indicative of inefficient biological filtration. One possible explanation may be a lack of essential trace elements for the bacteria colonizing the biofilter. This may also explain the apparent excitability and agitation of fish held in the Aquifer system. Another possibility is the higher total hardness in the Aquifer treatment water; however, this is unlikely to have affected the fish given seawater has a total hardness of approximately 6630 ppm. Therefore, modification of the Aquifer salt composition to add trace minerals may be necessary to improve biological filtration.

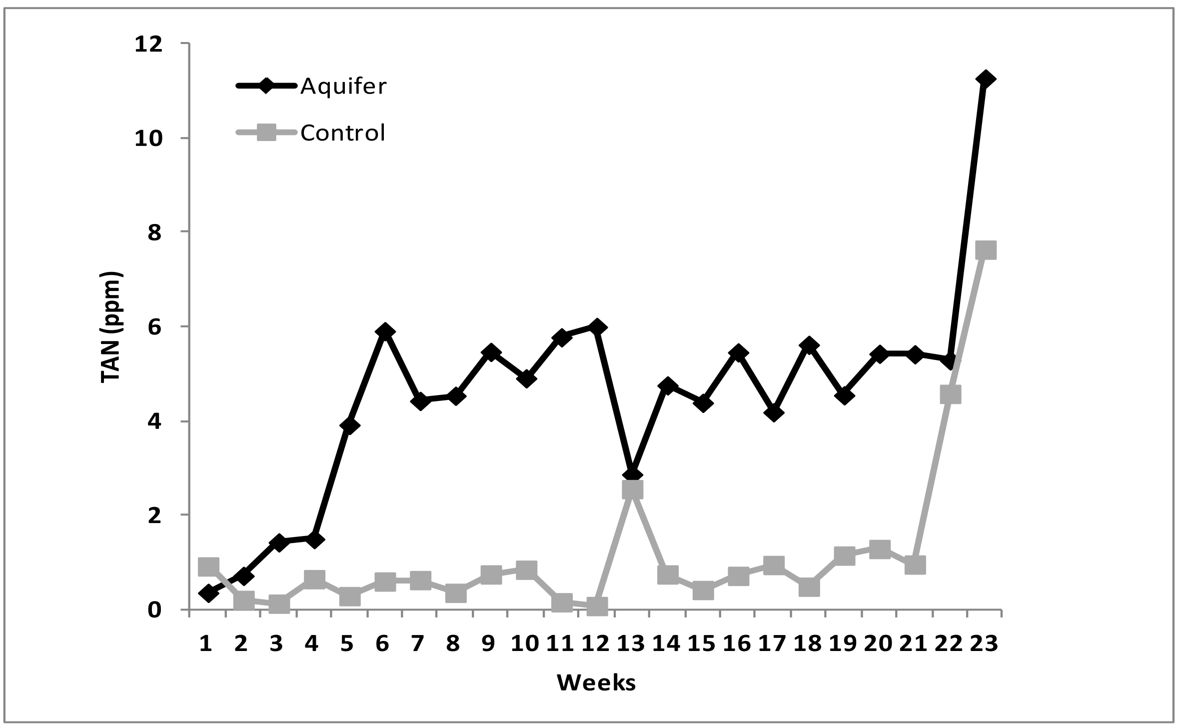


Figure 3.5: Weekly total ammonia nitrogen (TAN) over 23 weeks. (Note: Water quality was not measured in week 24)

Conclusion

Overall, there were no negative effects on fish growth performance, with weight gain, feed efficiency, and proximate carcass composition being similar between treatments. These results indicate that the major constituents of regional saline water aquifers are acceptable for the production of striped bass during the early growth phase, and suggest suitability for the culture of other euryhaline or saline fishes.

Chapter 4

Inland Saline Aquaculture: Environmental & Economic Considerations

S. Ganguly/ N. Rajagopalan

In this chapter, we discuss answers to the following questions:

- *Does the availability of saltwater confer a competitive advantage in marine aquaculture?*

- *How high are the economic barriers associated with the costs of disposal of saline effluent from marine aquaculture in an inland location such as Illinois?*

To answer these questions within the scope of this proposal, we assumed that recirculating aquaculture systems (RAS) will be used for fish rearing. We also relied on the literature to estimate effluent volumes and disposal costs based on reported marine aquaculture wastewater treatment methods.

<u>The Case for Recirculating Aquaculture Systems (RAS)</u>

Aquaculture has emerged as a means to meet the growing demand for marine fish amidst the decreased harvest from oceans. Presently, marine aquaculture facilities are located primarily in coastal areas in semi-open systems that are linked to the ocean. This practice can lead to problems such as discharge of nutrients and waste that adversely affect the environment and endangerment of wild stock due to transfer of diseases[10].

An alternative is the use of land-based marine recirculating aquaculture systems (RASs) that intensively culture fish. The primary advantages of RASs are:

- Improvement in growth: The culture conditions in a RAS are typically optimal for the fish and this enhances feeding efficiency and growth[15].
- Reduction in risk of disease outbreaks: Recirculating systems typically employ disinfection in the water treatment process, and, thus, reduce disease in the cultured fish.
- Reduction in water usage: RAS systems use less water compared to the more conventional approaches for rearing fish. The estimated water use for various freshwater fish production systems show decreases of more than two orders of magnitude with the use of RAS systems (Table 4.1)[2]. It has been reported that water use can be as low as 16 L/kg of fish produced in a state-of-the-art marine RAS[22].
- Improved treatment of effluent: It is generally more efficient to treat a concentrated, low-volume waste stream relative to a dilute, high- volume waste[13,15,18]. In RAS systems (Table 4.1) the effluent volume is greatly reduced but has higher nutrient concentrations potentially lowering treatment costs.
- Utilization of unsuitable land: RASs are appropriate for locations where land is unsuitable for other types of production. Examples of locations include post-mining land[16], urban areas[27], and arid regions [21].

These advantages coupled with the compatibility of RAS systems with the growing emphasis on locally grown foods bode well for the increase in RAS type systems for aquaculture.

Table 4.1: Estimates of water use[2] and hypothetical effluent concentrations for different types of culture systems[20] assuming no effluent treatment.

System Type	Water Use	Calculated Effluent Concentration[a]		
	L/kg fish	mg N/L	mg P/L	mg TSS/L
Cold Water Fish				
Single Pass	375,000	0.2	0.02	1.3
Serial Reuse	88,000	0.7	0.08	5.7
Partial Reuse	10,500	5.7	0.67	48
RAS	3,300	18	2.1	152
Warm Water Fish				
Serial Reuse	33,000	2.4	0.8	42
Ponds	1,800	44	15	780
Recirculating through wetland	3,600	22	7.8	390
RAS	105	760	27	13,000

[a] Effluent concentrations are calculated based on the assumption that no treatment takes place within the system. Feed conversion ratios for cold and warm water fish are 1.0 and 2.0 respectively.

However, RAS systems are not without disadvantages. RAS systems have high costs of capital investment, and labor. They are also more energy intensive due to requirements for aeration and water treatment. These factors necessitate a close look at the economic viability of RAS systems for fish rearing.

RAS operations achieve economic viability by either having large operations or through niche production of high value products. For example, an economic analysis of a commercially operating RAS with a 20-tonne/year production highlighted that even over a 10-year period the cumulative cash flow would be negative[4]. In the same study, hypothetical models for 50-tonne/year and 100-tonne/year RASs indicated that only the 100-tonne/year fish culture system would have positive cash flow and be economically viable.

Small-scale operations become economically viable by culturing appropriate fish species with high market value and through reducing their operating costs. Recent studies evaluating the feasibility of rearing three species (Pompano, Flounder, Hybrid Striped Bass) using saline ground water concluded that (a) hybrid striped bass was the most adaptable at the locations studied and (b) economic feasibility was constrained by market price for the product[1,7]. For example, the study concluded that market price has to exceed $4/pound for hybrid striped bass production to be viable for a 87,750 lbs/year facility.

In light of the above, it is clear the economic viability of marine aquaculture will be highly sensitive to location, cultured species, scale, and market conditions. Of special relevance to this project are costs imposed by the requirements for saltwater and the responsible management of saline effluent in an inland location. In the following sections, the technical aspects of wastewater treatment in a typical or baseline RAS are presented as background, followed by a discussion of alternative designs to answer the questions related to economic impacts of saline water availability and wastewater disposal.

Layout of a Marine Recirculating Aquaculture System

A marine recirculating aquaculture system (RAS) is a closed fish rearing system. Fish rearing introduces a number of contaminants into the water. These include excreted ammonia, carbon dioxide and fecal matter by fish; suspended matter due to uneaten feed and bacterial slough-offs; and a range of inorganic and organic matter resulting from bacterial action. The contaminants have to be removed or rendered into less toxic forms to allow for successful RAS operation. Some constituents such as oxygen have to be introduced as they are depleted due to fish and bacterial respiration.

The operations used in a typical RAS to control water quality are shown in Figure 4.1. The primary unit processes are: clarification or sedimentation; nitrification or biofiltration; carbon dioxide (CO_2) stripping; aeration or oxygenation; and disinfection. The clarification process removes suspended solids using settling basins and/or microscreen filters. The biofiltration process utilizes bacteria to convert ammonia into nitrate (nitrate is less toxic to fish) and to mineralize organic matter[3,5]. This process is followed by CO_2 stripping and oxygenation. A final disinfection process is sometimes employed to remove any disease-causing microorganisms.

In spite of the above treatment processes, contaminants such as nitrate build-up in the system and do have to be controlled. The most common way – the *baseline* scenario – is to replace a portion of the water (typically less than 10% of the system volume on a daily basis) with fresh water. The estimation of the makeup water requirement, wastewater generation, and sludge production is dealt with in the next section.

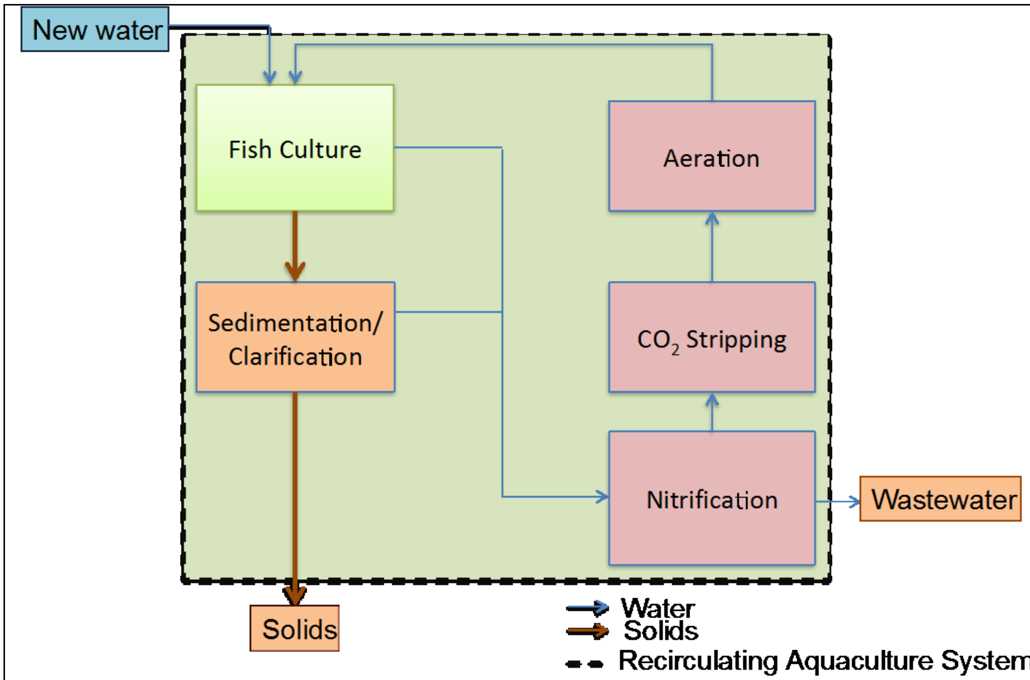


Figure 4.1. Unit processes of a *baseline* or typical recirculating aquaculture system

Mass Balance-based Design of a Nitrification-based Recirculating Aquaculture System – Baseline Scenario

This section deals with estimation of the volume of required makeup water and quantity of wastewater and solid waste discharge from a RAS.

The steps involved in the engineering design and operation of a nitrification-based *baseline* RAS follow from Timmons and Ebeling[24], Timmons and Losordo[23], and Losordo and Hobbs [14]. The supplementary sheet titled "Design Sheet" has the assumptions and calculations used in the engineering design. The "Design Sheet" provides the details of a *baseline* RAS, while the primary steps and important formulae of the engineering design are outlined here:

- Set the annual harvest of fish (lbs/year).
- Set the target level for water quality parameters in the culture tank.
- Compile data on feed composition, feed conversion ratio, and growth characteristics of the fish.
- Assume size of fish bought from outside nursery. Divide operation into three stages: juvenile, fingerling, and growout.
- Calculate growth cycle and growth stages of fish from juvenile to final growout. Determine stocking density, fish biomass, and feed requirements based on final week of growth in each stage. Determine tank sizing.

The growth of the fish is determined by a temperature unit approach, and formulae are provided here.

$$Growth\ (\frac{\text{cm}}{\text{month}}) = \frac{T - T_{base}}{TU_{base}}$$

Where: T = water rearing temperature,

T_{base}= lower temperature where fish growth is achieved, and

TU_{base} = monthly temperature units needed for 1 unit of growth

The length and weight of fish are related by a term called the condition factor (CF or K), and is given by:

$$Weight\ (g) = \frac{K\ (L_{cm})^3}{10^2}$$

Where: L_{cm} = length of fish (cm), and K = condition factor

Stocking density is the mass of fish that can be supported by the fish tank.

$$D_{density} = \frac{L}{C_{density}}$$

Where: $D_{density}$ = mass of fish stocked per unit volume (kg/m^3),

L = length of fish, and

$C_{density}$ = 0.45 (for hybrid striped bass)

- The number of fish, fish species, and their feeding rates determine the water flow and treatment requirements of the RAS. Assume efficiencies of operation for the solids removal and water treatment unit processes: sedimentation or clarification, nitrification, oxygenation and carbon dioxide stripping.

For each stage of fish growth, the depletion rates of dissolved oxygen, and the production rate of total ammonia nitrogen, suspended solids and carbon dioxide in the culture tank is calculated. Calculations involved in estimating the above rates for each stage of growth are provided in the supplementary sheets titled: “Juvenile Tanks”, “Fingerling Tanks”, and “Growout Tanks”, respectively. With reference to each of the three sheets, the inputs and outputs are as follows:

- Inputs to the treatment unit are the daily feed rate in the final tank of a stage, the treatment efficiency of the unit, and the required water quality parameters of the fish.

- Depletion/Production terms in the fish tank for oxygen, ammonia, CO_2, and suspended solids are given by the following:

P_{O2} = - 0.5 kg/kg feed consumed by the fish (negative because O_2 is consumed in tank)

P_{CO2} = 1.375 kg/kg of O_2 consumed

P_{TAN} = F x PC x 0.092 kg/day where F is daily feed rate kg/day, and PC is protein content of feed (%); TAN is total ammonia nitrogen

P_{solids} = 0.25 kg/ kg of feed (typically solids production is between 0.2-0.4 kg/kg of feed)

- For each treatment unit, the feasibility of maintaining the parameters within target levels using conventional treatment techniques such as aeration, or stripping is checked. For the cases examined here, all parameters could be maintained by internal treatment processes except for nitrate removal. Water exchange was required to maintain the target NO_3-N level at 100 mg/L. The solids produced were assumed to be separated and discharged as sludge at 3% concentration.
- Outputs of each stage of growth are the water exchange rate, the quantity of solids and sludge production volumes, and the requirement for new water. The last is assumed the same as the water exchange rate.

The cultured fish is hybrid striped bass, and the design of the system is as shown in the "Design Sheet". The RAS engineering design uses an example of a facility with an annual fish production of 100,000 lbs, growing juvenile fish from an initial size of 50g to market size of 750g.Table 4.2 provides the weight (and length) in the *final* week of growth in each stage, the corresponding fish biomass, stocking density, and daily feed requirement. It also provides an estimate of the required tank volume.

The sheets titled, "Juvenile Tank," "Fingerling Tank," and "Growout Tank." provide required makeup water volumes, effluent volumes, quantity of solids produced and sludge volumes produced. The "Summary" sheet puts together the design of the complete system; determines the overall requirement for makeup water; and calculates the discharge volumes of solids and effluent, as provided in Table 4.3. Note that the wastewater discharge volume is the *same* as the new water requirement of the system and is represented in daily values. As provided in Table 4.3, the makeup water and wastewater discharge estimates from the designed baseline RAS is around 41% of the system volume because it is based on the requirements of fish during the final week of growth in each of the growth stages. However, in a typical RAS, the makeup water exchange is at 10% of the system volume. Thus, for a more conventional estimate, Table 4.3 also provides make-up water requirement and wastewater discharge volumes at 10% exchange rate.

Table 4.2: Growth of fish, and required feed rate and tank volume in the *final* tank of each stage of the growth cycle.						
Stage	Initial	Final	Final Biomass	Stocking density	Feed rate	Tank Volume
	weight g (length cm)[a]	weight g (length cm)[a]	kg/tank	kg/m^3	kg/day-tank	m^3 (gal)
Juvenile	50.0 (13.6)	165.0 (20.2)	192	45	5.5	4.3 (1,129.4)
Fingerling	164.9 (20.2)	386.6 (26.9)	451	60	9.7	7.5 (1,992.6)
Growout	386.6 (26.9)	750.0 (33.5)	874	75	15.1	11.7 (3,099.3)

Table 4.3: Daily requirements for makeup water; the wastewater discharge of the RAS under two circumstances based on *final* week of fish growth at each stage: (1) at 41% exchange rate of water and (2) assuming 10% water exchange rate. The amount of sludge generated in the fish tank is based on final week of fish growth at each stage.								
	Juvenile		Fingerling		Growout		Total	
RAS parameter	10% xchg	41% xchg	10% xchg	41% xchg	10% xchg	41% xchg	10% xchg	41% xchg
Make-up[a,b] water (gal/day)	1,016	4,215	1,793	7,447	2,789	11,593	5,599	23,255
Wastewater discharge[c] (gal/day)	1,016	4,215	1,793	7,447	2,789	11,593	5,599	23,255
Sludge production rate (kg/day)	12		22		34		68	
Sludge volume at 3% solids (gal/day)	109		193		300		602	

[a] In the designed RAS, the water exchange (xchg) is about 41% of the system volume because all the calculations for water replacement rate are based on the requirements of the final week/tank in each stage of growth. This approach provides a margin of safety.

[b] In a typical RAS design, the makeup water exchange is at 10% of the system volume. So, makeup water and discharge volumes of water are assumed here as 10% of system volume. We also assume that the nitrate-N concentration of 100 mg/l is still attainable for a conservative estimate.

[c] The wastewater discharged from the system has to be replaced by saline makeup water, and hence the volume of makeup water is same as the wastewater discharge.

Disposal/Treatment of Saline Wastewater and Solids from a Land-based Marine Recirculating Aquaculture System

In a coastal cage culture system, the effluents are discharged into the ocean. With increasing culture intensity, it is becoming an environmentally unsustainable practice. In freshwater aquaculture systems, treated wastewater is discharged directly into the sewer, while the waste solids are stabilized and thickened prior to land application. However, saline wastewater and solids from land-based RAS would need much more careful management before disposal. The effluent volumes estimated in Table 4.3 need to be treated before discharge. Some methods applicable for the disposal of waste are shown in Figure 4.2.

These methods include:

1. Subsurface saltwater injection wells

2. Lagoons or waste stabilization ponds

3. Geotextile bags

Alternatively, the wastewater can be further treated to remove contaminants and reused within the RAS. Two options receiving attention are:

4. Denitrification using a carbon source

5. Integrated or polytrophic recirculating aquaculture system

Advantages of further treatment are an improvement in the sustainability of the operation, possibility of additional revenue generation in the form of other saleable products, and a reduction in wastewater volume. Detractors include additional operational complexity and higher financial outlays to name a few.

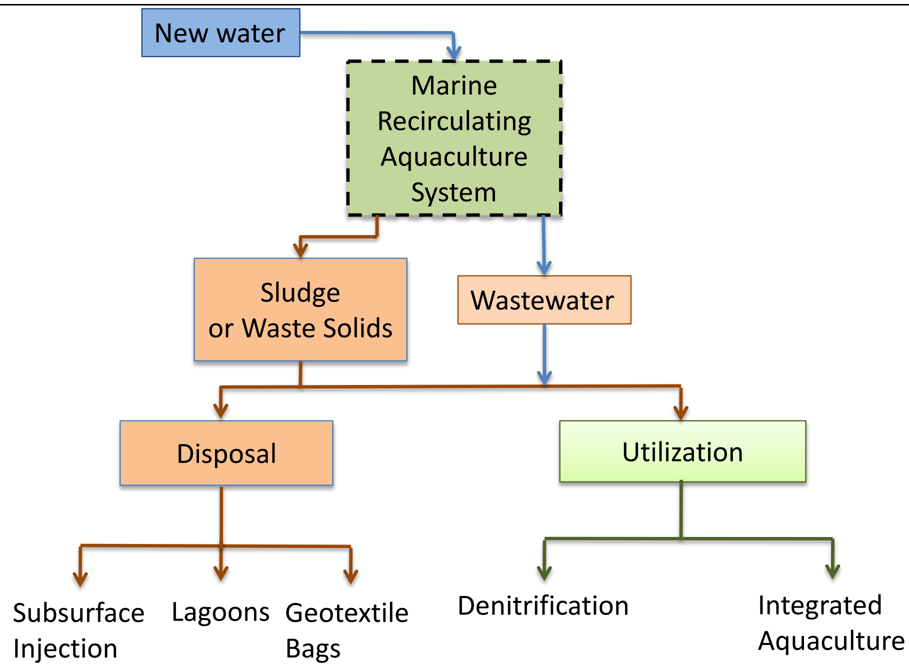


Figure 4.2: Methods to utilize or dispose wastewater and waste solids from a saltwater RAS

1. Subsurface Saltwater Injection Wells

Illinois has several saltwater injection wells where saline wastewater and solids from a land-based marine RAS can be transported to for disposal[6]. Such an operation will involve storage of wastewater and solids, followed by transportation and subsurface injection. In Illinois, subsurface injection is one of the cheaper disposal options, at about \$0.02/gal[11]. It can become a significant operating cost as the RAS operation intensifies, and larger volumes of wastewater and solids need disposal. The economic implication of using subsurface injection is discussed in the section on "Economic Feasibility of Land-based Marine RAS in Illinois."

2. Lagoons or Waste Stabilization Ponds

Aquaculture wastewater and solids are sometimes treated in lagoons or waste stabilization ponds (WSPs) that are specifically built to hold saline water. Use of WSPs is preferred when land is available at a reasonable cost. However, the stabilization of fish waste in open ponds can create odor problems, and over time solids accumulation may lead to loss in efficiency of the treatment. In cold climates, it is not possible to use WSPs during the winter months when the land is frozen. During this period, the storage of fish waste in tanks for later disposal can lead to high costs. According to reports[25,26], the cost of building fish waste storage facilities in Michigan ranged from \$79-\$132/m^3 (\$0.3-\$0.5/gal) of fish waste, as compared to subsurface injection that costs between \$13-\$19/m^3 (\$0.05-\$0.07/gal). As mentioned earlier, the cost of subsurface injection in

Illinois is about \$0.02/gal[11]. Hence, for cold climates it is more economical to do subsurface injection, instead of using WSPs.

3.Geotextile Bags

This is a more recent solids management method. It uses porous textile bags for storing and dewatering the solid waste stream from aquaculture facilities. Sometimes, flocculating or coagulating agents are utilized to aid the solids/liquid separation. In the context of waste from marine RAS, the thickened saline solids left in the geotextile bag will need to be disposed by subsurface injection or sent to the landfill. The saline wastewater leaches through the geotextile bags onto the gravel beds on which the bags are placed. The saline wastewater is recaptured, treated and reused.

4. Denitrification Using Exogenous or Endogenous Carbon Source

In a typical RAS, nitrate (NO_3) is the end product of the nitrification step. Nitrate concentrations in recirculating systems have been reported to reach 400-500 mg NO_3-N/L[8]. However, as exposure to nitrate levels as low as 200 mg NO_3-N/L have been found to negatively affect the immune system of hybrid striped bass[9], the nitrate is controlled through water exchange. The nitrate discharge causes eutrophication and algal blooms in receiving waters. In the USA, the U.S. Environmental Protection Agency (EPA) has placed nitrate and nitrite control on the priority list and reducing their concentration before discharge may be mandatory for recirculating systems.

The biological removal of nitrate and nitrite from wastewater can be achieved by denitrification. In denitrification, the bacteria reduce nitrate (NO_3^-) and nitrite (NO_2^-) to nitrogen gas (N_2). Denitrification is an anaerobic process, and works ideally in high nitrate and low oxygen conditions. It requires the availability of an organic carbon source to fuel the bacterial reduction process. The organic carbon source can be external to the recirculating system (exogenous). Typical carbon compounds used are methanol, acetate, ethanol, or glucose[12]. The organic carbon source can also be from the recirculating system (endogenous) as in the use of sludge or solid waste from the fish culture tank of the RAS. As shown in Figure 4.3, exogenous or endogenous denitrification coupled with the nitrification process allows recycle of most of the RAS wastewater to the culture tank. Both exogenous and endogenous types of denitrification were considered as improvements to the baseline RAS in order to reduce wastewater and solids discharge.

Exogenous Denitrification Design

The design of a denitrification unit was developed based on the total NO_3-N produced in the nitrification unit of the RAS. It was assumed that all of the ammonia-N from the fish tank was converted to NO_3-N in the nitrification unit, and its daily production rate for the designed RAS was 8,802 g NO_3-N/day. In the improved RAS design, denitrification is first considered using an exogenous organic carbon source. The exogenous denitrification design is developed in the "Denitrification" sheet, and results are provided in Table 4.4. Acetate is used as the exogenous organic carbon source, and the acetate consumption rate per unit of NO_3-N converted to N_2 gas was taken as 3.72 g COD/NO_3-N [24]. The addition of an acetate-based denitrification unit increases the sludge production to 655 gal/day relative to sludge production in the baseline RAS system of 602 gal/day. This increase is due to the additional sludge produced from the anaerobic growth of microorganisms that drive the denitrification process (converting NO_3 to N_2).

Endogenous Denitrification Design

In the second design of the denitrification system, an endogenous system design is developed and the details are found in the supplementary sheet titled, "Denitrification". The results from endogenous denitrification are provided in Table 4.4. The sludge from the fish tank is utilized to fuel the endogenous denitrification process and leads to reduction in overall generation of sludge. The endogenous denitrification system assumes the consumption rate of waste solids from the fish tank to be 5.7 g COD/NO_3-N[24]. Endogenously driven denitrification utilizing sludge from the fish tank lowers the overall sludge discharged from the system relative to the baseline and exogenous denitrification systems. The residual sludge in the denitrification unit depends on the extent of anaerobic digestion. The rate of sludge formation by heterotrophic denitrifying bacteria is typically 0.75 g VSS/g NO_3-N removed in the denitrification process[20]. The wastewater recycle from denitrification is based on results from a recent study of a land-based marine RAS using denitrification with waste solids. That study indicated that 1% of the system water was lost and needed replacement[22]. Therefore, in the designed denitrification system, 99% of the system water was assumed to be treated and recycled in the system based on results from Tal et al.[22].

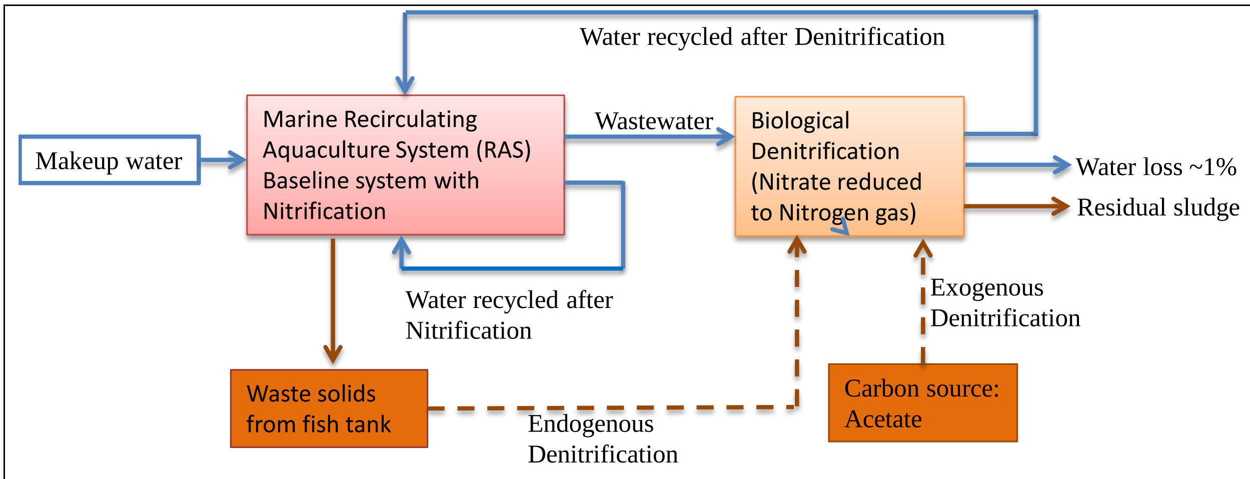


Figure 4.3: Recycling of wastewater from RAS by denitrification (exogenous or endogenous)

Table 4.4: Wastewater discharge volumes and sludge utilization in denitrification.				
Type of Treatment	Organic Carbon utilized in Denitrification (kg/day)	Sludge generated in Denitrification (gal/day)	Sludge discharged from RAS[a] (gal/day)	Wastewater discharged from RAS[b] (gal/day)
Baseline RAS (Nitrification only)	NA	NA	602[c]	23,255
Exogenous Denitrification with Acetate	31	53	655[d]	560[e]
Endogenous Denitrification with Waste Solids	33.5	58	365[f]	560[e]

[a] Sludge from nitrification unit is not included because it is the same in all treatment scenarios: baseline, exogenous and endogenous denitrification-based RAS design.
[b] Water utilized for removal of sludge from the RAS is not included.
[c] Sludge volume generated from the fish culture tank alone.
[d] Sludge volume increases in an exogenous denitrification system due to solids from the growth of denitrifying bacteria that drive the NO_3 removal process.
[e] Approximately 99% of the wastewater from a baseline system is assumed recirculated after denitrification. One percent of system volume (56,000 gal) is assumed lost due to evaporation and handling[22].
[f] In the designed endogenous denitrification system, the sludge formation is based on rate of denitrification of the heterotrophic bacteria with a solids retention time of 5 days, and the sludge formation rate is typically 0.75 g VSS/g NO_3-N removed by denitrifying bacteria[20].

In addition to the environmental benefits that come with recycling water and utilizing waste solids as in the denitrification process, it is important to understand the economic feasibility of treating the wastewater and solids in a land-based saltwater RAS. This is discussed in a later section entitled, "Economic Feasibility of Land-based Marine Recirculating Aquaculture System."

5. Integrated or Polytrophic Recirculating Aquaculture System

Integrated aquaculture system designs are focused on minimizing the environmental and economic impacts of intensive land-based marine RAS[10,11]. An integrated or polytrophic aquaculture system utilizes species from differing trophic levels to form an interdependent system that maximizes resource utilization; minimizes environmental impacts; and potentially improves the economics of the whole system. An integrated aquaculture system typically consists of finfish that sit atop the food chain. They are followed by one or more species that grow by extracting dissolved nutrients and organic carbon from the wastewater arising from finfish rearing and one or more species that utilize the solid waste. The organisms that grow on the waste stream are known as extractive organisms and could provide economic benefit in addition to wastewater or solids treatment. Microalgae and seaweed are examples of extractive organisms that are suitable for wastewater. Invertebrates such as crustaceans or marine worms can utilize solid waste.

Economic Feasibility of a Land-Based Marine Recirculating Aquaculture System

The economic implications of operating a recirculating aquaculture system (RAS) were compared using four cost scenarios relevant for land-based marine or saltwater systems. The details of the cost scenarios are provided in the supplementary sheet titled, “Summary.” As mentioned in the engineering design section, the volumes of makeup water requirement and wastewater discharge were per the final week of fish growth at each stage of its growth cycle and exchange rate was about 41% of the system volume. However, if all weeks of the fish growth cycle are considered in the design, then the water exchange rate of the RAS will be significantly lower. Typical water exchange rate of an RAS is about 10%. So, the costs associated with makeup water requirement and discharge of wastewater were estimated for both the 10% exchange and the 41% exchange rates.

In all of the *four cost analysis scenarios*, the residual wastewater and solids are assumed to be disposed using subsurface injection. In Illinois, subsurface injection is possibly the cheapest disposal option for every unit volume of waste, and is about $0.02/gal[11]. The four cost scenarios that are described here are based on results of the RAS design and estimates provided in Table 4.5. The water exchange rate determined the requirement for saline makeup water as well as wastewater discharge volume. The saline solids and wastewater were assumed to be disposed on-site by subsurface injection in a saltwater well. Hence, transportation costs were not included. In all scenarios the cost incurred for the disposal of solids from the nitrification unit was not included because it would be similar in every case. The water utilized in backwashing was also not included in calculating the water requirement of the designed RAS.

Cost Scenario 1: Baseline – The first cost scenario, known as baseline, considered a typical RAS consisting of all the unit processes of sedimentation/clarification, nitrification, carbon dioxide stripping, and oxygenation. Saline water at 1% salinity was considered to be synthetically produced by mixing mineral sea salt with municipal water. The cost of the synthetic saltwater was estimated to be $0.1/gallon.

Cost Scenario 2: Saline Groundwater – This scenario considered the use of saline water from a saline aquifer/other source (at $2/1000 gallons), instead of using synthetic saltwater as was done for the baseline scenario. As in the baseline, the saline aquifer water was diluted by municipal water to attain a salinity of 1%. The unit processes were the same as the baseline, and onsite subsurface injection was assumed for disposal of the wastewater and solids.

Cost Scenario 3: Denitrification using External Carbon Source (Exogenous) – In this scenario, denitrification of all of the effluent water from the nitrification unit was considered in addition to the unit processes of a typical or baseline RAS. The water source was 1% saline water obtained by mixing saline aquifer water with municipal water. Acetate was chosen as the carbon source for the exogenous design of the denitrification unit. The cost of using acetate is about $1.10/kg. The requirement of makeup water was based on experimental results of denitrification-based closed recirculating systems where about 99% of the system water has been reported recycled to the culture tank[18,22]. The 1% loss in system water was due to evaporation and handling of fish[22]. The waste solids were assumed to be disposed by onsite subsurface injection.

Cost Scenario 4: Denitrification using RAS Waste Solids (Endogenous) –In this scenario, the effluent from the nitrification unit was denitrified as in cost scenario 3 and 99% of the wastewater in the RAS was assumed recycled to the culture tank[22,17]. The water source was 1% saline water obtained by mixing saline aquifer water with municipal water. However, the denitrification process was endogenous because the waste solids from the fish tank were used as the carbon source in the denitrification process. The anaerobic denitrifying bacteria utilized the solids from the fish tank, and their growth produced a relatively small amount of sludge in the denitrification unit. The primary cost benefit comes from denitrifying the effluent water (from the fish tank) and recycling it back to the fish tank, reducing the need for new water. In addition, endogenous denitrification decreased the sludge disposal volumes.

Table 4.5: Cost estimates utilized in the four cost analysis scenarios.

Estimate	Cost	Units
Municipal water/Saline aquifer water	0.002	$/gallon
Make-up synthetic saltwater (salt and municipal water) at 1% salinity	0.106	$/gallon
Subsurface Injection	0.024	$/gallon
Fish Feed	2.20	$/kg
Sodium Acetate (carbon source)	1.10	$/kg

Evaluation of Cost Scenarios

The results of the four cost scenarios – baseline, saline groundwater, denitrification using acetate, and denitrification using RAS waste solids are presented in Table 4.6. As mentioned in the previous section, all four cost scenarios considered two water exchange design rates: one based on final week of fish growth at each stage of its rearing cycle, and a second one based on the 10% exchange system exchange rate that is more typical. The two water exchange rates impact denitrification due to varying volumes of water requiring treatment. Therefore, the acetate requirement and the sludge production in the exogenous denitrification scenario are both lower for the 10% exchange rate. Similarly, the requirement for sludge to drive denitrification in the endogenous case was lower for the 10% exchange rate compared to the 41% exchange rate.

Table 4.6: Costs of makeup water and disposal of wastewater and solids under two circumstances: (1) based on *final* week of growth of fish at each stage at 41% exchange and, (2) based on 10% system water exchange rate.

Cost Scenario	Primary Water Treatment Process	Cost of Makeup Saline Water[a] ($/year)		Cost of Wastewater Disposal ($/year)		Cost of Solids Disposal[b] ($/year)	
		10%	41%	10%	41%	10%	41%
Baseline	Nitrification	216,975	901,168	48,660	202,101	5,230[c]	5,230[c]
Saline Aquifer water	Nitrification	4,087	16,976	48,660	202,101	5,230[c]	5,230[c]
Denitrification: exogenous	Nitrification & Denitrification with Acetate	409[d]	409[d]	0[d]	0[d]	8,344[e]	18,164[e]
Denitrification: endogenous	Nitrification & Denitrification with waste solids	409[d]	409[d]	0[d]	0[d]	4,736[f]	3,176[f]

[a]Water utilized for removal of waste solids from the fish tank and denitrification system is not included because saline make-up water is not required for its removal.
[b] Sludge from nitrification unit is not included because it is the same across scenarios.
[c] Sludge volume generated from the fish culture tank alone.
[d] Approximately 99% of the wastewater from a baseline system is assumed recirculated after denitrification. 1% loss attributed to evaporation and handling[22].
[e] Sludge increases in an exogenous denitrification system due to denitrifying bacterial growth. Cost also includes the use of acetate for exogenous denitrification.
[f] Sludge from fish tank is utilized to fuel the endogenous denitrification process, and leads to reduction in overall sludge that needs to be managed and disposed.

For the 10% system water exchange rate, the annual cost of saline makeup water in the baseline scenario is about 53 times the cost in comparison to the saline groundwater scenario. The annual cost of wastewater disposal under this scenario is estimated to be $48,660 assuming subsurface injection. The costs of solids disposal for the baseline and saline aquifer systems will be similar. Adding the denitrification unit to the water treatment loop will remove the nitrates from the water, and result in recycling about 99% of the system volume[22]. The 1% loss in water is due to evaporation and handling. This means that almost all of the wastewater that was being disposed in the baseline RAS could instead be denitrified and recycled to the fish culture tank. In both exogenous and endogenous denitrification scenarios (as illustrated in Figure 4.3), the 1% makeup water is made up of saline aquifer and municipal water costing $409/year, while the wastewater disposal cost is zero. Using acetate as the carbon source in exogenous denitrification leads to an annual cost (including acetate purchase and sludge disposal) of about $8,344. In the final cost scenario, endogenous denitrification is carried out by using waste solids from the fish tank. There is no additional cost for purchase of an organic carbon source for denitrification, and the overall sludge discharged from the RAS is also reduced. The sludge-based denitrification lowers the annual waste disposal cost to $4,736 (for the 10% water exchange rate). This is higher than the cost with 41% exchange rate primarily due to differences in volume of water treated. A side-by-side comparison of the all the cost scenarios is provided in Figure 4.4. The cost scenarios reveal that the use of saline aquifer water and sludge-based denitrification substantially decreases the makeup water cost and significantly reduces the solids disposal cost.

Baseline	Saline Groundwater(GW)	Exogenous Denitrification (Acetate)	Endogenous Denitrification (Sludge)
Makeup water: Saltwater Disposal of wastewater and solids by subsurface injection	Makeup water: Saline aquifer GW diluted with municipal water Disposal of wastewater and solids by subsurface injection	Makeup water: Saline aquifer GW diluted with municipal water Recycled water: 99% after denitrification Disposal of solids only by subsurface injection	Makeup water: Saline aquifer GW diluted with municipal water Recycled water: 99% after denitrification Disposal of solids only by subsurface injection
Saline water: $216,975 WW disposal: $48,660 Solids disposal: $5,230 Cost avoidance: $0	Saline water: $4,087 WW disposal: $48,660 Solids disposal: $5,230 Cost avoidance: $212,888	Saline water: $409 WW disposal: $0 Solids disposal: $8,344 Cost avoidance: $262,112	Saline water: $409 WW disposal: $0 Solids disposal: $4,736 Cost avoidance: $265,721

Figure 4.4: Comparison of the annual cost of wastewater and solids disposal, and saline make-up water in a RAS with 10% water exchange rate. The annual costs avoided are in comparison to the baseline cost scenario

Conclusions

The questions we sought to answer in this chapter were:

- Does the availability of saltwater confer a competitive advantage in marine aquaculture?

Yes. The cost of saltwater in a typical or baseline RAS is significant and savings from utilization of saline aquifer water provides a material economic advantage. The composition of the saline aquifer water needs to be carefully determined in order to ascertain the level of pretreatment it may require before use in a marine land-based RAS.

- How high are the economic barriers associated with the costs of disposal of saline effluent from marine aquaculture in an inland location such as Illinois?

Figure 4.4 summarizes the estimated costs under various scenarios. It is emphasized that these are estimated costs and would need validation in practice. Interpreting the numbers in Table 4.6 with the above caveats, it appears that intensive treatment using both exogenous and endogenous denitrification would be advantageous to significantly lower the barriers of saline water disposal costs.

References

1. Brown B. 2007. "Evaluation of three fish species for culture using low salinity groundwater in the black belt region of Alabama". MS Thesis, Dept. of Fisheries and Allied Aquacultures, Auburn University http://etd.auburn.edu/etd/bitstream/handle/10415/169/Brown_Benjamin_56.pdf?sequence=1.
2. Chen S, Summerfelt S, Losordo T, Malone R. Recirculating systems, effluents, and treatments. *Aquaculture and the Environment in the United States*. 2002:119-40.
3. Chen S, Ling J, Blancheton J. Nitrification kinetics of biofilm as affected by water quality factors. *Aquaculture Eng.* 2006;34(3):179-97.
4. De Ionno PN, Wines GL, Jones PL, Collins RO. A bioeconomic evaluation of a commercial scale recirculating finfish growout system—An australian perspective. *Aquaculture*. 2006;259(1):315-27.
5. Díaz V, Ibáñez R, Gómez P, Urtiaga AM, Ortiz I. Kinetics of nitrogen compounds in a commercial marine recirculating aquaculture system. *Aquacultuure Engineering.* 2012 9;50(0):20-7.
6. Environmental Protection Agency, Underground injection wells in Region 5. http://www.epa.gov/r5water/uic/r5uicwells.htm
7. Gorman J. Economic feasibilty of utilizing saline groundwater of west Alabama to produce florida pompano in a recirculating aquaculture system. MS Thesis, Dept. of Fisheries and Allied Aquacultures, Auburn University 2009. http://etd.auburn.edu/etd/handle/10415/1692
8. Honda H, Watanabe Y, Kikuchi K, Iwata N, Takeda S, Uemoto H, et al. High density rearing of japanese flounder, paralichthys olivaceus with a closed seawater recirculation system equipped with a denitrification unit. *Suisanzoshoku*. 1993;41.
9. Hrubec TC, Smith SA, Robertson JL. Nitrate toxicity: A potential problem of recirculating systems. *Proceedings from successes and failures in commercial recirculating aquaculture conference*. 1996.
10. Klinger D, Naylor R. Searching for solutions in aquaculture: Charting a sustainable course. *Annual Review of Environment and Resources*. 2012;37:247-76.
11. Knutson C, Dastgheib SA, Yang Y, Ashraf A, Duckworth C, Sinata P, Sugiyono I, Shannon M, Werth CJ. Reuse of produced water from CO_2 enhanced oil recovery, coal-bed methane, and mine pool water by coal-based power plants. *DOE Report*. 2012 http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/pubs/05343FSRFG043012.pdf
12. Labelle M, Juteau P, Jolicoeur M, Villemur R, Parent S, Comeau Y. Seawater denitrification in a closed mesocosm by a submerged moving bed biofilm reactor. *Water Research* 2005;39(14):3409-17.
13. Lemarié G, Martin J, Dutto G, Garidou C. Nitrogenous and phosphorous waste production in a flow-through land-based farm of european seabass (dicentrarchus labrax). *Aquatic Living Resource*. 1998;11(4):247-54.
14. Losordo TM, Hobbs AO. Using computer spreadsheets for water flow and biofilter sizing in recirculating aquaculture production systems. *Aquacultue Engineering.* 2000;23(1):95-102.

15. Martins CIM, Eding EH, Verdegem MCJ, Heinsbroek LTN, Schneider O, Blancheton JP, et al. New developments in recirculating aquaculture systems in europe: A perspective on environmental sustainability. *Aquacult Eng.* 2010 11;43(3):83-93.
16. Miller D. Using aquaculture as a post-mining land use in West Virginia. *Mine Water and the Environment*. 2008;27(2):122-6.
17. NEOMAR, Germany, 2011. http://www.neomar.de/fileadmin/user_upload/Download/neomar_print_english.pdf
18. Piedrahita RH. Reducing the potential environmental impact of tank aquaculture effluents through intensification and recirculation. *Aquaculture*. 2003;226(1):35-44.
19. Riepe JR, Swann L, Brown P. Analyzing the profitability of hybrid striped bass cage culture. Illinois-Indiana Sea Grant Program, *Aqaculture Extension*; 1993.
20. Rittmann BE, McCarty PL. *Environmental Biotechnology: Principles and Applications.* Mc Graw-Hill Book Co.; 2001
21. Singer A, Parnes S, Gross A, Sagi A, Brenner A. A novel approach to denitrification processes in a zero-discharge recirculating system for small-scale urban aquaculture. *Aquaculture Engineering*. 2008;39(2):72-7.
22. Tal Y, Schreier HJ, Sowers KR, Stubblefield JD, Place AR, Zohar Y. Environmentally sustainable land-based marine aquaculture. *Aquaculture*. 2009;286(1):28-35.
23. Timmons MB, Losordo TM. *Aquaculture water reuse systems: Engineering design and management*. Elsevier Science Publishers; 1994.
24. Timmons MB, Ebeling JM, Center NRA. *Recirculating aquaculture*. Cayuga Aqua Ventures Ithaca, NY; 2010.
25. Williams F, Starr C. Evaluation of a filter press system to reduce moisture content of fish production wastes. *USDA SBIR report*. Bay Port Aquaculture Systems Inc.,West Olive, Michigan. 1995.
26. Williams F, Starr C. Evaluation of a filter press system to reduce moisture content of fish production wastes. *USDA SBIR report*. Bay Port Aquaculture Systems Inc.,West Olive, Michigan. 1990.
27. Zohar Y, Tal Y, Schreier H, Steven C, Stubblefield J, Place A. Commercially feasible urban recirculating aquaculture: Addressing the marine sector. *Urban Aquaculture*. 2005:159.

Supplementary Information

DESIGN SHEET

Design for Hybrid Striped Bass/Striped Bass Production in a Closed RAS

For Design purposes we assume that the growth characteristics of HSB and SB are similar

(yellow)	User input values	(green)	Output values
(blue)	Assumption	(tan)	Information

Table 1: Water Quality Parameters for Striped bass/Hybrid Striped Bass (Reference 24)

Parameter	Target Value	Units	Comments
Temperature	82.4	^{0} F	
	28.0	^{0} C	
Dissolved Oxygen	5.0	mg/L	DO
Total Ammonia-N	2.0	mg/L TAN	Sum of ionized ammonium and unionized ammonia
Ammonia-N	0.013	mg/L	
Nitrite-N	0.1	mg/L	
Nitrate-N	100.0	mg/L	Range 50-150
TSS	10.0	mg/L	
CO2	20.0	mg/L	
Salinity	10,000	mg/L or ppm	
pH	6.5-9	-	
Alkalinity(as CaCO3)	50-400	mg/L	

Table 2: Engineering Design Data for Hybrid Striped Bass (Reference 1 and 24)

Parameter		Design Value	Units	Comments
Tbase		10	^{0}C	
Tubase		5.47	^{0}C/(month per cm growth)	
Tmax		23.9	^{0}C	
Condition Factor	CF	720	L inch, W lb	
	K	1.99	L cm, W g	
Feed Conversion Ratio (FCR)			kg feed/kg biomass gain	
	juvenile	1.8		Reference 1
	fingerling	1.8		
	growout	1.8		
Density Factor	C	2.8	L inch	
		0.45	L cm	

Table 3: Design Data for Hybrid Stiped Bass Production

Parameter	Value	Units	Comments
Target Production	100,000	lb/yr	
	45,455	kg/yr	1 kg = 2.2 lbs
Fingerling size	50	g	
Market size	750	g	
Production weeks/yr	52		
Fish size classes	3		

Table 4: Growout period

Parameter	Value	Units	Comments
Length of fingerlings	13.6	cm	
Length of adult	33.5	cm	
Total change in length	19.9	cm	
Change in length/size class	6.6	cm	
Growth rate	3.3	cm/month	
	0.1	cm/day	30.5 days/month
Growout period	6.1	months	
Weeks in each size class	9.0	weeks/size class of fish	
Total number of weeks to harvest	27.0		

Table 5: Biomass Stocking Density (Reference 24)

Stage	Initial	Final	Final Biomass	Stocking density
	weight (g)	weight (g)	kg	kg/m^3
	length (cm)	length (cm)		
Juvenile	50.0	165.0	192.3	45.0
	13.6	20.2		
Fingerling	165.0	386.6	450.6	59.7
	20.2	26.9		
Growout	386.6	750.0	874.1	74.5
	26.9	33.5		

Weekly harvest weight	1,923	lbs per week
	874	kgs/week
Number of fish per tank	1,166	fish/tank

Table 6: Production Strategy

Stage	Final tank biomass	Final weight	Final-1 day weight	Weight gain on final day of 1 fish	Final day weight gain of a tank	Final feed rate
	kg	g	g	g	kg	kg feed/day-tank
Juvenile	192.3	165.0	162.4	2.6	3.1	5.5
Fingerling	450.6	386.6	382.0	4.6	5.4	9.7
Growout	874.1	750.0	742.8	7.2	8.4	15.1

Table 7: Tank Sizing

Stage	Final biomass	Stocking density	Tank volume (each)	Tank depth	Tank diameter	No of tanks per stage	Total tank volume
	kg	kg/m^3	m^3	m	m		m^3
Juvenile	192.3	45.0	4.3	1.0	2.3	9.0	38.5
Fingerling	450.6	59.7	7.5	1.2	2.8	9.0	67.9
Growout	874.1	74.5	11.7	1.5	3.2	9.0	105.6

Juvenile Tanks

RAS System with Nitrification Only

Stage Juvenile	Final feeding rate	5.5	kg/day/tank

Depletion or production terms: DO, TAN, CO_2, TSS		
Depletion term P for DO due to final feed rate	2.8	kg O_2/day-tank
	2,752,824.2	mg O_2/day-tank
Production term P for TAN	0.2	kg TAN/day
	177,281.9	mg TAN/day-tank
New water required to maintain nitrate concentration	1,772.8	L/day /tank
Production term P for CO2	3,785,133.3	kg CO_2/day-tank
	3.8	kg CO_2/day-tank
Production term P for waste solids (TSS)	1,376,412.1	mg/day
	1.4	kg/day

Culture System parameters		
No of tanks	9.0	
Tank diameter	2.3	m
Tank depth	1.0	m
Tank volume	1,129.4	gal
System volume	10,164.6	gal

Total Makeup water and solids volume for system (all tanks, assume based on final tank in each stage)		
Makeup water volume	4,215.4	gal/day
Solids production rate	12.4	kg TSS/day
Solids production volume (3% solids)	109.1	gal/day

Fingerling Tank

RAS System with Nitrification Only

Stage	**Fingerling**

Final feeding rate	9.7	kg/day-tank

Depletion or production terms for DO, TAN, CO2, TSS		
Depletion term P for DO due to final feed rate	4.9	kg O_2/day-tank
	4,863,369.5	mg O2/day
Production term P for TAN	0.3	kg TAN/day
	313,201.0	mg TAN/day-tank
New water required to maintain nitrate concentration	3,132.0	L/day-tank
Production term P for CO2	6,687,133.1	kg CO_2/day-tank
	6.7	kg CO_2/day-tank
Production term P for waste solids (TSS)	2,431,684.8	mg/day
	2.4	kg/day

Culture System parameters		
No of tanks	9.0	
Tank diameter	2.8	m
Tank depth	1.2	m
Tank volume	1,992.7	gal
System volume	17,933.9	gal

Total Makeup water and solids volume for system (all tanks, assume based on final tank in each stage)		
Makeup water volume	7,447.3	gal/day
Solids production rate	21.9	kg TSS/day
Solids production volume (3% solids)	192.7	gal/day

Growout Tank

RAS System with Nitrification Only

Stage	**Growout**

Final feeding rate	15.1	kg/day/tank

Depletion or production term for DO, TAN, CO2, TSS		
Depletion term P for DO	7.6	kg O_2/day-tank
	7,570,456.2	mg O_2/day
Production term P for TAN	0.5	kg TAN/day
	487,537.4	mg TAN/day-tank
New water required to maintain nitrate concentration	4,875.4	L/day-tank
Production term P for CO2	10,409,377.3	mg CO_2/day
	10.4	kg CO_2/day
Production term P for waste solids (TSS)	3,785,228.1	mg/day
	3.8	kg/day

Culture System parameters		
No of tanks	9.0	
Tank diameter	3.2	m
Tank depth	1.5	m
Tank volume	3,099.3	gal
System volume	27,893.9	gal

Total Makeup water and solids volume for system (all tanks, assume based on final tank in each stage)		
Makeup water volume	11,592.7	gal/day
Solids production rate	34.1	kg TSS/day
Solids production volume (3% solids)	300.0	gal/day

Denitrification at 10% water exchange

Total effluent volume of fish rearing system	5,599.2	gal/day
Total sludge volume of fish rearing system	601.8	gal/day

Acetate is exogenous carbon source for denitrification

Reference: 20 and 24

Step 1 Calculate the acetate consumption rate		
Acetate consumption rate per unit of N03-N utilized as electron donor	3.7	g COD/g N03-N
Concentration of NO3-N in the WW from Nitrification	100.0	mg NO3-N/L
Consumption of Acetate for removal of NO3-N	372.0	mg COD/L
Concentration of DO in influent to Denitrification reactor	2.0	mg DO/L
Consumption rate of Acetate for removal of DO	1.8	g COD/g O2
Consumption of acetate for removal of DO	3.6	mg COD/L
Total consumption of Acetate	375.6	mg COD/L
Total mass of acetate required for denitrification	7.5	kg Acetate/day

Step 2 Calculate the sludge production rate		
Sludge production rate from heterotrophic denitrifying bacteria using acetate	0.7	g VSS/g NO3-N
Total sludge production from denitrification	1.5	kg VSS/day
% Solids in waste stream removing the sludge	0.03	3% solids assumption
Daily volume of sludge from denitrification	48.4	L/day
	12.8	gal/day
Sludge volume from fish tank	601.8	gal/day
Total sludge volume from entire system	614.6	gal/day

Sludge from fish tank is Endogenous carbon source for Denitrification using Sedimentation Basin

Reference: 20 and 24

Step 1 Calculate the organic sludge consumption rate		
Sludge consumption per unit of N03-N utilized as e- donor	5.7	g COD/g N03-N
Concentration of NO3-N in the WW from Nitrification	100.0	mg NO3-N/L
Consumption of Sludge for removal of NO3-N	0.6	mg COD/L
Total mass of sludge required for denitrification	12.1	kg COD/day

Step 2 Check to ensure sludge from fish tank is more than sludge required for endogenous rxn		
Total mass of sludge produced in fish tanks	68.3	kg/day
Total COD of sludge from fish tank	102.5	kg COD/day
Excess COD available after denitrification	90.4	kg COD/day

Step3 Determine sludge remaining in sedimentation basin		
Sludge production from heterotrophic denitrifying bacteria (Rule of thumb)	0.8	g VSS/g NO3-N removed
Sludge produced by heterotrophic denitrifying bacteria	1.6	kg VSS/day
Residual or Unused sludge from fish tank	90.4	kg COD/day
	60.3	kg sludge/day
Total sludge from denitrification and unused from fish tank	61.9	kg sludge/day
% solids in waste stream removing the sludge	0.03	assumption
Daily volume of sludge from system	2062.5	L/day
	544.9	gal/day

Summary - With 10% Water Exchange in the system

Note: Water exchange rate is 10% of system volume. Sludge production (from fish tank) is based on final tank of each growth stage and is assumed to be same. However, denitrification-based sludge production will vary as per nitrate concentration

Fish biomass, feed rate, and volume using values for final tank of each stage

	Tank biomass	Feed rate	Tank Volume
	kg	kg/day-tank	m^3 or (gal)
Juvenile	192.3	5.5	4.3
			1,129.4
Fingerling	450.6	9.7	7.5
			1,992.7
Growout	874.1	15.1	11.7
			3,099.3
Total	1,517.0	30.4	6,221.4

Total system volume (all tanks; gal)	55,992.4

RAS makeup water and solids volume

Description	Juvenile	Fingerling	Growout	Units
Makeup water volume	1,016	1,793	2,789	gal/day
Sludge production rate	12	22	34	kg TSS/day
Sludge volume (at 3% solids)	109	193	300	gal/day

Total makeup saltwater volume	5,599	gal/day
Total sludge volume	602	gal/day
Total fish feed consumed per day (from baseline design)	273	kg feed/day

Cost Estimate

Municipal water/Saline aquifer water	0.0020	$/gal
Synthetic seawater	0.31	$/gal
Makeup saltwater	0.106	$/gal
Effluent saltwater disposal (Class II injection)	1.00	$/barrel
Salt water sludge disposal (undeground injection)	1.00	$/barrel
Fish feed cost	2.20	$/kg
Sodium acetate as organic carbon source/supplement	1.10	$/kg

Scenario 1

Annual Baseline Cost Scenario with onsite subsurface injection of solids and wastewater

	Juvenile ($/year)	Fingerling ($/year)	Growout ($/year)	Total ($/year)
Makeup saltwater	39,388	69,495	108,091	216,975
Effluent injection	8,833	15,585	24,241	48,660
Sludge injection	948	1,675	2,607	5,230
Total	49,170	86,756	134,940	270,865

Total annual cost of makeup water	$ 216,975
Total annual cost of effluent and sludge disposal	$ 53,890
Total annual cost of fish feed	$ 219,508

Comment: Typically, in a RAS the cost of fish feed is one of the largest operating costs (20-40%)

Scenario 2

Saline Groundwater (GW) Scenario - Ironton Galesville GW+ Municipal Water

Annual operating costs for makeup saltwater, on-site effluent and sludge injection

	Juvenile	Fingerling	Growout	Total ($/year)
Makeup saltwater	742	1,309	2,036	4,087
Effluent injection	8,833	15,585	24,241	48,660
Sludge injection	948	1,675	2,607	5,230
Total	10,524	18,570	28,885	57,978

Total annual cost of makeup water	$ 4,087
Total annual cost of effluent and sludge disposal	$ 53,890
Total annual cost of fish feed	$ 219,508

Cost avoidance from use of saline GW wrt Baseline scenario	**212,888**

Scenario 3	
Exogenous Denitrification using External Carbon Source Scenario (Acetate is used here)	

The effluent water is denitrified using Acetate as carbon source, and recirculated in the fish tanks
The makeup saltwater (at 1% salinity) is constituted from saline GW and municipal water (as in scenario 2)
Assume: 1% of the system volume is lost due to evaporation and handling

Makeup saltwater required to cover for 1% loss of water	559.9	gal/day
Sludge generated from Exogenous Denitrification	12.8	gal/day
Sludge from fish tank	601.8	gal/day
Total volume of sludge from fish tank and denitrification	614.6	gal/day
Total sodium acetate utilized for denitrification	7.5	kg/day

Annual operating costs for acetate denitrification, makeup seawater, on-site effluent and sludge injection	Total ($/yr)
Makeup seawater	409
Effluent injection	0
Sludge injection	5,341
Organic supplement for denitrification	3,003

Annual cost of sludge management (from fish tank and denitrification unit)	$ 8,344
Total annual cost	$ 8,753

Cost avoidance from reuse of saline GW by exogenous denitrification wrt Baseline scenario	**$ 262,112**

Scenario 4
Endogenous Denitrification using waste sludge scenario (from fish tank)

The effluent water is denitrified using the sludge (endogenous carbon source) from fish tanks

The unused sludge remaining in fish tanks, and the sludge produced from denitrification is the total sludge
The makeup saltwater (at 1% salinity) is constituted from saline GW and municipal water (as in scenario 2 and 3)
Assume: 1% of the system volume is lost due to evaporation and handling (Reference 22)

Makeup saltwater required to cover for 1% loss of recycled water	559.9	gal/day
Sludge generated in Endogenous Denitrification	1.6	kg VSS/day
Residual or unused sludge left in fish tank after denitrification	530.9	gal/day
Total volume of sludge from fish tank and denitrification	544.9	gal/day

Annual operating costs for sludge-based denitrification, makeup seawater, on-site effluent and sludge injection	Total ($/yr)
Makeup saltwater	409
Effluent injection	0
Sludge injection	4,736
Organic supplement for sludge-based denitrification	0

Annual cost of sludge management (from fish tank and denitrification unit)	$ 4,736
Total cost	$ 5,144

Cost savings from reuse of saline GW by endogenous denitrification wrt Baseline scenario	**$265,721**

Denitrification with 41% exchange of water

Total effluent volume of fish rearing system	23,255.4	gal/day
Total sludge volume of fish rearing system	601.8	gal/day

Acetate is exogenous carbon source for denitrification

Reference: 20 and 24

Step 1 Calculate the acetate consumption rate		
Acetate consumption rate per unit of N03-N utilized as electron donor	3.7	g COD/g N03-N
Concentration of NO3-N in the WW from Nitrification	100.0	mg NO3-N/L
Consumption of Acetate for removal of NO3-N	372.0	mg COD/L
Concentration of DO in influent to Denitrification reactor	2.0	mg DO/L
Consumption rate of Acetate for removal of DO	1.8	g COD/g O2
Consumption of acetate for removal of DO	3.6	mg COD/L
Total consumption of acetate (in terms of COD)	375.6	mg COD/L
Total mass of acetate required for denitrification	31.0	kg Acetate/day

Step 2 Calculate the sludge production rate		
Sludge production rate from heterotrophic denitrifying	0.7	g VSS/g NO3-N
Total sludge production from denitrification	6.0	kg VSS/day
% solids in waste stream removing the sludge	0.03	3% solids assumption
Daily volume of sludge from denitrification	201.0	L/day
	53.1	gal/day
Sludge volume from fish tank	601.8	gal/day
Total sludge volume from entire system	654.9	gal/day

Sludge from fish tank is endogenous carbon source for Denitrification using Sedimentation Basin

Reference: 20 and 24

Step 1 Calculate the organic sludge consumption rate		
Sludge consumption per unit of N03-N utilized as e- donor	5.7	g COD/g N03-N
Concentration of NO3-N in the WW from Nitrification	100.0	mg NO3-N/L
Consumption of Sludge for removal of NO3-N	0.6	g COD/L
Total mass of sludge required for denitrification	50.2	kg COD/day

Step 2 Check to ensure sludge from fish tank is more than sludge required for endogenous rxn		
Total mass of sludge produced in fish tanks	68.3	kg/day
Total COD of sludge from fish tank	102.5	kg COD/day
Excess COD available after denitrification	52.3	kg COD/day

Step 3 Determine sludge remaining in sedimentation basin		
Sludge production from heterotrophic denitrifying bacteria (Rule of thumb)	0.8	g VSS/g NO3-N removed
Sludge produced by heterotrophic denitrifying bacteria	6.6	kg VSS/day
Residual or Unused sludge from fish tank	52.3	kg COD/day
	34.9	kg sludge/day
Total sludge from denitrification and unused from fish tank	41.5	kg solids/day
% solids in waste stream removing the sludge	0.03	assumption
Daily volume of sludge from denitrification	1,383.1	L/day
	365.4	gal/day

Summary with 41% exchange

Fish biomass, feed rate, and volume using values for final tank of each stage			
Stage	Tank biomass kg	Feed rate kg/day/tank	Tank Volume m^3 or (gal)
Juvenile	192.3	5.5	4.3
			1,129.4
Fingerling	450.6	9.7	7.5
			1,992.7
Growout	874.1	15.1	11.7
			3,099.3
Total	1517.0	30.4	6,221.4

Total system volume (all tanks; gal)	55,992.4

RAS makeup water and solids volume				
Description	Juvenile	Fingerling	Growout	Units
Makeup water volume	4,215	7,447	11,593	gal/day
Sludge production rate	12	22	34	kg TSS/day
Sludge volume (at 3% solids)	109	193	300	gal/day

Total makeup saltwater volume	23,255	gal/day
Total sludge volume	602	gal/day

Total fish feed consumed per day (from baseline design)	273	kg feed/day

Cost Estimate		
Municipal water/Saline aquifer water	0.0020	$/gal
Synthetic seawater	0.31	$/gal
Makeup saltwater	0.106	$/gal
Effluent saltwater disposal (Class II injection)	1.00	$/barrel
Salt water sludge disposal (undeground injection)	1.00	$/barrel
Fish feed cost	2.20	$/kg
Sodium acetate as organic carbon source/supplement	1.10	$/kg

Scenario 1

Annual Baseline Cost Scenario with onsite subsurface injection of solids and wastewater

	Juvenile ($/year)	Fingerling ($/year)	Growout ($/year)	Total ($/year)
Makeup saltwater	163,351	288,590	449,227	901,168
Effluent injection	36,634	64,721	100,746	202,101
Sludge injection	948	1,675	2,607	5,230
Total	200,933	354,985	552,580	1,108,499

Total annual cost of makeup water	$ 901,168
Total annual cost of effluent and sludge disposal	$ 207,331
Total annual cost of fish feed	$ 219,508

Comment: Typically, in a RAS the cost of fish feed is one of the largest operating costs (20-40%)

Scenario 2

Saline Groundwater (GW) Scenario - Ironton Galesville GW+ Municipal Water

Annual operating costs for makeup seawater (dilute GI groundwater 6 times with municipal water), on-site effluent and sludge injection

	Juvenile ($/year)	Fingerling ($/year)	Growout ($/year)	Total ($/year)
Makeup saltwater	3,077	5,437	8,463	16,976
Effluent injection	36,634	64,721	100,746	202,101
Sludge injection	948	1,675	2,607	5,230
Total	40,659	71,832	111,816	224,308

Total annual cost of makeup water	$ 16,976
Total annual cost of effluent and sludge disposal	$ 207,331
Total annual cost of fish feed	$ 219,508

Cost avoidance from use of saline GW wrt Baseline scenario	**$ 884,191**

Scenario 3

Exogenous Denitrification using External Carbon Source Scenario (Acetate is used here)

The effluent water is denitrified using Acetate as carbon source, and recirculated in the fish tanks

The makeup saltwater (at 1% salinity) is constituted from saline GW and municipal water (as in scenario 2)

Assume: 1% of the system volume is lost due to evaporation and handling

Makeup saltwater required to cover for 1% loss of water	559.9	gal/day
Sludge generated from Exogenous Denitrification	53.1	gal/day
Sludge from fish tank	601.8	gal/day
Total volume of sludge from fish tank and denitrification	654.9	gal/day
Total sodium acetate utilized for denitrification	31.0	kg/day

Annual operating costs for acetate denitrification, makeup saltwater, on-site effluent and sludge injection	Total ($/year)
Makeup saltwater	409
Effluent injection	0
Sludge injection	5,692
Organic supplement for denitrification	12,472

Annual cost of sludge management (from fish tank and denitrification unit)	$ 18,164
Total annual cost	$ 18,573
Cost avoidance from reuse of saline GW by exogenous denitrification wrt Baseline scenario	**$ 1,089,926**

Scenario 4

Endogenous Denitrification using waste sludge scenario (from fish tank)

The effluent water is denitrified using the sludge (endogenous carbon source) from fish tanks

The unused sludge remaining in fish tanks, and the sludge produced from denitrification is the total sludge

The makeup saltwater (at 1% salinity) is constituted from saline GW and municipal water (as in scenario 2 and 3)

Assume: 1% of the system volume is lost due to evaporation and handling (Reference 22)

Makeup saltwater required to cover for 1% loss of recycled water	559.9	gal/day
Sludge generated in Endogenous Denitrification	6.6	kg VSS/day
Residual or unused sludge left in fish tank after denitrification	307.3	gal/day
Total volume of sludge from fish tank and denitrification	365.4	gal/day

Annual operating costs for sludge-based denitrification, makeup seawater, on-site effluent and sludge injection	Total ($/year)
Makeup saltwater	409
Effluent injection	0
Sludge injection	3,176
Organic supplement for sludge-based denitrification	0

Annual cost of sludge management (from fish tank and denitrification unit)	$ 3,176
Total cost	$ 3,584

Cost avoidance from reuse of saline GW by endogenous denitrification wrt Baseline scenario	**$ 1,104,914**