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Successes and failures of acoustics in the measurement of environmental impacts

Percy M. Washington[a], G.L. Thomas[b] and D.A. Marino[c]
[a]*GAIA NW Inc., 10522 Lake City Way, Seattle, WA 98125, USA*
[b]*Prince William Sound Science Center, Cordova, AK 99574, USA*
[c]*BioSonics Inc., 3670 Stone Way N., Seattle, WA 98103, USA*

ABSTRACT

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The use of hydroacoustics has grown in response to the need for more accurate information to manage fisheries. Parallel to its increasing importance to fisheries management has been the expansion of its use for environmental impact assessment. Applications of acoustic technology to estimate the vulnerability of fish to entrainment by cooling water intakes, irrigation drawdown, and turbine operations at hydroelectric dams have led to operational and engineering methods to minimize harmful effects on fish populations. In addition to reducing detrimental effects, the use of acoustics to estimate fish densities before and after underwater blasting operations has led to increasing work windows for bridge and harbor construction. The recent application of acoustics to measure nuisance growths of aquatic macrophytes in shallow, freshwater lakes is leading to techniques for quantitative assessment of fish habitat, which will be equal if not more important to environmental impact evaluations and fisheries management in the future. Successful applications of hydroacoustics to environmental impact assessment are primarily attributed to the researchers having the ingenuity to overcome common biological and engineering limitations, whereas, the failures are not.

INTRODUCTION

The continuous growth of the world's population has caused increased demands for the harvest of fisheries resources. As full exploitation of the economically attractive fishery resources is reached, more stocks will be overharvested and others will collapse (Royce, 1989). The challenge to management is to establish better regulation of fishery harvests so that fish populations can be maintained at high levels of abundance and surplus production. A prerequisite of establishing the high sustainable harvests of fish is having accurate enough information on the stock size to render timely and appropriate management advice to decision makers (Eggers, 1992).

Correspondence to: P.M. Washington, GAIA NW Inc., 10522 Lake City Way, Seattle, WA 98125, USA.

The technology and use of hydroacoustics has grown in response to the need for more accurate information to manage fisheries (Thorne, 1983). Moreover, acoustical information has been found useful for evaluating more than just the effects of fishing activities. Quantitative assessments of aquatic resources, such as fish stocks, are fundamental to determining causal relationships. One spin-off from the research and development of quantitative techniques for fish stock assessment has been the use of acoustics for assessing environmental impacts.

Application of hydroacoustic methods in environmental impact studies began in the early 1970s. Initial applications monitored fish entrainment in cooling systems of power plants (Thomas, 1979; Thomas and Johnson, 1980). Subsequent studies measured passage rates of juvenile salmonids past Columbia River dams (Carlson, 1982a,b), evaluated reservoir drawdown on standing stocks of fish (Thorne and Thomas, 1984), determined the effects of underwater blasting operations on fish assemblages (Thomas and Washington, 1986, 1987, 1988a,b, 1990), and the estimation of aquatic macrophyte biovolume (Thomas et al., 1990b). This paper reviews some successful applications and the most common causes of failure of acoustics for evaluating environmental impacts.

SUCCESSES

Estimation of the vulnerability of fishes to entrainment

In the early 1970s, power plants along the southern Californian coastline were required to show that they were using the best technology available to minimize fish entrapment. Despite the considerable effort expended to evaluate fish entrainment in cooling water intakes, these data were inadmissible without accounting for the fish density in the near field being affected by the intakes. Without definitive information to demonstrate that the best technology had been used to mitigate for fish losses, power companies faced a probable requirement of having to install multimillion dollar cooling tower technology. This presented a dilemma because many of the plants were in coastal zones with strict restrictions on vertical construction; they faced possible shutdown.

Between 1976 and 1980, Thomas (1979) and Thomas and Johnson (1980) applied mobile acoustic methods to estimate the temporal and spatial variability in fish density in the vicinity of nearshore cooling water intakes at Southern Californian coastal power plant sites. The first demonstration of density-dependent fish entrapment was made. This led to the study of entrapment vulnerability of fish. An index of entrapment vulnerability was developed. When modified for the effects of water quality, the index was used in a unique, in situ experimental design to determine operational and engineering approaches to minimize fish entrapment, such as reduced nighttime flow and velocity caps. This research provided a significant part of the best-technology demonstration requirement. Cooling tower installation, plant shutdowns, and huge costs to the public were avoided.

Estimation of downstream passage rates

Studies of the efficiency and effectiveness of juvenile salmonid bypass systems at Columbia River Basin dams have been conducted since the 1960s. Initially, special fish trap systems were designed and used to determine the location, timing and migration patterns of downstream emigrant fish through dams. Early information indicated that fish migrants which passed dams over the spillway survived at higher rates than those passing through turbines (Bell and DeLacy, 1972; Raymond and Sims, 1980).

Carlson (1982a,b) commenced stationary hydroacoustic sampling in conjunction with fish traps to evaluate the quality of catch data in 1979. He found that there was significant avoidance of traps by migrating fish which introduced an unknown bias into historical passage rate information by species, size, density and distribution of downstream emigrants passing through turbines and over spillways. Hydroacoustic methods are credited with having vastly improved the quality of information available on fish abundance, distribution and movement on downstream migrant passage through dams (Carlson, 1982a,b,c; Carlson et al., 1982; Karp and Sullivan, 1982; Dawson et al., 1982; Johnson et al., 1982, 1984; Gyldenege et al., 1983; Raemhild et al., 1983, 1984a, 1984b; Karp et al., 1984; Johnson and Schadt, 1986).

Today, hydroacoustics provide standard information for two primary purposes on the Columbia river: (1) identification of migratory periods so turbine and spill flow configurations can be regulated to decrease passage mortality and conserve water for energy production; (2) to experiment with different measures that could modify fish migration, and potentially increase the survival of downstream migrating smolts while reducing water spillage (Johnson et al., 1992).

Entrainment of fish from impoundments

A common problem in water storage reservoirs in the US is the loss of fish populations as water is drafted for irrigation, power generation, or other purposes. Often fish populations that reside in reservoirs constitute valuable economic resources which support sport or commercial fisheries. Unfortunately, data on stock size, distribution, and behavior required to estimate fish losses or how to minimize them are seldom available.

Hydroacoustic techniques are used successfully in assessing fish populations in lakes and reservoirs (Thorne, 1983; Thorne and Thomas, 1984). Early acoustic assessments of fish were limited to the limnetic zone. Thorne and Thomas (1984) showed how to extend sampling to near-surface and near-bottom species. These methods are applied to estimate fish populations in lakes and reservoirs throughout Alaska and the US where this information can help management decisions.

An example of this is found in the Yakima River Basin storage reservoirs in Washington State. These reservoirs are managed for irrigation purposes by the US Bureau of Reclamation, yet also provide significant habitat for sport fish species such as kokanee (land-locked sockeye salmon — *Oncorhynchus nerka kinnerli*). Mongillo and Faulconer (1980) suggested that a 'minimum pool' be established for reservoirs and maintained to protect the kokanee and other fish populations. Lacking sufficient data to determine the savings achieved by a 'minimum pool' management policy the scheme was not considered economically feasible as it traded potentially saleable water for an unknown savings of a fishery resource. In 1983 and 1984, hydroacoustics was used to estimate the kokanee population size before and after drawdown to minimum pool in Rimrock reservoir which provided the first evidence that minimum pool management was successful, and justifiable.

Effects of underwater blasting on fish

Underwater blasting for the maintenance and construction of waterways and harbors is practiced throughout the world. Underwater shock waves created by explosive processes can cause severe injury and death to nearby fish assemblages. The physical damage caused by explosion-generated shock waves has been documented by numerous researchers (Aplin, 1947; Hubbs and Rechnitzer, 1952; Hubbs et al., 1960; Kearns and Boyd, 1965; Christian, 1973; Falk and Lawrence, 1973; Yelverton et al., 1975; Fukuhara et al., 1978; Umezawa et al., 1978). The rapid rise, and subsequent fall of hydrostatic pressure to below ambient, are the properties of underwater explosions that cause damage to fish. Negative pressure waves are considered the primary cause of damage to internal organs of fish, especially to the gas bladder.

Numerous measures were historically used to predict the lethal range of a shock wave. The maximum shock wave overpressure, P_{max} (in bars or lb in^{-2}) was used to predict lethal range by Hubbs and Rechnitzer (1952), Hubbs et al. (1960), and Falk and Lawrence (1973). Sakaguchi et al. (1976) pointed out that explosions having the same P_{max} can have different rise times and duration pressures, and different effects on fish. Sakaguchi found higher positive correlations between damage and the energy flux density (E_f), but unfortunately predictions of the propagation of sound in field situations are difficult so pre-blast estimates of E_f are seldom reliable. Theoretical model predictions are generally inconsistent in predicting damage because of the inability to predict sound propagation in shallow areas with hard bottom, under ice cover, or in a variable detonation configuration. Even if theoretical estimates of lethal range were accurate, impacts of blasting on fishes would still be dependent upon the density and distribution of fishes in the impacted area. The temporal–spatial dynamics of fishes are often too variable to predict, requiring in-situ measurements. The application of hydroacoustical techniques is appropriate for this task because of sampling speed, and the relatively high precision of its estimates ($CV<0.25$). Traditional sampling with nets to estimate fish density is less precise ($CV>0.40$) and logistically unfeasible in most blasting areas.

The mortality resulting from underwater blasting on a fish assemblage is dependent upon fish density within the lethal range of the explosion. To minimize fish kills, fisheries management agencies in the north-Pacific US have established 'work-windows' during the year when blasting operations are permissible, usually between migrations of smolt or adult salmonids. 'Work-windows' often span several months and occur during spring, summer, or fall seasons when underwater construction is most logistically efficient. These restrictive measures are the result of an inability to theoretically predict within-season patterns of fish densities at specific sites.

Thomas and Washington (1990) used hydroacoustics to make rapid measurements of fish density in the vicinity of underwater blasting sites to estimate and minimize fish losses. Reconnaissance surveys were conducted to establish baseline data on the ambient densities of fish in the area. These estimates could be used to identify time intervals of low fish density. After selection of a low density period for blasting, pre-blasting surveys were conducted to estimate fish density. This estimate was compared in real-time to confirm low fish density conditions. Finally, post-blast surveys were conducted to measure the density and distribution of fish, and an estimate of fish mortality was calculated for remunerative purposes.

Typically, pre-blast fish assemblages were composed of primarily single fish and fish schools. After the blasting operations, schooling fish were dispersed as single targets throughout the water column. These schools were sometimes too dense to count and required echo-integration. Post-blast vertical distributions of fish allowed for higher precision estimates of fish density and provided a means to verify theoretical estimates of lethal range for the underwater blast on the fish assemblage.

At a blasting site in the Duwamish River, Washington, baseline surveys suggested that the site was dominated by small single fish targets, −70 to −45 dB (identified to be primarily embiotocids) and relatively dense fish schools (identified to be juvenile Pacific herring). In an August pre-blast survey, a high percentage of targets were large single fish and groups of large single targets too dense to count as single targets, up to −26 dB, which were identified as adult chinook salmon. The blasting operation was postponed and mortality to migrating chinook salmon avoided. Post-blast surveys were subsequently used to estimate the total fish mortalities caused by blasts. Mortalities were primarily subyearling juvenile Pacific herring, which because of size and numbers were of relatively small economic importance.

Estimation of the plant bed biovolume of aquatic plants

Nuisance infestations of aquatic macrophytes have become a common problem in freshwater lakes, reservoirs, and ponds throughout the world in the past decade (Rottman and Anderson, 1986; Thomas and Pauley, 1989). Management agencies with responsibility for water flow maintenance, navigation, recreational access, water quality, and fish production have plant control programs to reclaim lost open-water habitat.

Confounding the development of methods to control aquatic plants is the difficulty in verification of the changes in the plant assemblage which requires accurate and precise measures of plant abundance before and after treatment. Surface cover or plant biomass measurements are commonly used to detect changes in plant abundance and to examine plant control practices (Payne, 1982). The surface coverage of plants is often measured using aerial photography, but surface cover underestimates plant abundance of submergent plants or when water transparency is low (Benton and Newman, 1976). When high precision and accuracy is required for evaluating aquatic plant control practices, direct collection of macrophytes using quadrat and SCUBA techniques are conducted to collect data for biomass estimation (Greig-Smith, 1964; Downing and Anderson, 1985). Quadrat sampling is, unfortunately, laborious and expensive (Downing and Anderson, 1985).

Maceina and Shireman (1980) showed that measurements with a chart recording echo-sounder could be used to estimate several variables related to the vertical and horizontal extent of aquatic plants in the water column: percent coverage, percent vertical cross-sectional area, mean vegetation height, vegetation volume, and standing crop. Maceina et al. (1984) developed a regression model using acoustic range measurements of plant height and signal amplitude information of plant density to estimate aquatic plant biomass in individual lakes. However, Thomas et al. (1985) found amplitude information from plant echoes to be unreliable for estimating density using the echo-integration technique (Thorne, 1983). By classifying plant species by their expected densities, Duarte (1987) was able to predict biomass from acoustic measurements of plant height.

Thomas et al. (1990a) made acoustical measurements of the distance between the water surface, top of the aquatic plants, and bottom of the water column using chart recording echo-sounders. The vertical cross-sectional area (m^2), height (m), biovolume of aquatic plant beds (m^3), and variances were computed for three surveys of Devil's Lake, Oregon, in May, July, and September, 1986. Coefficients of variation for the plant bed biovolume estimates in May, July, and September were 0.18, 0.05, and 0.06, respectively ($n=14$). Coefficients of variation for plant biomass estimates (g m^{-2}) that were computed from SCUBA quadrant samples that were collected concurrently with acoustic surveys, were 0.98 ($n=48$), 0.81 ($n=90$), and 1.05 ($n=90$), respectively. The higher precision of biovolume estimates allow for a 5- to 18-fold greater capability to detect a change in the mean. Plant bed biovolume is similar to the plant biomass variable because it is a way to describe the abundance or size of the aquatic macrophyte community. However, the lower costs of the biovolume estimates allow for a 10- to 33-fold greater precision-for-cost which may prove useful to plant control programs since whenever possible the most efficient statistic should be used.

Both the biovolume and the biomass variables have important ecological information that must be considered for proper application. The plant bed biovolume variable is an indicator of spatial or habitat dominance, and the biomass variable is more closely related to absolute growth or production (Cox, 1970). In many cases, lake management is primarily concerned with the amount of commercial, recreational, or habitat space lost to or degraded by aquatic plants. Therefore, it is sometimes inappropriate to use biomass to evaluate plant control. In Devil's Lake, a change in species composition of a plant community was observed to cause increases in plant biomass despite significant reductions in plant bed biovolume (Thomas et al., 1990). In such situations, the plant bed biovolume variable is more suitable than biomass for monitoring changes in the plant abundance. In contrast, when a manager must estimate plant control program costs, plant biomass may be the most appropriate variable to choose.

Ecologically speaking, the plant bed volume variable provides an indicator of habitat quantity within areas occupied by plants and free of plants (open water). The quantity of plant-occupied and open-water habitats in littoral zones of lakes plays a significant role in the production of aquatic organisms because of intra- and interspecific habitat requirements and preferences. This would be especially true if the plants exerted a significant localized impact on the water quality in the plant beds, which they do (Frodge et al., 1990).

FAILURES

In the early 1960s when environmental impact concerns became a prominent social issue, fisheries scientists were required to develop predictive capabilities (Holling, 1978). Unfortunately, the profession was limited by poor quantitative and measurement techniques. Despite these shortcomings, numerous attempts were made to predict environmental impact using traditional methods. As a result, the majority of environmental impact assessments failed (Green, 1979).

Although the fisheries sciences have become more quantitative since the

1960s, we believe that the credibility of aquatic ecology is still in question because of its reliance on traditional catch per effort (c/f) techniques to measure fish density and distribution. This we believe is a failure of our institutions of higher learning who have done wonders to improve statistical approaches to handling data, but have done little to improve the quality of measurement data. As a result, inefficient and sometimes counterproductive assessments of environmental impact are still being conducted, and it is common for lawyers representing industry to expose this weakness when impact issues are disputed in the courts.

The primary reasons for continued failure can be identified by the adage 'garbage in, garbage out'. No matter how sophisticated the experimental design or the statistical sampling techniques are, if the data used to test, build, and verify the model vary by 30%, that is all you can expect from the predictions. In the majority of environmental impact work, fisheries biologists rely on c/f measures as indices of density. However, c/f equals density by activity (Green, 1979). Since activity, as well as density of fish could both vary from zero to several orders of magnitude, the indices of density were poor at best. From estimates for best-case c/f data it appears that a CV of 30% is exceptionally good (Conquest and Loveday, 1983) (D.R. Gunderson, personal communication, 1990). Furthermore, the environmental changes expected from the impact itself, such as elevated water temperatures, lower dissolved oxygen, higher acidity, reduced light, changes in water current velocity or direction, etc. were often variables that would be expected to affect a fish's activity too! Thorne (1983) also points out that the removal of fish by capture techniques exerts a mortality on fish assemblages that is independent of, but confounding to, the assessment of the environmental impact.

Conversely, by its nature, fisheries acoustics has focused primarily on measurement quality. In response to the need to have a technique that can: (1) measure fish abundance independent of activity, thus being able to measure activity separately from density, (2) measure density independent of the environmental parameters that are expected to change, and (3) measure fish density without influencing behavior or impacting fish through capture or removal, there has been a growing number of applications of hydroacoustics for environmental impact assessment (Thorne, 1983). The studies presented in this paper are by no means comprehensive, but are just a general review of contributions being made by this technology. Also, specific failures of the application have not really been discussed, even though with every successful application there were set-backs: unknown target strengths, boundary interference, bottom intrusion, species and size identification problems, survey design, human error, and more. We have not equated set-backs with failures because it is our experience that the inability to recognize, or engineer a solution to one or more limitations to acoustical techniques, is the failure. Fisheries acousticians recognize the measurement limitations of acoustics as their primary research objectives.

Every new application of acoustics undergoes a feasibility or developmental period in which the technology is applied to acquire information to assist decision-making. Generally, the goal of an application is to obtain an absolute measure of fish density. However, other information such as vertical and horizontal distribution, temporal patterns in distribution and behavior, distributional responses to environmental perturbations, are also found to be valuable to managers. Thus, even where acoustical techniques may fail to estimate absolute fish density, its application often provides ancillary information that is significant to the decision-making process.

As researchers and managers, we are left confronted with a bright outlook that the development and application of new measurement technologies will answer many old questions and create many new ones in their place. The net result of this will be to improve our understanding of aquatic ecology. This perspective is only clouded by the problem of getting our institutions of higher learning to begin to educate aquatic ecologists in the importance of measurement and train them with the technology that is required to protect our renewable aquatic resources. This will require an adoption of physics and technology into a curriculum that has thus far only spanned the first hurdle, improving its mathematical skills.

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