Sound Exposure Criteria (for Fishes) and Their Development

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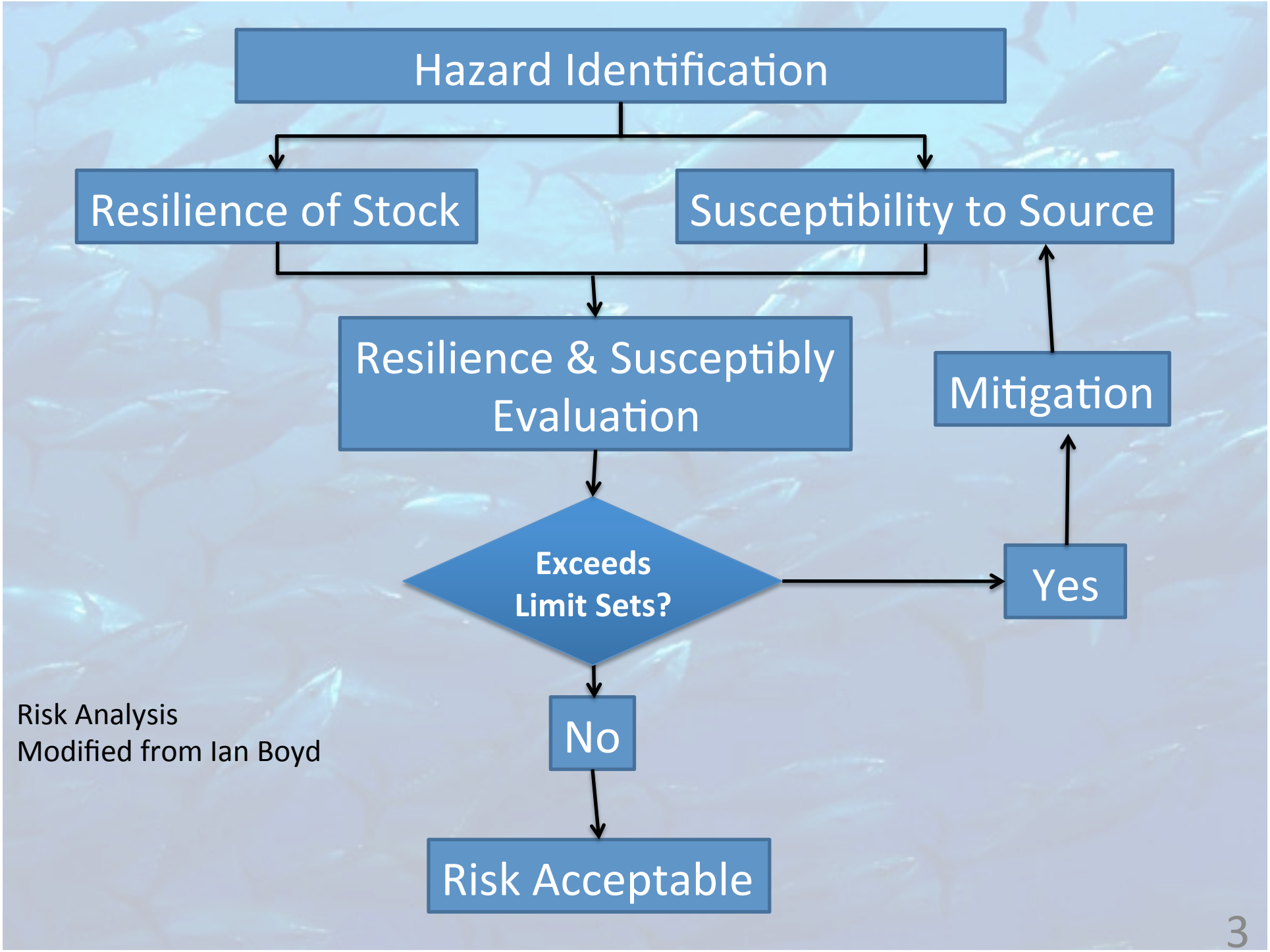
Potential effects of sound (function of sound level & type)

Sound level no longer results in any response

Relative Distance from Source Location



Risk Analysis
Modified from Ian Boyd

What Are the Issues?

- Mitigation is likely needed if a sound source impacts animals!
- But, need data on effects of sound on animals & then use these data to set levels of mitigation
- Problems:
  - Few data on how fishes, turtles, or invertebrates are affected by man-made sounds
  - Getting data is often difficult and expensive
  - Effects may differ for different sound sources (e.g., pile driving, seismic, shipping, sonars, explosions)
  - Numerous species (>33,000 fishes, >>50,000 invertebrates that might be able to hear). This diversity results in requiring study of many species

Current Criteria for Injury to Fish (USA)

Peak SPL	**208 dB re 1 µPa**
Single Strike SEL	**187 dB re 1 $\mu Pa^2 \cdot s$**
Cumulative SEL	**197 dB re 1 $\mu Pa^2 \cdot s$**

- **Note, SEL is total energy in a single sound and cumulative is sum of energy in all sounds (as in a sequence of pile strikes)**
- **NOT based on *best available science*!!!!**

Current Criteria for Behavioral Effects (USA)

- One number for onset of behavioral effects has for all species (from National Marine Fisheries Service): Sound pressure level of I50 dB re 1 IµPa as indicator of the noise level at which there is the potential for behavioral effects
- Not likely that exposure to this noise level will always result in behavioral modifications
- No one certain of origin of this value, but not based on experimental studies

Criteria for Behavioral Effects (Some UK Agencies)

- Specified (Nedwell *et al.* (2007) as weighted levels, above the dB_{ht}(*Species*):
  - 90 dB: Strong avoidance by almost all fish
  - 75 dB: Approximately 85% of fish react but there may be some habituation
  - <50 dB: Mild reactions in a minority of fish
- No data to support this. Assumes:
  - All species behave in the same way and respond in same way to the same sound levels
  - dB_{ht} based on ABR recordings, which are not valid measures of hearing sensitivity

What do We Actually Know about Effects of Human-Generated Sound on Fishes?

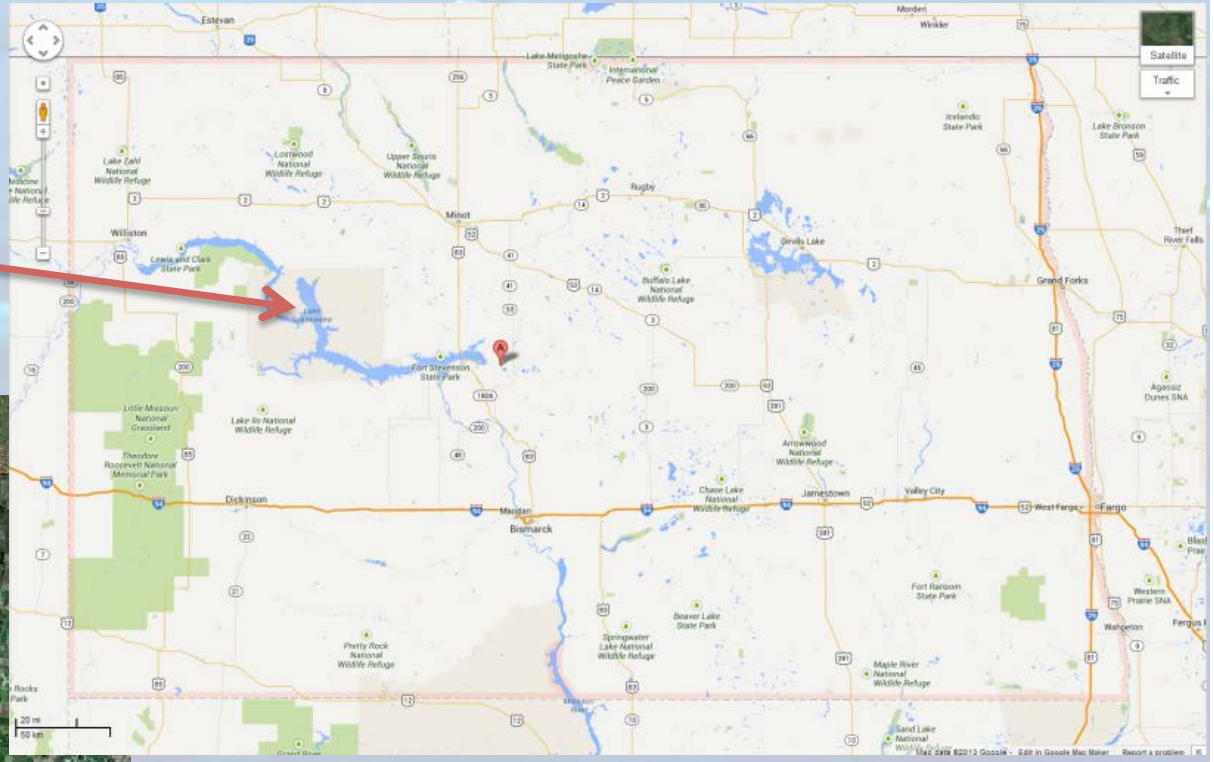
- Very little!
- Why very little?
  - Not many experiments
  - Hard to produce very loud sounds in the laboratory
  - Do not know if we can extrapolate between:
    - Sound sources
    - Species
  - Caged fish studies are not appropriate to give needed information on behavior

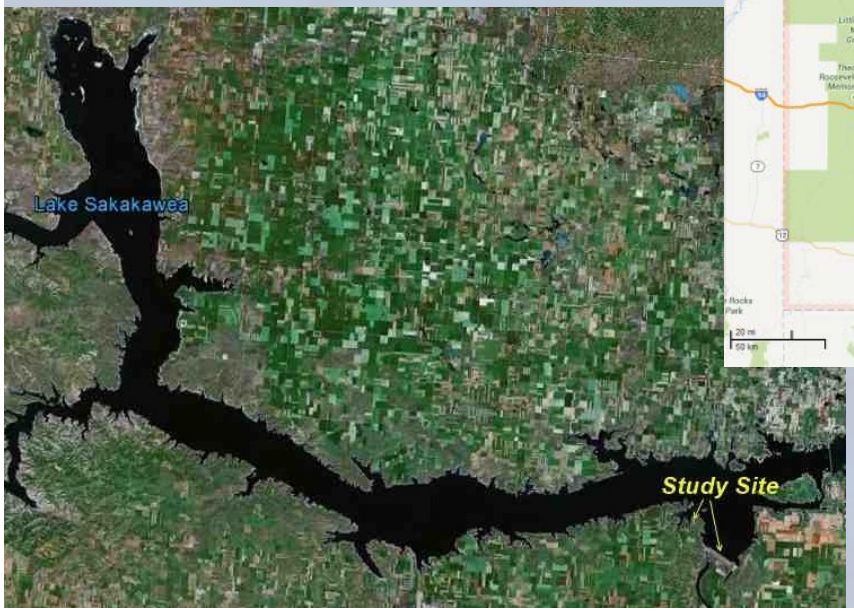
Some recent studies that give insight into potential effects

Effects of Seismic Air Gun Exposure on Fishes

(Popper, Hawkins et al. 2016)

Lake Sakakawea, North Dakota





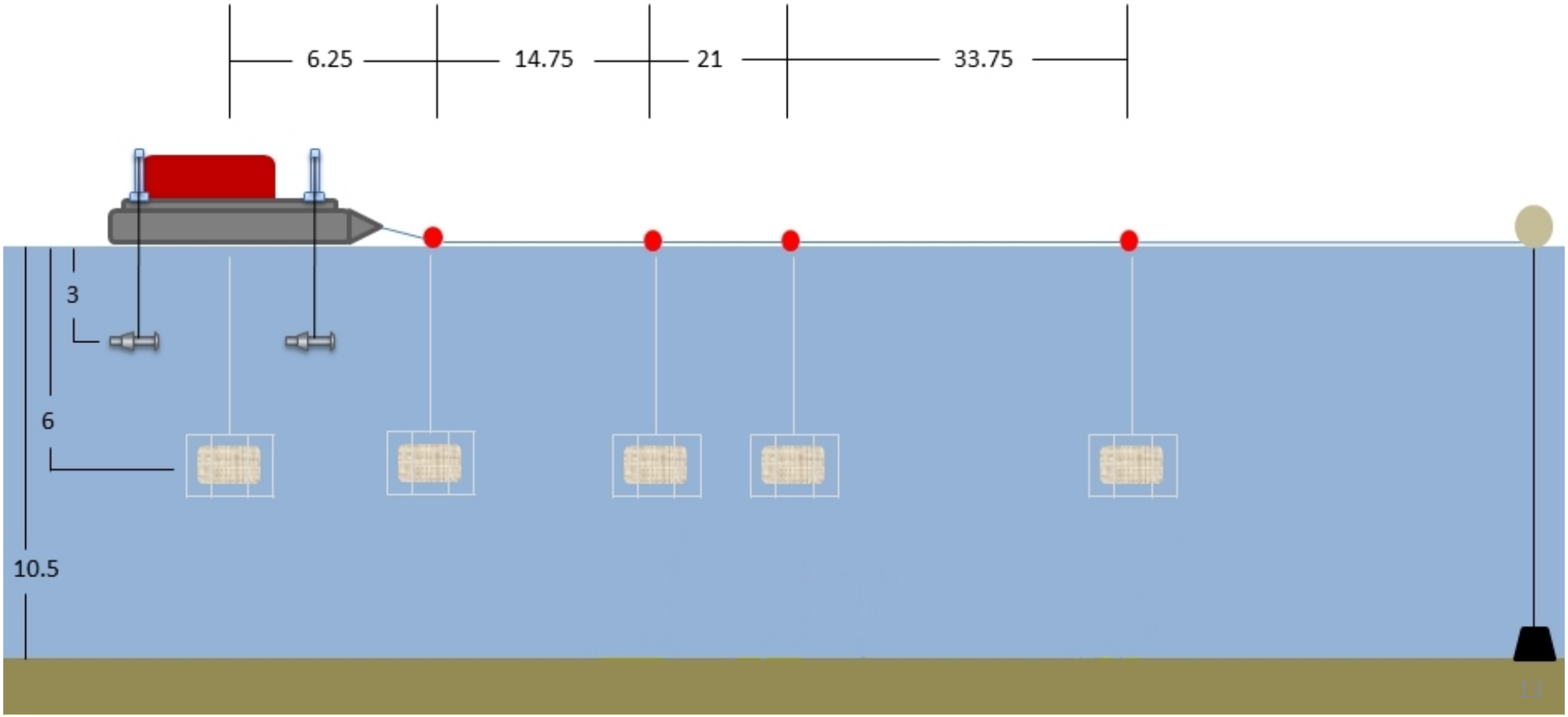
- **Study: determine effects of exposure to seismic airguns on two endangered species**
- **Examine effects on body tissues (through necropsy)**
- **Paddlefish and lake sturgeon**

Fish Exposure Paradigm

- Fish placed into test cages
- Lowered to depth
- Exposed to single seismic blast
- Raised to surface, put in holding tank, returned to hatchery
- Held 7 days, monitored for mortality
- At 7 days sacrificed
- Necropsy

Layout of Exposures

- Wanted dose/response relationship so exposed fish at significantly different distances determined by SPL
- Control did not get sound exposure



Results & Conclusions

- **Most intense sound:**
  - **peak: 231 dB re 1 µPa**
  - **SEL_{ss}: 208 dB re 1 µPa^2·s**
- **No animals died during sound exposure or during the 7 days after exposure**
- **No physical injury at any distance from source**
- **Exposure sound level higher than any SEL_{ss} in recent pile driving studies**
- **The likelihood of tissue damage is low unless the fish is very close to an airgun of much greater power than ones used in this study (and in a lake)**

Effects of Seismic Exposure on Hearing

(Popper et al., 2005; Song et al., 2008)

- Investigated effects on hearing in several species in Mackenzie river delta
- Broad whitefish
- Lake chub
- Northern Pike (adult & YOY)
- Also examined effects on ear tissues to see if there was damage

Experimental Paradigm

- Exposed fish to 5 or 20 seismic blasts
- Looked at changes in hearing
  - Right after exposure
  - 24 hours later (recovery)
- Results in terms of Temporary Threshold Shift (TTS)

- Sound levels:
  - Peak – 207 dB re 1 µPa
  - RMS – 197 dB re 1 µPa
  - SEL_{ss} – 177 dB re 1 $\mu Pa^2 \cdot s$

Results & Conclusions

- Effect of seismic exposure results in TTS in some species (e.g., lake chub), but not in others (e.g., broad whitefish)
- Hearing recovers 18-24 hours after exposure
- No damage found to the inner ears of any exposed fish
- No tissue damage
- Caveats:
  - Fish were captive, and therefore could not move between seismic shots
  - Need data from other species before conclusions reached

Effects of Pile Driving

(Halvorsen et al., 2012a, b; Casper et al., 2012, 2013a, b)

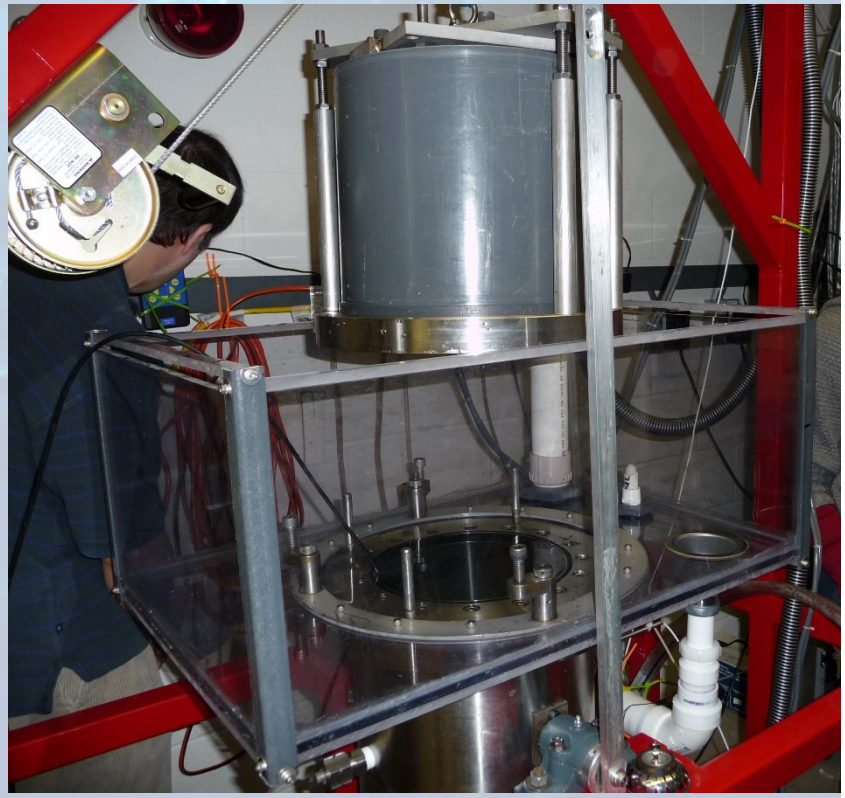
- Pile driving used in construction of bridges, piers, wind farms, etc.
- Sounds can be very loud, but there are few data on effects. Can be >250 dB re 1 µPa in water (very loud!!!!)
- Regulators limit the amount of sound fish can be exposed to before pile driving operation is shut down. The levels of sound proposed were not based on the "best available science" when they were put into place
- Current criteria not based on best available science

The Fundamental Issue

- How much sound energy can fish be exposed to before there is the onset of a physiological effect that could result in death or reduced fitness?
- Issue is accumulation of sound energy over the course of exposure to a source. Thus:
  - Exposure to one sound is likely not to have an effect
  - Exposure to repeated sounds may have an effect
  - Question: how much repeated energy will result in onset of harm

General Approach in Study

- **Fish placed into HICI-FT**
- **Exposed to sounds (varying # strikes and sound level)**



Example injury types

Mild

A: eye hemorrhage,

B, C: fin hematoma

Moderate

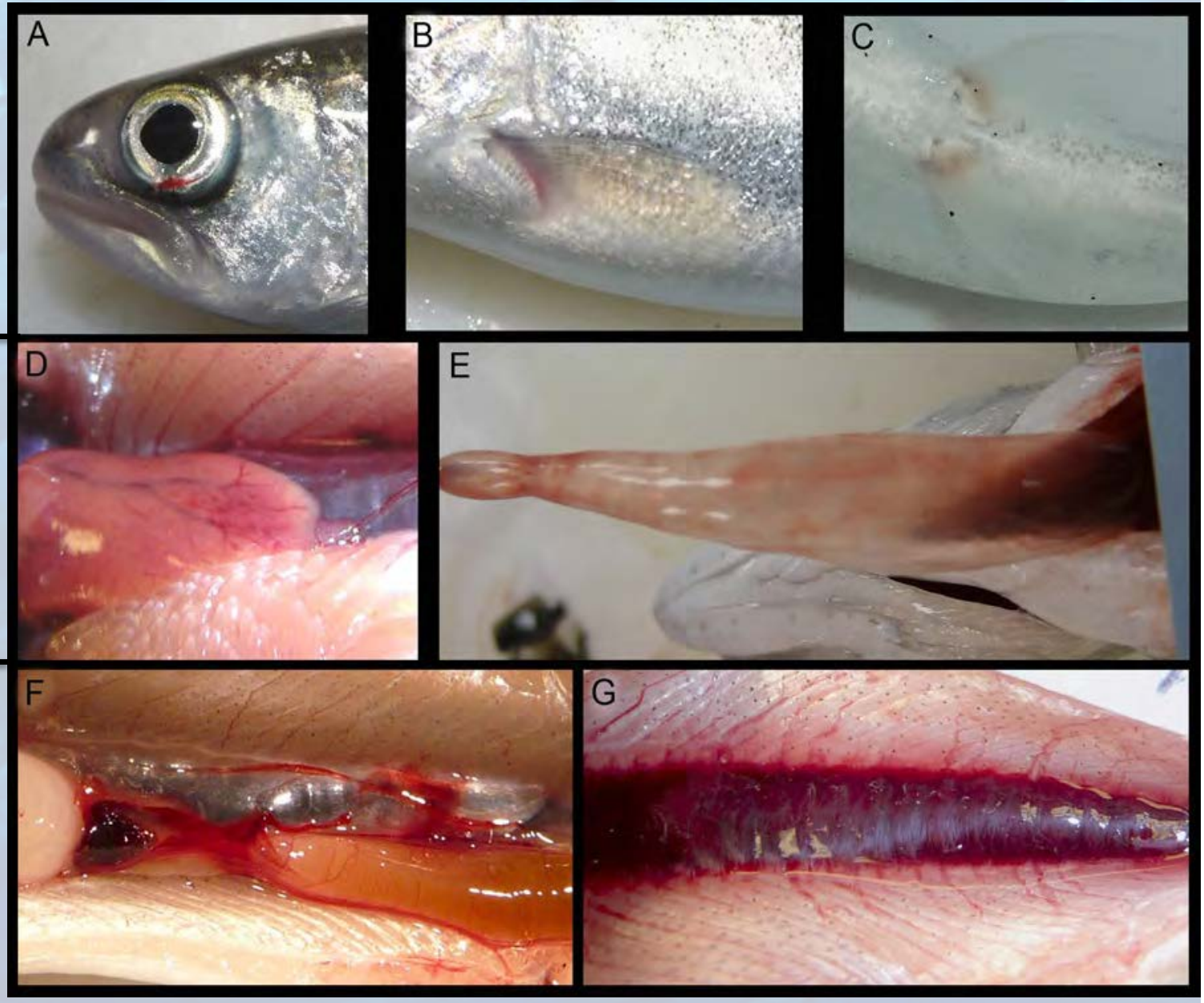
D: liver hemorrhage

E: bruised swim bladder

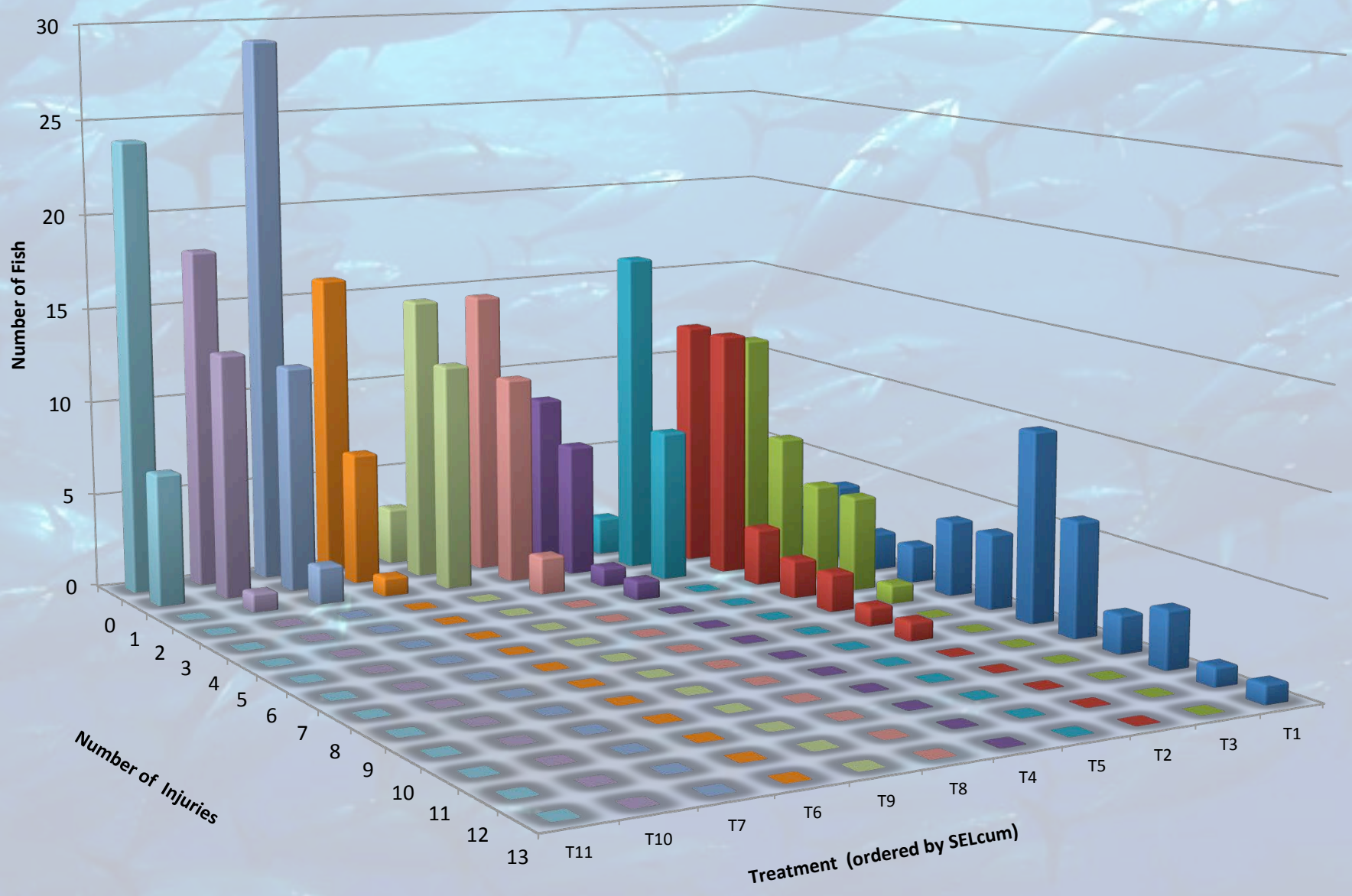
Mortal

F: intestinal hemorrhage

G: kidney hemorrhage.



Frequency of Injuries in Chinook



Overall Findings on Impulsive Sounds

- Onset of physiological effects at about SEL_{cum} of 207-210 dB
- Mortality does not occur until about SEL_{cum} of about 215 dB
- Effects are generally the same in species with very different morphologies
- No effects in fish without a swim bladder
- Recovery from non-mortal injuries takes less than 10 days
- No post-exposure injuries
- Ear damage (and presumably hearing loss) only at sound levels well above those that result in other effects

Implication of Findings

- Pile driving data show that onset of effects starts almost 20 dB higher than current standards
  - Means fish not harmed at regulatory levels
  - Much more work can be done without harm
- Results applicable internationally

Field Studies on Seismic Airguns

- Norwegian fisheries groups examined effects of seismic studies on fish catch rate
- Indication that catch rate declines in presence of airgun exposure & lasts for several weeks post exposure and then returns to normal
- Slotte et al. (2004) showed that rather than swim away, fish dive to greater depths

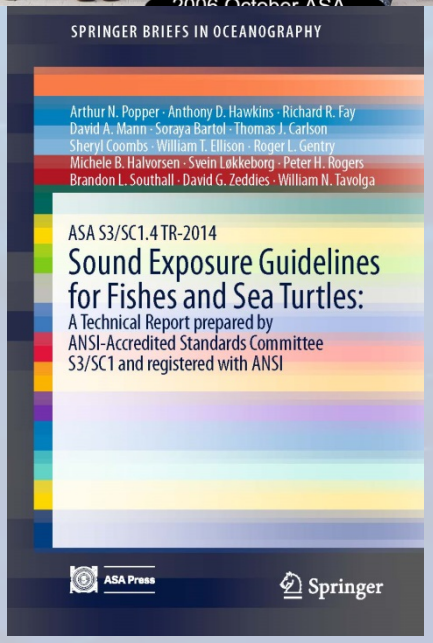
- Løkkeborg et al. (2012) showed opposite results – increase in catch rate during seismic exploration
- Recent studies in Alaska (Streever et al. in submission) show some displacement of fish near seismic studies
- Interpreting results from the studies, all from the same research group, hard:
  - Different species, locales, times of year, sound sources
- Points out difficulty in understanding data and extrapolating results within and between species

Current Needs for Future Mitigation Decisions

- Guidelines that are based on the best available science
- Understanding of what we know and do not know to guide future research (gap analysis)
- Funding for research to fill in the gaps in our knowledge

Developing Guidelines: Purpose

- Popper et al. (2014)
- Enable regulators and industry to have guidance as to what sound levels may result in *onset* of effects from various sound sources
- *Provide initial guidelines for determining amount of mitigation required for any particular project*
- In developing guidelines, need to account for different:
  - Sound sources
  - Species (and species diversity)
  - Types of responses
- Based on *best available science*
- We recognized that our proposed guidelines are interim and need constant update based on new science



Pile Driving Guidelines – An Example

Type of Animal	Mortality and potential mortal injury	Impairment			Behavior
		Recoverable injury	TTS	Masking	
Fish: no swim bladder (particle motion detection)	>219 dB SEL_{cum} or >213 dB peak	>216 dB SEL_{cum} or >213 dB peak	>>186 dB SEL_{cum}	Uncertain	Uncertain
Fish: swim bladder is not involved in hearing (particle motion detection)	210 dB SEL_{cum} or >207 dB peak	203 dB SEL_{cum} or >207 dB peak	>186 dB SEL_{cum}	Uncertain	Uncertain
Fish: swim bladder involved in hearing (primarily pressure detection)	207 dB SEL_{cum} or >207 dB peak	203 dB SEL_{cum} or >207 dB peak	186 dB SEL_{cum}	Uncertain	Uncertain
Sea turtles	210 dB SEL_{cum} or >207 dB peak	Uncertain	Uncertain	Uncertain	Uncertain
Eggs and larvae	>210 dB SEL_{cum} or >207 dB peak	Uncertain	Uncertain	Uncertain	Uncertain

But, What Don't We know?

- **Goal to identify what we don't know and priorities for future work – feed into improving Guidelines!**

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REVIEWS

Information gaps in understanding the effects of noise on fishes and invertebrates

Anthony D. Hawkins · Ann E. Pembroke · Arthur N. Popper

- **Normandeau (2012) Effects of noise on fish, fisheries, and invertebrates in the US Atlantic and Arctic from energy industry sound-generating activities. A Workshop Report for the US Dept. of the Interior, Bureau of Ocean Energy Management**

Topics in Gap Analysis

1: Background Levels of Sound in the Sea

2: Sources of Man-Made Sound

3: Sound Exposure Metrics

4: Sound propagation

5: Effects of Sound on Fishes and Invertebrates

6: Sound Production, Sound Detection and Exposure to Man-made Sounds – Invertebrates

7: Sound Production – Fishes

8: Sound Detection – Fishes

9: Masking

10: Effects of Sound in Terms of Injuries & Changes in physiology

11. Effects of Sounds upon Behavior

Some Highest Research Priorities

- **Understand aquatic soundscape from all sources, including baseline ambient conditions, how they change over time and space, and how they will be affected by additional human activities**
- **Main characteristics of the sound fields generated by human activities; expressed in terms that will enable their effects upon aquatic organisms to be assessed**
- **Effects of man-made sounds upon fishes and invertebrates**
- **Determine if mitigation measures reduce sound exposure and reduce and/or eliminate detrimental effects from sound-generating activities**
- **Describe experimental sounds properly; and conduct experiments under controlled acoustic conditions**

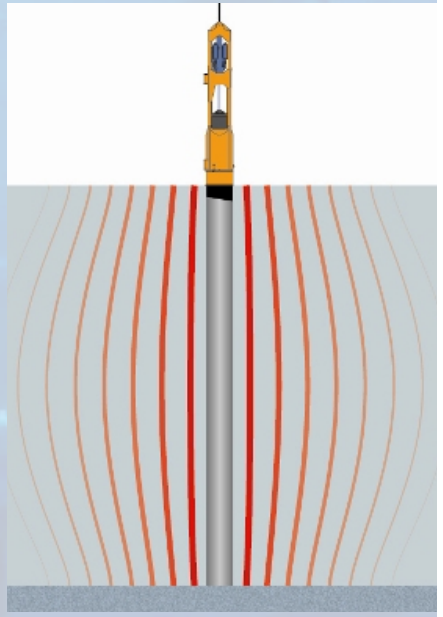
Most Critical Data Gap - Behavior

- Physiological responses, such as mortality and tissue damage, of limited importance since most fish are never close enough to the source to be affected this way
- BUT, how behavior is (or is not) altered by exposure to a sound source?
- Behavioral responses in the lab or in an enclosed area are not representative of how an animal would respond to the same stimulus in the wild
- Very hard to do behavior in the field due to problems in observing animals as they move around
  - Much easier in terrestrial vertebrates where can see animals
  - But critical if we are to make *any* statements re effects

- **Behavioral studies to date are very few for fishes, and even fewer for invertebrates**
- **And, results equivocal with many variables:**
  - **Different species**
  - **Different signals**
  - **Changes in response with age**
  - **Changes in response due to "motivation"**
  - **Changes in response at different types of day or Lunar cycle or time of year (etc.)**

Putting Mitigation in Context

- **The purpose of source mitigation is to lower the sound levels produced by man-made noise sources such as pile driving**
- **The fundamental question is *How Much Mitigation is Needed*?**



Two Approaches to Mitigation

- Set arbitrary level of mitigation (e.g., 10, 20, 30 dB) to cut the levels of man-made sounds
- Only mitigate if animal is affected by the sound
  - If no physiological and/or behavioral effects, then no need to lower the sound level
  - If there are physiological and/or behavioral effects, the goal should be to provide mitigation so that the sound level is below the level that causes the effect