Dissolved-gas supersaturation was monitored in the American River during 1982-1983 and 1985-1986. Dissolved gas levels during spring and summer were considerably higher than had been reported necessary to produce increased mortality due to chronic gas bubble trauma (gas bubble disease) in hatchery salmonids. The source of this gas supersaturation was from natural mechanisms: air entrainment, solar heating, and photosynthesis. During central California's major flood of February 1986, acutely lethal levels of gas supersaturation (200-240 mm Hg) were present in the American River and resulted in significant mortality of salmonid fishes at the American River and Nimbus hatcheries. The most probable source of this gas supersaturation was air entrainment at Folsom Dam. The impact of the high dissolved gas levels in hatchery water supplies was reduced with the installation of degassing structures in the raceway headworks.

INTRODUCTION

Dissolved-gas supersaturation can be a serious problem for aquatic animals under natural and hatchery conditions. In rivers with extensive hydro-power development, air entrainment at spillways is a major source of acutely lethal dissolved gas levels to fishes during high flow periods (Weitkamp and Katz 1980). In the Columbia and Snake river basins, dissolved-gas problems have necessitated modifications to spillways (Smith 1974) and water releases (USACE 1986) to protect juvenile salmonids. The presence of large reservoirs can significantly increase both magnitude and duration of downstream dissolved gas levels, even during non-spill periods. This may be due to the capture and retention of highly supersaturated water during the spring, and solar heating and photosynthesis within the reservoir.

Gas supersaturation (ΔP) was measured as the difference between total dissolved
gas pressure and the local barometric pressure (Fickeisen et al. 1975). The biological effects of a given ΔP depend on the depth of the animal in the water column, temperature, animal size and species, and nitrogen:oxygen ratio (Alder, Rice and Jensen 1985). Typically, a given ΔP will have a greater impact on fish in hatcheries than fish in open water due to differences in nutrition, longer exposure period, crowding, and shallow depth of most culture systems (Colt 1986). In a given river system, the level of gas supersaturation may show strong temporal and spatial variation. Information based on a small number of measurements may be highly misleading. Here we report our investigation into the seasonal variation of gas supersaturation in the lower American River in central California. The purpose of this study was to document the dissolved gas levels in the lower American and assess potential impact on fish under natural and hatchery conditions.

MATERIALS AND METHODS

The main fork of the American River is dammed in its lower portion by Folsom and Nimbus dams (river kms 46.6 and 33.0, respectively), and then flows into the Sacramento River at Sacramento (Fig. 1). Dissolved gas levels were generally monitored monthly during 1983 and 1985-86 at two locations: “hatchery” and “river”. The hatchery site was in the headworks of the earthen raceways of the Nimbus Salmon and Steelhead Hatchery, which receives its water by gravity flow behind Nimbus Dam (Lake Natoma). The river site was monitored from the bank of the river below the dam, between the Hazel Avenue Bridge and the hatchery fish barrier. Dissolved gas data for 1982 were taken from Colt (1984a) for the river site and at Discovery Park, 32.5 km downstream. There was little difference in that study in ΔP between the “river” and Discovery Park sites.

Gas supersaturation was measured with an ES-2 “Weiss Saturometer” (ECO Enterprises, Seattle, Washington). The saturometer was immersed in the water up to the pressure gauge (about 1 m) and pumped every 2 min until a stable reading was obtained (25-30 min). Water temperatures and dissolved oxygen (DO) concentrations were measured using a DO probe (YSI Model 54RC) and calibrated based on values developed by Weiss (1970). Measured DO readings were corrected for pressure using the barometric pressure from the nearby NOAA weather station at the Sacramento Executive Airport. Preliminary flow data from the Fair Oaks gauging station (about 200 m below the river site) were obtained from the U.S. Geological Survey.

RESULTS


During 1982, 1983, and 1985, the ΔP patterns were mixed: 1982 and 1983 patterns were relatively stable, while the 1985 ΔPs were stable during late winter-spring then declined from July through December (Fig. 2). The maximum ΔP occurred during the spring and early summer. Except for 1982 ($r^2 = 0.70$), the ΔP was not significantly
correlated with either flow or temperature. The yearly maximum ΔP measured ranged from 58 to 94 mm Hg (Table 1).

<table>
<thead>
<tr>
<th>Year</th>
<th>Site</th>
<th>Maximum ΔP (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982</td>
<td>river/discovery</td>
<td>72</td>
</tr>
<tr>
<td>1983</td>
<td>river</td>
<td>94</td>
</tr>
<tr>
<td>1985</td>
<td>river</td>
<td>56</td>
</tr>
<tr>
<td>1986*</td>
<td>hatchery</td>
<td>237</td>
</tr>
<tr>
<td>1986*</td>
<td>hatchery</td>
<td>79</td>
</tr>
<tr>
<td>1986*</td>
<td>river</td>
<td>195</td>
</tr>
<tr>
<td>1986*</td>
<td>river</td>
<td>82</td>
</tr>
</tbody>
</table>

*Flow > 300 m/s
*Flow < 300 m/s

Gas Supersaturation in 1986 - Flood Period

A major flood event occurred in the American River basin in February 1986 (Fig. 3). During February of that year, the measured ΔP in the river and hatchery were very high (195 and 237 mm Hg, respectively). The highest ΔPs were observed at the highest water flow, although not enough data were available to develop predictive regression curves. Also, the effects of Nimbus Dam on river ΔP was not conclusive.

Gas Supersaturation in 1986 - Nonflood Period

The ΔP was relatively constant in the river and hatchery during April-June and increased during July-December. ΔP was not significantly correlated with either flow or temperature in either the river or hatchery. In general, ΔP in the river was higher than in the hatchery during March-June (Fig. 2). The average temperature in the river was 0.2°C higher than in the hatchery during this same period.

DISCUSSION

Gas Transfer at Dams

The amount of air transferred into the water at a hydraulic structure depends on the velocity head of the jet into the tailwater, the shape of the jet, the basin length and depth, water temperature, initial dissolved gas level, and flow over the spillway (Johnson and King 1979). At a given dam, the ΔP resulting from air entrainment is typically a linear function of the spilled flow (D’Aoust and Clark 1980, USACE 1986, White et al. 1986). At very high flows, the ΔP-flow curve may flatten out or even decrease (Alderfice and Jensen 1985, USACE 1986) because of radical changes in the
Figure 2. Seasonal variation in the American River. Dashed line is the current USEPA criterion for fish of 76 mm Hg (total gas pressure = 110%).
Figure 3. Variation of (a) mean daily river flow and (b) $\Delta P$ upstream and downstream of Nimbus Dam during the 1986 flood.
flow patterns over the structure. For a given flow, a higher $\Delta P$ will result from higher dams due to greater jet velocity. At dams with several types of spillways, the resulting $\Delta P$ will depend strongly on the type of spillway(s) being used (White et al. 1986). The variation of $\Delta P$ with water flow in the American River showed the characteristic positive slope, but not enough data were collected during this relatively brief event to adequately define the curve.

**Gas Supersaturation Potential of Lower American River**

The hydraulic height of Folsom Dam is 82 m compared to 14 m for Nimbus Dam (USDI 1981). Therefore, the potential for dissolved-gas entrainment at Folsom Dam is probably greater than Nimbus due to its higher hydraulic height and resulting higher exit velocity (Roesser and Norton 1971, Johnson and King 1979).

The dissolved gas entrained in a series of dams such as Folsom and Nimbus dams will depend on several factors for each dam: (i) influent dissolved gas concentrations, (ii) hydraulic height, (iii) type of spillway(s), and (iv) turbine capacity. The turbine capacity at Folsom Dam (217 m$^3$/s) is greater than at Nimbus Dam (133 m$^3$/s) (USDI 1960a, 1960b). Folsom Dam has two types of spillways: eight gated ogee (12.8 m wide × 15.2 m high) and eight curved sluices (1.5 m wide × 2.4 m high) located in the spillway section (USDI 1960a). The sluices are used to regulate flows < 895 m$^3$/s as passed over the ogee spillways. The jet angle of the sluices is much shallower than the ogee spillways, and as a result, may produce less gas supersaturation per unit flow. The use of these two different types of spillways may aid to reduce the amount of entrained gas released from Folsom Dam during low flows compared to the potential from the 18 radial-gate spillways at Nimbus (USDI 50b).

Depending on the river flow, four different spill flow regimes are possible (Table 1). The observed change in $\Delta P$ as the water flowed over Nimbus Dam is due to the complex interactions of the differences in hydraulic heights, turbine capacities, and spillway characteristics of the two dams and the upstream gas conditions. A continuous monitoring system at a minimum of four points on the lower American River will be needed to fully document the gas entrainment characteristics of this sloped river system.

Table 1. Potential flow regimes affecting dissolved gas levels below Nimbus Dam, American River, California.

<table>
<thead>
<tr>
<th>Flow (m$^3$/s)</th>
<th>Folsom</th>
<th>Nimbus</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;133</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>134-216</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>217-895</td>
<td>yes - curved sluices</td>
<td>yes</td>
</tr>
</tbody>
</table>
during high water flows. The presence of dams on the American River probably has had a significant effect on gas supersaturation even when water was not being spilled due to a number of mechanisms. During the spring, the ΔP of the water filling the reservoir may be as high as 65 mm Hg (Colt 1984a), probably due to natural air entrainment in streams. Thus, Folsom Dam captures this supersaturated water and releases it over the next 6 months, or more. Assuming that Folsom Reservoir was filled in 1986 with saturated 12.1°C water in February, solar heating to 15.8°C in June could produce a ΔP = 59 mm Hg if no gas transfer occurred (Colt 1984b). Photosynthesis may also tend to increase the ΔP, especially in Lake Natoma due to its shallow depth. The slow decrease in ΔP during the summer was probably due to biological oxygen consumption that reduced the partial pressure of dissolved oxygen and due to increased degassing of nitrogen in the river as flow decreased. The lack of a consistent significant linear correlation between ΔP and temperature or flow is a result of these five complex mechanisms operating simultaneously.

The longest period of high ΔP during summer months occurred in 1983, a year with 234% of normal annual runoff (Fig. 2). During this year, the ΔP exceeded 76 mm Hg for at least 4.5 months. In contrast, following the flood in 1986 (79% of normal annual runoff), only one measurement exceeded 76 mm Hg. The variation of maximum yearly ΔP in the American River: during non-flood conditions may be influenced by the ΔP, temperature, filling rate of Folsom Reservoir, rate of temperature increase in the reservoir during the spring, biological oxygen demand in the reservoir, and reaeration in river. Additional research is needed to better identify the significant mechanisms that account for both the seasonal and year-to-year variation.

Effects of Gas Supersaturation in the American River

The present United States water quality criterion for gas supersaturation is 110% total gas pressure (TGP) or ΔP = 76 mm Hg (USEPA 1976). On a chronic basis, ΔPs in the range of 30-40 mm Hg can result in increased mortality of fish in hatcheries and shallow rivers (Cornacchia and Colt 1984, Alderdice and Jensen 1985, Wright and McLean 1985).

Significant mortality of salmonids occurred in the American River and Nimbus hatcheries during the flood period of 1986 (R. Ducey, Calif. Dept. Fish and Game, pers. comm.). While final hydrologic analysis of this flood has not been completed, it was a relatively rare event with a reoccurrence interval greater than 100 years. A perforated horizontal screen was installed at the exit from the headworks, so the water flowed over and through the screen as it entered the raceway. It has been the observation of hatchery personnel (R. Ducey, pers. comm.) that river flows greater than 1,000 to 1,500 m³/s will produce clinical signs of gas bubble trauma in the hatchery. Using a critical value of 1,000 m³/s, the last 22 years of stream flow data for Fair Oak gauging station were reviewed. There were 5 events that exceeded 1,000 m³/s for at least 4 days and 12 events that exceeded 1,000 m³/s for 2 days. These events were unevenly distributed over the reviewed time period, with the greatest frequency occurring during 1964-1970 and 1979-1986. Based on this flow data, the yearly
probability of gas bubble trauma problems may range from 0.23 to 0.77.

In the Columbia River Basin, elevated dissolved gas levels have been controlled by the addition of “flip-lip” spillway deflectors (Smith 1974), continuous monitoring and telemetry of dissolved gas levels on a real-time basis, and forecasting of dissolved gas levels and scheduling of spilling to control dissolved gas levels (USACE 1986). The impact of gas supersaturation could be reduced by installation of more efficient degassing systems at the hatchery (Cott 1986).

Gas supersaturation in the American River showed a characteristic seasonal change as well as significant year-to-year variation in the maximum level and duration of high ΔP. The presence of Folsom and Nimbus dams probably have a major influence on gas supersaturation in the lower American River.

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LITERATURE CITED


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