Associations of injury and mortality rates of Chinook salmon with TDG below dams in the Upper Willamette River

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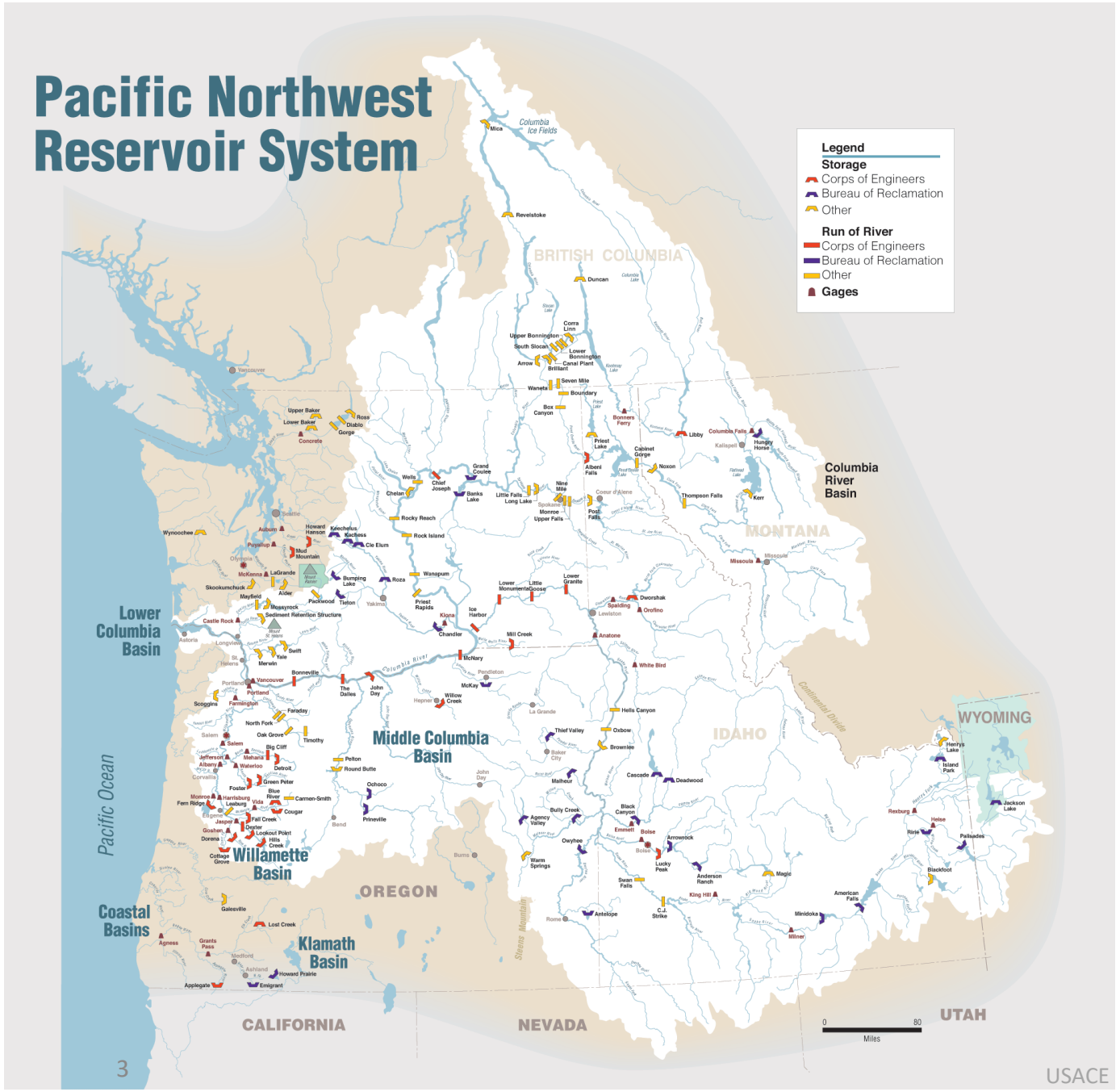
Integrated Passage Assessment

Chinook salmon *Oncorhynchus tshawytscha*

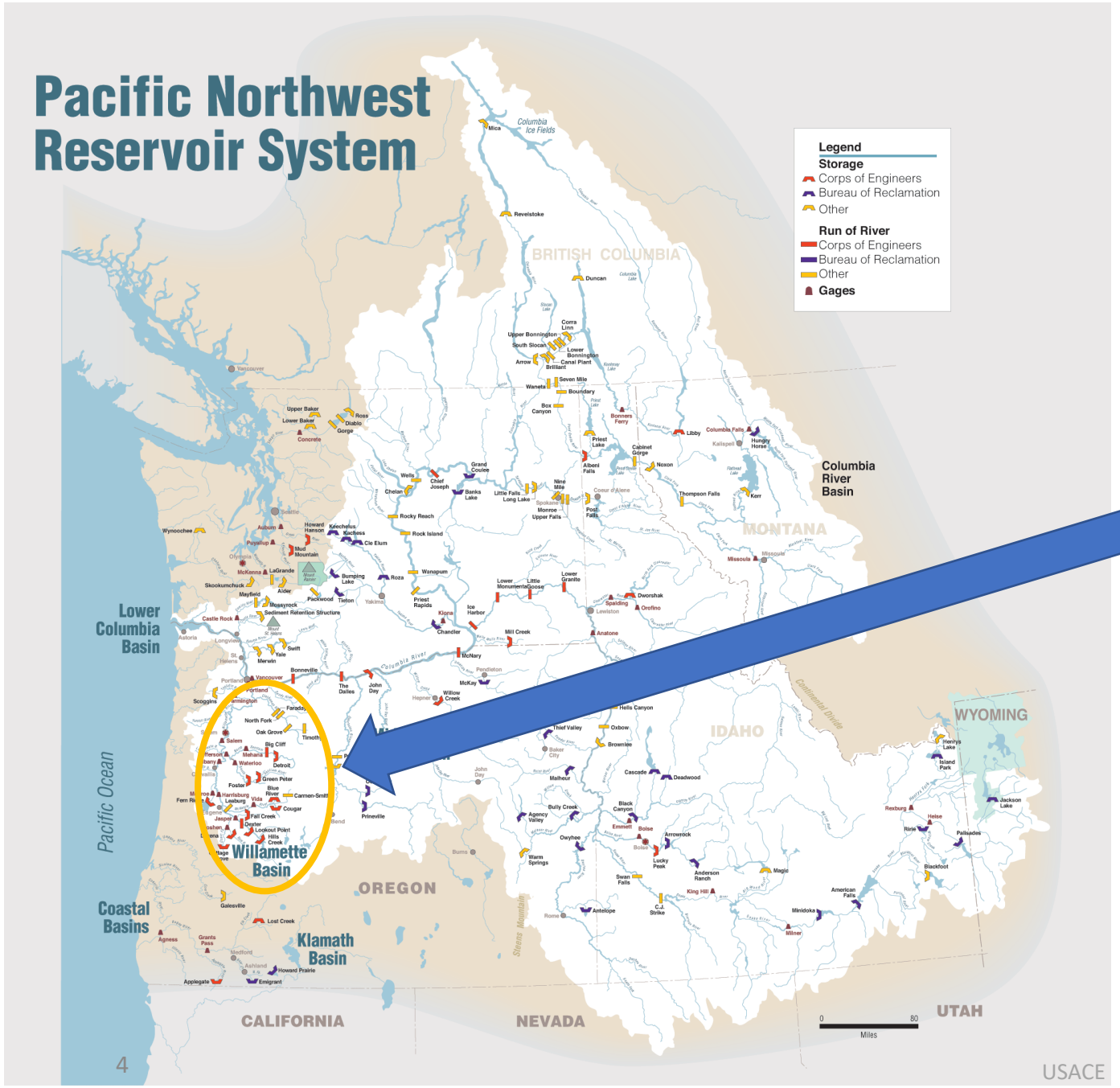
- Largest Pacific salmon: “King salmon”
- Rear in freshwater then migrate to ocean before returning as adults to spawn and die
- Many populations threatened due to:
  - Overfishing
  - Habitat loss
  - Water pollution and increasing temperatures
  - Increased pinniped predation
  - Dams

NOAA Fisheries; USACE; U.S. Department of Fish & Wildlife



- >60 dams in Columbia River Basin alone
  - Hydropower
  - Flood control
- Impacts on salmonid populations
  - Loss of access to spawning habitat above dams
  - Altered flow and temperature regimes downstream of dams
  - Total dissolved gas (TDG) supersaturation downstream of dams

Pacific Northwest Reservoir System

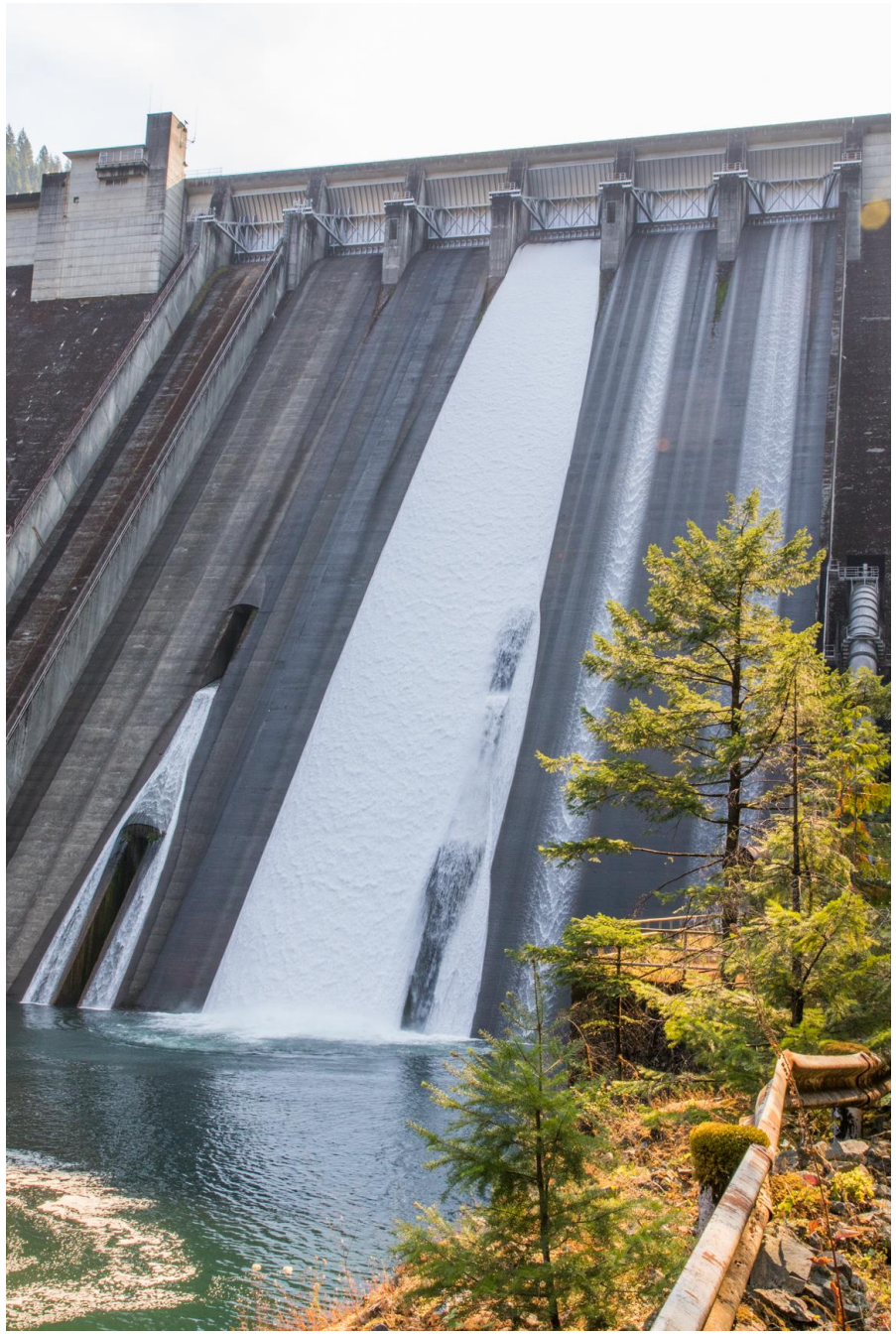


Upper Willamette River Spring Chinook salmon listed as threatened under ESA

USACE

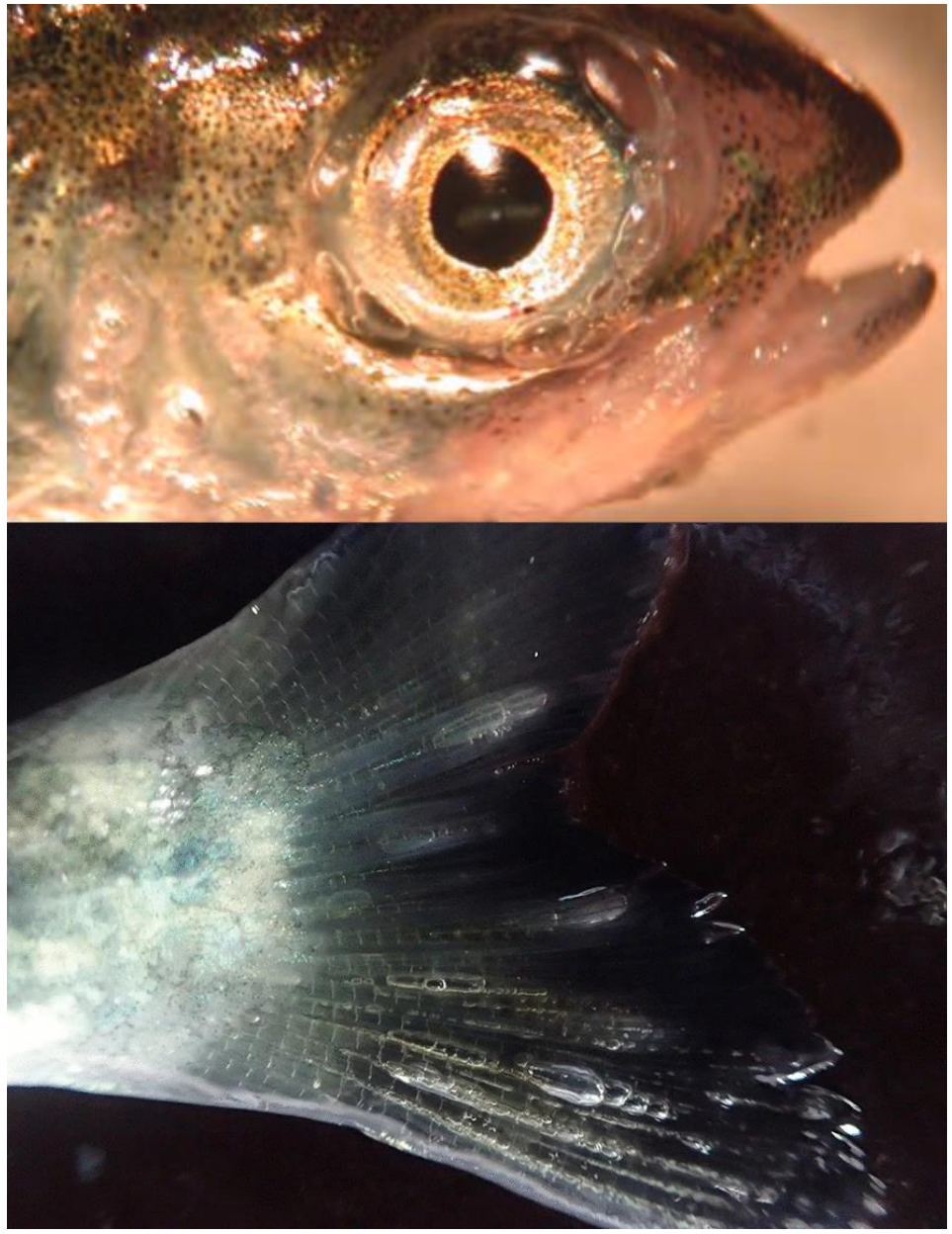
Total Dissolved Gas (TDG)

- TDG is the total amount of dissolved air in a water body
- Supersaturation occurs when water contains more dissolved gas than it can normally hold in solution at a given temperature and atmospheric pressure, i.e., >100%
- Water can contain more gas under high pressure or low temperatures
- Dam spill operations introduce air bubbles into water that is plunged deep into stilling basins or tailrace waters, entrained bubbles are dissolved into solution in deeper water
- When water returns to surface, where hydrostatic pressure is lower, it is supersaturated with TDG
- Oregon water quality standards state water saturation may not exceed 110% except under exceptional flood discharge



Gas Bubble Disease (GBD)

- GBD occurs when fish equilibrate with supersaturated TDG and gas bubbles form in small blood vessels
- Bubbles accumulate most visibly in fins, gills, eyes
- Causes sub-lethal effects that can lead to mortality
  - tissue necrosis
  - impaired development
  - increased vulnerability to disease
  - increased risk of predation
  - positive buoyancy
- Fish generally do not experience GBD at TDG <110% but threshold varies by species



Alaska Dept of Fish & Game; Stenberg et al. (2022)

Barotrauma-related injuries

- (Gas Bubble Disease)
- Bloating
- Eye haemorrhage
- Bleeding from vent
- Fin blood vessels broken
- Popeye
- … all apart from GBD may have causes other than TDG

Abatement measures to reduce TDG downstream

Operational

- Avoid passing flow via spillway
  - May compromise water storage and downstream temperature requirements
- Use multiple gates to spread total flow across spillway during spill operations

Structural

- Install spillway flow deflectors to prevent water plunging to depth
- Place boulders in the tailrace to increase dissipation

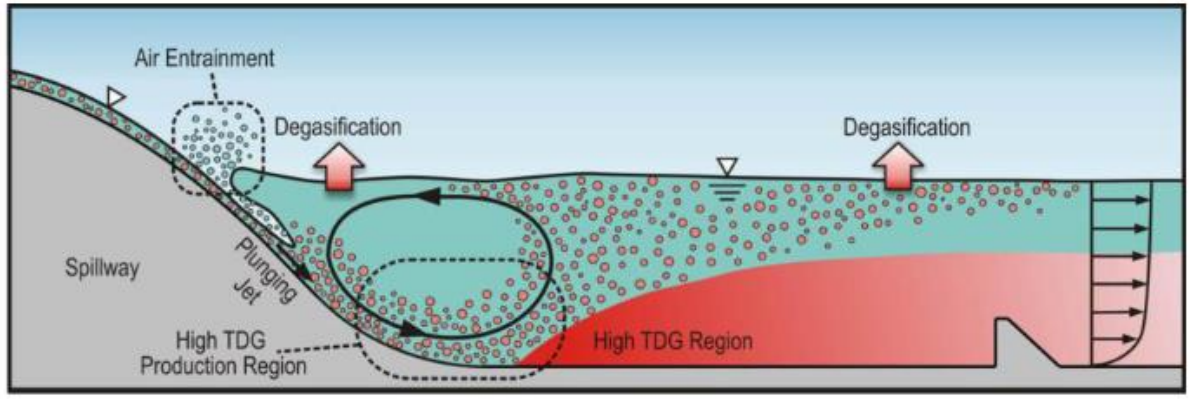


Figure 1. Air entrainment and TDG processes downstream of a spillway

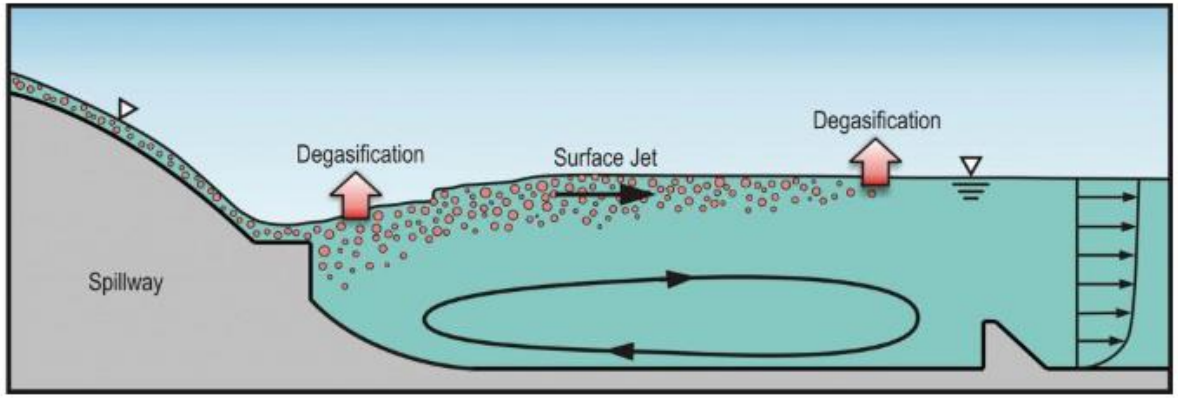


Figure 2. Surface jet in a spillway retrofitted with deflector on the spillway face

Politano et al. (2016)

Objectives

- Although well studied in the lab there is limited understanding of the effect of TDG on GBD and barotrauma injury incidence from field studies
  - Data on incidence require some form of fish trapping effort
  - Appear to be site-specific differences in level of TDG that causes an effect
- We aimed to understand the effect of TDG on GBD and barotrauma injury incidence in Chinook salmon caught below dams in the Upper Willamette River
  - Do TDG abatement measures reduce incidence?
  - Does the effect differ by site?
- Also examined for any relationship between mortality rates and TDG

Unpublished results – DO NOT CITE

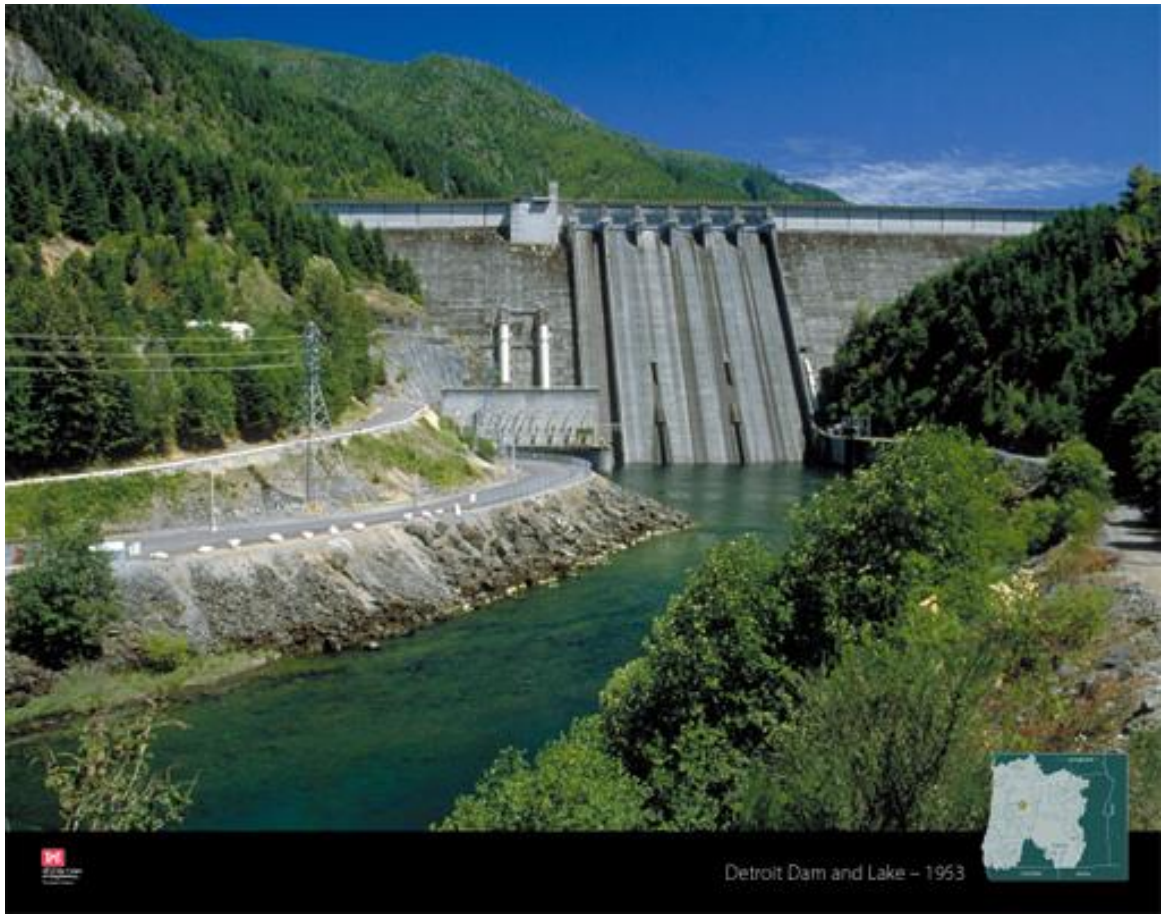
Data availability

- Juvenile Chinook salmon caught in rotary screw traps (RST) in dam tailraces
- RST typically used to monitor abundance and migration timing of juveniles
- Captured fish may also be assessed for injuries
- Willamette RST operated in two periods
  - 2011-2016 and 2021-2023
- Two traps operated where hydrological variables available in both periods
  - Spill at dams, TDG and discharge at USGS gages <1km downstream

Unpublished results – DO NOT CITE

Big Cliff Dam, North Santiam River

- Big Cliff Dam (182ft) is the re-regulating dam for Detroit Dam (450ft)
  - Provides consistent downstream flows as outflow from Detroit fluctuates



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Cougar Dam, McKenzie River

- Cougar Dam (519 ft)
  - Regulating Outlet (RO) tailrace
  - Turbine tailrace

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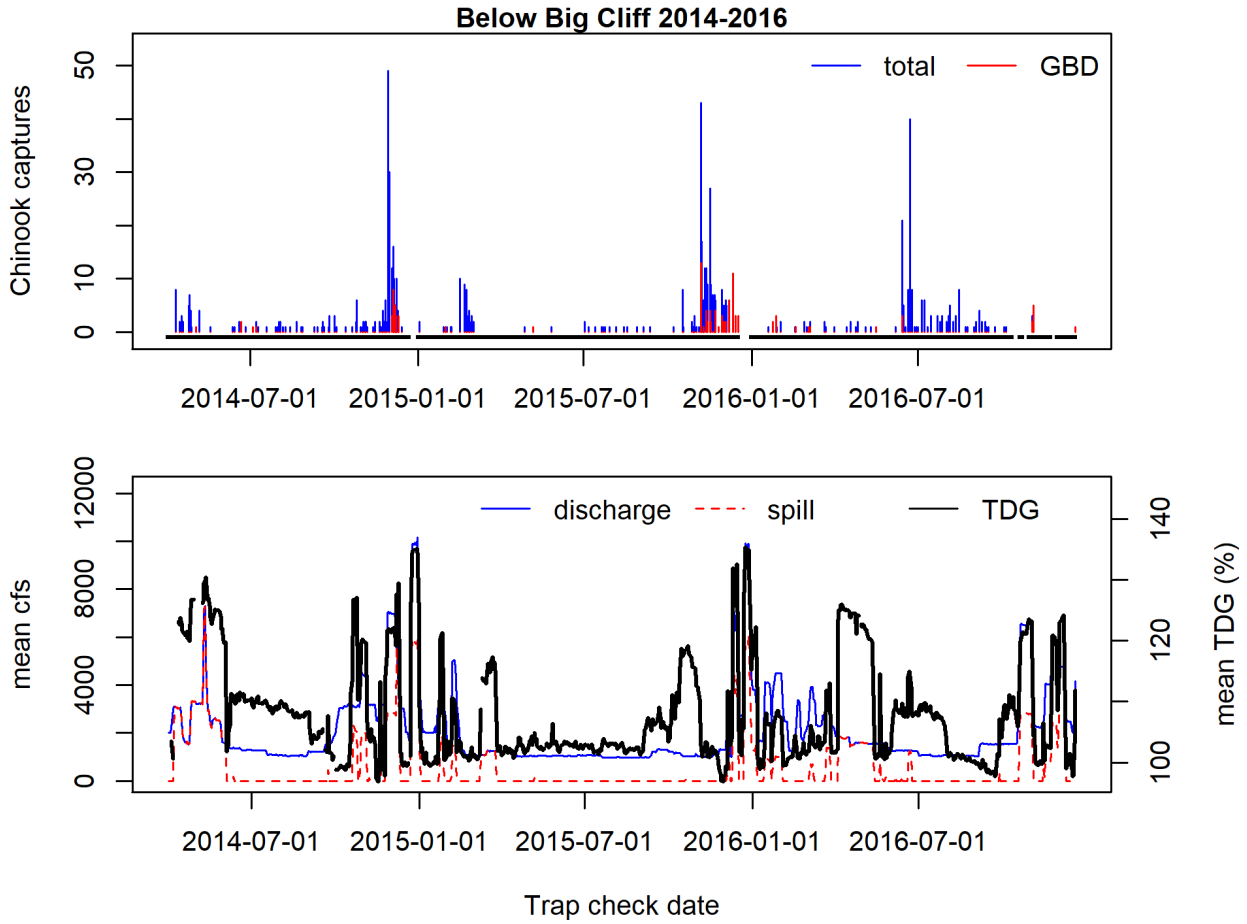
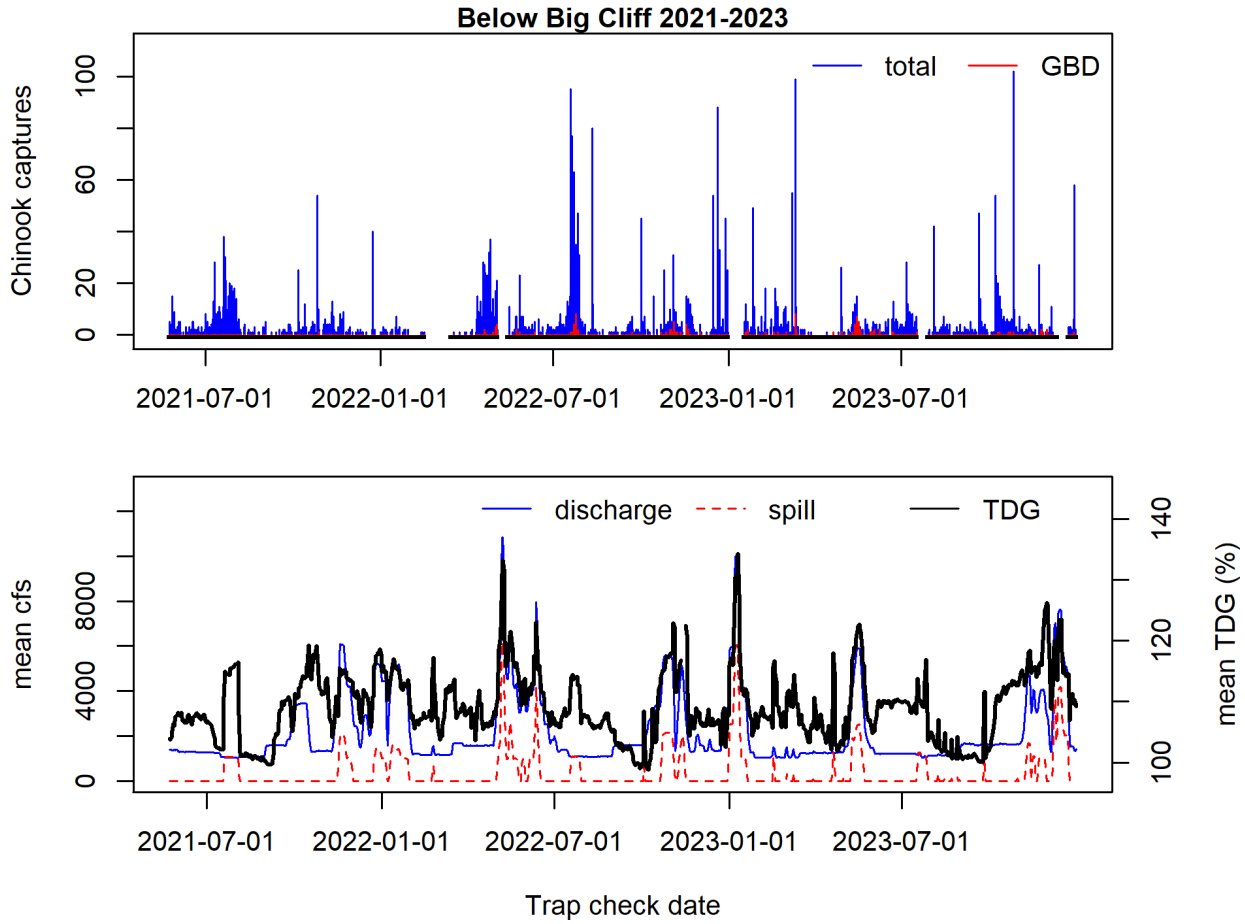
Big Cliff captures and hydrology





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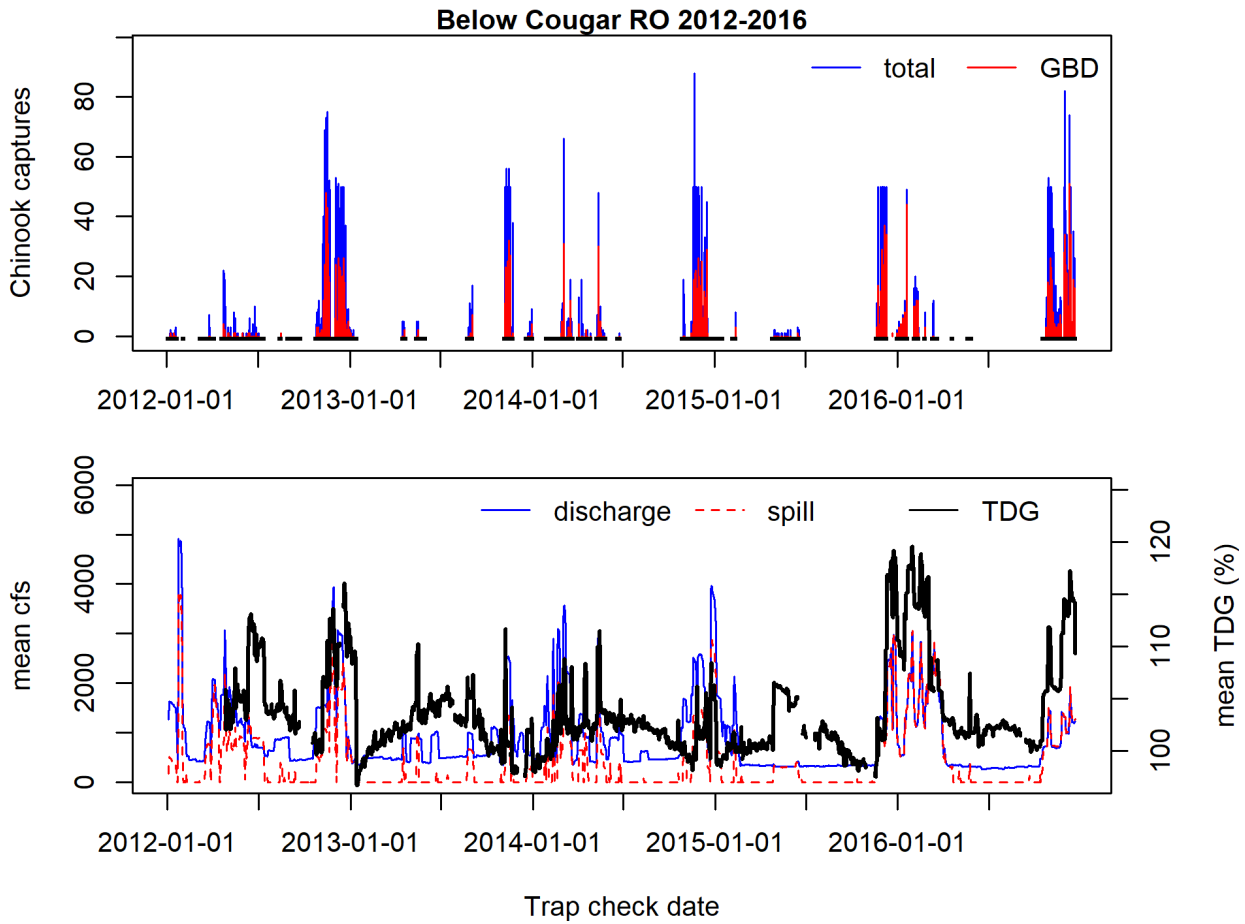
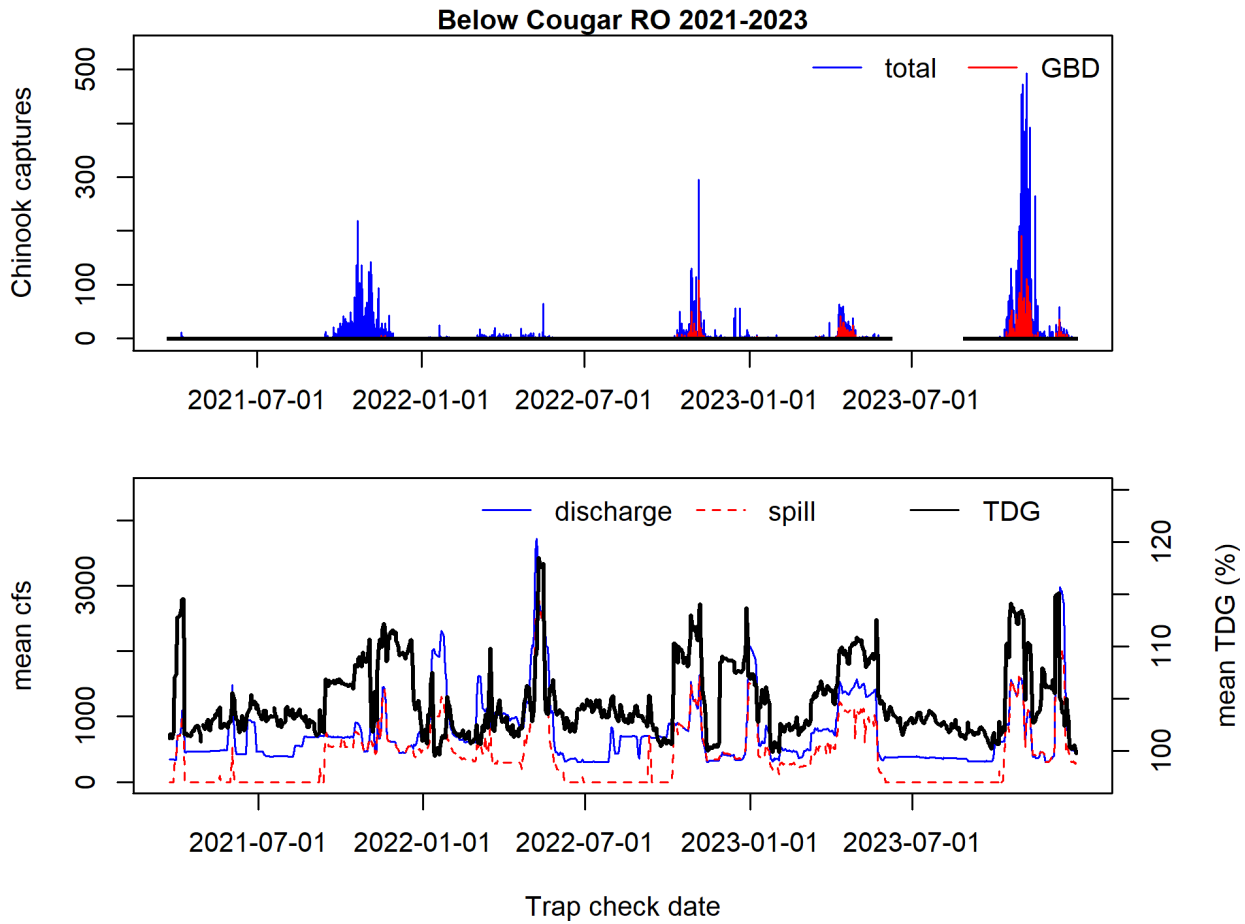
Cougar captures and hydrology





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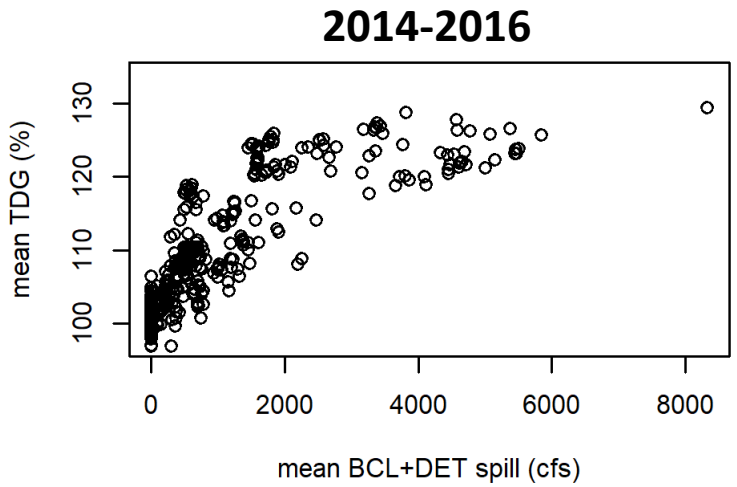
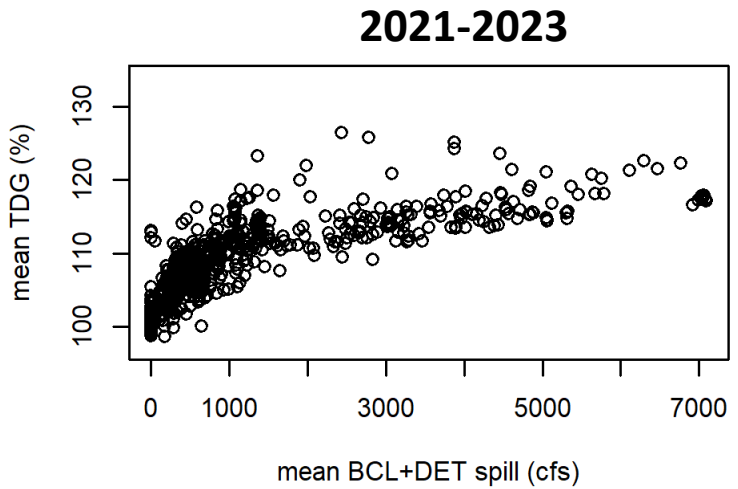
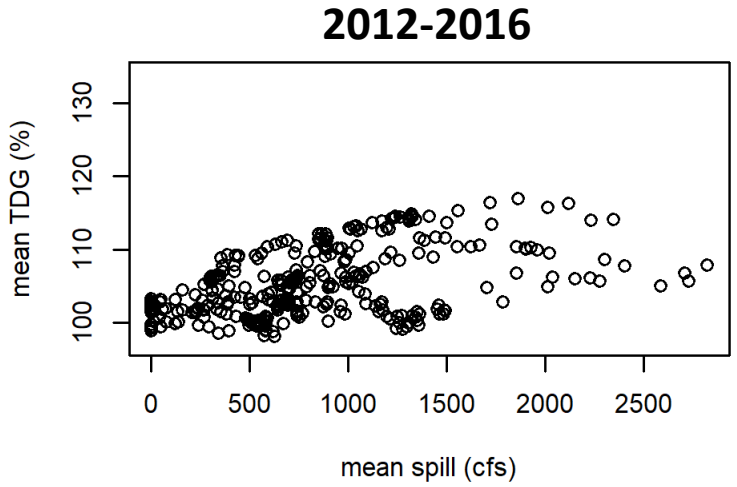
TDG vs. spill by trap event

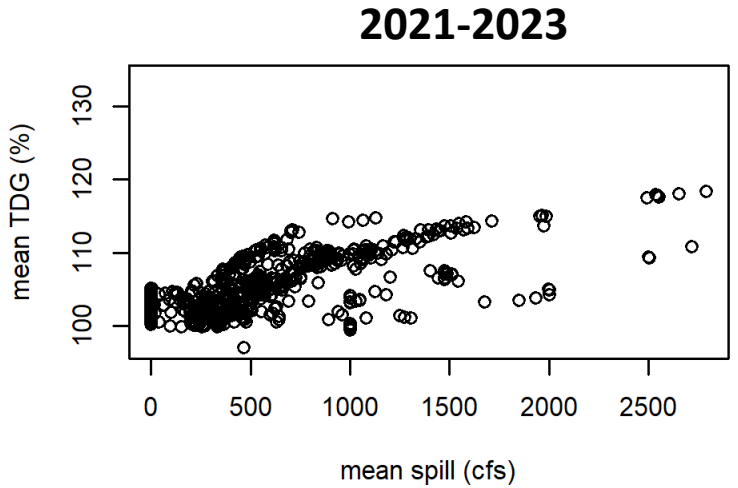
Big Cliff





Cougar





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Chinook salmon trapping outcomes

	Big Cliff		Cougar RO	
Years	2014-2016	2021-2023	2012-2016	2021-2023
Trap events	190	587	259	418
Trap hours (mean)	48	24	36	24
Spill (max cfs)	10,580	7,370	6,780	3,580
TDG (max %)	133.8	127.0	117.4	119.7
Total captures	743	4,054	5,147	12,654
Mean proportion with GBD	0.13	0.03	0.29	0.18
Mean proportion with barotrauma	0.29	0.14	0.45	0.32
Mean mortality rate	0.34	0.09	0.21	0.11

More captures, lower injury and mortality rates at both sites in 2021-2023 period

Binomial Generalised Linear Models

$Y_i \sim B(n_i, \pi_i)$

$E(Y_i) = \pi_i \times n_i$ and $\text{var}(Y_i) = n_i \times \pi_i \times (1 - \pi_i)$

$\text{logit}(\pi_i) = \alpha + \beta_1 \times TDG_i + \cdots$

Response variable Y_i is number injured or dead out of n_i Chinook salmon captured during trap event *i*

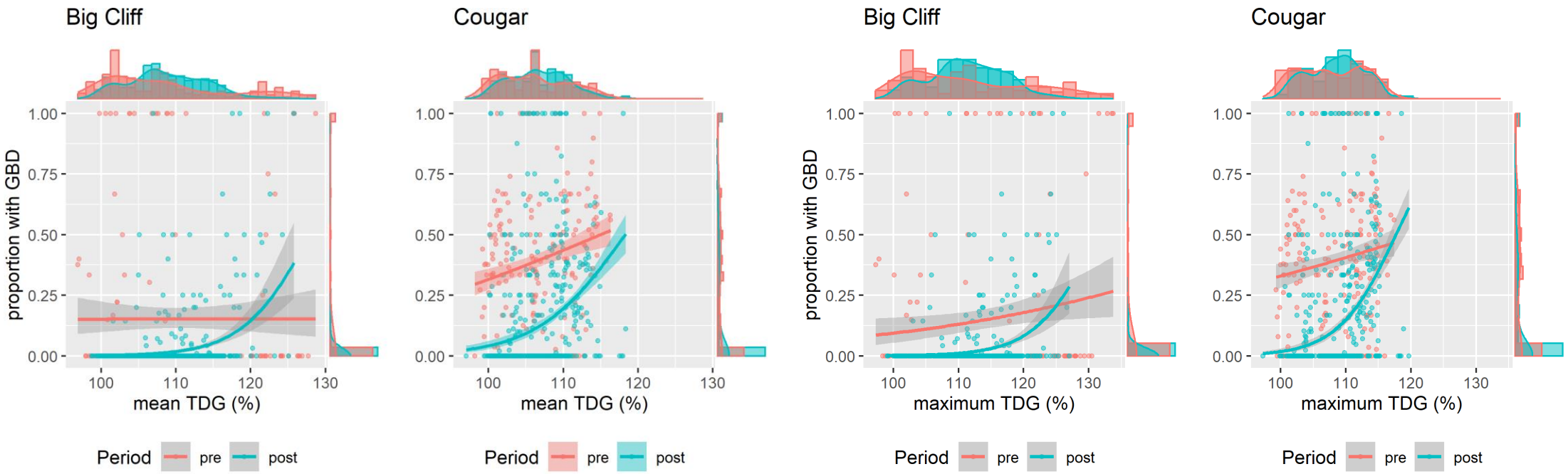
Overdispersed so fit quasi-binomial model

Explanatory variables considered:

- TDG (mean or maximum during trap event)
- spill (mean or maximum)
- mean length of n_i captured fish (mm)
- trap event duration (hours)
- water temperature (°C)
- season (spring/summer/fall/winter)
- site (Big Cliff or Cougar)
- period (pre or post abatement measures)

GBD: results

GBD: related to mean or maximum TDG?



- Data from RST below Big Cliff dam suggest no effect of mean TDG during trap events
- But significant effect of maximum TDG during trap events driven by TDG values >130%

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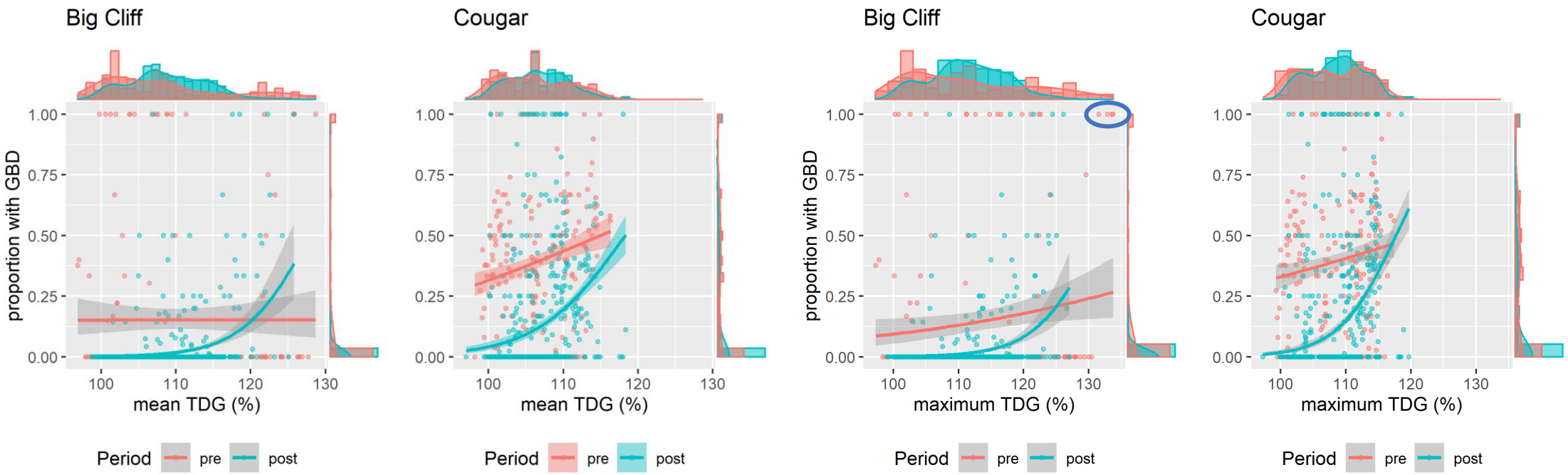
GBD: related to mean or maximum TDG?



- Data from RST below Big Cliff dam suggest no effect of mean TDG during trap events
- But significant effect of maximum TDG during trap events driven by TDG values >130%

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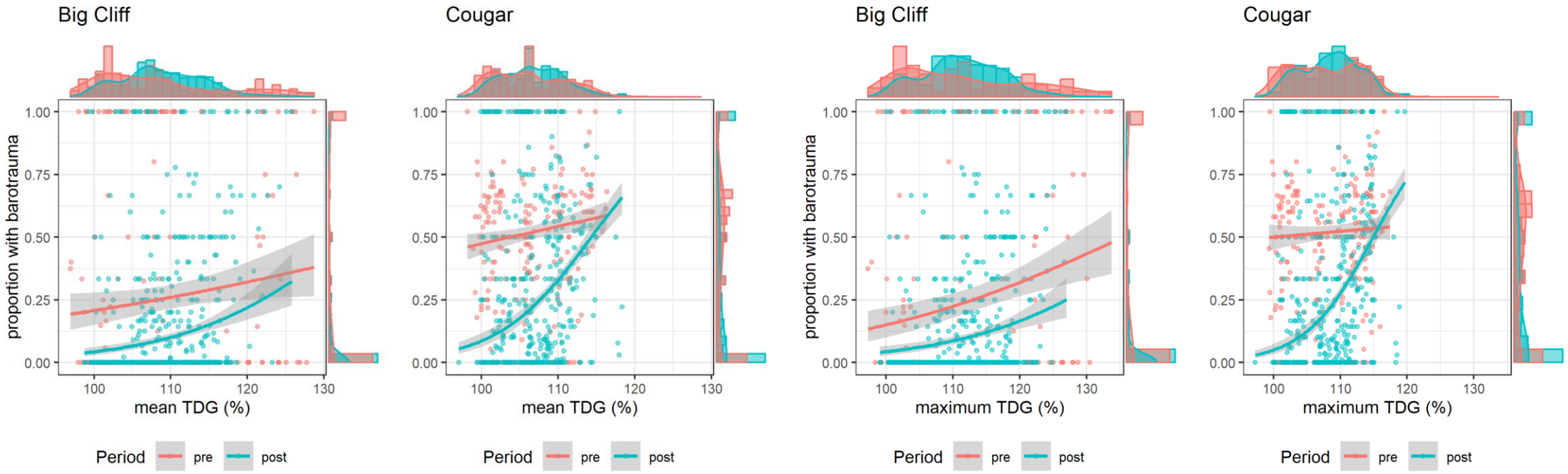
GBD: optimal model results

- Explored interactions between variables
  - TDG and temperature interaction retained as more GBD when TDG high and temperature low
  - Spill and length interaction retained as more GBD when spill high and fish were larger
- More GBD the longer fish held in traps
- More GBD below Cougar
- Less GBD post-implementation of TDG abatement measures

Coefficient	Estimate	Pr(>|t|)
max TDG	-0.075	0.01
temperature	-2.16	<0.001
max spill	0.0011	<0.001
mean length	0.023	<0.001
trap hours	0.018	<0.001
site [CGR]	2.91	<0.001
period [post-implementation]	-0.71	<0.001
max TDG : temperature	0.018	<0.001
max spill : mean length	-0.000006	<0.001

Barotrauma injury: results

Barotrauma injury: relationship with TDG



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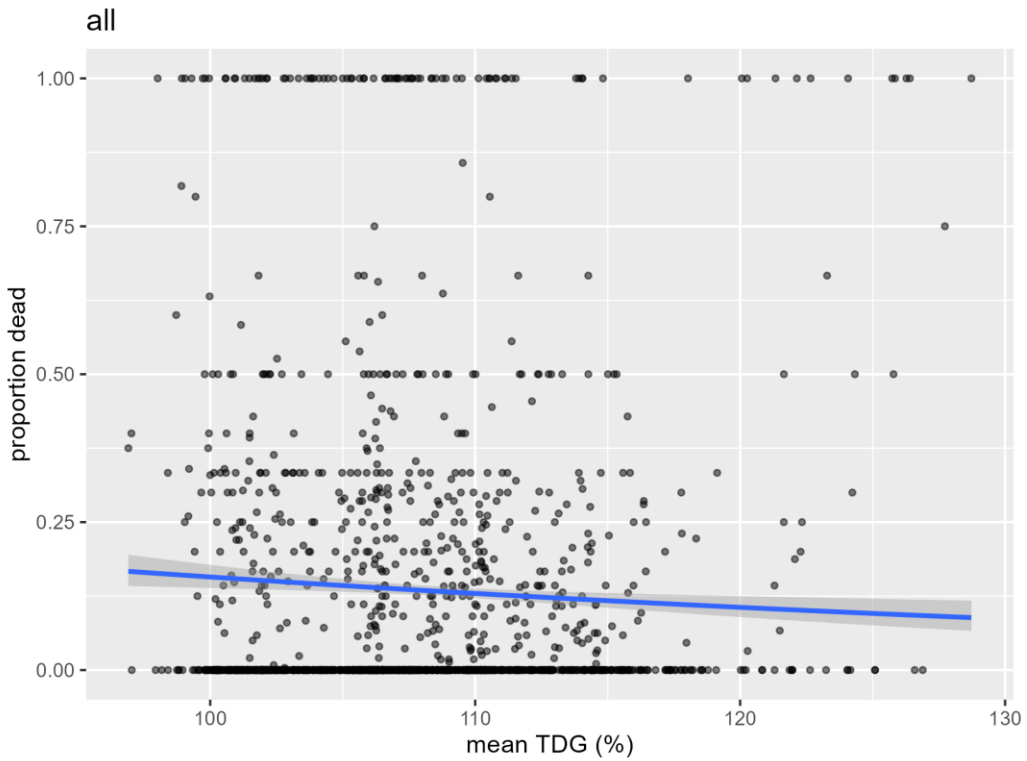
Barotrauma injury: optimal model results

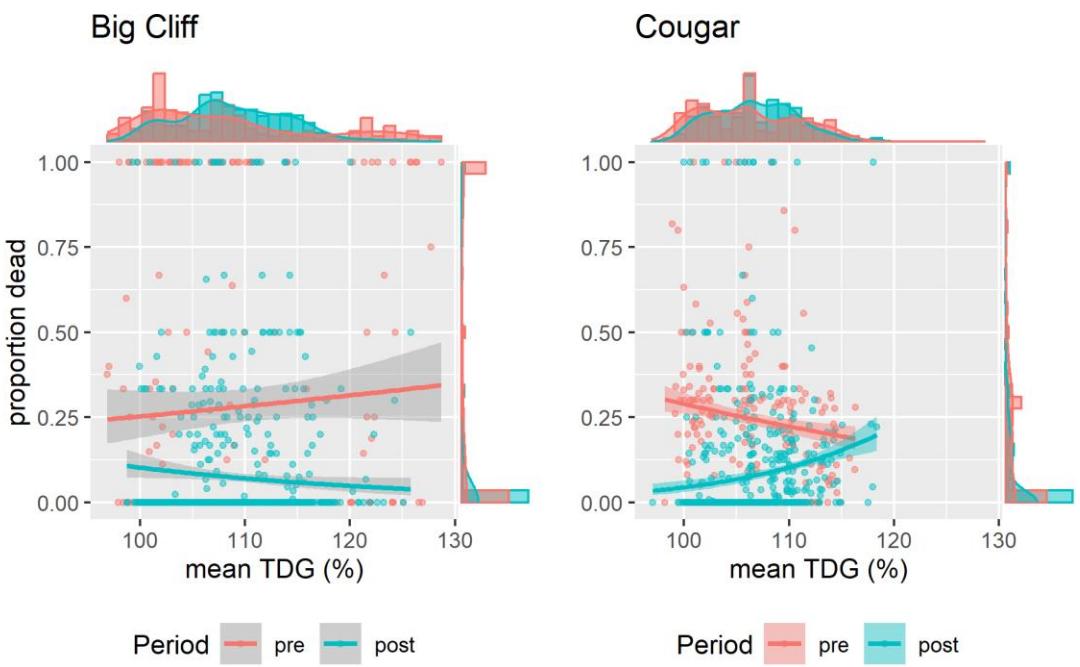
- Explored interactions between variables
  - Spill and length interaction retained as more barotrauma when spill high and fish were larger
- More barotrauma with higher TDG
- More barotrauma the longer fish held in traps
- More barotrauma at lower temperatures
- Less barotrauma in fall compared to spring
- More barotrauma below Cougar
- Less barotrauma post-implementation of TDG abatement measures

Coefficient	Estimate	Pr(>|t|)
mean TDG	0.053	<0.001
mean spill	0.0016	<0.001
trap hours	0.018	<0.001
mean length	0.024	<0.001
temperature	-0.072	0.001
season [summer]	-0.31	>0.05
season [fall]	-0.33	0.002
season [winter]	-0.21	0.09
site [CGR]	1.79	<0.001
period [post implementation]	-0.57	<0.001
mean spill : mean length	-0.000008	<0.001

Mortality: results

Mortality: relationship with TDG





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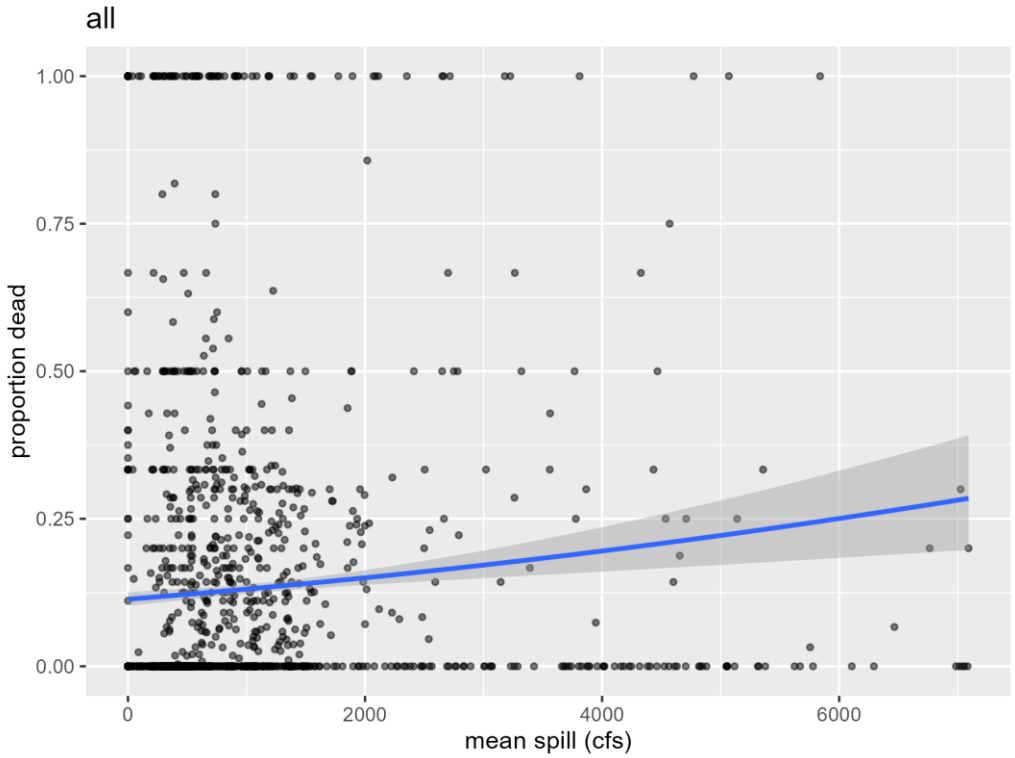
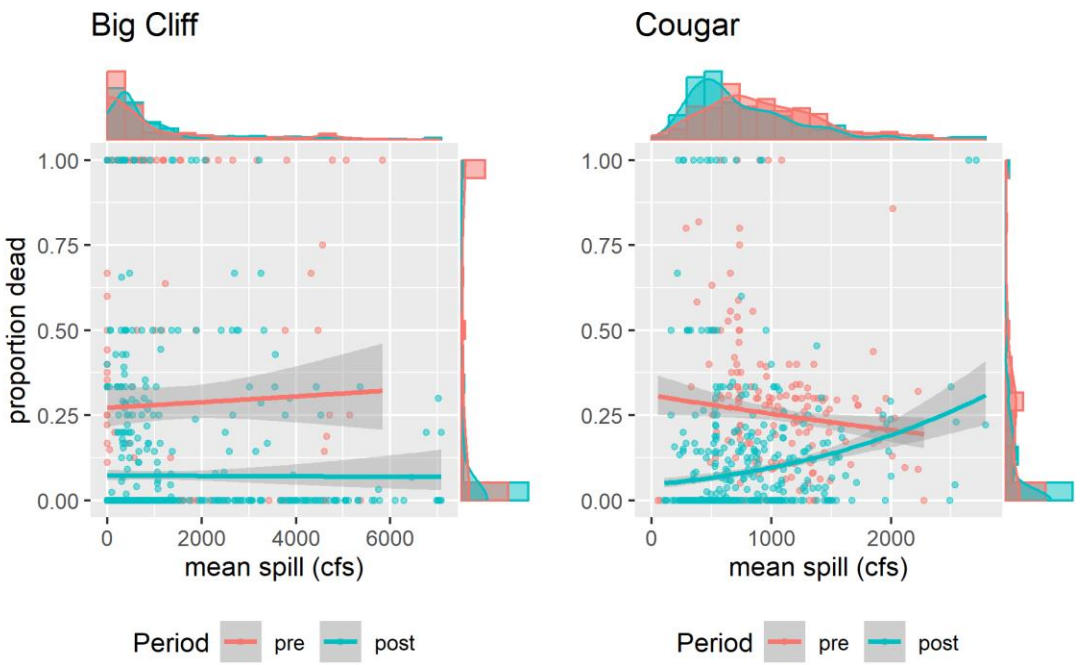
Mortality: relationship with spill





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Mortality: optimal model results

- Explored interactions between variables
  - Site and temperature interaction retained as when river cooler, mortality lower below Big Cliff but higher below Cougar
- TDG and spill not significant
- Higher mortality for larger fish
- Lower mortality in all seasons compared to spring
- Lower mortality post-implementation of TDG abatement measures

Coefficient	Estimate	Pr(>|t|)
mean length	0.028	<0.001
temperature	-0.018	>0.05
season [summer]	-0.823	0.001
season [fall]	-0.590	<0.001
season [winter]	-0.456	<0.001
site [CGR]	-0.321	>0.05
period [post-implementation]	-1.07	<0.001
temperature : site [CGR]	0.118	0.001

Conclusions

- Spill and TDG correlated, both reduced at Big Cliff after implementation of TDG abatement measures
- GBD/barotrauma incidence and mortality rates greater in first capture period compared to the second
    - Possible that injury incidence measured differently in second period, but two separate teams both recorded lower incidence
- Site-specific effects as although TDG lower below Cougar, GBD incidence was greater
- Larger juveniles suffer more, particularly when spill is high
- Maximum TDG levels >130% resulted in 100% incidence of GBD below Big Cliff
- RST do not sample entire population, trap efficiency typically <10%
- RST provide worst case scenario for GBD incidence as fish are held at surface so cannot depth compensate
- Mitigation measures to reduce TDG below 130%, e.g., through dam spill operations, appear to have reduced risks to threatened Chinook salmon populations

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