# THE EFFECTS OF LOADING DENSITY AND NET-PEN VOLUME ON THE GROWTH AND SURVIVAL OF COHO SALMON REARED IN SEAWATER

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# INTRODUCTION

Commercial production of Pacific salmon in floating saltwater net-pens is an expanding industry in the United States. At the onset of commercial pen production in 1970-71, 60 metric tons of salmon were produced in the United States (Mahnken 1975) whereas, the 1978 production for Puget Sound growers alone was estimated at 246 metric tons. Similar expansion with Pacific salmon is occurring in Europe.

To achieve maximum production in seawater net-pens, growers must optimize their rearing systems. Increasing loading density is one means of achieving this goal.

Various studies have addressed optimal loading density of salmonids in freshwater ponds, raceways, and troughs (Haskell 1955; Burrows and Combs 1968; Willoughby 1968; Piper 1970; Westers 1970; and Klontz et al. 1978). This information, however, cannot be applied directly to a saltwater net-pen system. The floating net-pen is unique, having all sides and bottom open for water exchange. The rate of water exchange is affected by tidal and current flow, net fouling (Milne 1972, 1975), and the swimming motion of the fish (Hisaoka et al. 1966; Novotny 1972). Furthermore, turbulent water flow through a net-pen is difficult to measure or relate to loading density.

Commercial net-pen growers of Pacific salmon aim for a harvest density of approximately 16.0 kilograms per cubic meter ($kg/m^3$) of water (Mahnken et al. 1970). This figure is generally not exceeded on a production scale because of the lack of information on effects of higher loading densities.

In July 1975, a study of loading density for coho salmon (*Oncorhynchus kisutch*) was begun by the National Marine Fisheries Service (NMFS) at the

Aquaculture Research Station near Manchester, Washington (Figure 1). The objective was to determine the effect of loading density and net-pen volume on growth and survival of coho salmon in floating seawater net-pens. The investigation was carried out in cooperation with a local commercial salmon producer, Domsea Farms, Incorporated.

A preliminary report was prepared for Domsea Farms in 1976. Since then, extensive analysis of the data has shown that our initial conclusions should be modified as discussed herein.

## METHODS AND MATERIALS

Loading density is defined as weight of fish per unit volume of water and expressed as kilograms per cubic meter. The test pens were located alongside a pier extending 244 m into Clam Bay on the western shore of central Puget Sound. Tidal currents up to 0.5 knot inside the bay exchange water through the pens. Flushing rate for the bay is about 6 hours (Collias and Benttinen 1967). Water depth at the test site ranges from 9 to 14 m depending on tide stage. Water temperature (1 m depth) and Secchi disc depths were observed daily. Current measurements were made periodically as were dissolved oxygen determinations from both inside and outside (ambient) the highest density 4.0 $m^3$ pen.

### FISH

In early July, approximately 70,000 0-age coho salmon (X = 20.0 g) in various stages of smoltification were transferred from freshwater raceways at Domsea's Gorst Creek Hatchery to a common saltwater holding pen in Clam

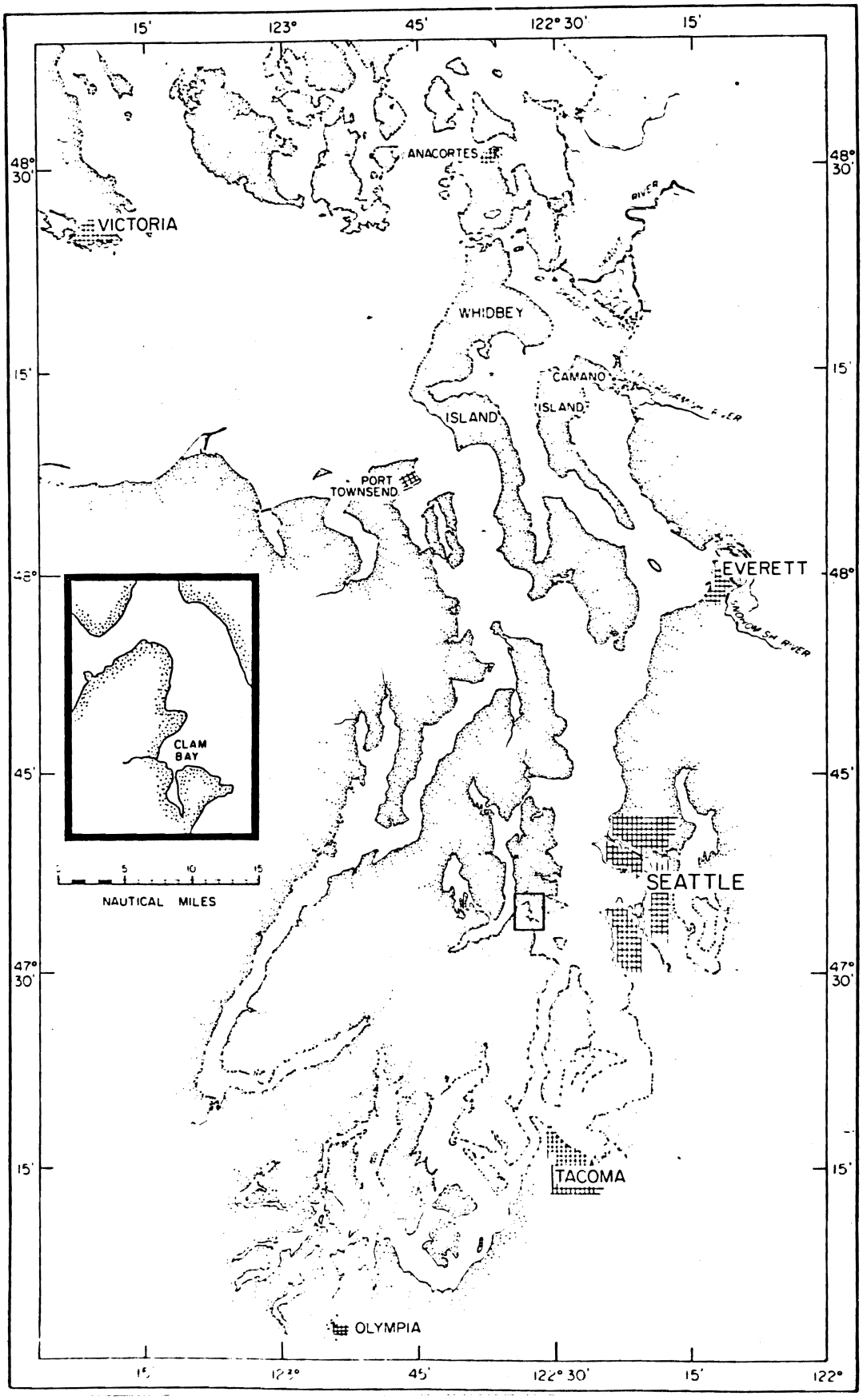


Figure 1.--Location of Manchester, Washington with respect to major population centers in the Puget Sound region.

Bay. The fish had been vaccinated intraperitoneally with heat-killed Vibro anguillarum prior to entry into salt water (Harrell et al. 1976). The fish were fed dry Abernathy feed[1/] in the common holding pen for 2 weeks prior to the experiment.

PENS

Net-pens were made of 16 mm stretch knotless nylon in three pen sizes: 1.2 x 2.1 x 1.5 m deep (4.0 $m^3$), 2.4 x 2.1 x 1.5 m deep (8.0 $m^3$), and 4.9 x 4.9 x 3.7 m deep (89.0 $m^3$). Plastic pipe frames placed in the bottom of each pen meintained the rectangular pen shape. A net covering was placed over the net-pens to eliminate predation by birds. The net-pens were suspended form the interior of three 5 x 5 m - perimeter float modules.

Fish were stocked in July at densities of 1.6, 3.2, 4.8, 8.0, and 11.2 $kg/m^3$. An additional 20% allowance was made in each pen at the onset of the test for mortality and parred fish. Parred fish, when placed in salt water, typically show slow or negative growth and high mortality. This allowance is included in the initial density. Reference to densities hereafter will refer to projected harvest densities unless otherwise noted. The 4.0 and 8.0 $m^3$ pens were replicated at densities of 8.0, 16.0, and 32.1 $kg/m^3$, but not at densities of 48.1 or 64.1 $kg/m^3$. Also there was no replicate 89.0 $m^3$ pen at a density of 32.1 $kg/m^3$ (Table 1).

1/ Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

TABLE 1.--Inventory of coho salmon test groups.

| Pen Volume $m^3$ | Projected harvest density $kg/m^3$ | Actual harvest density $kg/m^3$ | No. fish start | No. fish end | Elapsed days | Mortality Number | Mortality % | Unaccountable loss (gain) Number | Unaccountable loss (gain) % | Total loss Number | Total loss % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.0 | 8.0 | 9.0 | 254 | 189 | 154 | 49 | 19.3 | 16 | 6.3 | 65 | 25.6 |
| | 8.0 | 8.8 | 254 | 203 | 154 | 47 | 18.5 | 4 | 1.6 | 51 | 20.1 |
| | 16.0 | 10.4 | 509 | 265 | 155 | 86 | 16.9 | 158 | 31.0 | 244 | 47.9 |
| | 16.0 | 12.2 | 509 | 297 | 154 | 94 | 18.5 | 118 | 23.2 | 212 | 41.7 |
| | 32.1 | 35.2 | 1,018 | 926 | 154 | 94 | 9.2 | (2) 1/ | 0.2 1/ | 92 | 9.0 |
| | 32.1 | 29.6 | 1,018 | 720 | 154 | 117 | 11.5 | 181 | 17.8 | 298 | 29.3 |
| | 48.1 | 39.7 | 1,528 | 1,128 | 154 | 223 | 14.6 | 177 | 11.6 | 400 | 26.2 |
| | 64.1 | 59.9 | 2,036 | 1,702 | 154 | 314 | 15.4 | 20 | 1.0 | 334 | 16.4 |
| 8.0 | 8.0 | 8.0 | 491 | 393 | 153 | 88 | 17.9 | 10 | 2.0 | 98 | 20.0 |
| | 8.0 | 7.0 | 491 | 347 | 153 | 114 | 23.2 | 30 | 6.1 | 144 | 29.3 |
| | 16.0 | 15.7 | 982 | 847 | 153 | 218 | 22.2 | (83) 1/ | 8.5 1/ | 135 | 13.7 |
| | 16.0 | 7.7 | 982 | 508 | 154 | 155 | 15.8 | 319 | 32.5 | 474 | 48.3 |
| | 32.1 | 29.3 | 1,963 | 1,645 | 153 | 332 | 16.9 | (14) 1/ | 0.7 1/ | 318 | 16.2 |
| | 32.1 | 11.4 | 1,963 | 567 | 154 | 252 | 12.8 | 1,144 | 58.3 | 1,296 | 71.1 |
| | 48.1 | 44.2 | 3,169 | 2,665 | 153 | 409 | 12.9 | 95 | 3.0 | 504 | 15.9 |
| | 64.1 | 53.0 | 3,928 | 3,338 | 154 | 638 | 16.2 | (48) 1/ | 1.2 1/ | 590 | 15.0 |
| 89.0 | 32.1 | 23.5 | 22,342 | 14,055 | 155 | 2,042 | 9.1 | 6,245 | 28.0 | 8,287 | 37.1 |

1/ Indicates unaccountable gain in number of fish (e.g., fish jumping into adjacent pen).

## ESTABLISHING THE EXPERIMENT

For low loading densities (8.0 and 16.0 $kg/m^3$), fish were randomly dipped from the common holding pen. These fish were placed in a tared bucket, weighed (in bulk), counted, and distributed to the experimental pens until the predetermined initial loading density for each pen was reached (Table 1). Periodic subsamples were taken from the tared bucket by pouring a random number of fish into another bucket for individual length-weight measurements. Parr, transitional, and smolt fish, determined by external characteristics, were recorded for each subsample (Table 2).

At loading densities of 32.1 $kg/m^3$ and above, all fish were bulk weighed, but not all were counted because of the large number. To estimate the initial number of fish in these net-pens, buckets of fish removed for bulk weighing were periodically hand counted, establishing the bulk-weight/number relationship. Pen populations and weights were estimated from this relationship. Routine subsamples for individual length-weight were taken in the same manner as with low loading densities (Figure 2).

## GROWTH MONITORING PROCEDURE

A mortality record was kept for each pen. Dead fish were removed daily from all 4.0 and 8.0 $m^3$ test pens and twice weekly in the 89.0 $m^3$ pen. Moribund fish were examined and kidney smears cultured to detect bacterial disease.

Fish in each net-pen were checked monthly (July to December) for growth and condition. In pens of 8.0 and 16.0 $kg/m^3$, all fish were bulk weighed and counted (Table 3). Fish density in all other net-pens was estimated

Table 2.--Generalized visual criteria for the identification of parr, transitional, and smolt stages in coho salmon in fresh and salt water.

| Stage | Parr marks | External coloration | | Fin coloration | | | | Opercle |
|---|---|---|---|---|---|---|---|---|
| | | Dorsal | Ventral | Caudal | Anal | Ventral | Pectoral | |
| Parr | distinct | brown | yellow | yellow to orange | yellow to orange | yellow to orange | yellow to orange | bronze |
| Transi-tional | fading | greenish | cream | darken-ing & trans-lucent | clear-ing | yellow-ish | yellow to orange | gold |
| Smolt | absent | blue | white | clear, with dark band on pos-terior margin | clear, with white tip on pos-terior margin | clear | clear | silver |

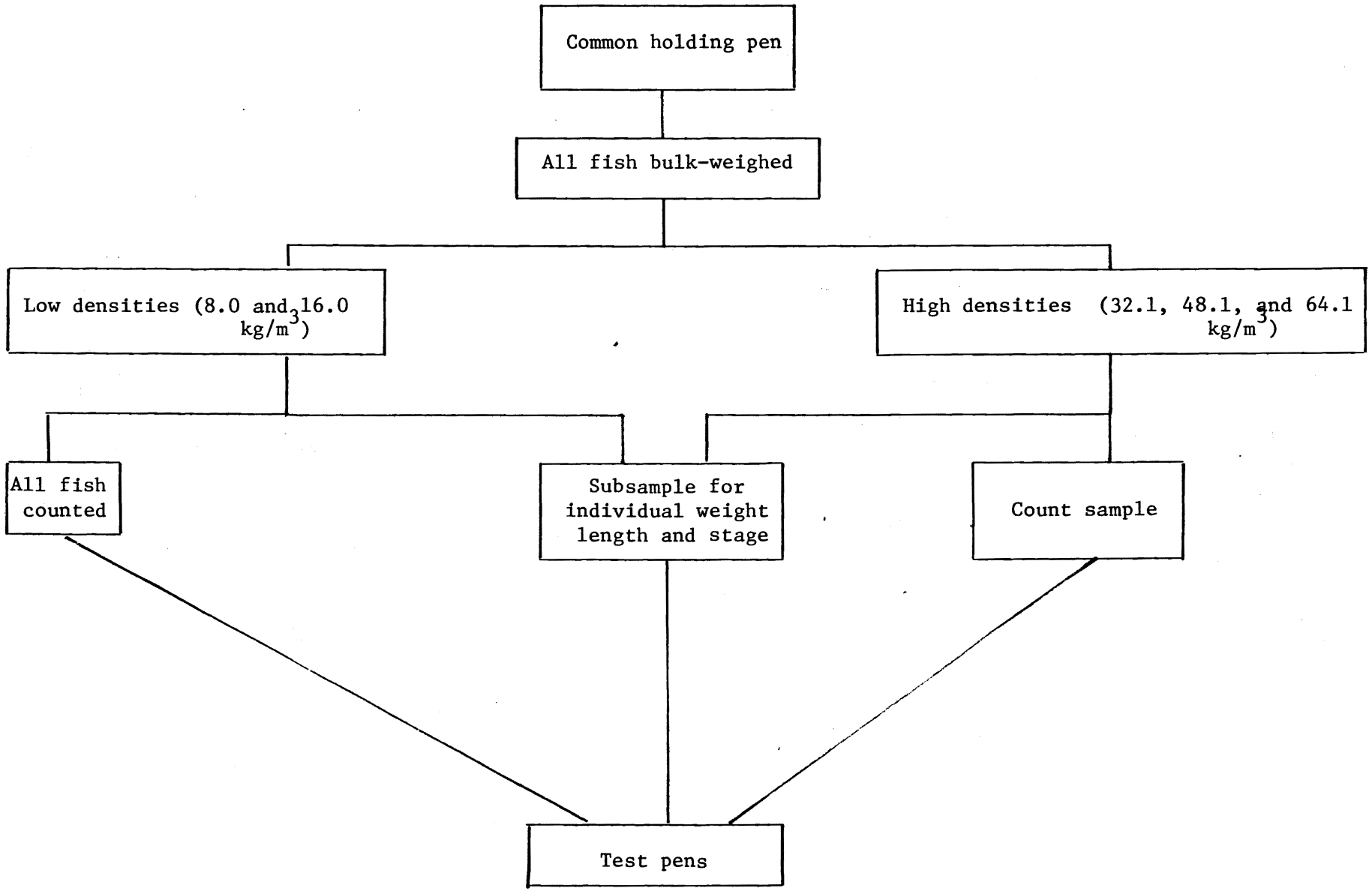


Figure 2.--Establishing test pens for coho salmon loading density study.

TABLE 3.--Subsample growth data for six measurement periods as related to pen volume and loading and loading density.

| Pen volume $m^3$ | Projected harvest density $kg/m^3$ | Stage of smoltification | | MEASUREMENT PERIOD Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|
| 4.0 | 8.0 | parr | mean wt.1/ | 14.3 | 14.3 | 15.2 | 18.0 | 27.8 | 20.8 |
| | | | s. d.2/ | 3.17 | 3.30 | 3.51 | 4.66 | 11.09 | 2.33 |
| | | | n 3/ | 16 | 59 | 8 | 6 | 6 | 2 |
| | | transitional | mean wt. | 17.6 | 23.7 | -- | 24.4 | -- | 42.4 |
| | | | s. d. | 1.65 | 5.64 | -- | 2.19 | -- | 3.60 |
| | | | n | 3 | 11 | -- | 2 | -- | 2 |
| | | smolt | mean wt. | 25.9 | 37.8 | 80.2 | 114.9 | 196.6 | 242.0 |
| | | | s. d. | 7.80 | 13.68 | 29.10 | 33.15 | 74.92 | 87.65 |
| | | | n | 26 | 177 | 35 | 35 | 31 | 29 |
| | | combined | mean wt. | 21.2 | 31.6 | 68.2 | 97.1 | 169.2 | 216.5 |
| | | | s. d. | 8.33 | 15.50 | 36.65 | 47.97 | 93.14 | 107.71 |
| | | | n | 45 | 247 | 43 | 43 | 37 | 33 |
| 4.0 | 8.0 | parr | mean wt. | 15.0 | 14.8 | 17.0 | 22.9 | 23.0 | 28.2 |
| | | | s. d. | 2.46 | 3.58 | 4.21 | 7.66 | 6.70 | 6.90 |
| | | | n | 11 | 54 | 5 | 8 | 10 | 8 |
| | | transitional | mean wt. | 17.0 | 22.3 | -- | 38.4 | -- | -- |
| | | | s. d. | 3.25 | 7.93 | -- | 16.06 | -- | -- |
| | | | n | 6 | 28 | -- | 4 | -- | -- |
| | | smolt | mean wt. | 26.1 | 38.0 | 63.6 | 99.4 | 175.6 | 199.1 |
| | | | s. d. | 6.77 | 11.28 | 25.70 | 34.28 | 56.11 | 74.99 |
| | | | n | 44 | 172 | 32 | 40 | 33 | 36 |
| | | combined | mean wt. | 23.2 | 31.3 | 57.3 | 82.9 | 140.1 | 168.0 |
| | | | s. d. | 7.56 | 13.89 | 28.84 | 43.07 | 81.63 | 95.04 |
| | | | n | 61 | 254 | 37 | 52 | 43 | 44 |

1/ Mean weight in grams.
2/ Standard deviation.
3/ Number of samples.

TABLE 3.--Continued.

| Pen volume $m^3$ | Projected harvest density $kg/m^3$ | Stage of smoltification | | MEASUREMENT PERIOD Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|
| 4.0 | 16.0 | parr | mean wt. | 14.2 | 14.3 | 14.0 | 18.1 | 20.5 | 22.0 |
| | | | s. d. | 2.80 | 2.59 | 4.11 | 5.60 | 6.57 | 5.07 |
| | | | n | 49 | 15 | 15 | 8 | 11 | 13 |
| | | transitional | mean wt. | 18.8 | 18.0 | 21.3 | 27.6 | -- | -- |
| | | | s. d. | 3.48 | 4.78 | 6.94 | 0.00 | -- | -- |
| | | | n | 16 | 6 | 5 | 1 | -- | -- |
| | | smolt | mean wt. | 25.0 | 37.0 | 62.4 | 116.0 | 175.5 | 214.6 |
| | | | s. d. | 5.94 | 11.06 | 22.88 | 34.14 | 50.46 | 62.92 |
| | | | n | 73 | 46 | 36 | 34 | 34 | 39 |
| | | combined | mean wt. | 20.4 | 30.2 | 45.7 | 95.7 | 137.6 | 166.4 |
| | | | s. d. | 6.92 | 13.74 | 29.15 | 50.11 | 80.36 | 100.23 |
| | | | n | 138 | 67 | 56 | 43 | 45 | 52 |
| 4.0 | 16.0 | parr | mean wt. | 14.5 | 14.6 | 16.9 | 15.7 | 17.8 | 20.1 |
| | | | s. d. | 3.10 | 2.56 | 4.43 | 5.39 | 4.43 | 5.15 |
| | | | n | 29 | 34 | 20 | 17 | 17 | 9 |
| | | transitional | mean wt. | 18.0 | 23.3 | 49.0 | -- | -- | 38.5 |
| | | | s. d. | 3.55 | 0.00 | 1.84 | -- | -- | 0.00 |
| | | | n | 8 | 1 | 2 | -- | -- | 1 |
| | | smolt | mean wt. | 25.6 | 42.0 | 76.1 | 129.4 | 193.1 | 226.5 |
| | | | s. d. | 6.40 | 15.64 | 28.60 | 41.74 | 71.94 | 67.15 |
| | | | n | 31 | 28 | 31 | 31 | 29 | 32 |
| | | combined | mean wt. | 20.0 | 26.9 | 52.7 | 89.1 | 128.3 | 177.8 |
| | | | s. d. | 7.22 | 17.19 | 36.01 | 64.33 | 102.66 | 105.83 |
| | | | n | 68 | 63 | 53 | 48 | 46 | 42 |

TABLE 3.--Continued.

| Pen volume $m^3$ | Projected harvest density $kg/m^3$ | Stage of smoltification | | MEASUREMENT PERIOD Jul. | Aug. | Sept | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|
| 4.0 | 32.1 | parr | mean wt. | 14.0 | 14.7 | 16.1 | 16.9 | 21.1 | 18.4 |
| | | | s. d. | 2.57 | 3.49 | 3.50 | 3.46 | 5.74 | 4.88 |
| | | | n | 13 | 20 | 23 | 22 | 15 | 15 |
| | | transitional | mean wt. | 16.1 | 18.0 | 24.4 | 30.8 | -- | 33.8 |
| | | | s. d. | 2.73 | 4.31 | 1.69 | 3.88 | -- | 0.00 |
| | | | n | 6 | 8 | 2 | 2 | -- | 1 |
| | | smolt | mean wt. | 24.4 | 38.0 | 72.3 | 111.9 | 168.8 | 217.0 |
| | | | s. d. | 6.93 | 12.58 | 21.25 | 34.27 | 52.29 | 71.66 |
| | | | n | 24 | 51 | 52 | 62 | 52 | 68 |
| | | combined | mean wt. | 19.9 | 30.1 | 54.3 | 85.7 | 135.8 | 179.4 |
| | | | s. d. | 7.18 | 14.91 | 31.50 | 51.41 | 77.26 | 101.24 |
| | | | n | 43 | 79 | 77 | 86 | 67 | 84 |
| 4.0 | 32.1 | parr | mean wt. | 14.1 | 14.6 | 18.0 | 19.8 | 19.1 | 20.2 |
| | | | s. d. | 2.19 | 3.18 | 4.70 | 6.21 | 6.15 | 4.11 |
| | | | n | 26 | 18 | 18 | 13 | 20 | 17 |
| | | transitional | mean wt. | 18.6 | 22.0 | 31.9 | 22.0 | -- | 39.1 |
| | | | s. d. | 4.53 | 4.41 | 10.42 | 2.59 | -- | 0.00 |
| | | | n | 10 | 7 | 5 | 3 | -- | 1 |
| | | smolt | mean wt. | 23.8 | 37.5 | 63.2 | 98.4 | 150.2 | 199.1 |
| | | | s. d. | 5.80 | 12.57 | 18.25 | 27.45 | 44.93 | 50.10 |
| | | | n | 45 | 51 | 64 | 74 | 65 | 71 |
| | | combined | mean wt. | 20.1 | 30.7 | 52.0 | 84.5 | 119.3 | 163.2 |
| | | | s. d. | 6.49 | 14.47 | 24.72 | 39.10 | 68.36 | 84.67 |
| | | | n | 81 | 76 | 87 | 90 | 85 | 89 |

TABLE 3.--Continued.

| Pen volume $m^3$ | Projected harvest density $kg/m^3$ | Stage of smoltification | | MEASUREMENT PERIOD Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|
| 8.0 | 48.1 | parr | mean wt. | 13.8 | 15.4 | 17.4 | 17.8 | 20.2 | 19.2 |
| | | | s. d. | 1.73 | 3.59 | 5.04 | 3.90 | 5.03 | 4.15 |
| | | | n | 20 | 53 | 27 | 18 | 18 | 58 |
| | | transitional | mean wt. | 15.7 | 15.4 | 26.2 | 22.9 | -- | -- |
| | | | s. d. | 3.31 | 2.22 | 6.25 | 3.47 | -- | -- |
| | | | n | 9 | 9 | 5 | 6 | -- | -- |
| | | smolt | mean wt. | 22.3 | 34.7 | 68.3 | 103.6 | 149.5 | 179.8 |
| | | | s. d. | 4.72 | 12.33 | 21.58 | 30.80 | 44.54 | 52.59 |
| | | | n | 29 | 77 | 59 | 21 | 87 | 180 |
| | | combined | mean wt. | 18.3 | 26.1 | 50.9 | 84.3 | 127.3 | 140.6 |
| | | | s. d. | 5.45 | 13.49 | 29.61 | 44.80 | 63.57 | 82.86 |
| | | | n | 58 | 139 | 91 | 105 | 105 | 238 |
| 8.0 | 64.1 | parr | mean wt. | 13.8 | 14.7 | 16.1 | 16.5 | 17.8 | 18.2 |
| | | | s. d. | 2.59 | 2.68 | 3.26 | 4.15 | 3.84 | 4.75 |
| | | | n | 52 | 21 | 26 | 30 | 47 | 101 |
| | | transitional | mean wt. | 16.6 | 16.8 | 22.6 | 22.5 | 33.7 | 31.7 |
| | | | s. d. | 2.17 | 2.40 | 6.35 | 7.38 | 10.48 | 5.81 |
| | | | n | 27 | 4 | 5 | 11 | 3 | 16 |
| 8.0 | 64.1 | smolt | mean wt. | 23.1 | 35.0 | 56.8 | 98.2 | 133.1 | 169.9 |
| | | | s. d. | 6.18 | 12.31 | 21.22 | 30.50 | 44.44 | 52.61 |
| | | | n | 102 | 66 | 62 | 97 | 89 | 272 |
| | | combined | mean wt. | 19.5 | 29.5 | 43.6 | 74.4 | 92.0 | 124.8 |
| | | | s. d. | 6.49 | 13.83 | 25.64 | 44.81 | 65.62 | 81.75 |
| | | | n | 181 | 91 | 93 | 138 | 139 | 389 |

TABLE 3.--Continued.

| Pen volume $m^3$ | Projected harvest density $kg/m^3$ | Stage of smoltification | | MEASUREMENT PERIOD Jul. | Aug. | Sept | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|
| 4.0 | 48.1 | parr | mean wt. | 13.8 | 16.6 | 15.6 | 17.4 | 19.8 | 20.2 |
| | | | s. d. | 1.95 | 3.87 | 4.04 | 3.68 | 6.64 | 8.36 |
| | | | n | 40 | 14 | 19 | 26 | 24 | 27 |
| | | transitional | mean wt. | 16.9 | 19.5 | 19.0 | 26.4 | -- | 32.7 |
| | | | s. d. | 3.18 | 5.01 | 4.86 | 2.68 | -- | 5.96 |
| | | | n | 12 | 7 | 6 | 2 | -- | 5 |
| | | smolt | mean wt. | 23.0 | 33.3 | 60.4 | 97.1 | 152.9 | 201.5 |
| | | | s. d. | 5.84 | 12.91 | 18.77 | 33.18 | 50.41 | 61.20 |
| | | | n | 49 | 65 | 68 | 65 | 65 | 78 |
| | | combined | mean wt. | 18.6 | 29.1 | 48.6 | 73.3 | 117.0 | 149.4 |
| | | | s. d. | 6.17 | 13.27 | 25.41 | 45.81 | 73.43 | 96.78 |
| | | | n | 101 | 86 | 93 | 93 | 89 | 110 |
| 4.0 | 64.1 | parr | mean wt. | 13.6 | 14.4 | 16.6 | 16.3 | 19.3 | 17.9 |
| | | | s. d. | 2.67 | 3.81 | 4.12 | 4.20 | 7.30 | 4.33 |
| | | | n | 59 | 19 | 20 | 32 | 19 | 29 |
| | | transitional | mean wt. | 17.2 | 17.9 | 33.3 | 22.2 | -- | 40.1 |
| | | | s. d. | 2.94 | 3.88 | 6.32 | 5.23 | -- | 1.27 |
| | | | n | 16 | 8 | 5 | 8 | -- | 2 |
| | | smolt | mean wt. | 23.9 | 35.4 | 66.9 | 94.8 | 135.8 | 176.4 |
| | | | s. d. | 5.23 | 13.28 | 17.10 | 34.18 | 50.05 | 56.13 |
| | | | n | 98 | 62 | 54 | 118 | 89 | 115 |
| | | combined | mean wt. | 19.8 | 29.3 | 52.1 | 75.2 | 115.3 | 143.0 |
| | | | s. d. | 6.47 | 14.58 | 26.52 | 44.88 | 63.69 | 81.48 |
| | | | n | 173 | 89 | 79 | 158 | 108 | 146 |

TABLE 3.--Continued.

| Pen Volume $m^3$ | Projected harvest density $kg/m^3$ | Stage of smoltification | | MEASUREMENT PERIOD Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|
| 8.0 | 8.0 | parr | mean wt. | 13.8 | 15.7 | 16.6 | 18.5 | 19.3 | 23.0 |
| | | | s. d. | 2.30 | 1.63 | 4.36 | 3.46 | 5.13 | 5.08 |
| | | | n | 46 | 11 | 14 | 9 | 9 | 12 |
| | | transitional | mean wt. | 17.4 | 20.2 | 49.3 | 25.5 | -- | -- |
| | | | s. d. | 1.58 | 4.83 | 0.00 | 6.19 | -- | -- |
| | | | n | 6 | 3 | 1 | 6 | -- | -- |
| | | smolt | mean wt. | 24.2 | 39.7 | 61.9 | 116.3 | 153.0 | 203.0 |
| | | | s. d. | 6.69 | 13.57 | 21.05 | 33.89 | 48.93 | 63.98 |
| | | | n | 113 | 33 | 41 | 41 | 53 | 43 |
| | | combined | mean wt. | 21.0 | 39.9 | 50.3 | 90.9 | 133.6 | 163.7 |
| | | | s. d. | 7.35 | 15.64 | 26.74 | 51.28 | 65.57 | 93.90 |
| | | | n | 165 | 47 | 56 | 56 | 62 | 55 |
| 8.0 | 8.0 | parr | mean wt. | 14.4 | 16.5 | 17.0 | 13.4 | 21.4 | 22.6 |
| | | | s. d. | 2.85 | 4.08 | 4.27 | 2.18 | 5.74 | 6.85 |
| | | | n | 52 | 18 | 20 | 9 | 17 | 11 |
| | | transitional | mean wt. | 18.3 | 20.8 | 48.4 | 23.3 | 50.8 | 45.7 |
| | | | s. d. | 3.12 | 4.10 | 32.87 | 9.68 | 0.00 | 0.00 |
| | | | n | 10 | 2 | 3 | 6 | 1 | 1 |
| | | smolt | mean wt. | 24.6 | 35.6 | 66.9 | 104.6 | 153.3 | 183.5 |
| | | | s. d. | 5.72 | 12.44 | 22.52 | 34.20 | 44.53 | 50.73 |
| | | | n | 63 | 27 | 32 | 43 | 63 | 38 |
| | | combined | mean wt. | 19.9 | 27.6 | 47.8 | 82.0 | 124.4 | 145.3 |
| | | | s. d. | 6.69 | 13.47 | 30.10 | 48.58 | 67.28 | 81.65 |
| | | | n | 125 | 47 | 55 | 58 | 81 | 50 |

TABLE 3.--Continued.

| Pen volume $m^3$ | Projected harvest density $kg/m^3$ | Stage of smoltification | | MEASUREMENT PERIOD Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|
| 8.0 | 16.0 | parr | mean wt. | 14.5 | 15.5 | 15.7 | 17.6 | 19.1 | 22.8 |
| | | | s. d. | 2.34 | 3.92 | 3.96 | 1.20 | 7.69 | 7.25 |
| | | | n | 30 | 23 | 12 | 6 | 14 | 30 |
| | | transitional | mean wt. | 18.0 | -- | 30.3 | -- | -- | -- |
| | | | s. d. | 2.21 | -- | 1.97 | -- | -- | -- |
| | | | n | 8 | -- | 2 | -- | -- | -- |
| | | smolt | mean wt. | 23.6 | 35.5 | 64.0 | 107.4 | 150.3 | 190.8 |
| | | | s. d. | 5.13 | 13.08 | 21.54 | 36.32 | 45.45 | 58.13 |
| | | | n | 33 | 32 | 54 | 72 | 55 | 91 |
| | | combined | mean wt. | 19.1 | 27.1 | 54.5 | 100.5 | 123.7 | 149.2 |
| | | | s. d. | 5.79 | 14.27 | 26.99 | 42.38 | 66.90 | 88.62 |
| | | | n | 71 | 55 | 68 | 78 | 69 | 121 |
| 8.0 | 16.0 | parr | mean wt. | 13.6 | 14.5 | 17.1 | 18.5 | 20.2 | 20.5 |
| | | | s. d. | 2.34 | 3.77 | 4.58 | 4.54 | 6.10 | 4.89 |
| | | | n | 16 | 12 | 26 | 30 | 32 | 30 |
| | | transitional | mean wt. | 15.5 | 17.0 | 26.2 | 32.2 | -- | 31.8 |
| | | | s. d. | 1.51 | 3.30 | 11.09 | 9.68 | -- | 0.00 |
| | | | n | 5 | 4 | 7 | 2 | -- | 1 |
| | | smolt | mean wt. | 24.7 | 32.5 | 61.9 | 105.9 | 152.5 | 199.4 |
| | | | s. d. | 5.48 | 11.08 | 19.34 | 31.20 | 42.37 | 39.73 |
| | | | n | 25 | 50 | 62 | 62 | 62 | 54 |
| | | combined | mean wt. | 19.8 | 28.3 | 47.0 | 76.4 | 107.5 | 134.3 |
| | | | s. d. | 6.88 | 12.34 | 26.11 | 48.48 | 71.85 | 92.08 |
| | | | n | 46 | 66 | 95 | 94 | 94 | 85 |

TABLE 3.--Continued.

| Pen volume $m^3$ | Projected harvest density $kg/m^3$ | Stage of smoltification | | MEASUREMENT PERIOD Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|
| 8.0 | 32.1 | parr | mean wt. | 13.5 | 15.5 | 16.1 | 16.9 | 18.5 | 21.2 |
| | | | s. d. | 2.52 | 4.10 | 5.30 | 3.54 | 5.27 | 6.95 |
| | | | n | 19 | 29 | 22 | 29 | 29 | 39 |
| | | transitional | mean wt. | 14.5 | 18.3 | 31.9 | 25.3 | -- | 43.1 |
| | | | s. d. | 2.81 | 3.10 | 1.35 | 1.41 | -- | 9.47 |
| | | | n | 7 | 5 | 3 | 2 | -- | 2 |
| | | smolt | mean wt. | 23.2 | 34.1 | 65.6 | 110.3 | 159.8 | 190.8 |
| | | | s. d. | 6.32 | 14.44 | 21.12 | 38.89 | 44.75 | 59.31 |
| | | | n | 25 | 46 | 74 | 74 | 55 | 106 |
| | | combined | mean wt. | 18.4 | 26.4 | 53.6 | 82.9 | 111.0 | 143.8 |
| | | | s. d. | 6.73 | 14.39 | 27.86 | 53.64 | 76.70 | 91.10 |
| | | | n | 51 | 80 | 99 | 105 | 84 | 147 |
| 8.0 | 32.1 | parr | mean wt. | 14.1 | 14.3 | 19.2 | 17.4 | 19.8 | 19.8 |
| | | | s. d. | 2.31 | 3.53 | 4.96 | 3.51 | 4.46 | 5.34 |
| | | | n | 40 | 26 | 18 | 17 | 13 | 15 |
| | | transitional | mean wt. | 15.8 | 19.2 | 36.1 | 25.7 | -- | 41.2 |
| | | | s. d. | 3.02 | 5.16 | 0.00 | 7.60 | -- | 0.00 |
| | | | n | 21 | 2 | 2 | 9 | -- | 1 |
| | | smolt | mean wt. | 24.5 | 36.2 | 65.5 | 107.7 | 176.3 | 237.8 |
| | | | s. d. | 5.85 | 12.46 | 24.02 | 31.46 | 43.86 | 69.93 |
| | | | n | 48 | 25 | 56 | 75 | 86 | 53 |
| | | combined | mean wt. | 19.0 | 24.8 | 53.8 | 85.2 | 155.7 | 187.6 |
| | | | s. d. | 6.56 | 14.05 | 28.76 | 47.09 | 67.01 | 110.61 |
| | | | n | 109 | 53 | 76 | 101 | 99 | 69 |

TABLE 3.--Continued.

| Pen volume $m^3$ | Projected harvest density $kg/m^3$ | Stage of smoltification | | MEASUREMENT PERIOD Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|
| 89.0 | 32.1 | parr | mean wt. | 13.8 | 15.9 | 14.4 | 15.7 | 19.5 | 18.9 |
| | | | s. d. | 2.56 | 3.91 | 3.29 | 4.84 | 5.62 | 4.90 |
| | | | n | 169 | 142 | 49 | 25 | 70 | 287 |
| | | transitional | mean wt. | 16.2 | 21.0 | 23.2 | 23.4 | 28.8 | 31.2 |
| | | | s. d. | 2.80 | 4.97 | 10.38 | 3.58 | 4.08 | 6.30 |
| | | | n | 98 | 27 | 14 | 7 | 4 | 28 |
| | | smolt | mean wt. | 23.8 | 44.5 | 73.5 | 122.6 | 174.2 | 216.2 |
| | | | s. d. | 5.92 | 15.25 | 24.53 | 43.93 | 54.22 | 67.75 |
| | | | n | 281 | 280 | 69 | 97 | 112 | 572 |
| | | combined | mean wt. | 19.4 | 34.0 | 46.2 | 96.5 | 112.8 | 146.5 |
| | | | s. d. | 6.54 | 18.26 | 33.99 | 59.43 | 86.63 | 108.60 |
| | | | n | 548 | 449 | 132 | 129 | 186 | 887 |

using average subsample weights, bulk-weight/number relationship, and mortality records (Figure 3). Subsamples for length and weight were taken periodically in all pens as described previously (Establishing the Experiment). At the conclusion of the study, the entire contents of each net-pen were bulk weighed and counted except the 89.0 $m^3$ pen (density 32.1 $kg/m^3$) where all fish were bulk weighed, but only random subsamples were counted.

### FISH MAINTENANCE

During the test, the fish were fed Abernathy dry feed, four times daily. Feed amounts were based on percent body weight at the time of each sampling according to feed schedules established for coho salmon in salt water (Mahnken personal communication). Total fish weight in each pen was estimated biweekly from projected growth, and feed rations were upgraded accordingly.

## RESULTS AND DISCUSSION

### ENVIRONMENTAL FACTORS

Water temperature, transparency, and dissolved oxygen (DO) were monitored during the study. Water temperature alone was not a critical factor. Peak 5-day mean surface temperatures in late July and early August (Figure 4) were within the limits for coho salmon (Moring 1973).

Water transparency, an indirect measurement of phytoplankton standing stock, was measured daily using a Secchi disc (Figure 5). During the three 24-hour periods in which DO was measured (September, October, and December), there was an inverse relation to water transparency noted. In general, water transparency was low in July and increased gradually until

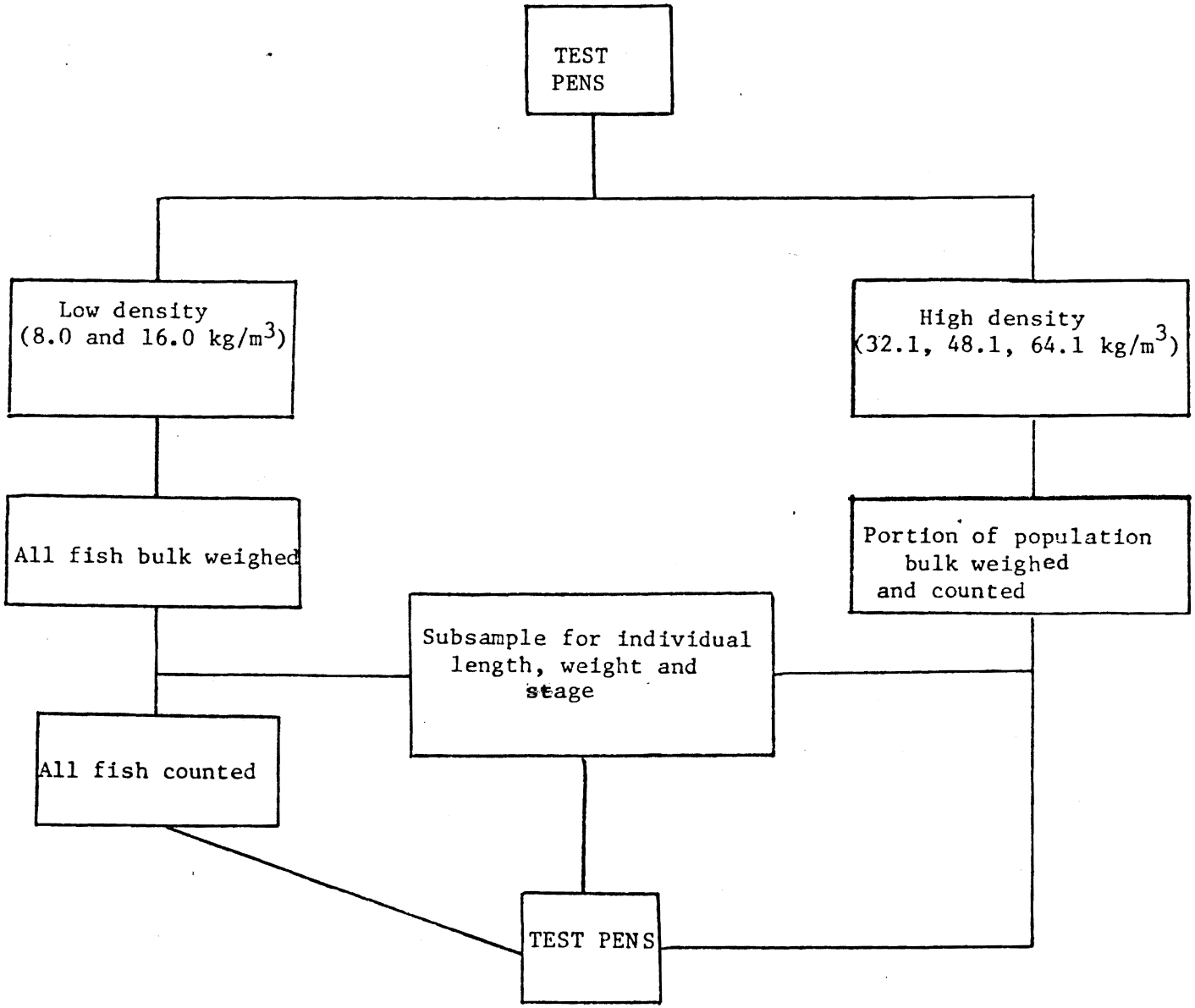


Figure 3.--Growth and survival monitoring procedure for coho loading density study.

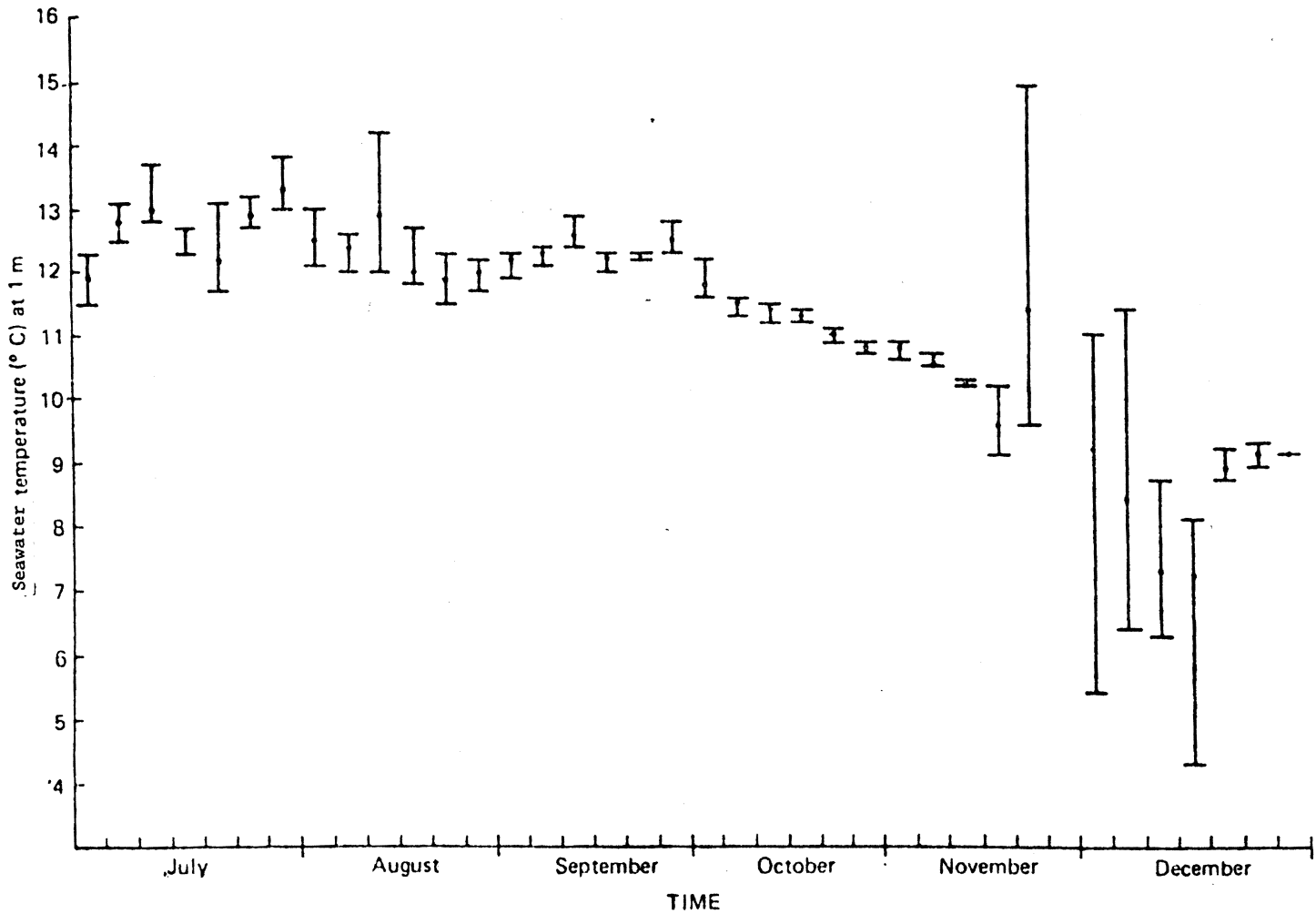


Figure 4.--Five-day mean seawater surface temperature at Clam Bay, Puget Sound, Washington during study period. Bars indicate temperature range.

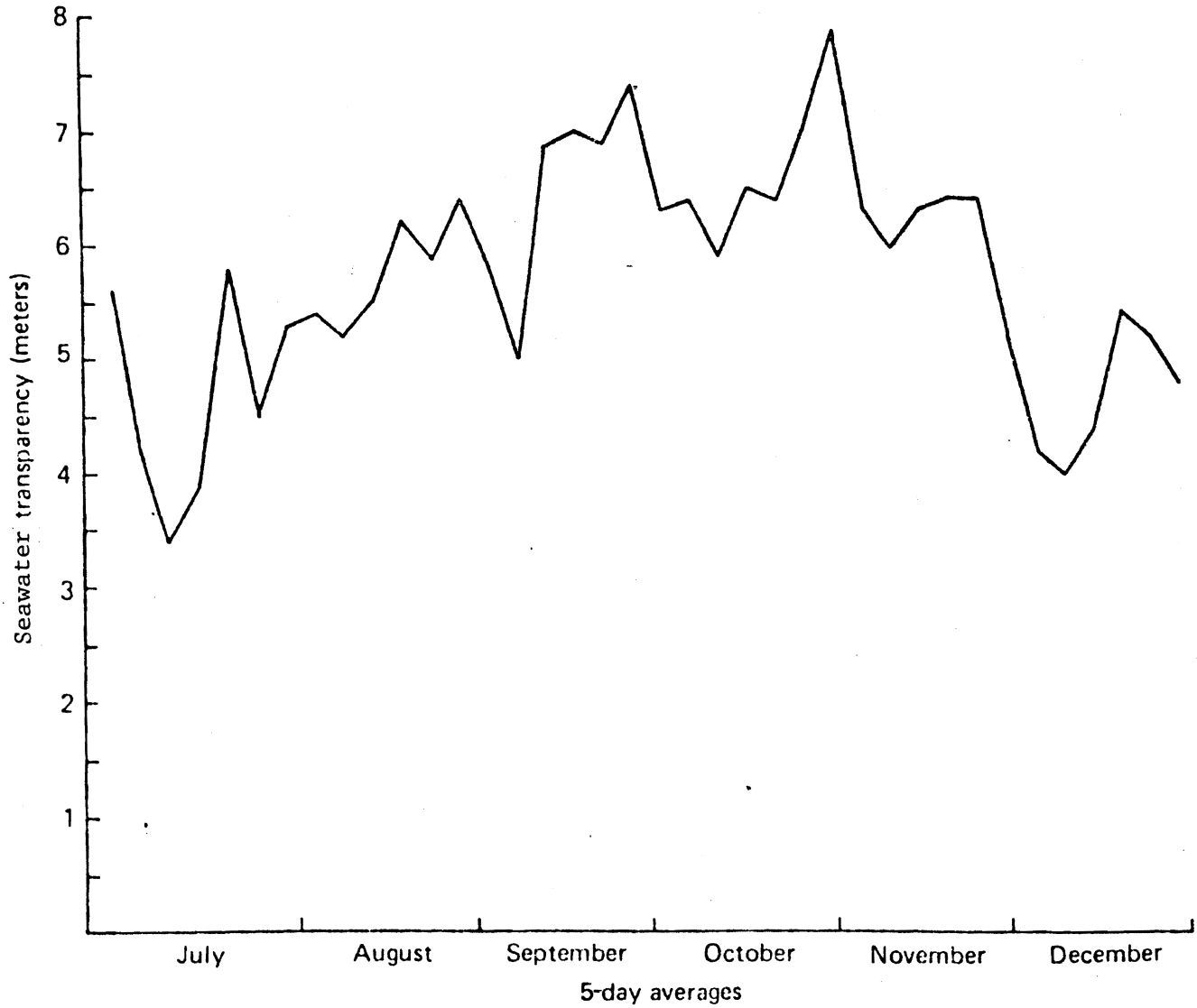


Figure 5.--Seawater transparency in Clam Bay, Puget Sound, Washington as determined by Secchi disc during the study period.

mid-September. A decrease in water transparency during early winter was attributed to an increase in turbid freshwater runoff and not phytoplankton growth.

DO is a factor that can limit loading density in seawater net-pens. The critical level of DO for salmonids is 6 parts per million (ppm) in fresh water; fish are stressed below this level (Jones 1964). If sublethal DO levels are prolonged, food consumption and fish growth are greatly reduced (Davison et al. 1959; Herrmann et al. 1962). This effect is presumed to occur in seawater at the same DO levels.

The annual average of surface DO for central Puget Sound is 11 ppm in early spring (April-May) and a minimum of about 6 ppm in early autumn (Friebertshauser et al. 1971). This autumn depression is primarily from surface water being replaced by water of lower DO from depth (Moring 1973).

The autumn DO depression is a critical period for the culture of fish in net-pens, for water already at or near the critical DO level is further lowered by the presence of fish. This was observed in a test pen during late October when ambient (i.e., outside pen) DO was 5.8 to 7.4 ppm while inside the 4.0 $m^3$, pen (64.1 $kg/m^3$) DO was 3.4 ppm. This low DO lasted up to 10 minutes on both days of monitoring and occurred during a period of slack water and reduced water transparency (Figure 5). No difference between pen and outside DO measurements had been detected during the early September DO measurement period when ambient DO was 8.6 to 8.7 ppm and water transparency was low.

A difference between inside and outside pen DO was also detected during the final DO measurement period in December. In December, the ambient DO was 7.9 to 9.9 ppm, but the DO level inside the 4.0 $m^3$ pen (64.1 $kg/m^3$)

was consistently lower by 0.3 to 3.0 ppm. In all periods, DO generally followed the rise and fall of tidal current velocity which in turn corresponds to the tidal cycle.

Free flow of water through a net-pen is obstructed by fouling organisms attached to the netting. As the amount of fouling increases, metabolic waste removal and DO are reduced. The exchange of water in and out varies greatly as fouling increases (Honma 1971). In addition, fouled nets are deformed by currents more than clean nets reducing the volume that can be used by fish (Okabayashi 1958). In September, the pens were relatively clean of fouling organisms compared to the October and December DO monitoring periods, and this partly explains the lack of a detectable difference between DO inside and outside net-pens at that time. In addition, there was greater tidal exchange in September.

MORTALITY AND OTHER FISH LOSS

Mortality remained low in all test pens throughout the test period and was never serious enough to require medication. Tissue samples from moribund fish were plated on an irregular basis, and 15.7% of these contained furunculosis (*Aeromonas salmonicida*). Mortality among the parred fish at the onset of the study was primarily from this disease.

Vibriosis strains 775 and 1669 were detected but accounted for only a few mortalities (6.5% of the plated fish). This disease increased near the end of the study as blood titer levels dropped.

Mortality did not exceed 23.2% for any one test group (Table 1). Temporary increases in mortality, up to 0.3% per day, occurred primarily among the parr and transitional stages after each monthly sampling period.

Mortality records were kept on each net-pen to estimate average fish growth per test period. Major discrepancies between actual count and inventory records occurred among several test pens (Table 1). These losses were from holes in nets, predation, unhooked pen corners, and dead fish not removed from the net-pen. The major loss was thought to be from otters which were trapped in the vicinity of the net-pens after the study.

Unaccounted for losses or gains (e.g. fish jumping to adjacent pens) ranged from 8.5 to 58.3% in individual net-pens at the end of the study (Table 1). The rate, time, and the manner in which the losses occurred cannot be determined due to only partial population sampling of the net-pens during the course of the study. Inventory discrepancies precluded statistical and detailed descriptive interpretation of the data as related to the effect of pen volume and/or loading density on growth, survival, and status of smoltification. The study did, however, suggest several trends that will be described.

LOADING DENSITY AND PEN VOLUME EFFECTS

The observed trends are based on the growth and survival of smolted fish. Parr and transitional stage fish, even though possibly influencing the behavior, growth, and survival of the smolts, contributed little to the biomass and showed slow growth. However, because of the unaccountable fish losses, the effect of the parr and transitional stage fish on the smolts could not be determined.

No effect of pen volume on the growth of smolted fish was seen during the 5 months of testing (Figure 6). However, by the 4th month a loading density effect on mean smolt weight began to appear. These differences,

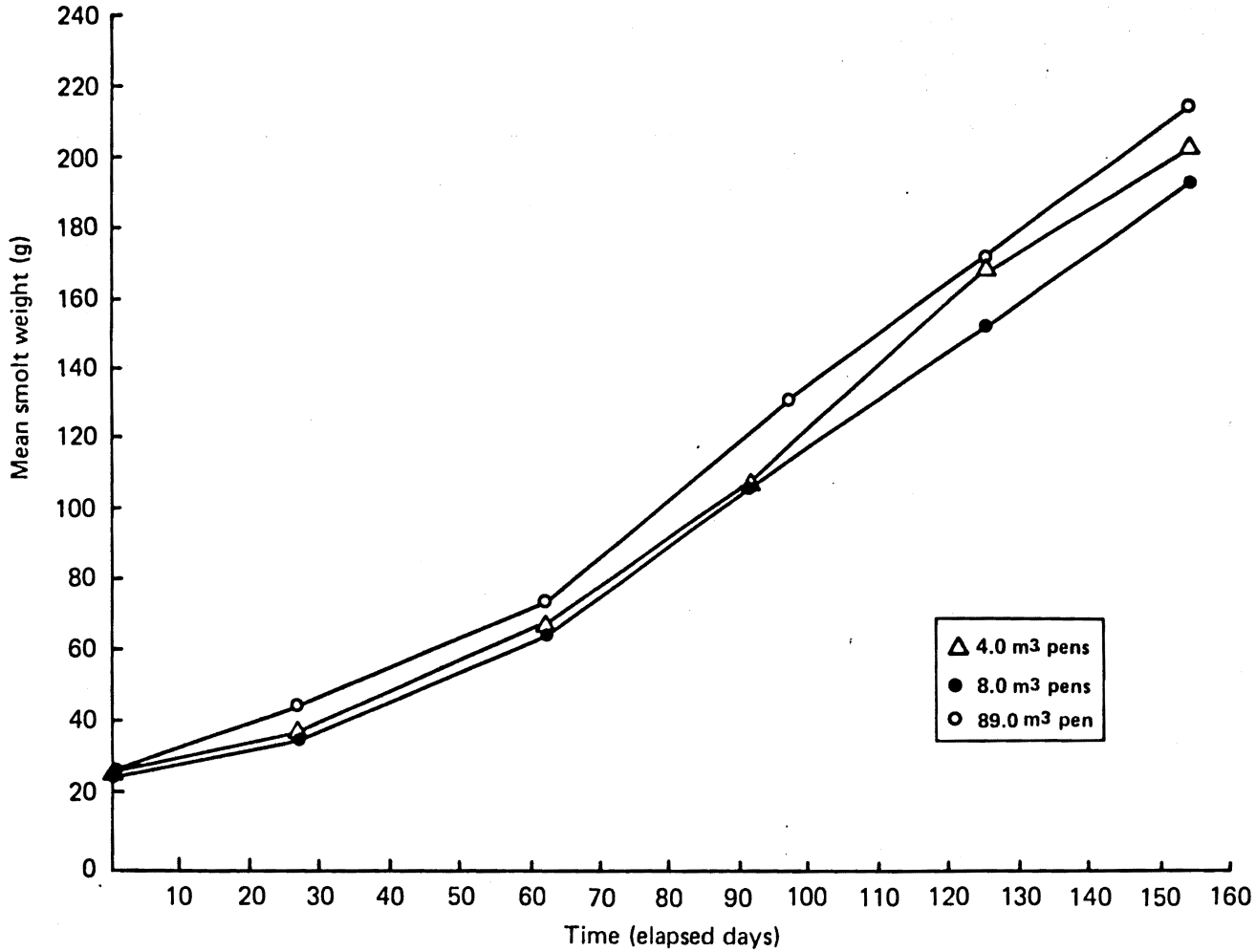


Figure 6.--Mean smolt weight vs time for combined loading densities at three pen volumes.

however, cannot be statistically evaluated because of the unaccountable losses and high standard deviations among the test groups (Table 3).

There was a tendency for growth of the smolted fish to be inversely related to density. There was no specific deflection point in the growth curves which could be related to density. We believe, however, that a density effect did occur, but the significance of the effect cannot be specified because of unaccountable fish losses.

## CONCLUSIONS AND RECOMMENDATIONS

No statistical evaluation and little descriptive interpretation of the loading density and pen volume data could be performed because of the extensive unaccountable fish loss from the test pens and the high standard deviations of mean weight among the test groups.

Although the results of the study were affected by unaccountable fish loss, there were two general trends: 1) growth of smolted fish was generally inversely related to density. No specific deflection point in growth as related to density could be shown because of the above stated problems; and 2) there was a tendency for a change in growth rate between the different density test groups for the three pen volumes after the 4th month of culture.

For unknown reasons, the fish in the 89.0 $m^3$ pen at a density of 32.1 $kg/m^3$ performed as well as those in the 4.0 $m^3$ pens.

The outcome of this study points to the problems of unaccountable fish losses or inventory accountability--a problem not only with large scale

experimentation but with those involved with fish production. Unless this problem is solved, little meaningful data can be derived from large scale studies such as the one conducted.

It is recommended that once the problem of inventory discrepancy is overcome, that a study again be conducted to determine optimal loading density of Pacific salmon in floating net-pens. This study should be conducted over several years to also evaluate the effects of environmental conditions and disease transmission. The study should also use various pen sizes from the sizes used in this study to those used in production systems. If no pen volume effect is shown, future studies may then use small test pens to evaluate the interactions of density, fish size, species, disease transmission, etc. on growth and survival at other rearing sites with corresponding low risk.

Environmental conditions become increasingly important as the number of net-pens in a rearing system is increased. Increasing the number or the arrangement of pens may alter water exchange rates. This may result in reduced DO and/or accumulation of metabolic wastes. One strategy may be to use concentric zones of pen density with lower densities near the center of the pen system and increasing outward. Density zonation may then allow more efficient use of existing rearing facilities and help to increase production.

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