Population Monitoring Work Group Meeting

December 12, 2018

Meeting Materials:

Meeting Agenda

Meeting Minutes

Fake Minnows, Probability, and Fish Statistics [presentation]

Brown Trout in the Lees Ferry Reach of the Colorado River - Evaluation of Causal Hypotheses and Potential Interventions [report, not included]

Caplan, Noon, Hubert, and Fraser Panel Recommendations [spreadsheet]

Developing an Integrated Population Model for Rio Grande Silvery Minnow in the Middle Rio Grande

Draft Survival of Wild Rio Grande Silvery Minnow in the Middle Rio Grande [draft, not included]

Survival of Wild RGSM in the MRG [presentation]

Reviewer Comment Table

Draft I: Review of the "Analytical Framework for Evaluating the Proposed Water Management and Maintenance Actions on Rio Grande Silvery Minnow, Southwestern Willow Flycatcher, and Yellow-Billed Cuckoo and Their Critical Habitats" With Recommendations for Future Analytical Considerations [draft]

Developing an Integrated Population Model for Rio Grande Silvery Minnow [presentation]

Middle Rio Grande Endangered Species
Collaborative Program
Est. 2000

Population Monitoring Work Group
Meeting Agenda

December 12, 2018
8:30 AM – 3:00 PM
Location: U.S. Bureau of Reclamation – 555 Broadway Blvd NE #100

Conference Call-in Information:
(712) 451-0011 Passcode: 141544#

8:15 – 8:30	**Arrival**	
8:30 – 8:45	**Welcome, Introductions, Agenda and Materials Review, Updates and Announcements** • Google Drive	*Debbie Lee*
8:45 – 9:00	**Review and Summary of Last Meeting** • Action items ➢ **Decision**: Approval of September 2018 Meeting Minutes	*Grace Haggerty*
9:00 – 10:00	**Proposed Conceptual Model for RGSM** • Presentation • Brown Trout work • Q&A and Discussion	*Charles Yackulic*
10:00 – 10:10	**Break**	
10:10 – 11:10	**RGSM Survival Analyses** • Presentation • Q&A and Discussion	*Rich Valdez*
11:10 – 12:10	**Refined Bayesian Analysis** • Presentation • Q&A and Discussion	*Ara Winter*
12:10 – 12:20	**Break *(Working Lunch - bring cash if ordering in from DG's Deli)***	
12:20 – 12:50	**Additional Updates from Small Groups** • Conceptual Base Model • Functional Analysis of CPUE Flow • Survival Analysis • PopMon FY19 Work Assignment • Peer review verification	

12:50 – 1:50	**Key Questions for Analyses** • Given morning discussions and panel recommendations, what are the top questions that the group should work on? • What are the management implications for these? ➢ **Decision**: The analyses to undertake next ➢ **Action Item**: Assignments for further analyses	*Debbie Lee (facilitator)*
1:50 – 2:00	**Break**	
2:00 – 2:30	**Identification of Other Data and Information** *(All to bring lists of what they have or know about)* • Non-PopMon Data sets • Past efforts (e.g. PVA, PHVA)	*All*
2:30 – 2:45	**USU Draft Report** • Discussion of draft report • Comments on draft report due December 14	
2:45 – 3:00	**Next Steps and Meeting Summary** ➢ **Action Item**: Final Review of PMWG Charge ➢ **Action Item:** Report out to EC in January	*Debbie Lee*
3:00	**Adjourn**	

Middle Rio Grande Endangered Species
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Population Monitoring Workgroup (PMWG)
Meeting Minutes

December 12, 2018
8:30 AM – 3:00 PM
Location: U.S. Bureau of Reclamation – 555 Broadway Blvd NE #100

Decisions:

✓ Next meeting will take place on March 7th.

Actions:

WHO	ACTION ITEM	BY WHEN
WEST	Set up a Google Drive and send out a request to PMW members for emails to access a shared drive	ASAP
Joel Lusk and Rich Valdez	Send Ara Winter data for incorporation into his Bayesian modeling efforts	ASAP
Joel Lusk	Send Brian Hobbs a request for Bui data	ASAP
Grace Haggerty	Send water management spreadsheet to WEST for distribution to the PMW and/or inclusion in the shared Google Drive	ASAP
Grace Haggerty, Rich Valdez, and Joel Lusk	Revise the PMW charge to reflect the conversation at the PMWG meeting, specifically with management in mind	January 4
All	Provide any RGSM habitat availability information to Charles Yackulic utilizing the shared Google Drive, when available	January 11
All	Provide any RGSM survival resources to Rich Valdez utilizing the shared Google Drive, when available	January 11
All	Review revised PMWG charge	January 15
Grace Haggerty	Report on 2018 PMWG activities to the EC	January 23
Ara Winter	Continue modeling efforts and prepare a presentation to update PMWG members at the next meeting	March 7
Charles Yackulic	Continue to refine the RGSM population model with consideration for RGSM age classes and habitat availability, and prepare a presentation to update PMWG members at the next meeting	March 7

Next Meeting: March 7, 2019

Action Items Review

- Debbie Lee , WEST, discussed the challenges related to setting up a Google Drive. Security clearances within WEST and Program stakeholder agencies have made access to a Google Drive a challenge. It was suggested that it may be necessary for stakeholders to use alternate email addresses to access Google Drive.
    - ➢ **Action Item: WEST will set up a Google Drive and send out a request to PMWG members for emails to access a shared drive**
- Ashley Tanner, WEST, gave an overview of the previous PMWG meeting. She encouraged all work group members to review the previous meeting's minutes (sent out on 12/11/2018). She mentioned that there were several instances in the last meeting where questions were asked, but never specifically answered.

Presentation: "Developing an integrated population model for RGSM" by Charles Yackulic, USGS[1]

- Charles began his presentation by speaking to the importance of being able to discuss models and analyses prior to even looking at data, and with consideration for all the hypotheses that people have. He also spoke to the importance of relating hypotheses to management decisions.
    - He discussed the brown trout modeling efforts and implications for management decisions (shared with workgroup as read-ahead).
    - He gave an overview of the RGSM Population Model.
- In response to Charles's presentation, the PMWG members made the following comments and posed the following questions:
    - Question: What is the longest known surviving stocked RGSM?
        - Answer: About 700 days, though it could be less. There's definitely fish that live 365+ days, and up to 600, but not sure how many or how long specifically.
    - Question: Do you (Charles Y. and the Glen Canyon AM Program) have different models for the different species, and then try to work them together (such as the brown trout model)? When you built your model, did you accommodate natural vs. man-made conditions on the river?
        - Answer: A lot of the models were based on historical flows, and not many of those models have "stuck." Humpback chub have a strong relationship to temperature, and we know that these areas historically saw temperatures of up to 30˚C, which would be problematic for the chub. So the conditions we're in now are better than what they might have experienced historically. With regard to coupling models, there's the estimation side and the modeling side. For the forward modeling, it's easy. You consider the range for what the interactions are for these species and model that forward.
        - Follow up: You can consider things that are outside of the box of what you've observed. You can pull groups of people together to propose different hypotheses and test them based on what you know about the system. This can help you consider things that may not be on your radar, but may be important to the system.
        - Follow up: For the humpback chub, it became clear that the controversy was about the trade-offs in impacts on resources. It then became a conversation about valuation of resources as opposed to impacts on the species.

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[1] Please see Charles Yackulic's presentation, "Developing an integrated population model for Rio Grande Silvery Minnow."

        - This gets at the intractable dilemma, which states that there is no single management action that will result in benefits for all of the species.
- One PMWG participant noted that Charles's model has similarities to the Population Viability Analysis (PVA) efforts undertaken several years ago; however this model is more elegant.
- The PMWG participants were generally positive about Charles' presentation, and the direction he was taking the model. The following suggestions were made to improve the model:
    - Include habitat availability.
    - Include a finer break down in the age class distributions (e.g., Year 1, Year 2, and Year 2+).
        - Charles noted that this would help determine how rare the older age classes are and the relationships between the age classes from year to year.
        - Stocking may complicate determining the year-to-year relationship, but can be incorporated into the model.
- The PMWG participants made the following comments about Charles's presentation:
    - Charles mentioned designed flows, but there is very little potential for that in the MRG.
    - I would like to see the April/May spring flow hypotheses tested.
    - Charles's effort should coordinate with the Utah State University (USU) effort, as it is important those two models come together in some way. The reach concept is really quite strong, which was a conclusion of the USU work. This may play into how this modeling effort moves forward.
    - One participant noted that with regard to the spatial models, he liked seeing the simpler model first. Adding in the aspect of then examining how fish may move at smaller spatial scales, such as the 200m segments, was useful.
- During the discussion, PMWG participants made the following suggestions for future studies and analyses:
    - Some of the really bad years suggest that there might be a lot more broodstock out there than we're catching. A study could be designed to test how many older fish are out there in poor water years/low flow conditions.
    - What roles do stocked fish play, demographically, in the RGSM population when there's a low water year? A survival analysis on marked fish could be possible..
- One PMWG participant cautioned the group to keep management implications in mind. There are many questions that can be answered, but are those questions ones of scientific debate, or do they impact management decisions?
- PMWG participants discussed the age classes of RGSM. The following comments were made:
    - Length frequency data does not necessarily correspond with age information. After a certain size class, individual variation becomes too great to distinguish between different age classes.
        - One participant suspected there are overlapping lengths for different age fish, or stacking of ages.
        - There are 4 year old fish at the City of Albuquerque BioPark, and fish lengths range from 55mm to 90mm. I do think there's a limit to the length-age relationship.
    - The question of the management implication of the age question was raised.
        - It would be useful to know how many bad years in a row can we have.
            - There have been unexpected responses following 2-3 years of no spring flow that we can't necessarily explain.

        - Management implications may include spacing out augmentation to prevent domestication selection.
            - Some of this has been done.

Presentation: "Fake minnows, probability, and fish statistics" by Ara Winter (BEMP)[2]

- Ara Winter, Bosque Ecosystem Monitoring Program (BEMP), presented an overview of Bayesian approaches to modeling, and how that approach can be applied to RGSM.
    - He discussed the difference between peer review and peer input.
    - He gave an overview of RGSM model outputs, and discussed how we can begin to ask questions of the model with respect to reach, methodology, other covariates, and eventually, predictions into the future.
    - BEMP will be putting together Program R and modeling workshops sometime in 2019. They are anticipating Program involvement.
- During the discussion around Ara's presentation, the following questions and comments were raised:
    - Question: What is of greater value: looking at uncertainty around the age-cohorts in vonB, or would a consolidated model, as Ara built, be more valuable?
        - Answer: You need to incorporate actual individual variation in L infinity, which has been traditionally done with mark-recapture information. Age designations can be designed to be dependent on certain factors, such as flow conditions in the prior year. A fish may be more likely to be older if the flow conditions that year were poor (so they're likely to be fish that carried over from the year before). Charles's intent was not to focus too much on age-growth relationships in this species, as there didn't seem to be too much variation in year-to-year growth. It seems that survival and recruitment may be more important factors in the model.
    - Comment: You left out the middle child – maximum likelihood. You can incorporate random effects in frequentist approaches. Bayesian stuff can be slower when you get into more complex models. Some frequentists vs. Bayesian discussion took place here with regard to the costs/benefits of each.
        - ➢ Joel Lusk and Rich Valdez will send Ara Winter data for incorporation into his Bayesian modeling efforts.

Presentation: "Survival of Wild Rio Grande Silvery Minnow in the Middle Rio Grande" by Rich Valdez (SWCA/NMISC)[3]

    - Rich Valdez discussed the approaches to estimating RGSM survival and mortality.
    - He gave and overview of data used, assumptions, and model used.
    - He discussed the results of the RGSM survival modeling.
- PMWG participants raised the following questions in response to Rich's presentation:
    - Question: Have you plotted the year-specific age-0s vs. the year-specific age-1s?
        - Answer: No, however Dan Goodman and Phil Miller did some of that work.
    - Question: Are there other papers/reports that should be included in this "Survival for RGSM" table?
        - Answer: Yes, there are some papers/reports either in review, published, or that people can send along.
- PMWG participants provided the following comments on Rich's presentation:

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[2] Please see Ara Winter's presentation slides, "Fake minnows, probability, and fish statistics."

[3] Please see Rich Valdez's presentation slides, "Survival of Wild Rio Grande Silvery Minnow in the Middle Rio Grande."

    - The potential impact the schooling behavior of the RGSM should be considered.
        - A participant disagreed, noting that if the school is present at a sampling site, we'll catch them all. The problem becomes when the population is so low that we can't find the school. Seining is a very appropriate method of capture for this species.
    - There was some discussion regarding dry sites and the treatment of dry sites by ASIR. The group discussed how dry sites may impact population estimates and river-wide CPUE estimates over the course of the year.

        - ➢ The group members will provide any RGSM survival resources to Rich Valdez utilizing the shared Google Drive, when available.

Update on Peer Review Panel Recommendations

- Prior to the meeting, Ashley and Eric Gonzalez, Reclamation, met and updated the statuses of each of the panel recommendations, excluding those from the most recent Caplan et al. report. These updates were based on the contracts and recent reports.
- One PMWG member asked how prioritization factored in. Ashley responded that it depends on what the workgroups want to do. There are 2 sets of prioritizations presently: the one designated by the panel (if given) and the one designated by a work group (if given). The (orginal) genetics peer review panel prioritizations were especially difficult to work with and were not included.
- In response to the conversation, incorporate participant asked if genetics should be incorporated into Charles's population model. This would help determine how many fish are needed for spawning (genetically) in the spring in order to tailor augmentation to what is needed.
    - The survivorship rates are also fairly critical; of stocked fish, of naturally spawned fish, different age classes, etc.

Update on the PMWG's Charge

- Grace Haggerty, NM Interstate Stream Commission (NMISC), informed the PMWG that the small group assigned to update/edit the charge did not have the opportunity to meet prior to the December meeting. The charge up for review contains the July 2012 objectives and associated action items. The timeline was updated as much as possible with consideration for Charles Y.'s involvement in the workgroup. It might be useful to have a discussion regarding the RGSM monitoring plan and what is our ultimate goal/objectives for the Program.
- PMWG participants made the following suggestions to the charge:
    - If the group wanted to address issues with monitoring methods, gear, and etc., then a new task may be needed.
    - Include the management context the PMWG operates within. If we need to know status and trends, then the current monitoring program is pretty good for that. But there are more specific questions being raised about management actions and how they impact the RGSM population that the current program is not designed to answer.
        - The point was made that the management needs differ depending on the agency or individual.
- The discussion also touched on the future direction for the work group. One participant advocated for a forward-looking focus, noting that looking at what has been done and critiquing it leads to negative feelings.
    - One participant observed that the charge for the work group has morphed: the PMWG started out trying to evaluate and refine the RGSM monitoring program, but is now

using the monitoring data in a synthetic/integrated model. The group can then assess the inferences of the model and assess the data based on modeling efforts and the needs of those modeling efforts. While the data can give us a certain amount of information, the group can also determine where we need to know more.

- One participant suggested that rather than focusing on assessing the current population monitoring program, the PMWG aims to design a program that answers what we need it to. We can then model our design, implement that monitoring design, compare that to the existing RGSM population monitoring program, and then assess what we've learned. The general approach of "I want to change this" is less helpful than "I want to do this because we would learn this."
- There are related conversations happening in the Executive Committee (EC) and Science/Habitat Restoration Work Group (ScW/HR). At the last EC meeting, there was conversation about having Program recovery goals. The ScW/HR is working on prioritizing scopes of work and other activities. The PMWG knows the data, and as they work through this modeling and identify where additional data are needed, then they could kick that out to the ScW/HR to write a SOW.
- One participant noted that there was potential to use the population model to talk about recovery goals. Follow up: The recovery goals conversation has to happen at the EC level.
  - One participant noted that the recovery goals are something to be approached with caution. What if the recovery goals for the Program don't match the recovery goals set by the biological opinions (BOs) or don't meet agency needs? There could be a conflict there with the USFWS. There is a potential for using this model to talk about recovery goals.
  - Another participant suggested that the recovery goals conversation has to happen at the EC.
- The conversation shifted back to the charge and the forward-focus of the group.
  - The group had a discussion regarding the utility of focusing on the RGSM monitoring program. They also had a short discussion about the RGSM CPUE threshold of .3, and whether that should be something the group should focus on. It was generally decided that the .3 threshold was a "BO thing" and not appropriate for this group to focus on.
- The ultimate goal of the PMWG should be to support the adaptive management framework.
- Analyses that help us interpret the RGSM population monitoring data, including determining the relationship between CPUE and abundance. Another aspect of AM is prioritizing what you do; so we need to find more efficient (better and cheaper) ways of doing things.
  - What are the uncertainties that, when addressed, could inform management? What type of monitoring can be designed to meet those uncertainties? What kind of modeling do we need to do to test those uncertainties? We could implement new designs in the field, and ultimately aim to tie this into the AM framework.
  - It would be helpful to have a conversation with the Adaptive Management Work Group (AMWG) about what the PMWG is doing and thinking about.
  - In response to a question about the possible management actions on the river, one individual informed the group of past workshops where different management tools were identified. Technical groups were formed that were supposed to be working on this; but the effort was never completed. The BO informs a lot of the water management options as well.

    - One person suggested that the PMWG undertake an exercise to define our management options, our uncertainties, and then looked at the data. This would help identify some of the "need to know" questions.
    - The Minnow Action Team (MAT) has already gone through a lot of the different scenarios, and it would not be hard to update.
  - **Action item: Grace Haggerty will send water management spreadsheet to WEST for distribution to the PMWG and/or inclusion in the shared Google Drive**
- There was discussion about revising the PMWG charge to capture the above conversation.
  - Add a 4th bullet to the charge to acknowledge that the RGSM Population Monitoring program is important to the Collaborative Program as it provides data for appropriate models and informs AM decisions. No monitoring program is perfect, nor can it provide everything. However, if you use it in an integrated model approach, it can help to inform management actions.
  - A participant asked if one of our main goals would still be recommending changes to the RGSM population monitoring program. The answer given by another participant was yes.
  - Include reference to the management context and management implications in the Introduction of the charge.
    - **Action Item: Grace Haggerty, Rich Valdez, and Joel Lusk will revise the PMWG charge to reflect the conversation at the PMWG meeting, specifically with management in mind.**
- One person recommended that if there is a change in RGSM population monitoring, to plan to have overlap between the two methods. It does make things more expensive, which politically can be challenging. This individual also cautioned that, while discussions of specific management implications are important, the connections to management are not always direct.

Next Steps Based on Today's Presentations, Analyses, and Conversations

- There are mesohabitat data available that can be provided to Charles to inform his population model.
  - Possible mesohabitats include runs, riffles, pools, backwaters, and maybe floodplains.
  - Bui did some habitat availability work that included top width, velocity, and depth. They utilized cross-section data and models to give you wetted width for a given discharge. A relationship between wetted width and RGSM was observed.
      - **Action Item: Joel Lusk will send Brian Hobbs a request for the Bui data.**
  - Some habitat availability mapping has been done:
    - SWCA did some mapping for a habitat restoration site, however it was very small.
    - TetraTech recorded some wetted width information, including depth and velocity.
  - Our understanding of mesohabitat change at different discharges does not have to be exact. The important thing to understand is the magnitude of change in mesohabitat availabilities at different flows.
- Related to habitat availability, the following comments were made:
  - Sampling at high flows is actually easier because you've filled up the river and there's less space for fish to go to. They concentrate into where they can. At high flows, physically accessing different areas of the river becomes the primary sampling challenge.
- Other questions that were raised include:

    - Is there a way to scale up CPUE based on what you think the relationship may be between discharge and habitat availability? We just scaled it to the total flooded area.
    - What is the capture probability for a variety of different gear types?
        - It is possible to get at variability in capture probabilities over time by gear type if you correlate the metrics collected at the time to the data collected. For example, folks who analyze breeding bird survey data use covariates that were measured on the day of the survey to assess variability of capture for each species.
    - If you have a small amount of water, do you maximize survival or recruitment?
        - Once we get the base model down, we may be able to explore this question.

- **Action Item: The group will provide any RGSM habitat availability information to Charles Yackulic utilizing the shared Google Drive, when available.**

Identification of Other Data and Information

- Debbie noted that on the agenda was the question: What are the data out there that can help us answer some of these questions? This is likely an ongoing action item for the group.
    - Ashley stated that in order to be able to realistically answer the "what data are out there" question, we have to have an objective; a clear need identified for these data. Otherwise, the question becomes too large and tedious to answer in any reasonable time frame.
- Other questions that participants identified as possible issues for the PMWG to work on include:
    - SWCA has been working on gaining a better understanding of the relationship between the floodplain and RGSM larvae. They had discussed developing a larval budget estimate. Given floodplain inundation, what is larval production?
    - It would be useful to try and link RGSM survival with some of those habitat restoration sites. Some additional monitoring was done around these sites that may be used to assess that. There was interest in looking at different gear types in the river, and in looking at different age classes of fish that may be present in the river. There was also interest in assessing how are RGSM are responding to flow and floodplain inundation.
    - Wintertime is a time we don't know much about. RGSM are driven by a production strategy in the spring, and a survival strategy in the summer. We saw a huge decline in fish this late summer (2018).
        - The river was at 36˚C this summer during fish rescue. These fish were likely highly stressed during a 2-3 weeks period that could have affected the population decline we saw in late summer.

USU Draft Report

- There was an announcement that comments on the USU draft report are due by Friday, December 14th. Comments should be submitted using the comment form to Kenneth Richards at Reclamation.
- Several PMWG members noted they had submitted comments:
    - One stated that their comments were favorable and supported USU's and Reclamation's efforts.
    - One stated a belief there is a difference by reach, and we commented about that. We also commented on the use of annual flows, which has limited utility to managers.
- One participant asked if the USU contract is going to be a phased approach. This person was hoping that the second part of their work would be to evaluate those criteria (CPUE of .3 and etc.) in the HBO.

    - Brian Hobbs, Reclamation, responded that there will be a second phase. Kenneth Richards is the contact person for this contract, and all questions should be directed to him.
- Several PMWG members expressed the desire for interaction between the PMWG and the USU researchers, particularly with regard to Charles's modeling efforts.

Next Meeting

- ➢ **Grace Haggerty will report on 2018 PMWG activities to the EC.**
- The next PMW meeting will take place on March 7th.
    - Potential presentations include:
        - Ara Winter will continue modeling efforts and prepare a presentation to update PMW members at the next meeting.
        - Charles Yackulic will continue to refine the RGSM population model with consideration for RGSM age classes and habitat availability, and prepare a presentation to update PMW members at the next meeting.
        - Rich Valdez may have a presentation related to larval survival on the floodplain.

Meeting Participants

Thomas Archdeacon
USFWS

Dave Campbell
USFWS

Lynette Giesen
USACE

Eric Gonzalez
Reclamation

Grace Haggerty
NMISC

Mo Hobbs
ABCWUA

Shay Howlin
WEST

Debbie Lee
WEST

Joel Lusk
USFWS

Anne Marken
MRGCD

Kate Mendoza
ABCWUA

Michael Porter
USACE

Ashley Tanner
WEST

Rich Valdez
SWCA/NMISC

Ara Winter
BEMP

Matt Wunder
NMDGF

Charles Yackulic
USGS

Steve Zipper
SWCA

Fake minnows, probability, and fish statistics.

Dr. Ara Winter

THE UNIVERSITY OF NEW MEXICO

BEMP
Bosque Ecosystem Monitoring Program

BOSQUE SCHOOL
Challenging Education

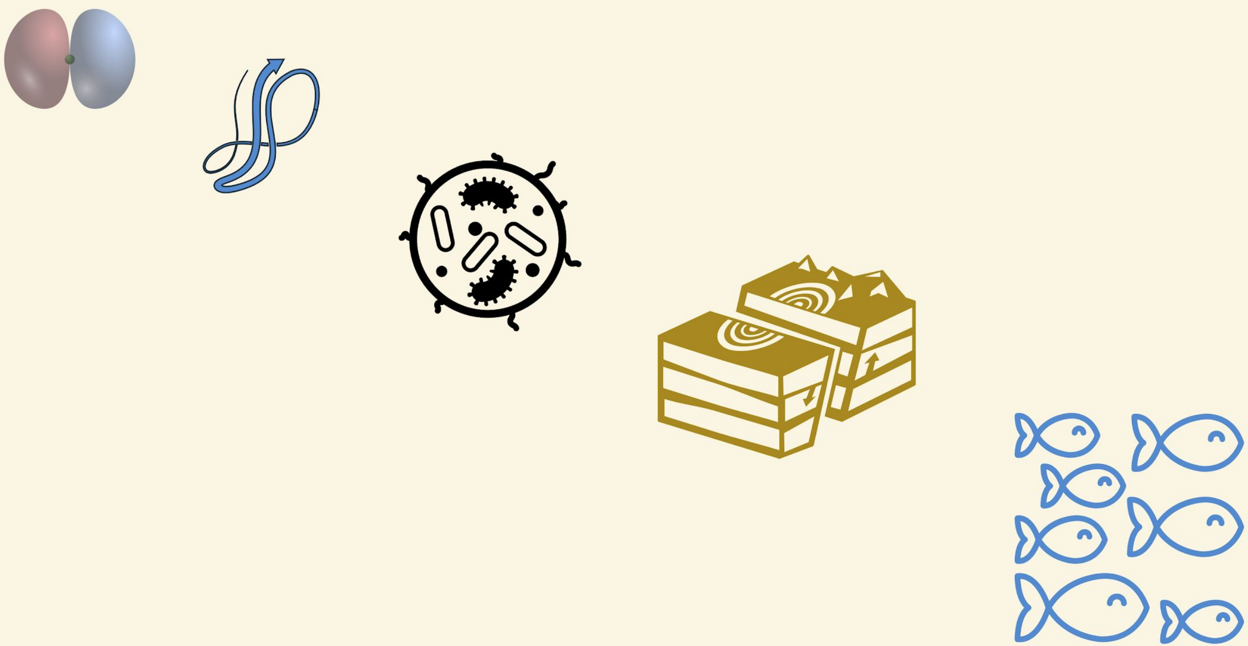
From probability to probability.

Dissertation was all Bayesian.

Three chapters.

Scaled from microbes to marine fisheries.

From atoms to whales peer reviewed.

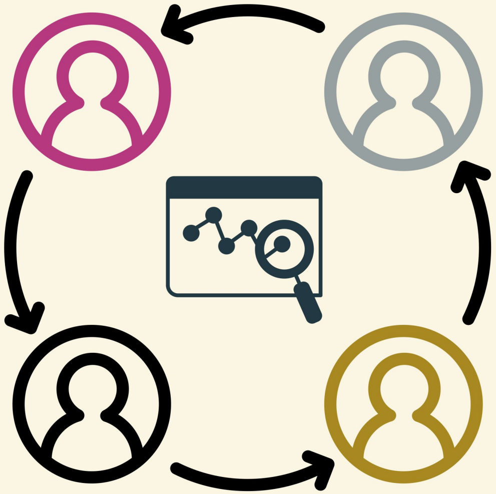


It is the day to day details that matter.

Teach.

Learn.

Live.

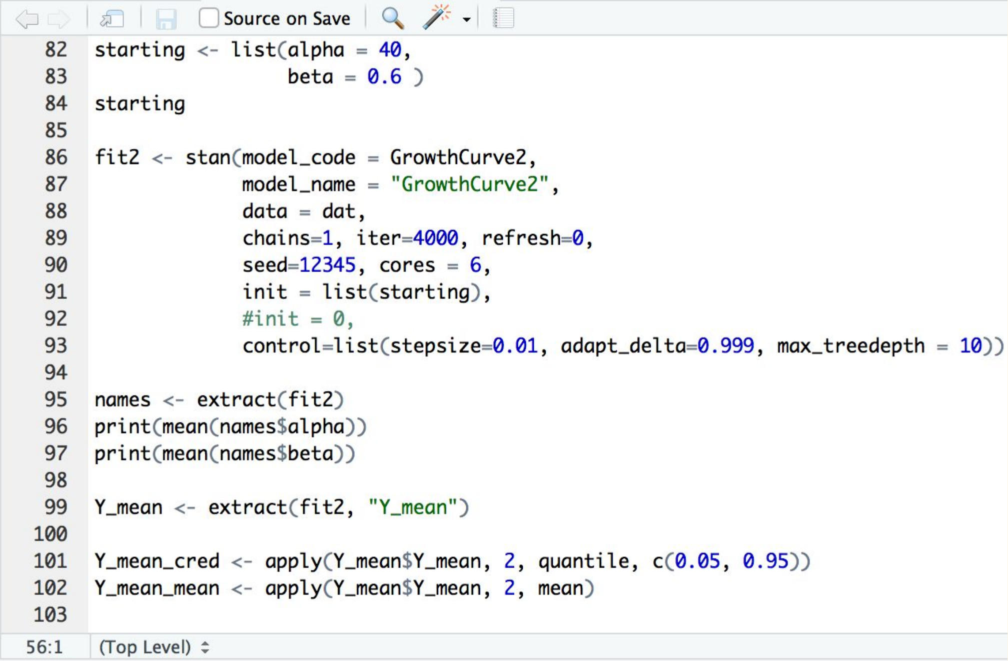


Stan is a probabilistic programming language.

Runs in R or python.

Reproducible workflow.

Human readable.



```
starting <- list(alpha = 40,
                 beta = 0.6 )
starting

fit2 <- stan(model_code = GrowthCurve2,
             model_name = "GrowthCurve2",
             data = dat,
             chains=1, iter=4000, refresh=0,
             seed=12345, cores = 6,
             init = list(starting),
             #init = 0,
             control=list(stepsize=0.01, adapt_delta=0.999, max_treedepth = 10))

names <- extract(fit2)
print(mean(names$alpha))
print(mean(names$beta))

Y_mean <- extract(fit2, "Y_mean")

Y_mean_cred <- apply(Y_mean$Y_mean, 2, quantile, c(0.05, 0.95))
Y_mean_mean <- apply(Y_mean$Y_mean, 2, mean)

```

The model is broken up into blocks.

data {}

parameters {}

transformed parameters {}

model {}

generated quantities{}

Von Bertalanffy Growth Function.

$$E[L|t] = L_\infty(1 - e^{-K(t-t0)})$$

In **Stan** we express this as:

```
transformed parameters {

m[i] = alpha * (1 - exp(-beta * (x[i]-x0))) }
```

Lots of funny symbols mean something?

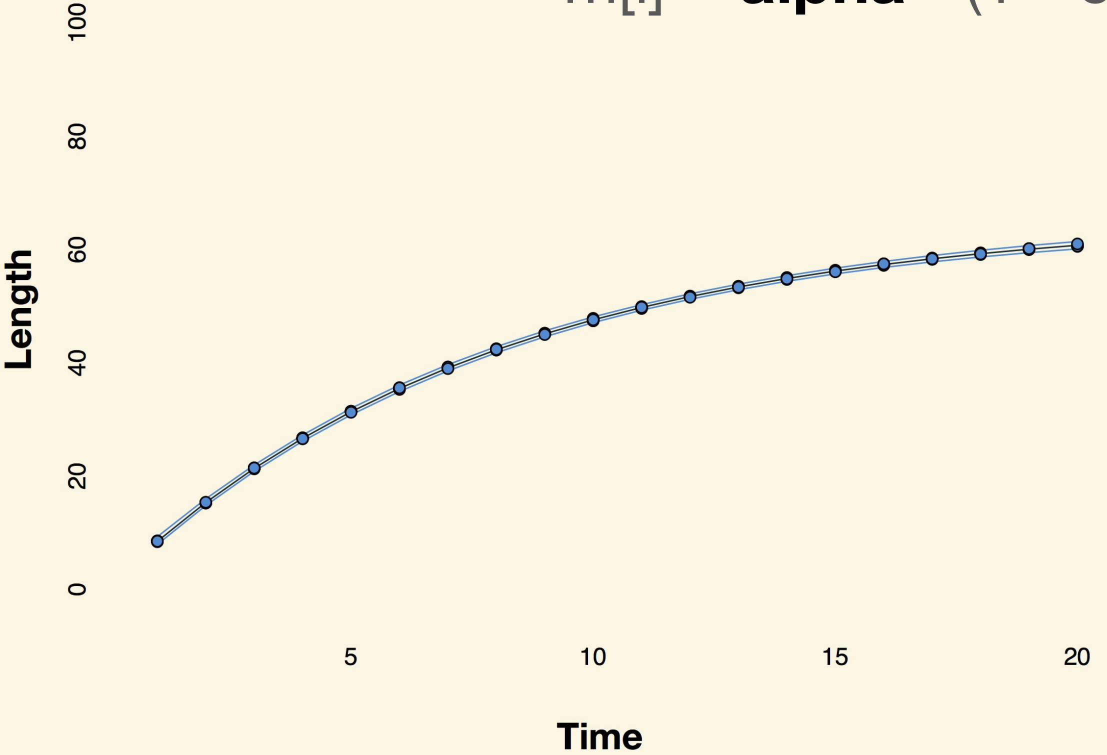
m[i] = **alpha** * (1 - exp(-**beta** * (x[i]-x0)))

alpha is the **asymptotic average length-at-age**

beta is the **Brody growth rate coefficient, yr^{-1}**

This curve is described by these estimates.

m[i] = **alpha** * (1 - exp(-**beta** * (x[i]-x0)))



In the frequentist model estimates are fixed.

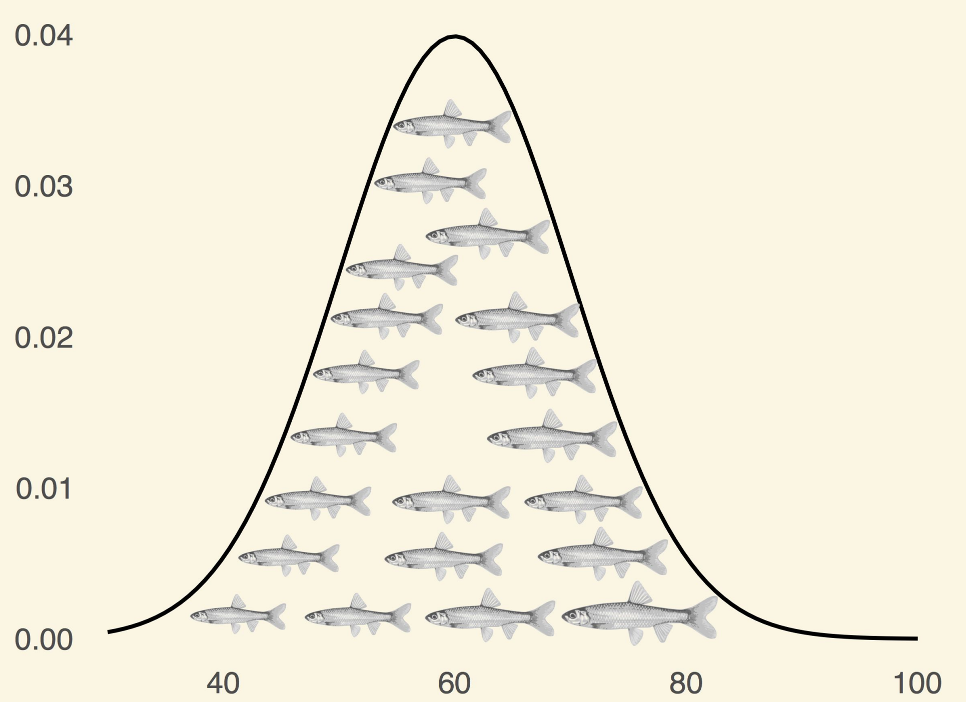
alpha – asymptotic average length-at-age 90

beta – Brody growth rate coefficient, yr^{-1} 0.6

How far is the data off from the curve?

Bayesian estimates are populations.

alpha – asymptotic average length-at-age



Frequentist models are one approach.

One of many ways to do inference.

Statistical procedures.

Evaluate under modeled long-run frequency properties.

Bayesian models are data models.

One of many ways to do inference.

Statistical procedures.

Evaluate under various assumptions.

How far off is the model from the data?

Our knowledge of what might happen.

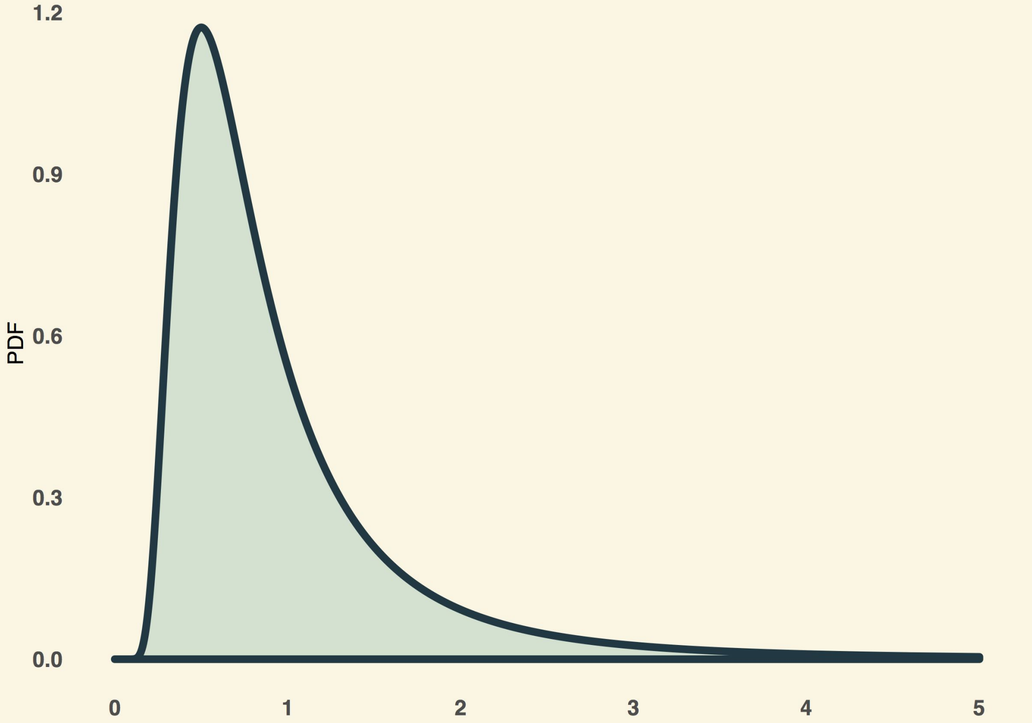
Given the data.

Given a set of parameters.

Not “how often things will actually happen.”

Priors are based on our knowledge.

beta – Brody growth rate coefficient, yr^{-1} 0.6



In the land of no p-values.

P-values

Combination of real effects and chance.

The result was consistent with being due to chance.

Not a probability.

P-values have issue mathematical and philosophically.

Assumes no systematic error in the data.

Binary outcome under the NHT.

Low p-values do not indicate evidence of a strong effect.

It’s one piece and not privileged.

Good Bayesian practices are good frequentists practices.

Relevant to a theory.

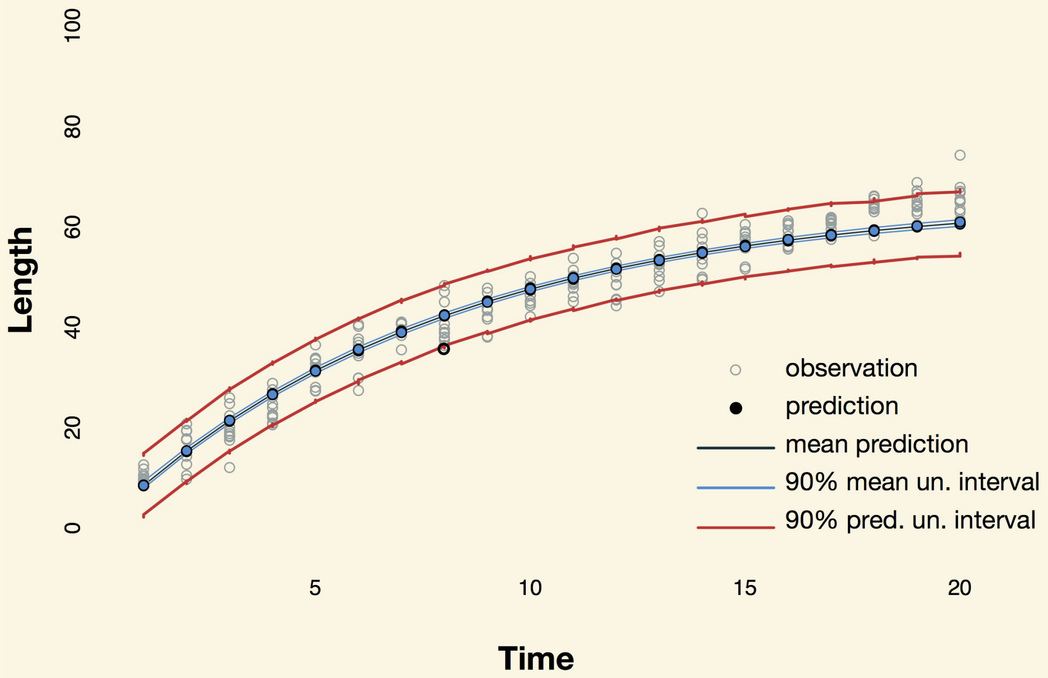
Applied question of interest.

Interpretation is sufficiently accurate.

Gelman, 26 September 2017

We want probability of estimates.

What are the uncertainty around my estimates?

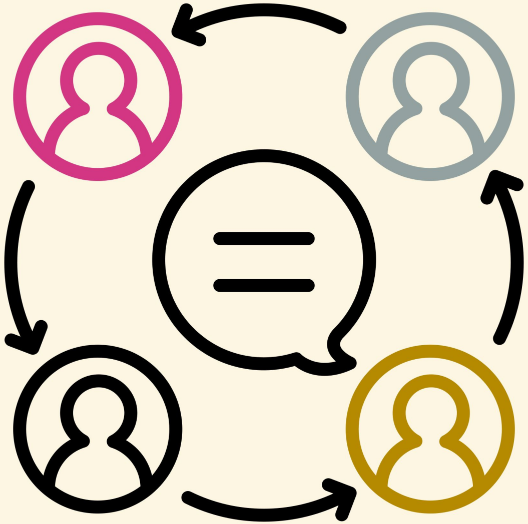


Good model building is based on outside peer input.

Independent.

Outside.

Experts.



Which is different from peer review.

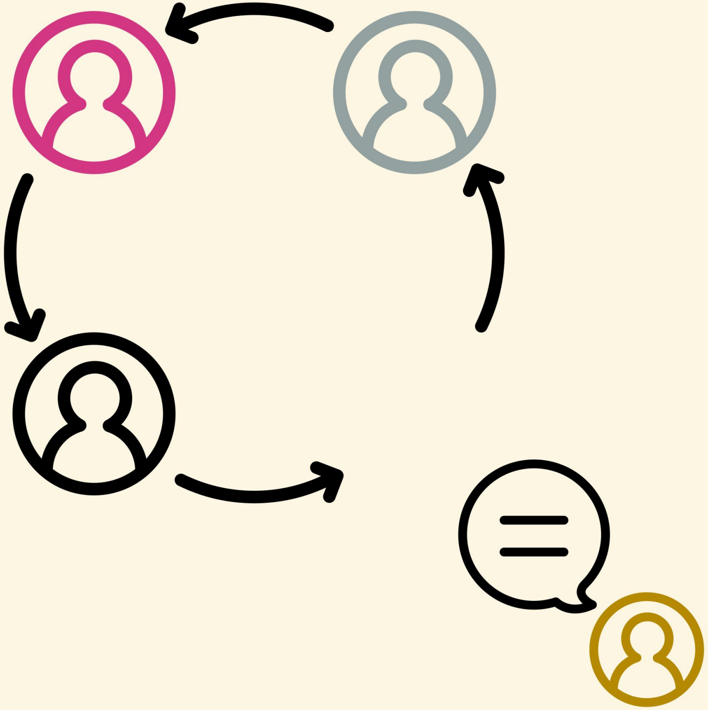
Blind or double blind.

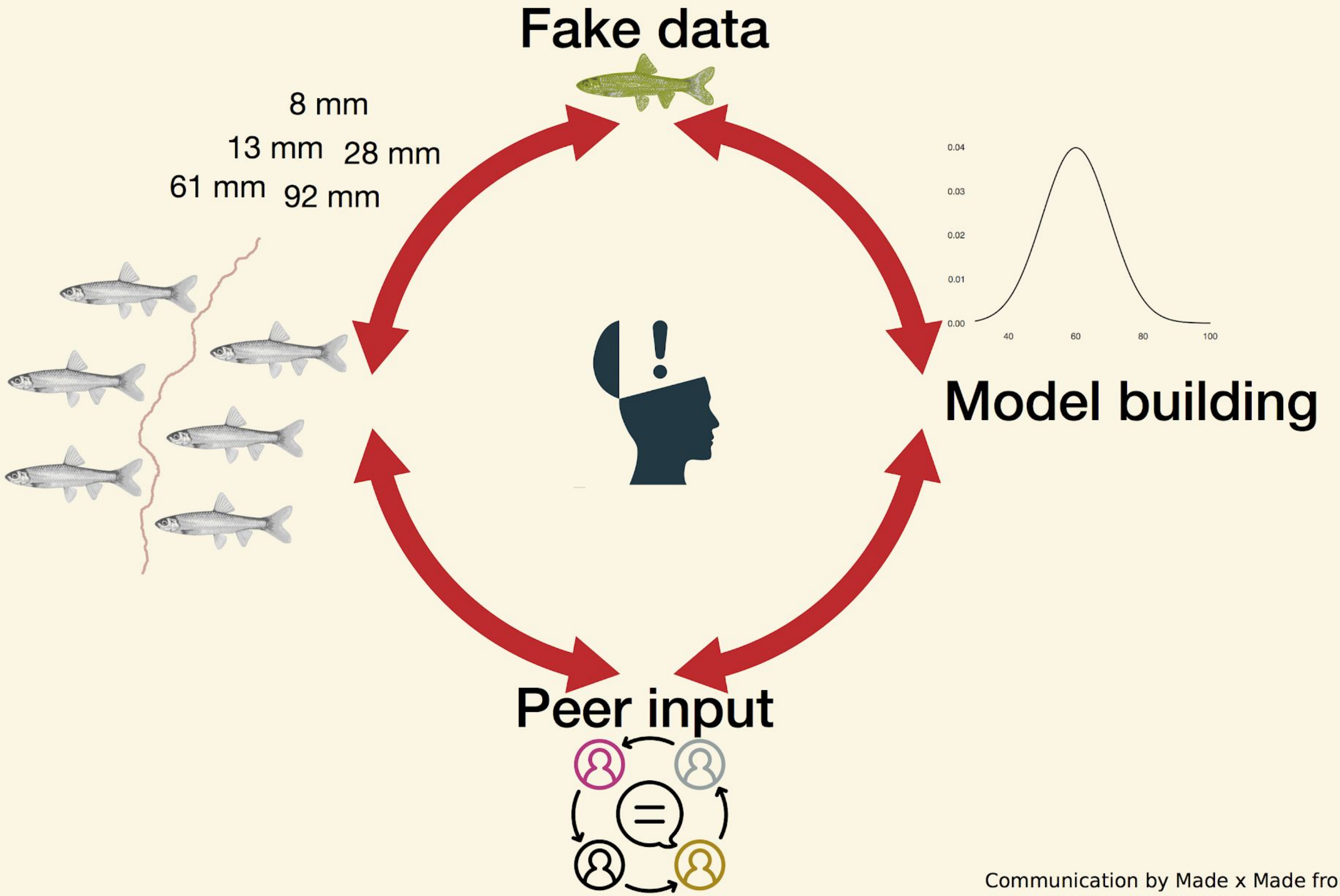
Independent.

Outside.

Experts.

Ongoing.





Fake data

Model building

Peer input

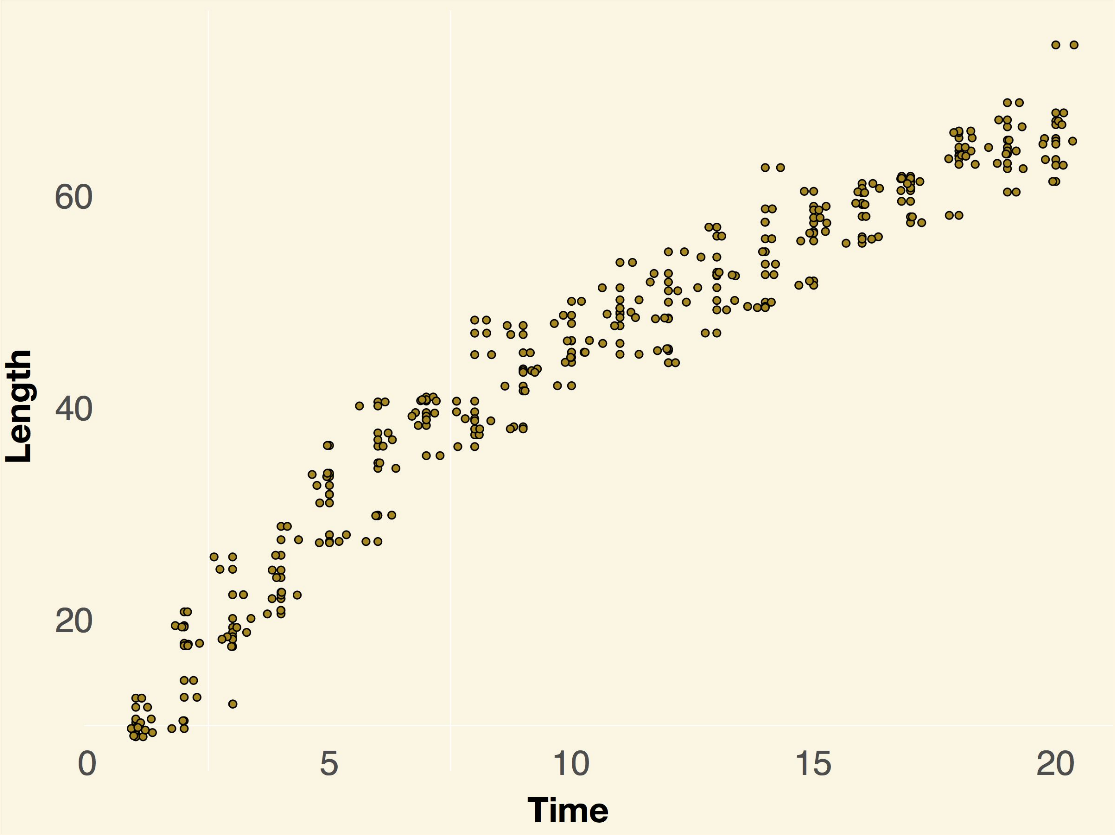
Communication by Made x Made from the Noun Project
Idea by Gilbert Bages from the Noun Project

We compared models and I failed in one place.

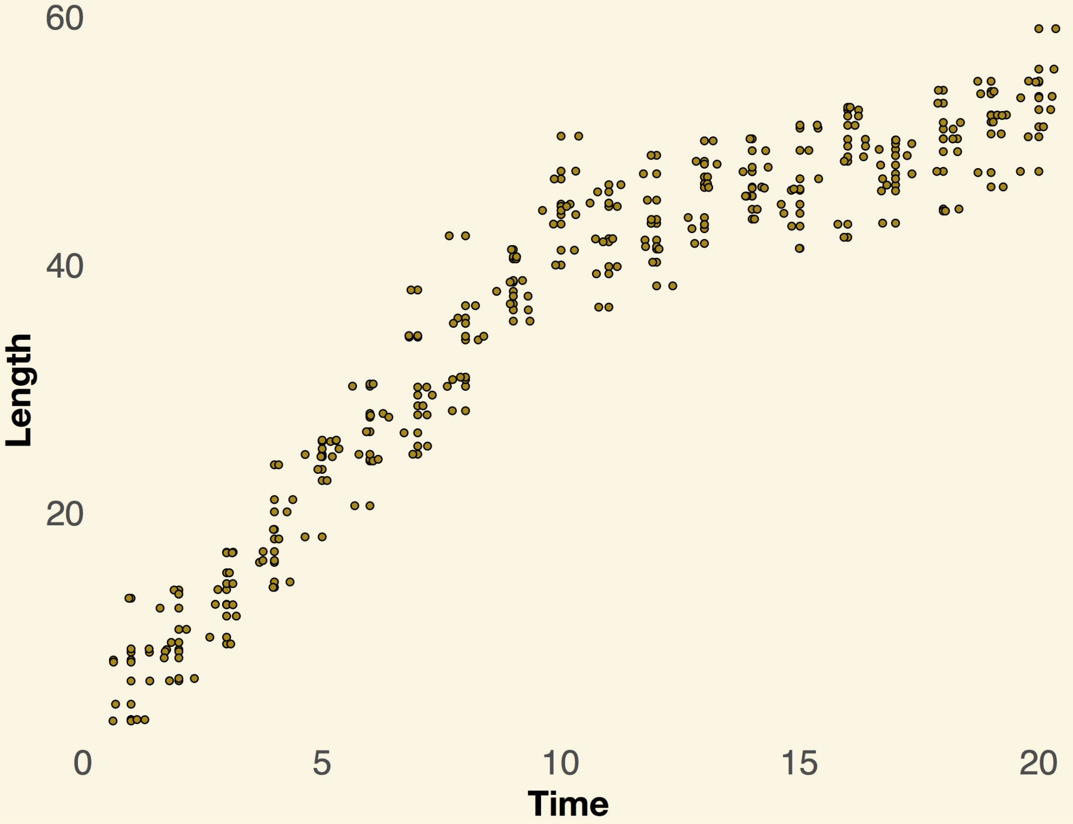
```
m[i] = alpha * (1 - exp(-beta * (x[i] - x0)))
```

And they log transformed that data.

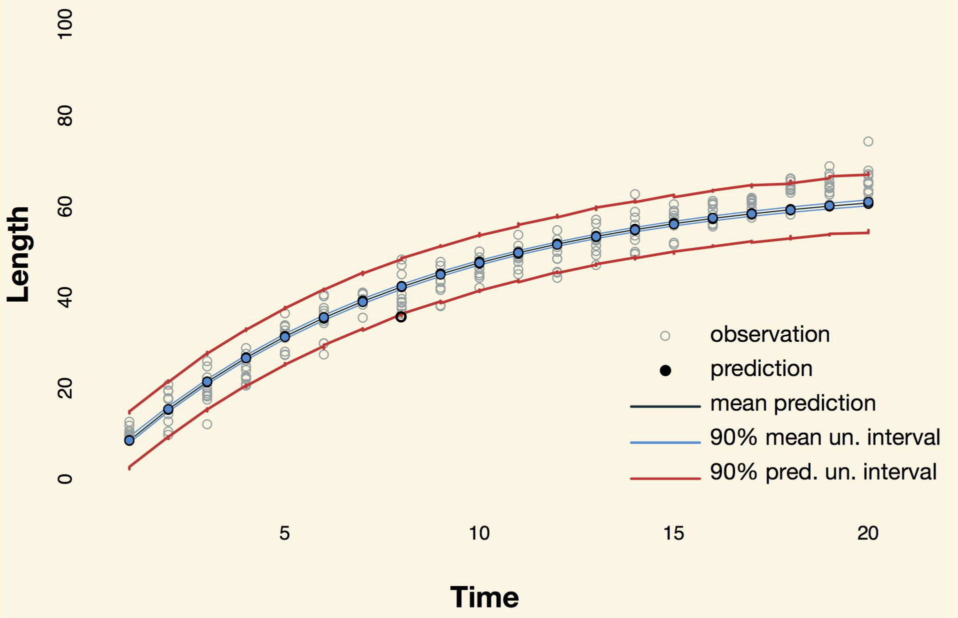
Now we can model the Southern Reach.

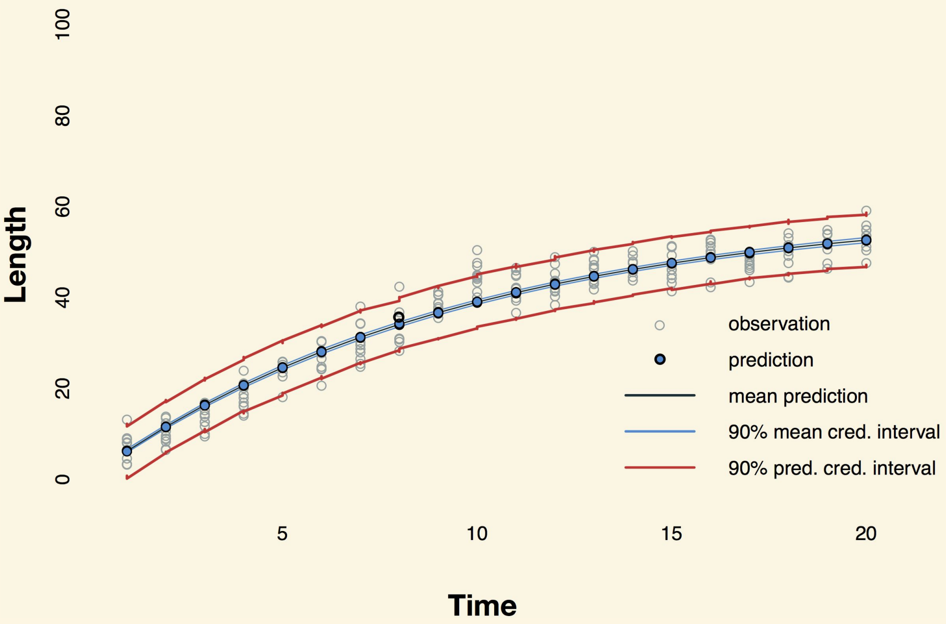


Now we can model the Northern Reach.



North to South are slightly different.



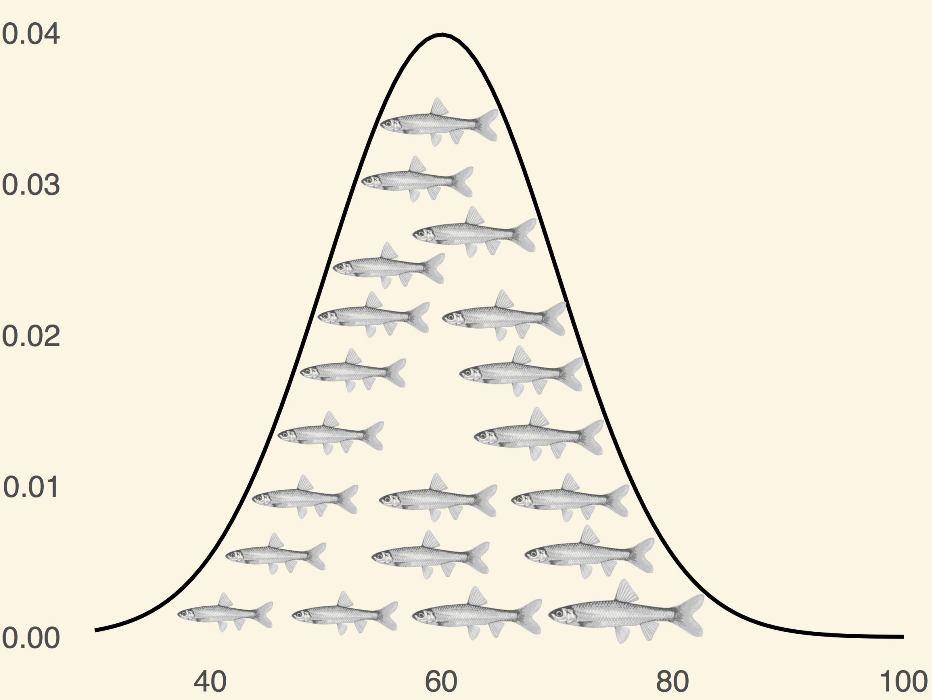


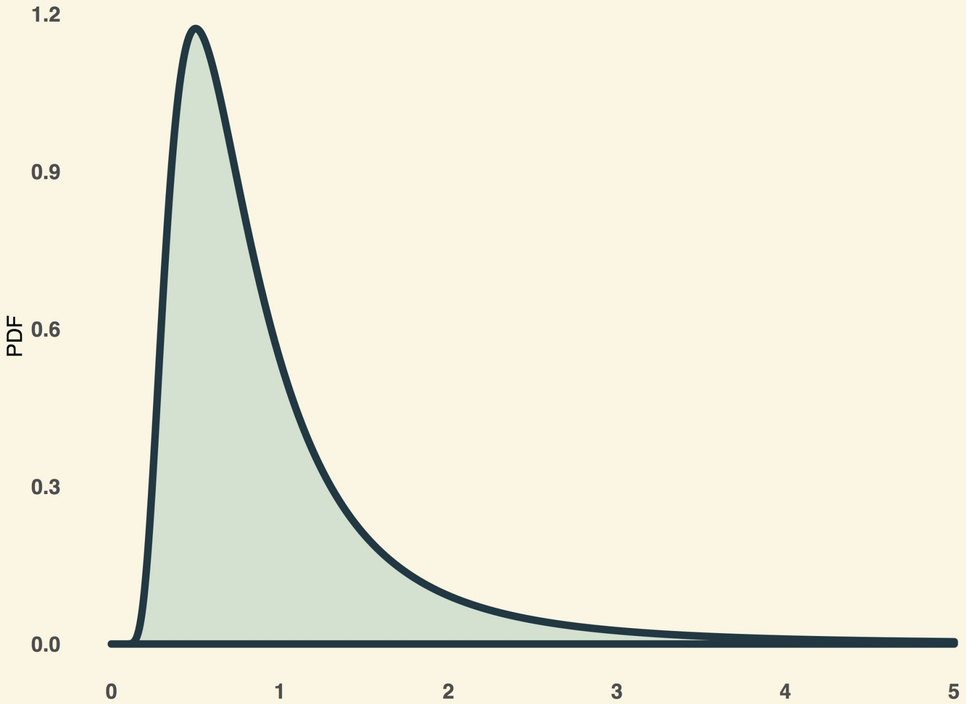
What’s cool is that alpha and beta aren’t fixed.

Northern Reach	**Southern Reach**
alpha 60.05	alpha 65.88
beta 0.10	beta 0.13

Why are alpha and beta not fixed?

Bayesian models are data models.





We learn more about our system.

How much does reach or sub-reach impact alpha and beta?

How does methodology influence alpha and beta?

Other covariates?

Predict ten years forward.

What are the next steps?

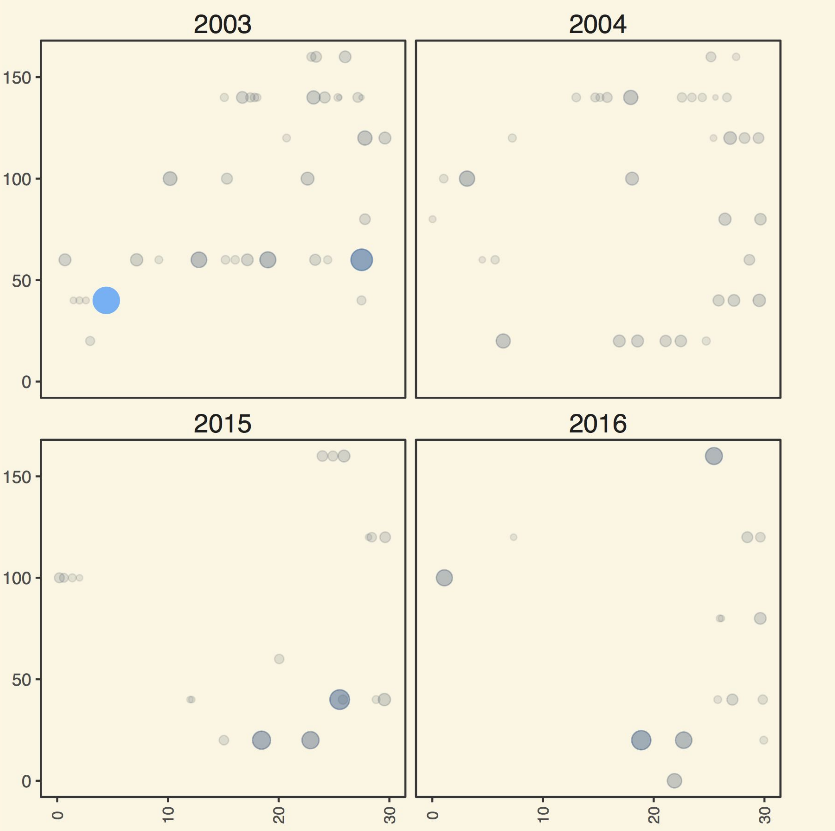
Run the real data through.

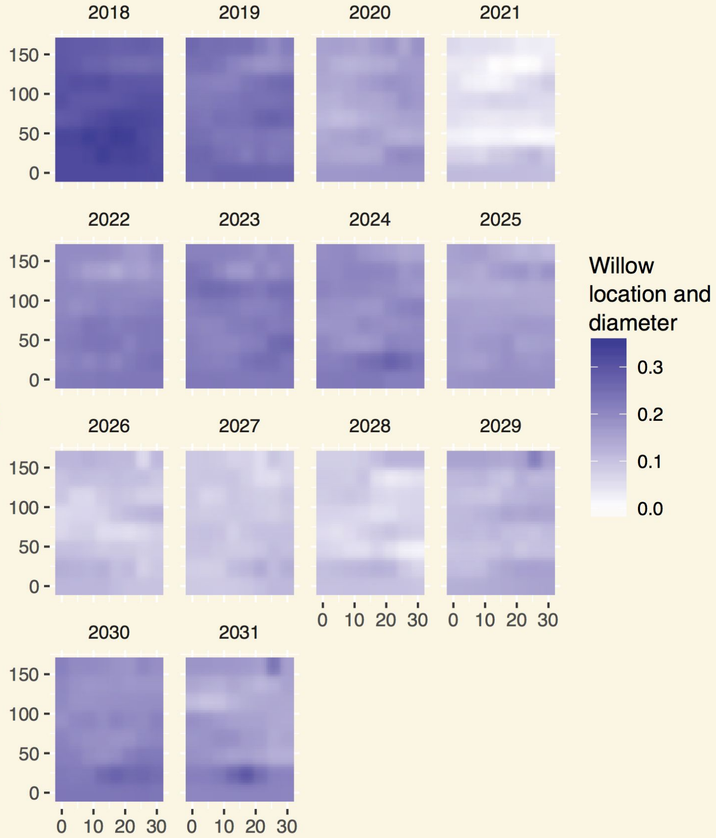
Hierarchical modeling.

Writing and journal peer review.

R and modeling workshops.

The willow problem.





Report	Page Number	Recommendation Number	Recommendation	Panel Priority	MRGESCP Original Priority	MRGESCP Current Priority	Sequence	Comments	Status
Fraser et al. 2016	4	Reporting Rec. 1	Sometimes it is not clear how Ne estimators relate to purpose. The reports could improve the explanations for why certain approaches were adopted.	1	0				Osborne et al. report now using different estimators and explaining them (2017 report)
Fraser et al. 2016	4	Reporting Rec. 2	Develop a biological relevant and realistic benchmark for critically low levels of genetic diversity. One possible way to set a benchmark would be to estimate the 95% confidence interval (CI) for genetic diversity (expected heterozygosity [He] and number of alleles [Na]) using all samples across time and space. If the diversity falls below the CI, then more aggressive management actions may be warranted.	1	0				Osborne et al. reported a 95% confidence interval in her 2017 report.
Fraser et al. 2016	4	Reporting Rec. 3	There needs to be a clear statement of the hypothesis and predictions being tested. For example, a simple hypothesis is whether there is a difference in estimates of genetic diversity between the pre- and post-augmentation periods. If this is the case, one approach would be to use a linear model to compare the estimates pre- and post- augmentation. Although time should be included as a co-variate, there is no effect of augmentation on observed heterozygosity corrected for sample size (Hoc) ($t = 1.95$, $p = 0.071$).	2	0				
Fraser et al. 2016	4	Reporting Rec. 4	The authors need to redefine pre-augmentation (1987, 1999) and augmentation periods (post 1999) given the augmentation that took place in 2000 and 2001. They may not be able to conclude strongly whether genetic diversity of the natural spawning population has changed. However, the authors can say that augmentation has maintained genetic diversity throughout the augmentation period, with the provision that this conclusion is based on the nine microsatellite loci evaluated, which might not reflect genome-wide variation.	2	0				
Fraser et al. 2016	4	Reporting Rec. 5	Microsatellite loci may no longer be the most effective markers for the purpose as the cost of newer, genotyping-by-sequencing (GBS) approaches has become more affordable for largescale throughput of many individuals. The limitations of microsatellites relative to other genetic markers such as single nucleotide polymorphisms (SNPs), and trade-offs associated with different genetic markers in relation to RGSM genetic monitoring goals, are discussed in detail under Questions 2, 8, 9, 10, and 13 (particularly 13).	2	0				The high through-put markers SOW is currently in contracting.
Fraser et al. 2016	4	Reporting Rec. 6	The Genetic Project PIs may also wish to examine genetic diversity / Ne variation over time using a piecewise regression as these can be used to find any breakpoints in the data; also referred to as segmented regression. If a breakpoint is identified say for pre- versus post-augmentation, then separate regressions can be run for each section. This approach can also identify points in time where there are temporal changes in genetic diversity.	3	0				

Fraser et al. 2016	16	Question 13 Rec. 1a	The panel therefore recommends that both neutral and adaptive genetic variation be monitored over time in RGSM in the future using a larger, more diverse set of genetic markers. Genotyping-by-sequencing (GBS) or related equivalent would provide more confident estimates of genome-wide neutral genetic variation (Nac, Ho) in RGSM because it would more likely represent the entire genome (for more information on GBS and related NGS approaches and their practical benefits for conservation genetics monitoring, see the review of Allendorf et al. 2010)...thus we recommend examining phenotypic variation for important life history traits (size/age maturity, growth rate), behavioral traits (anti-predator behavior, risking taking behavioral syndromes) and morphology (body shape as it relates to flow regime).	2	0				The high through-put markers SOW is currently in contracting.
Fraser et al. 2016	17	Question 13 Rec. 1b	Sampling of floodplains should be considered and included where feasible to ensure that the genetic characteristics of RGSM are adequately represented in egg collection samples.	1	0				SOW description developed
Fraser et al. 2016	18	Question 13 Rec. 2a	Conduct random sampling of annual egg collections from nature, to include not only the main channel but also the floodplains, for subsequent hatchery rearing (e.g., current collections only come from the main channel of the Rio Grande River, not on floodplains).	1	0				SOW description developed
Fraser et al. 2016	18	Question 13 Rec. 2b	Rear RGSM in environmental conditions that resemble natural environmental conditions as much as possible. This will reduce relaxation of selection or non-random survival at egg/early life stages in relation to habitat selection/settlement, behavioral/physiological characteristics, anti-predator responses etc. Specific recommendations for RGSM hatcheries include: (i) early juvenile environmental enrichment that resembles critical floodplain habitat (temperature, substrate, flow, turbidity, pH, conductivity, food sources, natural daylight); and (ii) some exposure to natural predators, or at the very least, mimicking of predators to stimulate anti-predator conditioning.	1	0				The BioPark and Dexter raises RGSM on natural foods as much as possible, and some outside. Ponds at Los Lunas and in Dexter are exposed to predators. Will need additional documentation from the facilities to determine what the characteristics are at each facility (diatoms, predator exposure, other environmental conditions). Gut analysis and stable isotope analysis done as well. SOW description developed.
Fraser et al. 2016	18	Question 13 Rec. 2c	RGSM live longer in captivity and the breeding program uses 4-year old fish as brood stock. By contrast, in the wild the breeding population is comprised largely of 1-year old fish. Thus, it will be prudent to evaluate the phenotypic effects of older brood-stock. Also, because larger fish have about 4x as many eggs as younger adults (10,000 vs. 2,500), and there is also likely higher variance in egg production among 4-year old fish compared to the variation in egg production among 1-year old fish. This could undermine efforts to equalize family sizes. Thus, using younger fish as brood stock will reduce the likelihood of un-intentional domestication selection, and also result in higher effective population sizes (due to reduced variance in egg production among females).	1	0				Dexter does not use 4 year old fish anymore; documented in their annual report. BioPark does not use 4 year old fish.
Fraser et al. 2016	18	Question 13 Rec. 2d	Equalize contributions of different adults in the captive broodstock to new broods/lots as much as possible.	1	0				Not currently possible. Requires a change in spawning protocol. Communal spawning vs. pairwise spawning (having the SNP's developed will enable this to become a SOW).

Fraser et al. 2016	18	Question 13 Rec. 2e	Rear RGSM so as to maintain the growth trajectories typical of wild-raised fish (i.e., Age 1 fish in captivity should exhibit the same range of sizes of Age 1 fish in the wild). At present, either faster growing individuals may be unintentionally selected for, or other fish phenotypes (e.g., size, condition, body shape) may not match natural sizes upon release.	1	0				First cut would be to have each facility provide fish length distributions for each age class of fish. Compare to lengths observed on the river. This could be a modifcation to current contracts. Additional phenotypic or behavioral comparisons would be a SOW.
Fraser et al. 2016	19	Question 13 Rec. 2f	Rear RGSM on natural diet if possible; diet appears natural at early life stages, but diet appears supplemented in later life stages (pellet feed).	1	0				The BioPark, Dexter, and Los Lunas raise RGSM on natural foods as much as possible, and some outside.
Fraser et al. 2016	19	Question 13 Rec. 2g	Minimize the duration in captivity as much as possible before release; domestication selection is reduced with less captive exposure (see Frankham 2008 and Fraser 2008).	1	0				Release is currently as early as possible. USFWS is currently examining the effectiveness of a February release.
Fraser et al. 2016	19	Question 13 Rec. 3a	Maximize the information gained from re-stocking efforts of hatchery-raised fish back into the river in order to test particular scientific hypotheses and inform adaptive management.	2	0				Being looked at in small pieces, but too large overall to address right now comprehensively.
Fraser et al. 2016	19	Question 13 Rec. 3b	In addition (or alternatively if resources are limited), the genetics survey could focus on characterizing whether the year classes maintained in the hatcheries change over time in their genetic constitution as a consequence of differential mortality.	2	0				SOW description developed
Fraser et al. 2016	20	Question 13 Rec. 3c	Monitoring of domestication selection could include DNA fingerprinting (GBS) of wild-caught egg collections. An investigation into whether non-random changes to genome-wide variation were occurring at successive early life stages relative to the same stages in the wild would provide evidence that the hatchery environment is resulting in domestication selection.	3	0				Not currently possible. Requires the SNP study to be complete.
Fraser et al. 2016	23	Recommendation 1	A flow chart should be constructed for each year that gives detailed numbers for: eggs and dates taken, disposition of eggs/larvae to specific rearing sites, broodstock maintained, actual breeding strategy, disposition of eggs/larvae to specific rearing sites, pooling of larvae prior to stocking, stocking sites, source of juveniles, and dates. These data should be standardized and collected for each hatchery engaged in fish production and the data should be made available electronically to all interested parties. Deviations from planned methodologies (such as the inclusion of approximately 10,000 eggs from unplanned spawning in a broodstock tank) should be noted in the flow chart.	1	0				Could do a modification to contracting to add this to the reports. May require additional funds.
Fraser et al. 2016	23	Recommendation 2	When deviations from planned methodologies result in the production of offspring, those offspring should not be released into the wild. Release of these offspring into the river could have a negative effect on the overall genetic diversity of the population. Providing flexibility in the next recovery permit should allow such surplus fish to be properly handled, whether used for research or held until natural death in the hatchery.	1	0				Dexter uses these fish for Big Bend population. Unsure about other facilities.

Fraser et al. 2016	23	Recommendation 3	All broodstock and sufficient subset of the pre-release juveniles should be genotyped and the contribution of each broodstock individual determined. These results can be used to gain a more accurate, precise and biologically relevant estimate of Ne for each year class. This approach avoids the inherent assumptions and excessive variance associated with the Ne estimators currently employed. This should be done every year. Developing a high throughput method would facilitate more rapid genotyping.	1	0				The broodstock from Dexter and the BioPark were genotyped, and fish to be released in the fall will be genotyped. The high throughput makers SOW is currently in contracted.
Fraser et al. 2016	24	Recommendation 4	The Genetics Management and Propagation Plan and/or the Augmentation Plan should have a detailed methodology as to what will be done should a drought lasting more than three/four years occurs or all four year classes of broodstock are lost to a major hatchery accident.	1	0				Wade Wilson sent the DRAFT RGSM Gentics Management and Propagation Plan out on August 9, 2018
Fraser et al. 2016	24	Recommendation 5	The Science Workgroup (led by the Program) and the Genetics Workgroup (led by the USFWS) should integrate the genetics data and the decision-making more carefully. Specifically, there should be more translation of the genetics research into the adaptive management process, hatchery broodstock practices, and the integration of the past 15 years of research (genetics and ecology combined).	1	0				Will be incorporated into the AM process.
Fraser et al. 2016	24	Recommendation 6	A more stable, consistent funding stream for the genetics research (e.g. an extended funding cycle) would ensure that all critical, temporally important genetic studies are accomplished each year (e.g., broodstock genotyping, pre-release juvenile genotyping). Cost will vary depending on the analysis and goal. At the time of writing this report, the RGSM program can expect to require approximately $50-150/individual for GBS or RAD-seq if outsourced to a genomics facility (including individual sample preparation, but not including salary for a research associate for sample preparation, data filtering and data analysis); a minimum of 30-40 individuals per year is recommended. Other genetic assessments do not require the amount of genetic data generated from GBS; any parentage assignments of offspring generating from mixed matings in the hatchery, for example, would be expected to cost approximately $5-10/individual (not including personnel salaries), and so could be (and should be) conducted on larger numbers of individuals (1000s).	1	0				MRGESCP has been able to steadily fund RGSM genetics monitoring.
Fraser et al. 2016	24	Recommendation 7	The use of only four year fish as broodstock may compromise the maintenance of genetic diversity because of the possibility of non-random, differential survival of individuals in the hatchery. Crosses should include younger fish. As a consequence of using younger fish as broodstock with lower fecundity, more fish will be needed to produce the quota of eggs and this will increase the effective number of breeders.	1	0				Dexter does not use 4 year old fish anymore; documented in their annual report. BioPark does not use 4 year old fish.
Fraser et al. 2016	24	Recommendation 8	It will be useful to conduct an evaluation of whether domestication selection is occurring in the hatcheries. This could be done using an appropriate genetic analysis and/or measuring quantitative traits to assess phenotypic variation of each captive cohort during each year in captivity.	1	0				Pheotypic aspect discussed above and genetics aspect requires SNPs to be complete.
Fraser et al. 2016	24	Recommendation 9	We recommend the use of the term “naturally spawned” in place of the term “wild” to refer to fish captured in the river that do not have an elastomeric tag; this assumes that all augmentation fish received a tag. It is likely that all fish captured in the wild have experienced some hatchery influence in their ancestry.	2	0				Dexter has adjusted their internal terminology.

Fraser et al. 2016	25	Recommendation 10	If possible, the augmentation team should consider artificially spawning broodstock in a one female by one male mating scheme, all the while maintaining the same total number of broodstock adults spawned (or increasing this number). This would allow equalizing family size as families are combined.	2	0				Requires SNPs to be complete.
Fraser et al. 2016	25	Recommendation 11	Relatedness should be calculated for broodstock prior to use to choose specific crosses that avoid inbreeding. If group spawning continues, relatedness estimates could be used to ensure that potential spawners in a group have low kinship.	2	0				Requires SNPs to be complete, as well as paired vs. communal spawning work.
Fraser et al. 2016	25	Recommendation 12	To facilitate adaptive management, experimental studies comparing the survival and reproductive success of subsets of RGSM from different stocking strategies and hatchery facilities in nature would also shed light on the extent to which domestication selection is a concern in the recovery program.	2	0				USFWS is tagging fish from different facilities and also comparing fall vs. spring release strategies. This will be a 2-3 year study. Reproductive success would be a separate SOW that will be intensive/difficult to the monitor.
Fraser et al. 2016	25	Recommendation 13	A study using next-generation sequencing technology (e.g., GBS, RAD-seq) should be done with pre-augmentation samples and post-augmentation year classes to determine how the genome as a whole has changed over time. At the time of writing this report, the RGSM program can expect to require approximately $50-150/individual for such an assessment (more for RAD-seq) if outsourced to a genomics facility (including individual sample preparation, but not including salary for a research associate for sample preparation, data filtering and data analysis); a minimum of 30-40 individuals per year is recommended.	2	0				The high through-put markers SOW is currently in contracting.
Hubert et al. 2016	28	1	Separate the catch and effort data from the small-mesh seine and the fine-mesh seine into two data sets and compute separate CPUE indices for each gear type, as well as for individual age classes captured in each gear type.	Not given	1				ASIR reported CPUE by gear type and age class in their 2017 Population Monitoring report.
Hubert et al. 2016	28	2	The CPUE from the small-mesh seine is primarily an index of the relative abundance of a single cohort of RGSM (i.e., the most recent cohort) that is recruited into the gear late in the summer and captured into the summer of the following year. The precision of the index can be improved by exclusion of older cohorts. A separate CPUE index can be computed for older cohorts. Consider the use of length-at-age data and frequency histograms to identify cohorts.	Not given	1				ASIR addressing this recommendation using 2 length/age classes - Age 0 and Age 1+
Hubert et al. 2016	28	3	Only larval fish should be included in the computation of CPUE indices from the fine-mesh seine because of this gear’s selectivity for this life stage.	Not given	1				ASIR reported CPUE for larval fish only using the fine-mesh seine, and used the small-mesh seine for all other age classes.
Hubert et al. 2016	28	4	An aspect of the CPUE data that warrants attention is the treatment of zero catches in data analyses. Inclusion of dry sample sites as zero CPUE values when analyzing CPUE data for RGSM in the MRG should be avoided. Field data records and the database in which the RGSM CPUE data are stored allow dry sampling sites to be distinguished from sites that were sampled and no RGSM were caught. The problem arises during statistical analyses because the naughty naughts (observations of zeros at dry sampling sites) are treated in the same manner as the zero catches at fished sites where no RGSM are caught.	Not given	1				ASIR excluded dry sites in their analyses. Dry sites are replaced.

Hubert et al. 2016	28	5	Survey designs should strive to minimize false zeros resulting from: (1) an inappropriate sampling design (e.g., sampling in mesohabitats avoided by RGSM) and (2) ineffective survey methods (e.g., insufficient sampling effort to detect an organism when it is present).	Not given	1 and 2				Preliminary analysis from Population Monitoring WG shows that rare mesohabitats are sampled at a higher proportion than they exist in the environment (Valdez 2018)
Hubert et al. 2016	29	6	The proportions of various mesohabitat types sampled are likely to bias CPUE indices because the catchability coefficient probably differs among mesohabitat types and RGSM are likely to be selective for specific mesohabitat types. We recommend that better understanding of the influence of mesohabitat type on CPUE be developed and used to account for variability in CPUE indices. Further, we recommend that estimation of mean site-specific CPUE be improved by addressing the variable number of mesohabitats that are sampled at any given site and the amount of sampling in each mesohabitat type. We recommend estimation of mean site-specific CPUE from individual seine hauls (which are distinguishable in the database as of 2006); mean CPUE at each site is then computed from the individual CPUEs at each of the 18-20 mesohabitat units sampled per site.	Not given	1 and 2				ASIR has reported CPUE by mesohabitat type in their 2016 and 2017 reports. Some additional efforts towards this recommendation have been made by the DAT (Valdez 2018)
Hubert et al. 2016	29	7	Environmental factors (e.g., turbidity, water temperature, substrate size, depth, current velocity, and discharge) during sampling are likely to bias CPUE indices because of their influence on catchability. We recommend that better understanding of the influence of measurable environmental factors on the catchability of each seine type be developed and used to account for variability in CPUE indices.	Not given	3				Sampling is not conducted above a certain CFS.
Hubert et al. 2016	29	8	Factors influencing detection and catchability of RGSM in seines need to be determined and incorporated into the sampling design to permit more robust estimation of CPUE.	Not given	1				
Hubert et al. 2016	29	9	Measures of CPUE for RGSM from the MRG are currently identified as recovery standards for the species. We recommend modification of recovery standards to be explicit regarding the gear, sampling design, sampling techniques, data analysis, and life stage, as well as protocols used to compute the CPUE index.	Not given	0				
Hubert et al. 2016	29	10	We recommend depiction of the relationship of hydrological covariates and estimates of the mean annual CPUE for RGSM derived from the mixture model. Those relationships should use the October data from 1993 to 2014. Further, we recommend that such analyses be repeated for catch data collected in 2006 to the present, but using the individual seine-haul approach to estimate CPUE.	Not given	1				ASIR included some hydrological variables as covariates in their estimated desitiy models. More covariates of interest may be identified. The HBO assesment by Utah State University will look at hydrological covariates and CPUE. No analysis is being conducted at the individual seine-haul level.
Hubert et al. 2016	29	11	We recommend that the assumptions of the mixture models be fully defined and that the results of analyses be interpreted with consideration of the assumptions and the effects of the potential violation of assumptions.	Not given	1				ASIR included a table in their 2017 Population Monitoring Report detailing assumptions, violation implications, violation risks, and mitigation precautions.

Hubert et al. 2016	29	12	A greater number of sampling sites would improve the accuracy and precision of status assessments and improve estimates of RGSM CPUE and spatial distribution, especially at the reach scale. A greater number of sampling sites in each of the three reaches would facilitate status and trend estimates at the reach scale. To make statistically rigorous reach-scale CPUE estimates, 20-50 sites per reach are recommended. A design with substantially more sites and longer site lengths should be more effective at detecting RGSM when they are at low densities or demonstrating patchy distributions.	Not given	1				ASIR monitored 10 additional sites during the 2017 monitoring period and reported the results in their 2017 Population Monitoring report.
Hubert et al. 2016	29	13	When river flows decline so that dry sampling sites occur among the 20 fixed sites sampled by the Monitoring Program, the ability to make inference regarding CPUE of RGSM over the MRG is impaired. The current 20-fixed-site sampling is not adequate when dry sampling sites occur. An ancillary randomized sampling design is recommended at such times to be able to make inferences about RGSM abundance and distribution throughout the entire MRG. Such a random sampling design would entail sampling at many more sites over the length of the MRG. An ancillary design of this type would enhance the feasibility of assessing the abundance and distribution of RGSM in the MRG during years of low flows and when the species is likely to occur in low abundance.	Not given	0				ASIR sampled replacement sites whenever the river was dry at a standard or additional site.
Hubert et al. 2016	30	14	Consider using key drivers of mesohabitat variability, such as current velocity, substrate size, and water depth at specific locations where seines are deployed, to replace the mesohabitat factor in the mixture models.	Not given	2				May be considered in the next SOW
Hubert et al. 2016	30	16	Examine the historical availability of mesohabitats in the MRG relative to discharge. If these two measures can be linked, then annual or monthly discharge may provide a good surrogate of mesohabitat availability.	Not given	2				
Hubert et al. 2016	30	17	Evaluate alternatives to the parametric mixture model, in particular, Bayesian hierarchical models, for estimating annual CPUEs.	Not given	2				
Hubert et al. 2016	30	18	Use classification and regression trees, boosted regression trees, or random forests to examine relationships between hydrologic variables and CPUE for identifying thresholds above or below which CPUE exhibits changes.	Not given	1.5				
Hubert et al. 2016	30	19	Implement directed studies using different sampling designs, such as multi-year, multi-site, before-after-control-impact (BACI) designs to enhance understanding of the response of the population to changes in river discharge, habitat rehabilitation projects, and availability of mesohabitats.	Not given	3				
Hubert et al. 2016	30	21	Conduct stock-recruitment studies to determine how the abundance of fall recruits relates to the abundance of spring spawners. Investigate the effects of spring and summer discharges on the stock recruitment relationship to enhance understanding of the dynamics of RGSM. Implement a spring sampling protocol at spawning sites to estimate the number of spring spawners, and compare with October results for several years; such studies may provide useful data on RGSM population dynamics and limiting factors.	Not given	3				
Hubert et al. 2016	30	22	Complete a study of age-specific fecundity and survival rates based on pre-breeding (fall) population estimates, spring spawners, and hatchery supplementation. Results from this study could be used to estimate population recovery and extirpation potentials as a function of altered flow regimes and stocking.	Not given	3				Not completed in MRGESCP, however Caldwell et al. report (2018) addresses age-specific fecundity, but not survival.

Hubert et al. 2016	30	23	Consider genetic fingerprinting and epigenetic studies, including bar-coding and gene-expression, of presumed wild and hatchery fish to help determine hatchery contributions to the spring spawners and the long-term risks to the wild population.	Not given	0				
Hubert et al. 2016	30	24	Expand the analyses in Dudley et al. (2015) to assess flow regime and habitat fragmentation effects on RGSM occurrence and abundance and suggest preliminary flow regimes for rehabilitating the wild RGSM population.	Not given	3				
Hubert et al. 2016	31	Observation Beyond the Scope 1	Attention to long-term climate-change issues and integration with climate-change planning efforts was not evident to the expert panelists (from the readings or from discussions at the December workshop) regarding how the Cooperative Program and Monitoring Program plan to address markedly lower flows and higher water temperatures.	Not given	Not given				
Hubert et al. 2016	31	Observation BTS 2	The MRG lacks minimum instream flow requirements to assure recovery. A major element of discussion by program scientists and interested parties during the workshop focused on low-flow periods and the potential for survival of RGSM during those periods when portions of the MRG have no observed surface flows or when there is no measurable discharge at gaging stations. It became evident to the external panelists that there are no specified minimum instream flow requirements or guidelines for the MRG. Minimum instream flow requirements or guidelines would not only enhance the potential for recovery of the RGSM in the MRG, but they would enable the current 20-site design of the Monitoring Program to be used to assess continuously status and trends of the RGSM stock in the MRG.	Not given	Not given				
Hubert et al. 2016	31	Observation BTS 3	The Monitoring Program assesses relative abundance of the RGSM in October; the young-of-year fish encountered at this time are likely to include the progeny of hatchery fish that were stocked the previous year (in November), survived the winter, and successfully reproduced. As such, the Monitoring Program is measuring the ability of hatchery stocking to contribute to or maintain a population in the MRG. Understanding of the dynamics of the RGSM population and the effects of changes in water resources in the MRG is hindered by confounding of environmental and hatchery-fish effects. There is a need for Monitoring Program scientists to effectively disentangle the source of new recruits (Creel et al. 2015), in particular the relative contribution of hatchery-origin fish and naturally spawned wild fish. One suggestion is to apply individual-based models (IBMs) to simulate changes in the system (e.g., cessation of stocking, decreased discharge rates) and assess those effects on RGSM populations (see e.g., Rose et al. 2013a and b). IBMs are used to describe population outcomes by tracking the fate of the individual fish that compose the population. As such, these models allow individual fish to exhibit unique combinations of growth, survival, fecundity, and movement probabilities. Although this is a powerful approach for the study of animal populations, IBMs require large amounts of data. Thus, the feasibility of this approach will depend on the depth of knowledge of basic biological processes for RGSM in the 1186 MRG.	Not given	Not given				

Hubert et al. 2016	31	Observation BTS 4	In recent years, low RGSM abundance has led to salvaging fish from residual pools and the introduction of hatchery reared fish to supplement the RGSM population. This creates a dilemma of providing fish to preclude RGSM extinction versus creating a domesticated hatchery-dominated population ill equipped to survive the rigors of a highly stressed environment. Therefore, additional genetic fingerprinting and epigenetic studies of presumed wild, hatchery, and hatchery-originated progeny are needed to determine hatchery contributions to the spring spawners and the risks thereof to the wild population (Quinones et al. 2014; Trushenski et al. 2015; Carmichael et al. 2015)...The question of greatest concern here is the degree to which the population has become, or is becoming, a largely hatchery-derived population with reduced survivability in the face of climate change and other physical and chemical habitat alterations. This becomes of greatest concern when wild populations are naturally and anthropogenically constricted in numbers relative to the numbers of hatchery-origin fish added to the population. Because of such natural and anthropogenic pressures, the highly variable RGSM population likely will continue to be reduced and the wild population may be extirpated (Lawson 1993; Cowley 2006). Continuation of current hatchery augmentation practices should include a rigorous risk/benefit analysis.	Not given	Not given				0
Hubert et al. 2016	32	Observation BTS 5	Although not explicitly discussed during the December workshop, the current recovery plan and criteria for the RGSM (USFWS 2010) are based on the 20-fixed-site sampling protocol. Recovery criteria for the MRG include presence of unmarked and age-0 RGSM at 75% of all sites per reach in October; an October CPUE of >5 RGSM/100 m2 in all sites in a reach for five consecutive years; and age-0 RGSM in 75% of all sites in a reach for five consecutive years. To the degree that insufficient October flows limit sampling of all 20 sites, those recovery criteria cannot be met. In addition, the recovery plan implicitly assumes that genetic exchange is generally in a downstream direction, that the wild RGSM genetic composition has been preserved, and that unmarked fish have a wild genotype. However, those assumptions may be negated by ongoing hatchery practices as discussed above in Observation 4.	Not given	Not given				ASIR sampled at replacement sites when a fixed or additional site was found to be dry. They also added 10 additional sites in 2017.
Hubert et al. 2016	32	Observation BTS 6	The analyses in Dudley et al. (2015) could lead to quantitative instream flow and habitat studies and be used to assess flow regime and habitat fragmentation effects on RGSM occurrence and abundance and then used to set preliminary system-wide instream flow criteria for rehabilitating RGSM. This is because current rehabilitation actions such as salvage, stocking of hatchery fish, and local flow and physical habitat manipulations have only local or temporary effects compared with the system-wide effects of major diversion dams and basin-scale land use (e.g., Wang et al. 2003; Hughes et al. 2005, 2014). Normalizing flow regimes, improving fish passage, and extensively lowering floodplains would help rehabilitate a species such as the RGSM (Williams et al. 1999; Tockner et al. 2000; Dudley et al. 2015; Novak et al. 2015); admittedly, such rehabilitation measures may be costly. Although portions of the MRG have experienced periods of natural drying and flooding historically, anthropogenic increases in the frequency or extent of drying and anthropogenic decreases in the frequency and extent of flooding, together with passage barriers, likely reduce the potential of wild RGSM to persist and flourish in the MRG (Hughes et al. 2005; Novak et al. 2015).	Not given	Not given				

Hubert et al. 2016	33	Observation BTS 7	During the workshop, the panelists noted that a number of organizations and agencies were engaged in research on RGSM in the MRG (i.e., US Fish & Wildlife Service, Bureau of Reclamation, and Army Corps of Engineers). However, the expert panelists did not identify whether formal procedures for sharing outcomes and results from these studies are in place, for example, via annual multi-day research review and discussion meetings with all Cooperative Program and Monitoring Program partners. In addition, models to describe the hydrodynamics of the MRG have been developed, but fish population studies do not appear to make use of these models. The water resource problems in the MRG are complex and water management actions affecting discharge and flow in the river affect the population of RGSM. An annual research review or similar activity may help to strengthen information exchange and advance scientific understanding of the issues in the MRG.	Not given	Not given				Planning 2019 MRG Science Symposium
Hubert et al. 2016	33	Observation BTS 8	An adaptive management program may help to improve understanding of the relationship between management actions in the MRG and the status of the RGSM population. We understand that such an approach will soon be implemented for the MRG and encourage the Collaborative Program to pursue a rigorous adaptive management program. Adaptive management is typically viewed as a partnership between management agencies and agencies engaged in research to address critical uncertainties in the system. Partnerships are key because new knowledge about the system will be obtained only when research and management work hand-in-hand. In adaptive management, (1) the science problems must be defined in a clear manner that permits design of targeted investigations; (2) conceptual and simulation models are then used to investigate responses of the system to potential management interventions; (3) direct, purposeful manipulations are implemented and the response of the system measured in a statistically reliable manner; and (4) analyses and synthesis of outcomes are completed in a timely manner to support robust decision-making. Adaptive management in the MRG would benefit from a conceptual model of the system that integrates water use, hydrodynamics, and fish population responses. It is unclear if such a model exists, but it is imperative to develop such models to ensure that management manipulations will provide sufficient contrast and ensure a measurable result.	Not given	Not given				Planning 2019 MRG Science Symposium and working towards an Adaptiveme Management Framework for the program.
Hubert et al. 2016	33	Observation BTS 9	In addition to adaptive management, Collaborative Program partners and collaborators may wish to consider other tools such as scenario planning (Baker et al. 2004; Hulse et al. 2004; Allen and Gunderson 2011; Rowland et al. 2014) and resilience building (NYC 2013; Norfolk 2014). Scenario planning may be an effective management approach when uncertainty about the system is high and factors that affect the system are not readily controlled (e.g., amount of snow pack available for replenishment of rivers). In this approach, alternative futures are explored with the goal of identifying improvements to current management actions. This may be a good strategy to pursue now, perhaps together with adaptive management. As uncertainty about the system declines (through learning derived from targeted research studies and adaptive management), we suggest implementing a resilience building approach. The approach is effective when driving factors remain uncontrollable and system uncertainty is low. Many coastal cities have adopted this approach in the face of rising sea levels (e.g., New York City [NYC 2013] and Norfolk, VA [Norfolk 2014]).	Not given	Not given				

Hubert et al. 2016	33	Observation BTS 10	The research done on the RGSM warrants publication in high-level peer reviewed journals. The Expert Panel was provided 14 documents to help it prepare for the December workshop. Of those 14, only 2 were published in, or submitted to, a peer-reviewed journal by a member of the Program; however, the results and interpretations included in the annual reports should be published in journals. Similarly, the Expert Panelists were shown agency reports at the Workshop that were not included in the preselected workshop reading materials that likely had received thorough agency review, but apparently had not yet been submitted for journal publication. In the scientific world, peer-reviewed journal publication is the standard by which research is judged. Publishing in such journals would add increased scientific credibility to the Collaborative Program, and funding the time needed to prepare and revise journal manuscripts should be included in the research grants of the Monitoring Program.	Not given	Not given				SOWs developed through the Program now accommodate the cost of peer-reviewed publication.
Noon et al. 2017	17	A1	Clarify the relationship between the annual catch-per-unit-effort and true population size by estimating catchability.	1	1				
Noon et al. 2017	18	A2	Determine the key, age-specific, life history sensitivities of the RGSM (that is, use eigenanalysis methods to determine which vital rates [survival and/or reproduction] most affect rathes of population change.	1	3				
Noon et al. 2017	18	A3	Estimate age-specific survival rates	1	3				
Noon et al. 2017	19	A4	Estimate age-specific fecundities of wild fish.	1	3				
Noon et al. 2017	19	A5	Using statistical modeling, estimate the relationships between RGSM demographic rates and A.) hydrological factors (flow magnitude and duration, summer drying of the channel); and B.) abiotic environmental factors (temperature, turbidity, salinity); and C.) biotic factors (predation, completion, prey availability).	1	3				
Noon et al. 2017	20	A6	Evaluate the existence and strength of any density-dependent factors that may be limiting population growth.	2	Not given				
Noon et al. 2017	20	A7	Model the potential effects of hatchery augmentation on population dynamics and the significance of hatchery fish to achieving recorvery objectives.	Not given	Not given				
Noon et al. 2017	20	A8	Determine if the collection and translocation of salvage fish during summery drying periods contributes signficantly to population dynamics.	Not given	Not given				The USFWS is in the very preliminary stages of assessing survival post-fish salvage. A portion of rescued fish are being brought back to the USFWS facilities for evaluation.
Noon et al. 2017	21	B1	Development and deplyment of "vertically-intergrating" Moore egg collectors	1	Not given				
Noon et al. 2017	21	B2	Improved assessments of relations between possible environmental cues that trigger spawning activity.	1	Not given				Temperature degree days and photoperiod SOW currently addresses a few potential environmental cues.
Noon et al. 2017	21	B3	Establish size-specific fecundities of natural-spawning RGSM.	2	Not given				
Noon et al. 2017	22	C	Clarify the detail of annular mark formation on otoliths and firmly establish the longevity of RGSM	2	Not given				SWCA currently addressing this for larval fish only (to get hatch date).
Noon et al. 2017	22	D1	Estimate the spatial extent and hyrdaulic quality used by RGSM for key life-stages (spawining, larval rearing, juvenile and adult survival). Estimate how these habitats are distributed in the river channel and floodplain in each MRG reach under a range of discharges and seasonal flow regimes.	Not given	Not given				
Noon et al. 2017	23	D2	Establish the proximate trigger(s) for spawning by evaluating the effects of flow velocity, temperature, rate of increase in flow velocity, or some combination of these factors.	Not given	Not given				Temperature degree days and photoperiod SOW currently addresses a few potential environmental cues.

Noon et al. 2017	23	D3	Determine the roles and relative contributions to fish production (age 0 recruitment and survival of all age-classes) of channel and floodplain habitat in a reach of channel and floodplain typical of the MRG.	Not given	Not given				
Noon et al. 2017	24	D4	What is the management potential for fish production (recruitment and survival of age 0 fish) in each reach of the MRG if the annual peak flow, and thus the nature and range of available habitats, is permanently limited below historic levels of availability.	Not given	3				
Noon et al. 2017	24	E1	Establish the age composition of the RGSM population, including A.) application of distribution seperation methods to estimate age composition, and B.) gear selection study.	1	Not given				Horowitz et al. 2018 addressed age composition, and some additional work done by Valdez (2018)
Noon et al. 2017	25	E2	Determine how the vertical and horizontal distribution of RGSM eggs in the MRG mainstream channel varies as a function of flow and location?	1	Not given				M.Porter (?)
Noon et al. 2017	25	E3	Calculate revised CPUE values as mesohabitat-specific levels and do not combine across mesohabitat types. The meso-habitat specific CPUE calculated for the most abundadnt high density mesohabitat type should be used for assessment of trend in abundance of the RGSM population at the October sampling date.	2	2				ASIR has reported CPUE by mesohabitat type in their 2016 and 2017 reports. Some additional efforts towards this recommendation have been made by the DAT.

Developing an integrated population model for Rio Grande Silvery Minnow in the Middle Rio Grande

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Summary

The goal of this proposal is to provide the context for, and a description of, an integrated population model for Rio Grande silver minnow (RGSM). We provide a general description and some details, however based on past experience, we expect that some aspects of the model will change as we begin to actually confront it with data, are made aware of additional data, and have further discussions with experts in RGSM biology. We have attempted to detail our understanding in the hopes that any significant misunderstanding or gaps in our knowledge can be corrected early in the process by the community of biologists with more experience. We divide our proposal into 6 sections, beginning with a brief description of our philosophy to applied monitoring, followed by an overview of the main components of the RGSM monitoring and research program. The third, and longest, sections provides details on the proposed approach to modelling including both a description of the underlying demographic model and a list of issues/concerns that would be good to discuss further. We then conclude with three short sections discussing the relevance of the proposed model to prior review of the monitoring program, the potential need for expert elicitation, and the expected outcomes of the modelling exercise.

1. Evaluating monitoring and research – the importance of the management context

Fisheries and wildlife management can often be improved by a better understanding of the population dynamics of a species of concern. Management actions can be informed both by an understanding of the causes of variation in species' vital rates (e.g., survival, fecundity, movement, etc.) and by a basic understanding of the magnitude of given parameters (e.g., is adult survival high or low). While management targets can be set without explicit consideration of a species' vital rates, incorporation of an understanding of vital rates into management decisions often allows managers to maintain species' targets at lower costs. In some instances, optimal management strategies may also depend on the state of species of concern, where state may refer to population size, occupancy, or some other measure. In these cases, management may be improved by increasing precision of state variable estimates. However, just because an aspect of a species' biology (e.g., a given vital rate or state parameter) is uncertain does not mean that this uncertainty should matter to a manager. In some instances, an aspect of a species' biology may be uncertain but still not change the optimal management action from a set of candidate actions. Uncertainties that imply different management actions can be referred to as "critical uncertainties". When evaluating monitoring and research programs, focus should ideally be on critical uncertainties, rather than just uncertainties per se.

One challenge to identifying critical uncertainties is that formal evaluation of different management actions requires an ability to predict (with associated uncertainty) the outcomes of different actions. Prediction, in turn, requires integrating knowledge gained from research and monitoring with expert judgement into a model or a set of models that represent different competing hypotheses about a species' population dynamics. So, in order to determine whether monitoring is addressing critical uncertainties, it can be helpful to first evaluate monitoring in the context of an integrated model that links monitoring and research data to potential management actions.

Here we propose a modelling framework for Rio Grande silvery minnow (hereafter RGSM) in the reach of the Rio Grande bounded by the Cochiti and Elephant Butte Dams. From our perspective, some aspects of the framework are more resolved than others and we expect that aspects of the model may change over a few iterations based on comments from the group and additional experience with the data. While we are fairly confident that the underlying demographic model is maintaining the key features of RGSM demography, we are less certain about the degree of spatial realism necessary and we expect more changes in the spatial aspects of the model. Fitting this model using existing monitoring and research data alone may not lead to intelligible inferences without outside information (e.g., assumptions about one or more parameters). As a result, one outcome of this modelling exercise may be to highlight critical uncertainties in the form of assumptions, or elicited parameter values, as opposed to estimable parameters. To the extent that it is possible, we have tried to highlight assumptions we are aware of a priori, but others may become apparent as we construct a model(s). While our goal here is to not to assess a set of management actions, our hope is to develop a tool that could be used for that purpose.

2. RGSM – existing monitoring and research

Long-term monitoring of RGSM has occurred primarily through sampling of 20 standard sites via seining and larval seining at various times of year since 1993. The sites were chosen from a larger set of nearly 100 sites that were previously sampled from 1987 to 1992 (Platania, 1993). Since 2017, the number of standard sites has been augmented to 30 during May and October, but remains the standard 20 during April, and June - September. Sites are located in three reaches (listed in order from upriver to downriver) known as the Angostura, Isleta, and San Acacia reaches, which previously contained 5, 6, and 9 sites respectively, but now contain 10 sites each. During certain times of year, portions of the Rio Grande dry, including sites in both Isleta and San Acacia reaches. Prior to 2017, dry sites were treated as zeros. Beginning in 2017, replacement sites were identified, using a variety of criteria (see Dudley et al., 2017), which are sampled when standard sites are dry.

Sampling occurs monthly from April through October. Sampling of each site in each month consists of 18 – 20 seine hauls using a 3.1 m x 1.8 m small-mesh seine (ca. 4.8 mm) through various meso-habitats with a semi-structured approach for sampling different meso-habitat types. Since 2002 data are available in terms of individual hauls. Prior to 2002, catch data were aggregated at the site scale, however habitat types and effort associated with individual hauls were still recorded. In addition, two samples are taken in each month at each site using a 1.2 m x 1.2 m fine-mesh seine (ca. 1.6 mm) in shallow low velocity mesohabitats. Effort is calculated by the length of individual seine hauls and the seine width. In some years, sampling has also occurred during winter months as well, and the same protocol was used.

Fish from each seine haul are held between seine hauls, so there is no chance of the same fish being caught twice within a sampling event. All RGSM are measured using standard length in mm and inspected for Visible Implant Elastomer (VIE) tags. Sampling recovers fish born in the Rio Grande, as well as fish captively bred and stocked during late-November / December. Stocking began in the Angostura reach in 2001 and was expanded to all reaches in 2005. All stocked fish are tagged with VIE that indicates the year of stocking, however, individuals are not given new VIE marks precluding traditional mark-recapture analysis. Fish that are too small to accurately identify in the field are sacrificed for identification in a laboratory setting.

Additional information on RGSM population dynamics comes from a series of shorter-term studies including: 1) the population estimation study from 2008-2011 (Dudley et al., 2009; 2012); 2) the November occupancy study which involves 4 repeated surveys of the 20 standard sites and has been conducted from 2005 through present (Dudley et al., 2018), 3) data from salvage missions led by USFWS, 4) catch data obtained using two seines during 4 trips from 2013-2015, but only collected in the

Angostura reach, 5) data on fish movement (Archdeacon and Remshardt 2012), and 6) potentially lab based estimates of fecundity and/or survival.

3. Proposed modeling framework

Underlying all the iterations of models we imagine is a relatively simple model of RGSM population dynamics. We begin by discussing the shared components described in Fig 1 and then consider different approaches to addressing space. We describe the most general form of each component, recognizing that data availability may force us to make additional assumptions and/or fit a simpler model. Once the general structure of the model is agreed upon it can be modified, through the addition of covariates, to address competing hypotheses about drivers of demographic rates (Fig 2).

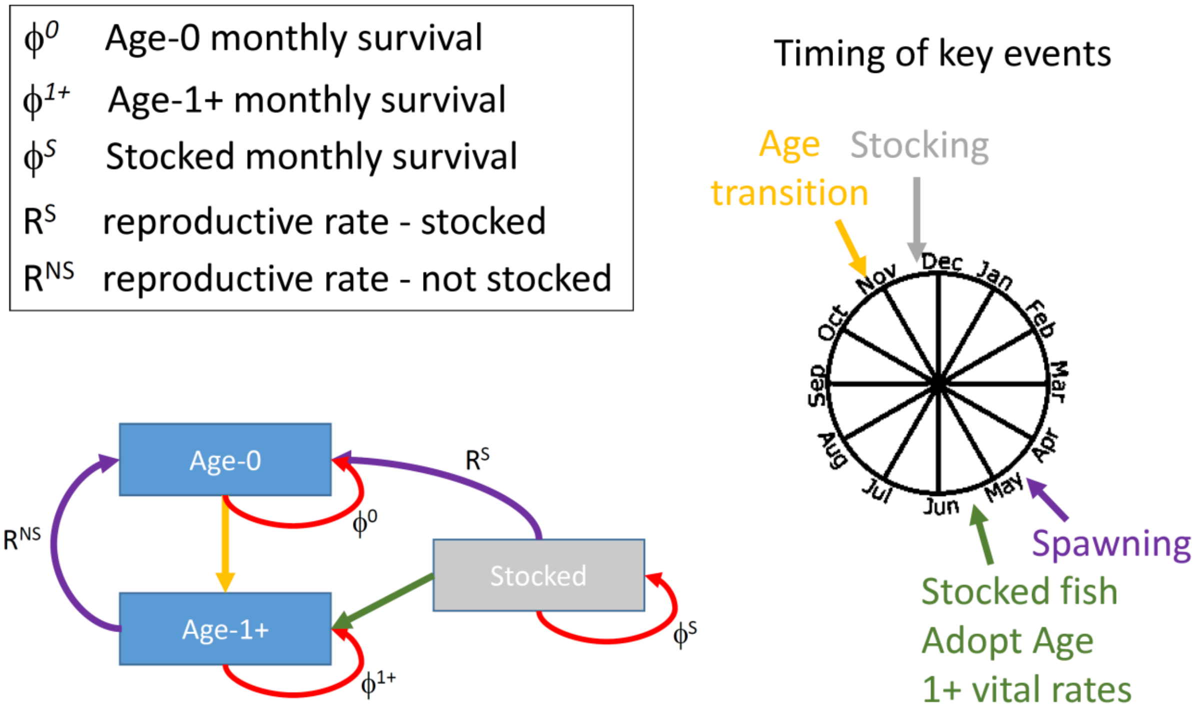


Figure 1: Schematic representation of RGSM demographics, including definition of key vital rates, representation of transitions between three states represented in the model, and timing of key events over the course of a calendar year.

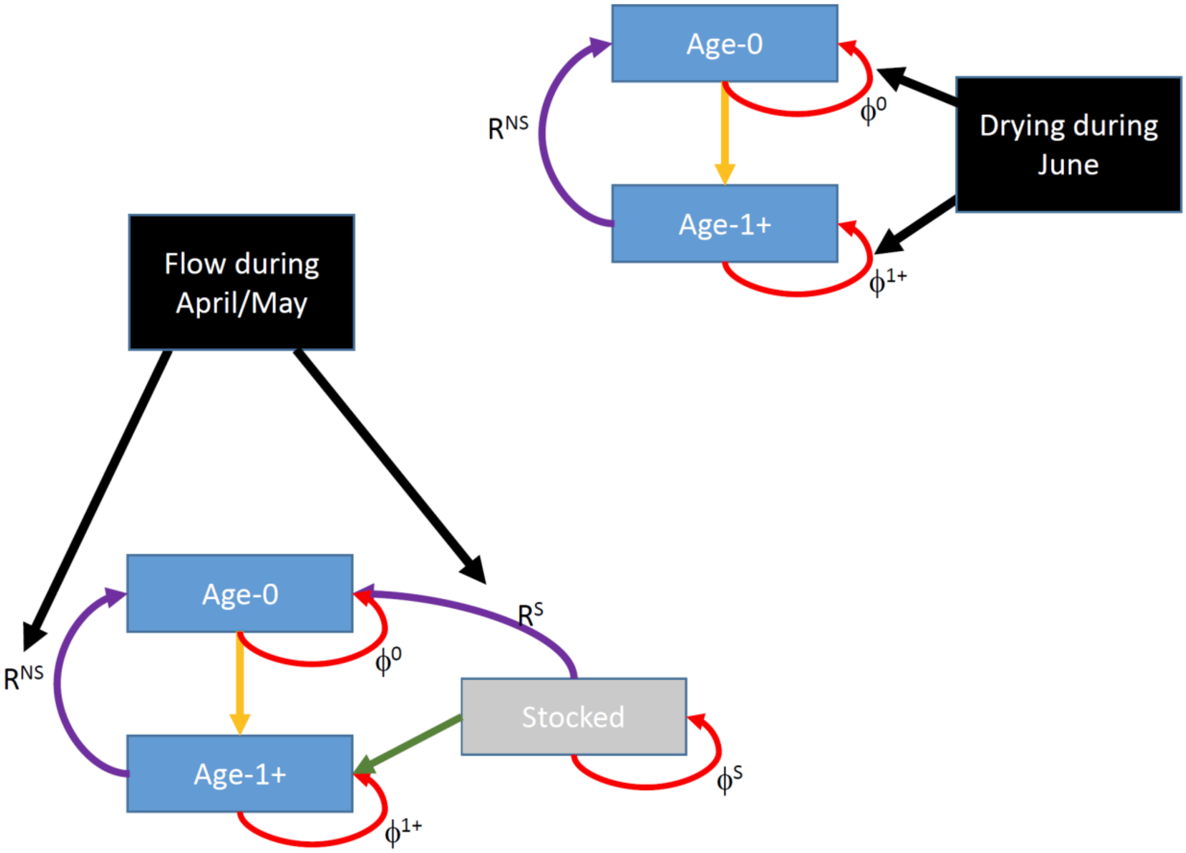


Figure 2: Examples of hypotheses for different demographic rates. (lower left-hand) Managers may be interested in how well different aspects of flow correspond to temporal variation in recruitment. Strength of evidence for different predictors can be calculated using metrics like multilevel R^2. If competing predictors are highly correlated and imply very different management, it may be worthwhile to consider a set of covariates (instead of just the "best" one) in making decisions and it may even be worthwhile to design experiments to disentangle these covariates. (upper right-hand) Managers may also want to consider hypotheses related to various potential drivers of over-summer survival in both Age-0 and Age-1+RGSM.

A. The Basics

Recruitment. Consider a stylized version of RGSM population dynamics. During April, recruitment of age 0 RGSM is estimated based on some function of environmental covariates and the abundance of adults. One version of this function could be:

$$N_t^0 = R_t^{NS} N_t^{1+} + R_t^S N_t^S \qquad \text{(Equation 1)}$$

where N_t^0 is the number of recruits (age 0) produced in April, N_t^{1+} are the number of adult RGSM alive in April that were not stocked in the prior winter (but could have been stocked more than 1 year prior), R_t^{NS} is the per capita rate of production of recruits per unstocked adult, N_t^S is the number of stocked RGSM remaining from the prior winter, and R_t^S is the per capita rate production of recruits by stocked adult. Per capita recruitment could then be modelled by the following equations:

$$\log(R_t^{NS}) = \alpha_0 + \beta\boldsymbol{X} + \eta_t \qquad \text{(Equation 2)}$$

$$\log(R_t^{S}) = \alpha_0 + \alpha_S + \beta\boldsymbol{X} + \eta_t \qquad \text{(Equation 3)}$$

$$\eta_t \sim N(0, \sigma_R) \qquad \text{(Equation 4)}$$

Where a log-link restricts R_t^S and R_t^{NS} to positive values, α_0 is the intercept for unstocked adults, α_S is the difference in log-recruitment for adults stocked in the prior winter, $\boldsymbol{X}$ represents a matrix of time-specific, standardized covariates hypothesized to drive recruitment (e.g., some aspect of flow during April/May; Fig 2), β represents a vector of estimated coefficients, and η_t represents a random effects to account for temporal variation not explained by covariates and is drawn from a normal distribution centered on zero with standard deviation σ_R. Equations 2 and 3 assume that R_t^S and R_t^{NS} differ by a constant percentage given by e^{α_S} but have the same temporal dynamics. If there was reason to believe that the temporal dynamics of capita recruitment differed between groups β and η_t could be made to differ between groups. Alternatively, if α_S overlaps zero, this would suggest that stocked adults have the same level of per capita recruitment as unstocked adults (and/or that there is insufficient information to discern differences between these groups). Initial examination of data may also suggest the existence of more complex recruitment relationships embodied in Beverton-Holt, Ricker, or Shepherd equations which can be incorporated through modifications to equations 1-3, however jumping to these equations may be problematic in that it is unclear whether stocked and unstocked individuals should be weighted equally in estimating recruitment.

Survival and transitions. We estimate survival for three groups, age – 0 individuals between April and November, stocked individuals after they are stocked in November, and age – 1+ individuals year round. Age – 0 individuals are assumed to adopt age – 1+ survival rates beginning in November, and during early testing we would test the hypothesis that stocked individuals transition into age – 1+ survival rates in April, under the assumption that differences between stocked and unstocked individuals in terms of vital rates should have dissipated after some months (i.e., we hypothesize that stocked individuals survive poorly in their initial months, but then began to survive at rates comparable to naturally produced individuals.) Since the population is generally not monitored between November and April, we will likely estimate a single survival rate during this period scaled for six months unless monthly covariates are tested. On the other hand, survival from April to November is almost certain to be estimated for each month with a functional form given by:

$$\operatorname{logit}(\varphi_t^0) = \delta_0 + \gamma_0 \boldsymbol{Y} + \xi_t^0 \qquad \text{(Equation 5)}$$

$$\operatorname{logit}(\varphi_t^{1+}) = \delta_{1+} + \gamma_{1+} \boldsymbol{Z} + \xi_t^{1+} \qquad \text{(Equation 6)}$$

where a logit-link restricts survival of age – 0, φ_t^0, and age – 1+, φ_t^{1+}, to values between 0 and 1, δ_0 and δ_{1+} are intercepts for age-0 and age-1+ survivals, γ_0 and γ_{1+} are a vector of coefficients, $\boldsymbol{Y}$ and $\boldsymbol{Z}$ represent matrices of covariates, and ξ_t^0 and ξ_t^{1+} represent random effects drawn from normal distributions centered on zero. Whereas most covariates included in $\boldsymbol{Y}$ will be likely be environmental (i.e., flow, water temperature, etc.) in nature, we will also likely include estimates of average fish size to account for the strong dependency of survival in young fish on body size.

Abundance. Our model will begin in the April of the first year. In the first period, initial abundance of age 1+ RGSM, $N_{t=1}^{1+}$, is an estimated parameter, and the initial abundance of age 0, $N_{t=1}^{0}$, will be derived from equation 1. Between April and November, abundance in each class will be deprecated by the appropriate survival rate. In November, the abundance of surviving age – 0 fish, N_t^0, will be added to the abundance of surviving age – 1+ fish to estimate the total abundance of age – 1+

fish. The abundance of age – 0 fish will be set equal to zero until the next April. The abundance of stocked fish in November, N_t^S, will be based on actual number of fish stocked. Although, stocked fish will assume age – 1+ survival and reproductive rates after April of their first year, their abundances will be tracked separately, so that we can take advantage of the extra information available from the deprecation of VIE marks over time.

Catchability/capture probability. Capture probability will be estimated separately for age – 0 and age – 1+ fish using the following equations:

$$\text{logit}(p_t^0) = \rho_0 + \kappa_0 \boldsymbol{U} + \nu_t^0 \qquad \text{(Equation 5)}$$

$$\text{logit}(p_t^{1+}) = \rho_{1+} + \kappa_{1+} \boldsymbol{V} + \nu_t^{1+} \qquad \text{(Equation 6)}$$

Where ρ_0 and ρ_{1+} are the intercepts of age – 0 and age – 1+ detection probability, κ_0 and κ_{1+} represent vectors of estimated coefficients, $\boldsymbol{U}$ and $\boldsymbol{V}$ represent matrices of covariates and ν_t^0 and ν_t^{1+} are random effects drawn from normal distributions centered on zero. Whereas environmental covariates included in ***X, Y,*** *and* ***Z*** should be calculated for the interval they represent, environmental covariates present in $\boldsymbol{U}$ and $\boldsymbol{V}$ should most likely be calculated based on conditions at the time of sampling. Depending on whether data is incorporated at the haul or site scale, additional complexity may need to be incorporated into equations 5 and 6. Regardless of the scale our expectation would be to link our latent (unobserved) abundance estimates to catch data, by multiplying the predicted abundance at the appropriate scale by the associated capture probability, and using this as the lambda values for a poisson distribution. We will also investigate a negative binomial distribution, if there is additional heterogeneity not absorbed by the various random effects.

A note on d vs. p. Detection probability (estimated in occupancy analyses, referred to here as *d*) is linked, but also fundamentally different from capture probability (*p*). The specific relationships between *p* and *d* depends on the site abundance, *n*. Specifically, Royle and Nichols showed that:

$$d = 1 - (1 - p)^n \qquad \text{(Equation 7)}$$

In other words, the probability that a species is detected at a site is equal to 1 minus the probability that all individuals are not captured. This distinction is important because variation in *d* between meso-habitats can occur from variation in *p* across habitats alone, variation in *n* alone, or variation in both *p* and *n.*

A note on CPE vs. N. If we assume meso-habitat specific catch per effort (in units of fish per 100 m^2), c_j, meso-habitat availabilities (in units of 100 m^2), τ_j, *J* total meso-habitats and meso-habitat specific detection probabilities, p_j, then the expectation for total abundance, *N,* can be expressed as:

$$N = \sum_{j=1}^{J} \frac{\tau_j c_j}{p_j} \qquad \text{(Equation 8)}$$

Given the high correlation observed between mean cpe, $\bar{c}$, and abundance estimates, $\widehat{N}$, during the population estimation study it is tempting to conclude that variation in availability and detection are ignorable. If the purpose of $\bar{c}$ was only to distinguish years of high and low RGSM abundance during the fall, then we believe this argument is sound. However, this is not the only way in which $\bar{c}$ is being used and the high correlation between $\bar{c}$ and $\widehat{N}$ is potentially misleading. Consider two uncorrelated random variables, A and B, and their product C. When the variance in A is four times the variance in B, C will be correlated to A with an R^2 of ~0.8, however if the variance of A is lowered to a quarter of the variance in B, the R^2 between to C and A drops to ~0.2. So if we assume that variation due to availability and detection is constant (variable B in the above example), we should expect a high R^2 when comparing cpe and N calculated over a wide range of cpe's and a much lower correlation if we fixate on subtle variation in cpe. In addition, the reported correlation is for October samples when flow and thus τ_j are likely similar across years – we know τ_j will vary more as we look across months of the year.

Confounding. If fit to the RGSM monitoring data alone, the model outlined above is likely to suffer from confounding between various parameters (in particular *p* and *N*). Additional data from the November repeat surveys and the population estimation study should prove valuable in allowing for separation of various parameters, but may or may not be sufficient. For example, it may be necessary to also incorporate information from lab studies or other species. We expect the model to have the most difficulty estimating survival, capture probabilities and abundance for age 1+ RGSM given the low and variable catch of this class of fish.

Growth. In the proposed model, we would not model growth per se, rather we assume that growth is relatively constant among years and that age-0 and age- 1+ can be reliably differentiated based on length. We are less certain that age – 1 and age -2+ fish can reliably be differentiated, which is what has led us to proposed lumping these classes. Importantly, we carry surviving age-1 fish forward into the next year so the only reason to include an additional age class is if survival or fecundity is expected to vary substantially between these age classes. Based on initial feedback, we are considering adding in an age-2+ class, but we expect such a class will contribute to the difficulty already expected in estimating survival and fecundity for age- 1+ (see last section).

B. Open challenges – how much spatial realism to include?

There are a number of issues related to the degree of spatial realism that is necessary and desirable in the population model and which are unresolved in our mind. At one extreme, we could envisage a fully spatial model with a resolution equal to the size of each site. Drying and meso-habitat availability could be estimated from various sources and imputed using flows in periods there were not direct measurements. RGSM in reaches that dry would die, naturally move, or be salvaged. Rewetted areas would be recolonized over time. Such an approach would be data-intensive and require more parameter inputs than a simpler approach, but might better reflect drivers of decline and recovery in the population. At the other extreme, we could fully pool data across sites, ignoring both meso-habitat and station information. Such an approach would be quicker and require a different set of assumptions, but sacrifices even the most basic understanding that the three reaches of the study area differ or differences between meso-habitats. One can also imagine models of intermediate complexity. In the following sections, we further discuss some of these spatial issues.

Site drying. Site drying represents a clear change in τ_j at the site level. If half the sites have dried, τ_j within wetted sites is unchanged, and c_j remains unchanged, then by definition 50% of RGSM have died. If fish from dried sites move into wetted sites (either naturally or through salvage operations), then this must be reflected in values of τ_j and/or c_j. Estimates of the proportion of dried sites can be based either on the proportion of standard sites that are dried, and/or from datasets that cover the whole river. The Riverize data will likely be important if we adopt an approach that attempts to model all sites (not just those that are sampled) – and will likely be useful even if we choose a simpler approach to space. This Riverize data includes daily data on which sections of the river are completely dry and has been collected since 2002, but with differences over time. For example, from 2007 to 2016 this dataset occurred at a spatial grain of 0.5 kilometers, when from 2017 onwards the spatial grain became 0.1 km. One challenge with the earlier years will be determining how to downscale the data to a 200 m resolution. If data on drying are only available in some time periods, but not all – we can develop site-specific relationships between discharge at various stations and the probability of drying.

Habitat availability. There is marked variation in catch between mesohabitats and most of the variation is likely due to variance in underlying abundances. (The population estimation study found only minor differences between mesohabitats in capture probability. On the other hand, these capture probability estimates by meso-habitat were likely based primarily on age – 0 fish, and age – 1 fish may have more variable capture probabilities. Furthermore, most sampling occurs via a different technique than the one used in the population estimation study and this difference could induce more variation in capture probability among meso-habitats.) While it is straightforward to estimate c_j for different meso-habitats, this information is not useful unless it can be combined with information concerning τ_j. We are aware of a couple different sources of estimates of τ_j, including estimates from the standard stations and from the population estimation stations for each October from 2008 to 2011, a USGS study that estimated τ_j at 15 1-km sites during two sets of flows. Scaling these estimates to other discharges involves dealing with a couple challenges: 1) there is a need to estimate, at the very least, how the wetted width of the river varies at different discharges, and 2) many of the habitats associated with higher cpe's are found along the river's edge and their availability may vary nonlinearly with discharge. There is some potential to analyze range-lines surveyed every ten years alongside a 1-D flow routing model to estimates these factors, but this analysis is ongoing.

Movement. Movement between portions of the river is important for explaining recolonization of previously dried areas, or as a possible explanation when catch increases dramatically in a particular site (e.g., if a wetted site's abundance increases as neighboring sites dry). A simple approach to movement, would be to only model movement between sampled sites and assume they are representative of the whole reach. A more complex approach would be to model movement between all potential sites in the study reach and would only make sense if information on drying was also available at this scale. We might also be able to use information from Archdeacon and Remshardt (2012) to fit a dispersal kernel.

4. Relevance to past reviews of monitoring program

The modelling exercise proposed here touches on many recommendations made by the Hubert et al. and Noon et al. reviews of the RGSM monitoring program. In particular, the proposed modelling partially or entirely address at least eight of the Hubert et al. recommendations (specifically, recommendations 1-4, 7, 16, 21 and 22) and at least eight of the Noon et al. recommendations (specifically, recommendations A1, A3-A8 and D3).

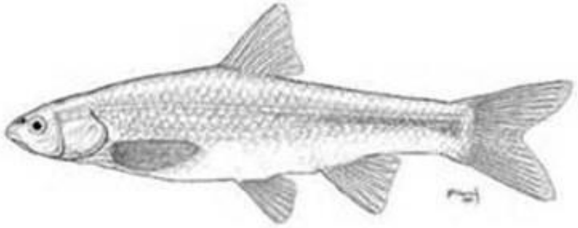
5. Expert elicitation

At some point during the iterative process of model development it may be useful to undertake expert elicitation during a population monitoring group meeting. Expert elicitation is a process by which different contributors provide estimates of parameters that may be difficult to directly estimate from data including their uncertainty in these parameters. Typically, this process involves three steps. In the first step, multiple contributors provide estimates of parameter values and associated uncertainty, then in the second step, the distribution of estimates is evaluated by the group as a whole and member provide the rationale for their initial conclusions. In the final step, contributors are given an opportunity to change their estimates if arguments put forward by the group have changed their reasoning. This process can be a useful approach for identifying a reasonable range for parameters and for highlighting why different contributors may think of a system in very different ways. It may also be useful to have a group develop a priori hypotheses for the covariates that may be driving temporal variation in various parameters.

6. Expected outcome(s)

The main goal of model development it to develop a tool that could be used for various decision-making processes, including comparison of management actions and prioritization of research and monitoring projects. We expect that the process of model development will highlight gaps in our understanding. It is our expectation that the process of model development will lead to 1 or more peer-reviewed journal articles. All members who are interested in contributing in terms of data preparation, development of a priori hypotheses, and/or writing are encouraged to do so and will be included as co-authors if they are interested and make significant contributions.

Survival of Wild Rio Grande Silvery Minnow in the Middle Rio Grande



Richard A. Valdez, Ph.D., SWCA

Population Monitoring Workgroup Meeting

December 12, 2018

Science Panel Recommendations

Hubert et al. (2016)

- *"(22) Complete a study of age-specific fecundity and survival rates based on pre-breeding (fall) population estimates, spring spawners, and hatchery supplementation. Results from this study could be used to estimate population recovery and extirpation potentials as a function of altered flow regimes and stocking."*

Noon et al. (2017)

- *"Regression estimators where the survival of an initial cohort of RGSMs is followed over a yearly time-step (see Skalski et al. 2005, page 210; Goodman 2011). This study requires estimates of the initial abundance of a cohort at time t and its abundance at time t+1. Cohorts could be age-specific if the CPUE data were partitioned by age-class to derive age-specific survival estimates."*

Approaches used to Estimate Survival and Mortality

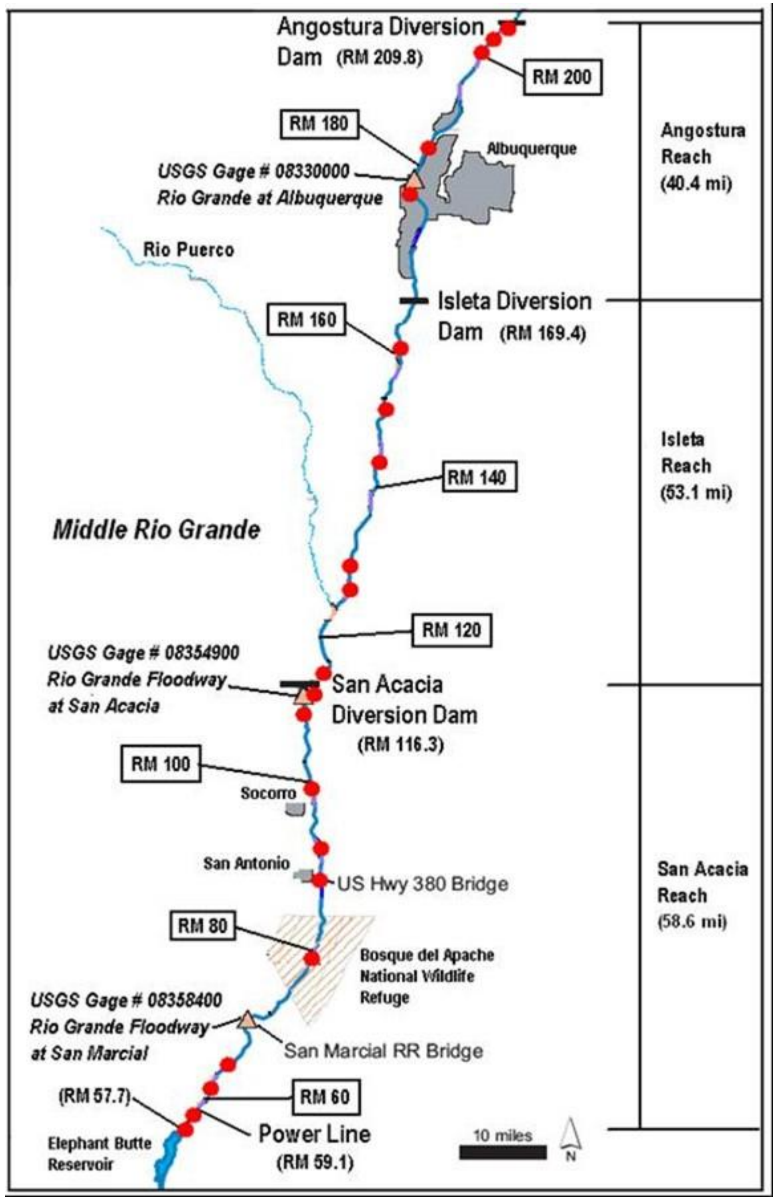
- Tagging Studies (mark/recaptured)
  - Cormack-Jolly-Seber, Brownie Models: multiyear tagging studies are used to estimate natural mortality based on recaptures

- Growth Parameters (assumes relationship between size and mortality)
  - Pauly’s, Ault and Ehrhardt Models: based on correlation of M with von Bertalanffy growth parameters (K and $L\infty$) and temperature (Gunderson 2002)
  - Beverton and Holt (1957) model: $Z = K * (L\infty - \text{Ł}) / (L\infty - \text{Ľ})$

- “Catch Curves” (regress abundance over time)
  - “Exponential decay models” (Ricker, Beverton and Holt, Sparre and Venema)

Data Used for This Analysis

- RGSMPopMon_1993-2017_XLSX.xlsx
- Considerations:
  - CPUE was computed by station.
  - Sample Period CPUE (approx. mean monthly CPUE).
  - Three reaches combined.
  - “Dry Site” not included to avoid false zero.
  - Only unmarked fish were included.
  - Fish from isolated pools were included.
  - Capture probability not considered and no covariates added to the models.



Mortality and Survival

Instantaneous mortality rate is used to estimate the number of individuals remaining after time by integrating dN/dt (Miranda and Bettoli 2007) and is expressed as:

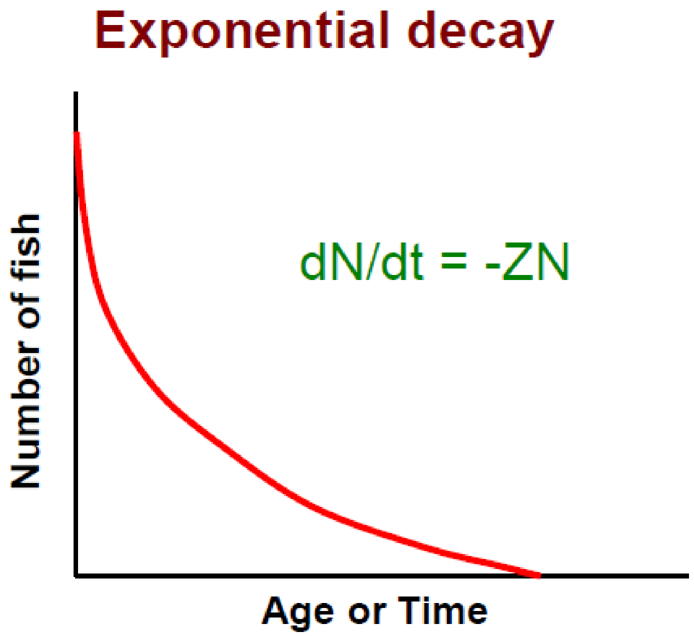
Where: $N_t = N_o e^{-Zt}$

- N_t = individuals in the population at end of time t,
- N_o = estimated number of individuals at start of time t, and
- Z = instantaneous mortality rate.

The exponential function is fit to the data as:

Where: $y = ae^{-Zt}$

- y = predicted CPUE for time t,
- a = y intercept,
- Z = instantaneous rate of mortality, such that
- the slope of Nt vs t (-Z) = rate of survival (set as a daily time step).



Survival Analysis by Goodman (2009, 2010)

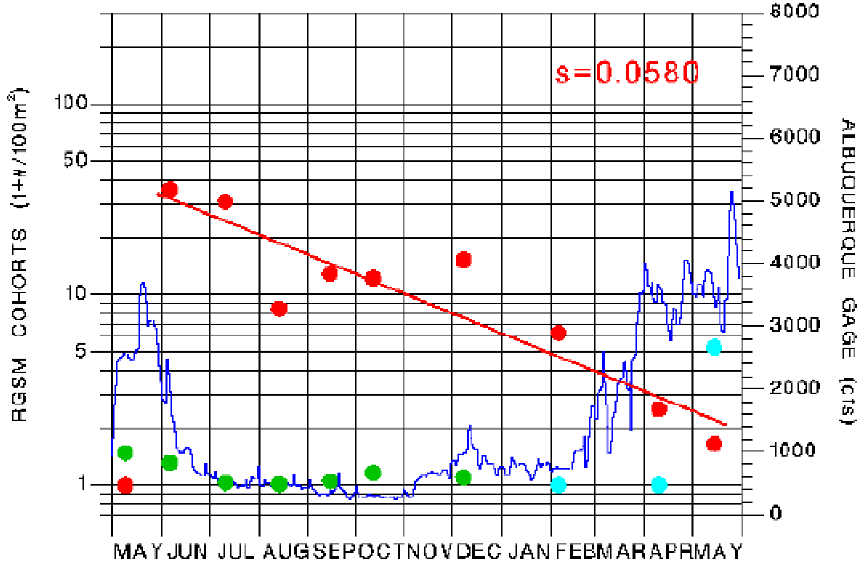
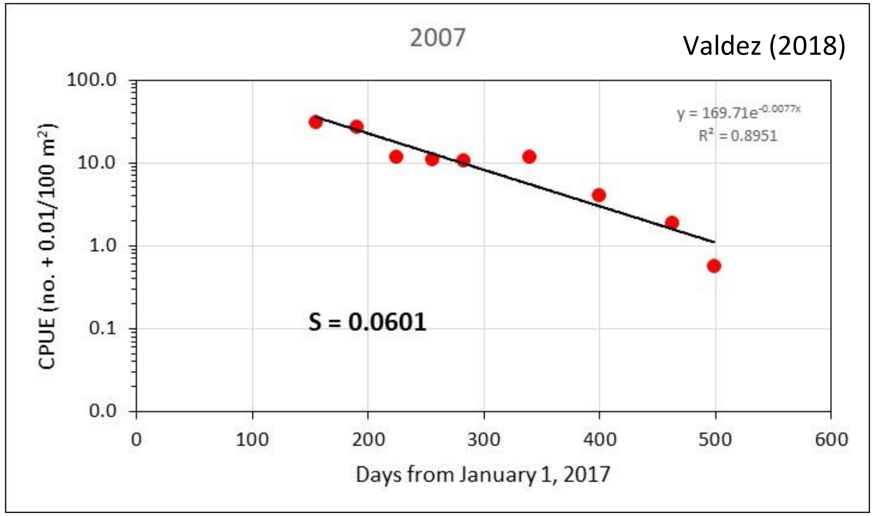


Figure 1: 2007 cohort, all reaches combined. Fish density is on a log scale. Dots are monitoring bouts. Red is that year's cohort; green is last year's 1+; cyan is next year's YOY. Blue line is daily flow. Survival is fraction expressed on an annual basis, estimated from slope of the log regression.

Goodman, D. 2010. Parameter estimation strategy for the PVA: I. Deterministic dynamics and environmental covariates. Draft Report, Montana State University, Bozeman, MT.



Valdez (2018)

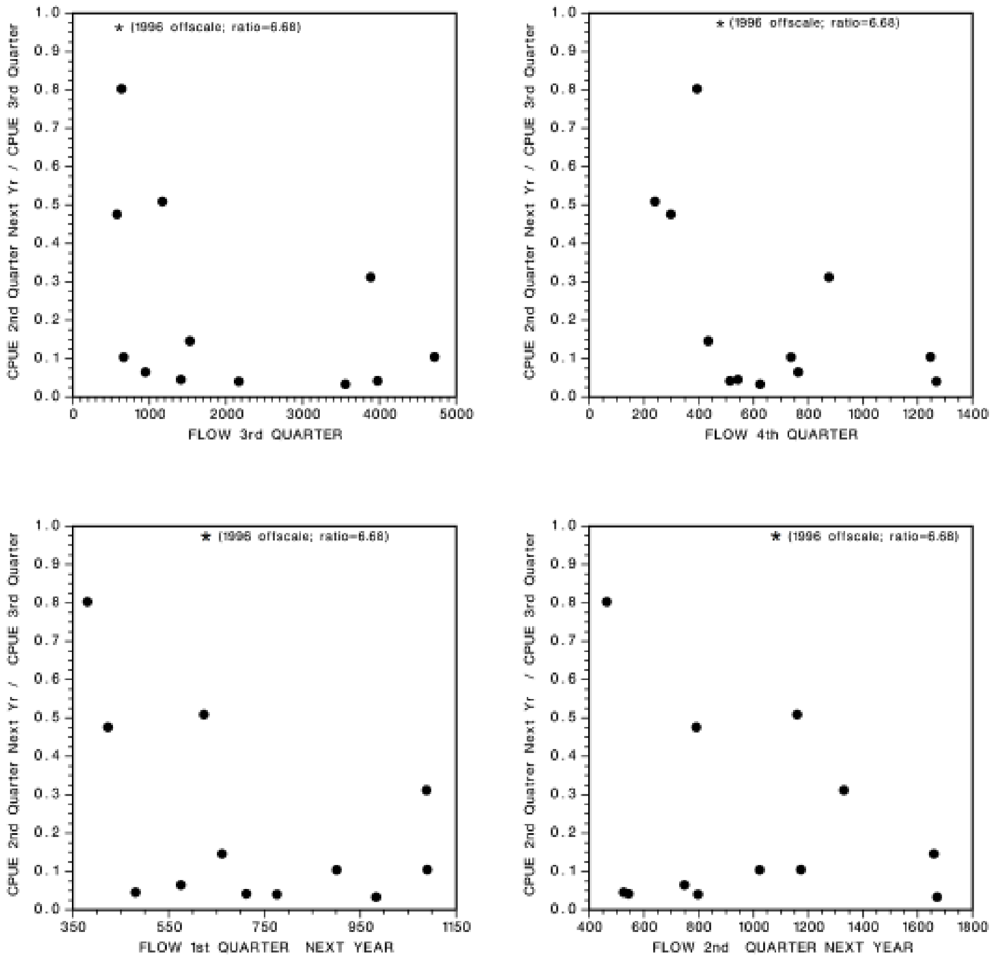
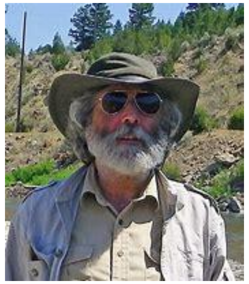


Figure 14: Survival from reproductive pulse till next spring as measured by plotting ratio of 2-nd quarter CPUE next year over 3-rd quarter of current year against quarterly flow summary.

Goodman, D. 2009. Rio Grande silvery minnow PVA: relating quarterly monitoring summaries to the synthesis. Draft Report, Montana State University, Bozeman, MT.



Computation of Daily, Monthly, Annual Survival

Daily: $\hat{S}_{\text{daily}} = \exp(-Zt)$

Monthly: $\hat{S}_{\text{daily}}^{30} = \hat{S}_{\text{monthly}}$

Annual: $\hat{S}_{\text{daily}}^{365} = \hat{S}_{\text{annual}}$

May-Dec (age-0): $\hat{S}_{\text{daily}}^{244} = \hat{S}_{\text{May-Dec}}$

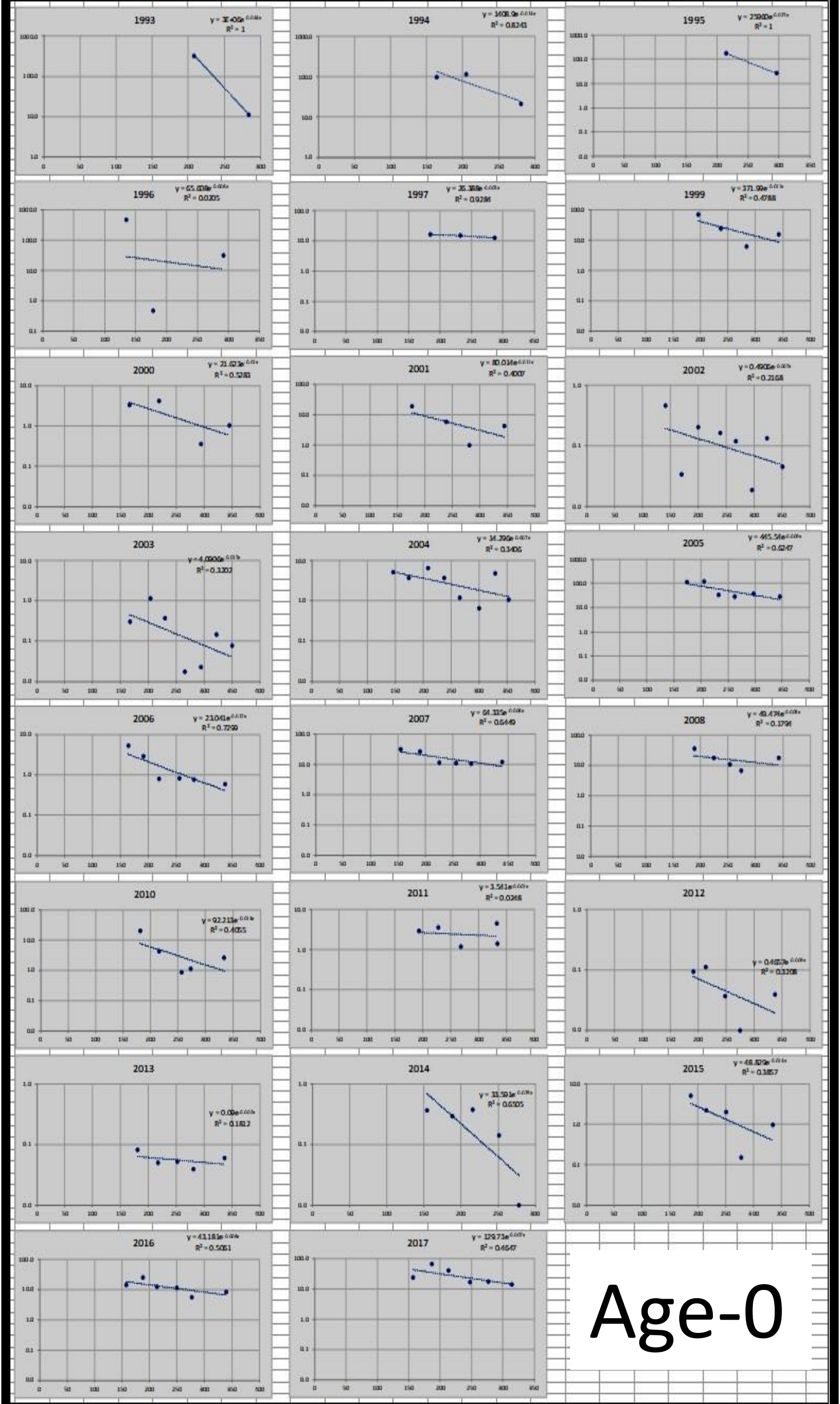
Survival Tables

Age-0

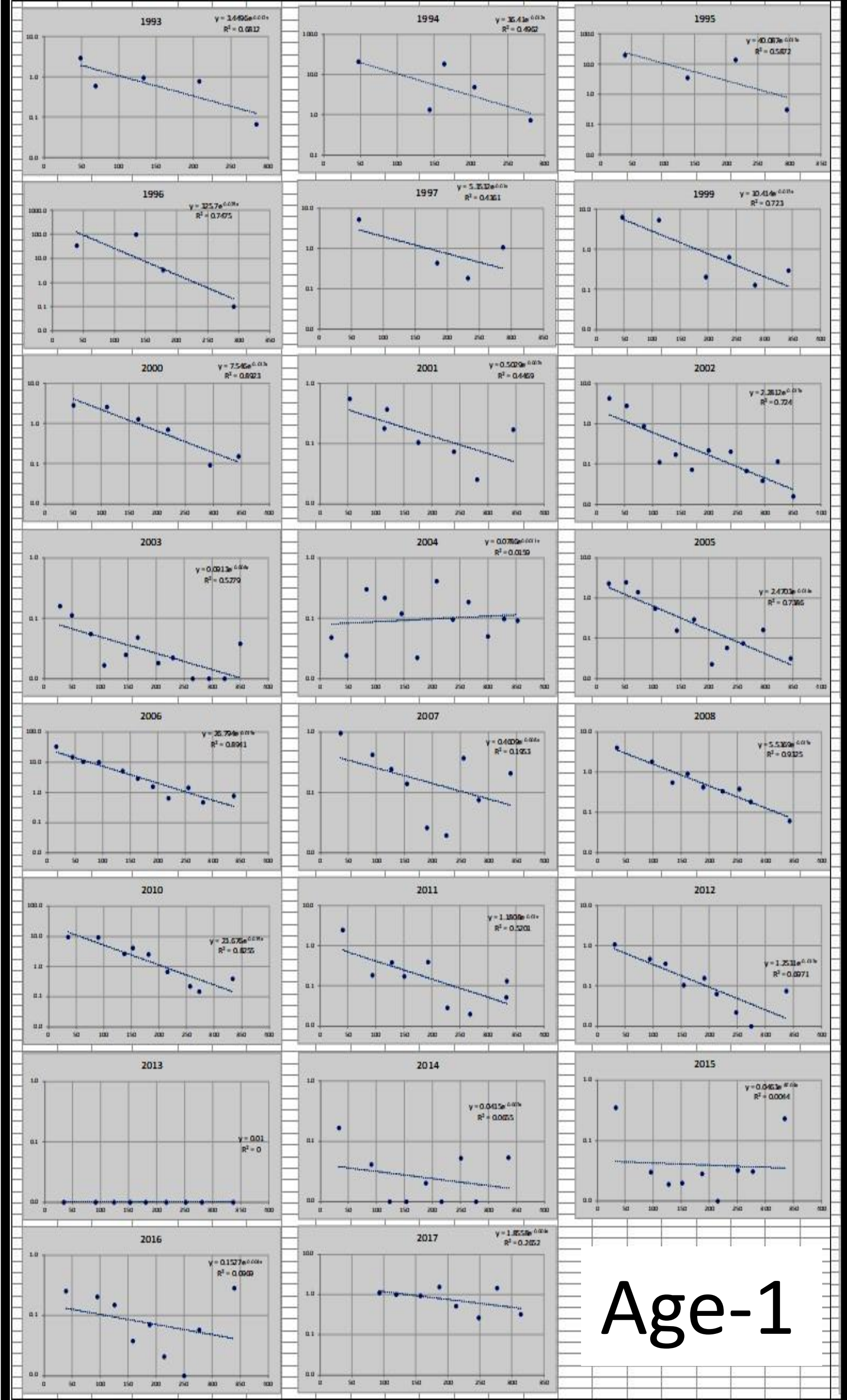
Year	Year Class	Sample Periods	R^2	-Z	Daily S	Monthly S	Annual S	Apr-Dec S
1993	1993	2	1.00	-0.044	0.957	0.267	0.0000001	0.00002
1994	1994	3	0.82	-0.014	0.986	0.657	0.006	0.033
1995	1995	2	1.00	-0.023	0.977	0.502	0.0002	0.004
1996	1996	3	0.02	-0.006	0.994	0.835	0.112	0.231
1997	1997	3	0.93	-0.003	0.997	0.914	0.335	0.481
1998	1998	--	--	--	--	--	--	--
1999	1999	4	0.46	-0.011	0.989	0.719	0.018	0.068
2000	2000	4	0.53	-0.010	0.990	0.741	0.026	0.087
2001	2001	4	0.40	-0.011	0.989	0.719	0.018	0.068
2002	2002	8	0.22	-0.007	0.993	0.811	0.078	0.181
2003	2003	7	0.32	-0.013	0.987	0.677	0.009	0.042
2004	2004	8	0.34	-0.007	0.993	0.811	0.078	0.181
2005	2005	6	0.62	-0.009	0.991	0.763	0.037	0.111
2006	2006	6	0.73	-0.012	0.988	0.698	0.013	0.054
2007	2007	6	0.64	-0.006	0.994	0.835	0.112	0.231
2008	2008	5	0.18	-0.005	0.995	0.861	0.161	0.295
2009	2009	--	--	--	--	--	--	--
2010	2010	5	0.41	-0.014	0.986	0.657	0.006	0.033
2011	2011	5	0.02	-0.001	0.999	0.970	0.694	0.783
2012	2012	5	0.32	-0.009	0.991	0.763	0.037	0.111
2013	2013	5	0.18	-0.002	0.998	0.942	0.482	0.614
2014	2014	5	0.65	-0.025	0.975	0.472	0.0001	0.002
2015	2015	5	0.39	-0.014	0.986	0.657	0.006	0.033
2016	2016	6	0.51	-0.006	0.994	0.835	0.112	0.231
2017	2017	6	0.46	-0.007	0.993	0.811	0.078	0.181
				Means:	0.989	0.736	0.105	0.176
				Minima:	0.957	0.267	0.0000001	0.00002
				Maxima:	0.999	0.970	0.694	0.783

Age-1

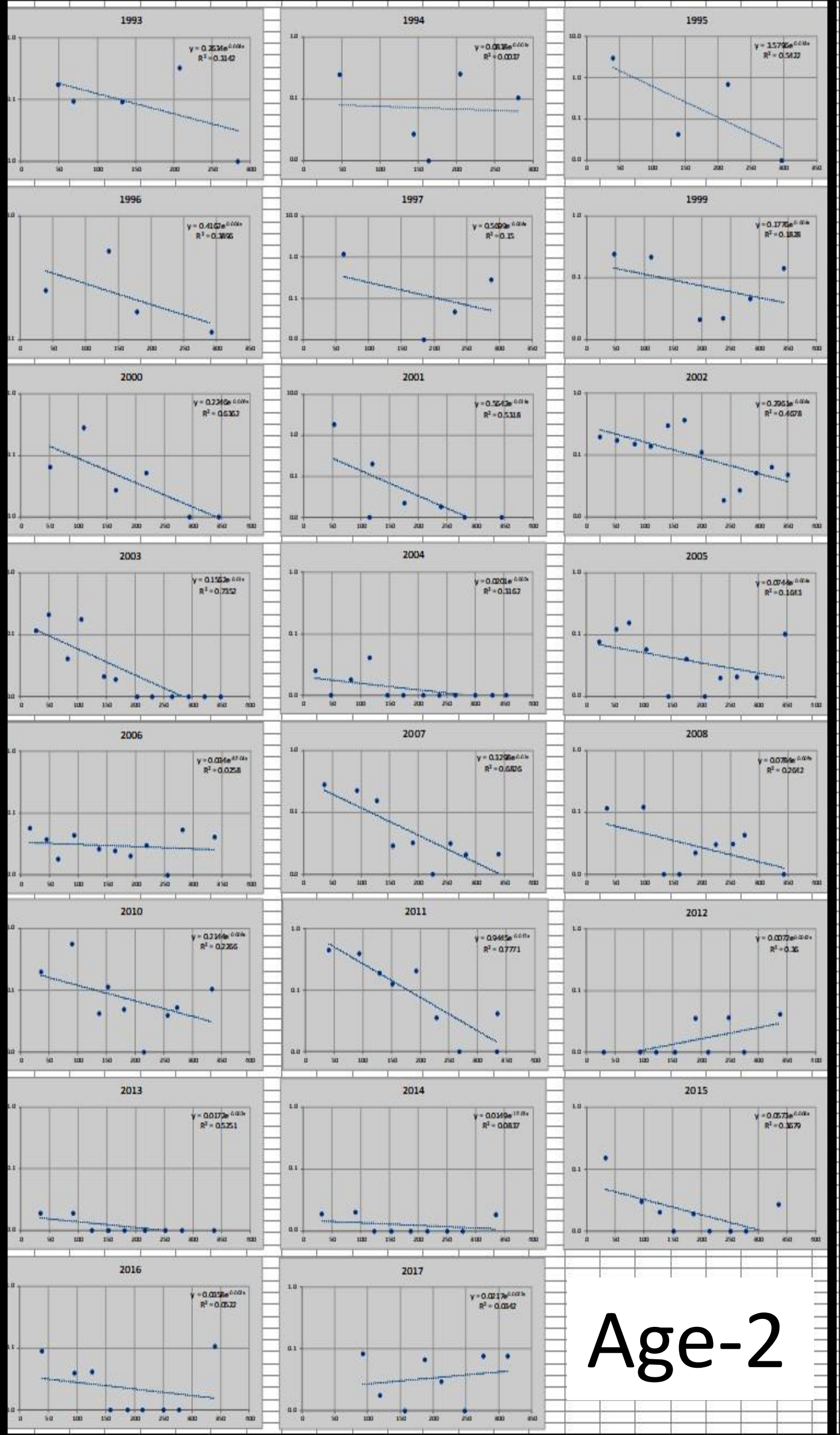
Year	Year Class	Sample Periods	R^2	-Z	Daily S	Monthly S	Annual S
1993	1992	5	0.68	-0.012	0.988	0.698	0.013
1994	1993	5	0.50	-0.012	0.988	0.698	0.013
1995	1994	4	0.59	-0.013	0.987	0.677	0.009
1996	1995	4	0.75	-0.025	0.975	0.472	0.0001
1997	1996	4	0.44	-0.010	0.990	0.741	0.026
1998	1997	--	--	--	--	--	--
1999	1998	6	0.72	-0.013	0.987	0.677	0.009
2000	1999	6	0.89	-0.012	0.988	0.698	0.013
2001	2000	7	0.45	-0.007	0.993	0.811	0.078
2002	2001	12	0.72	-0.013	0.987	0.677	0.009
2003	2002	12	0.53	-0.006	0.994	0.835	0.112
2004	2003	12	0.02	-0.001	0.999	0.968	0.669
2005	2004	11	0.74	-0.014	0.986	0.657	0.006
2006	2005	11	0.89	-0.013	0.987	0.677	0.009
2007	2006	9	0.20	-0.006	0.994	0.835	0.112
2008	2007	9	0.94	-0.013	0.987	0.677	0.009
2009	2008	--	--	--	--	--	--
2010	2009	9	0.83	-0.015	0.985	0.638	0.004
2011	2010	9	0.52	-0.010	0.990	0.741	0.026
2012	2011	9	0.70	-0.013	0.987	0.677	0.009
2013	2012	9	0.00	--	--	--	--
2014	2013	9	0.07	-0.003	0.997	0.914	0.335
2015	2014	9	0.01	--	--	--	--
2016	2015	9	0.10	-0.004	0.996	0.887	0.232
2017	2016	8	0.27	-0.004	0.996	0.887	0.232
				Means:	0.990	0.740	0.092
				Minima:	0.975	0.472	0.0001
				Maxima:	0.999	0.968	0.669



Age-0

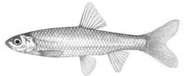


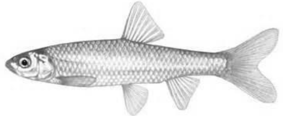
Age-1

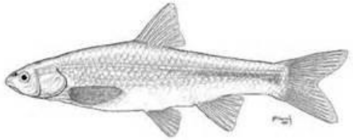


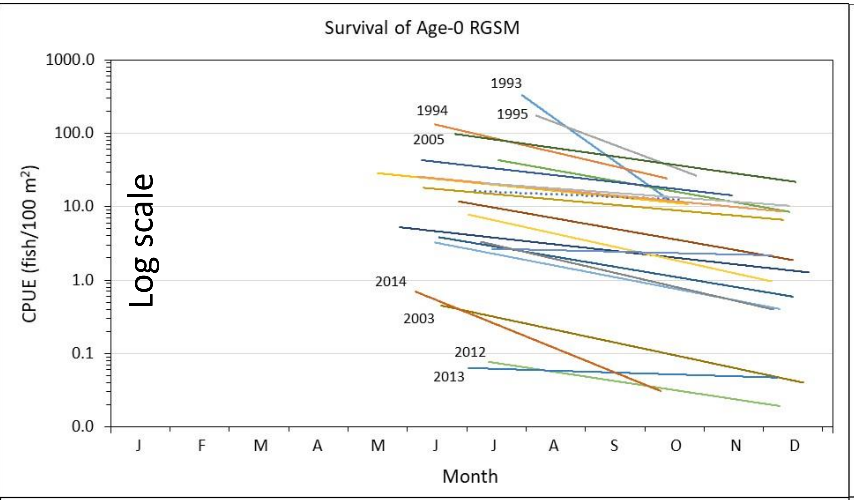
Age-2

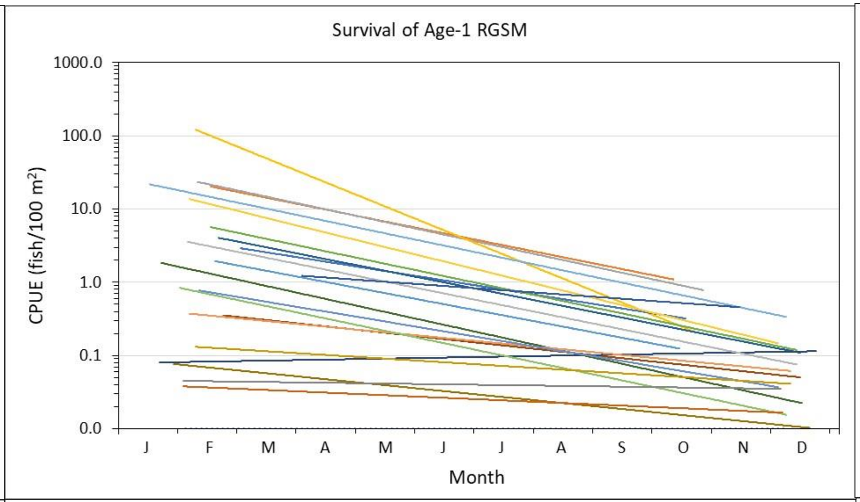
Survival by Age

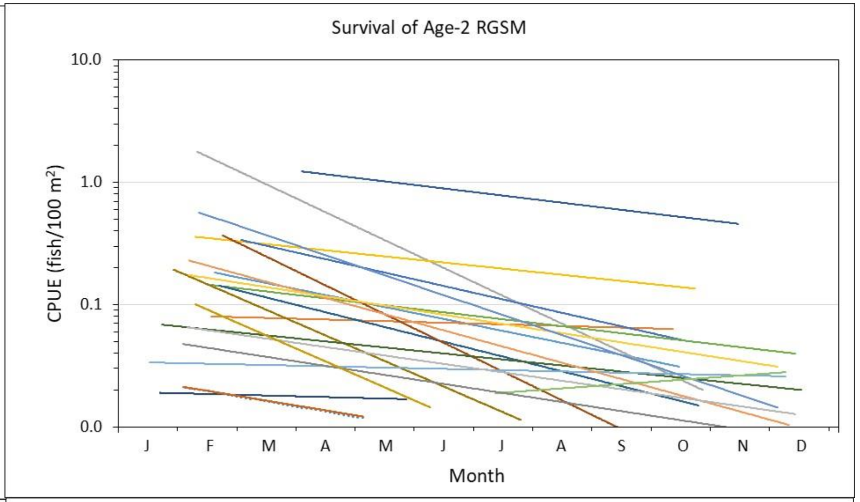


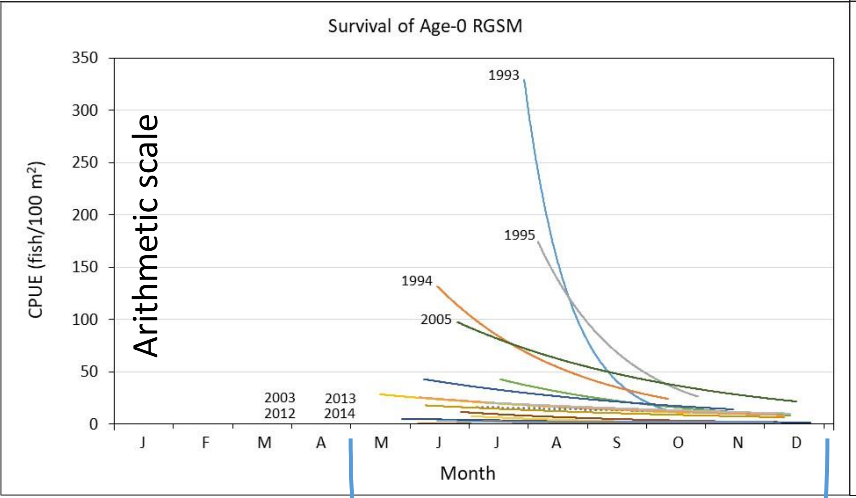


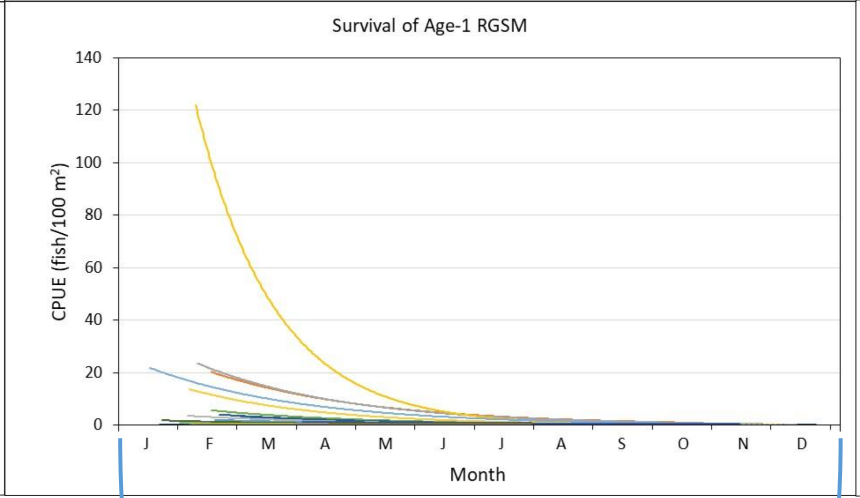


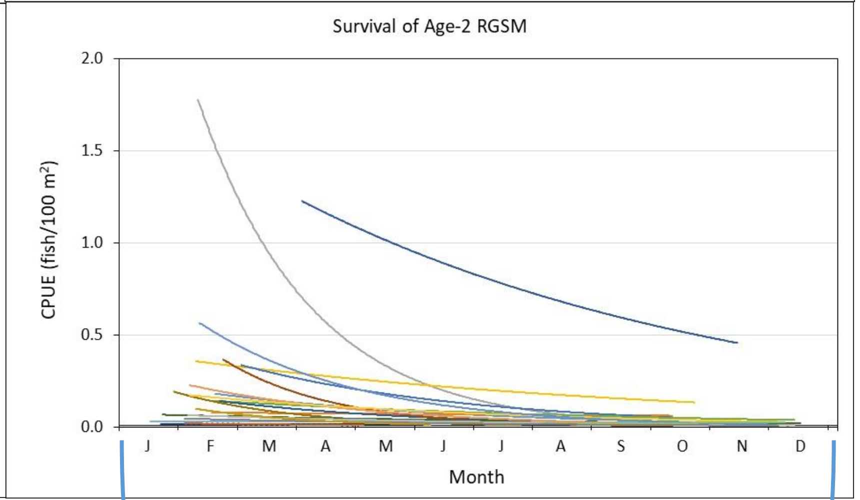












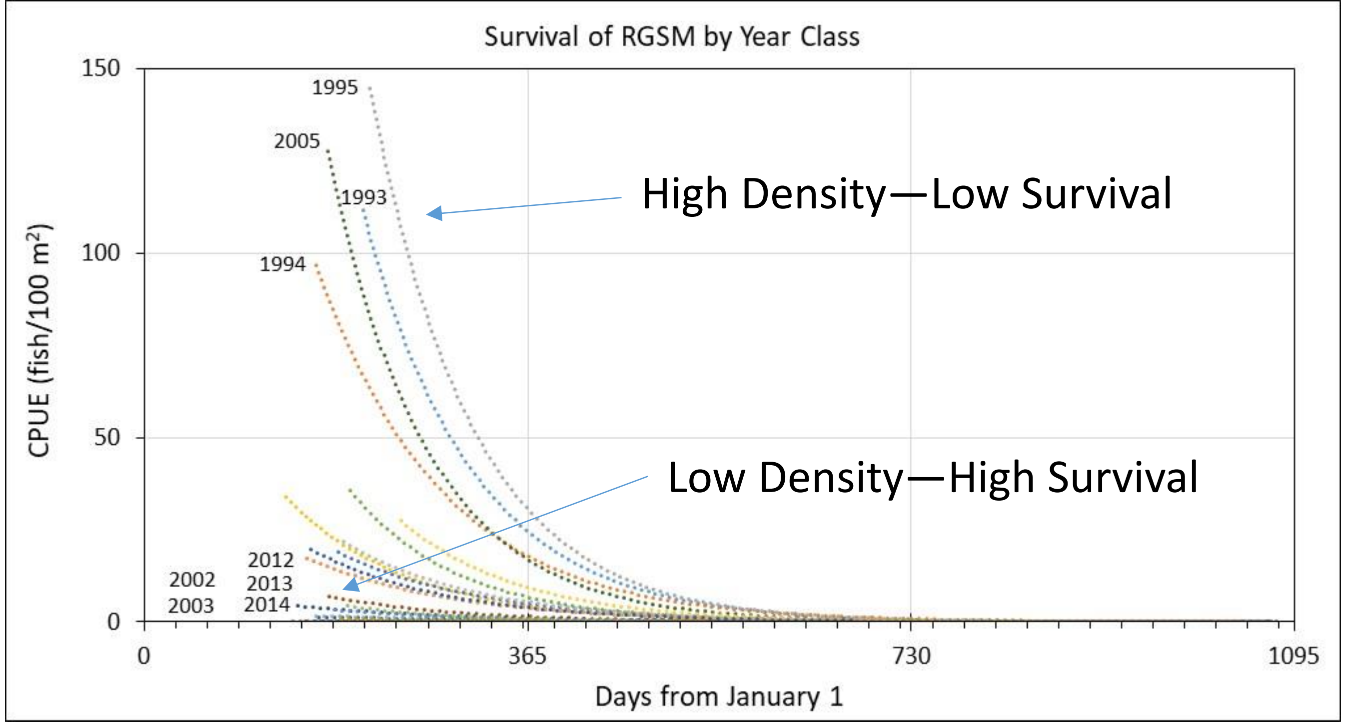
Age-0 Survival = Apr 1 – Dec 31

Note: full recruitment to the gear (seines) occurs May, June, or July

Age-1 Survival = Jan 1 – Dec 31

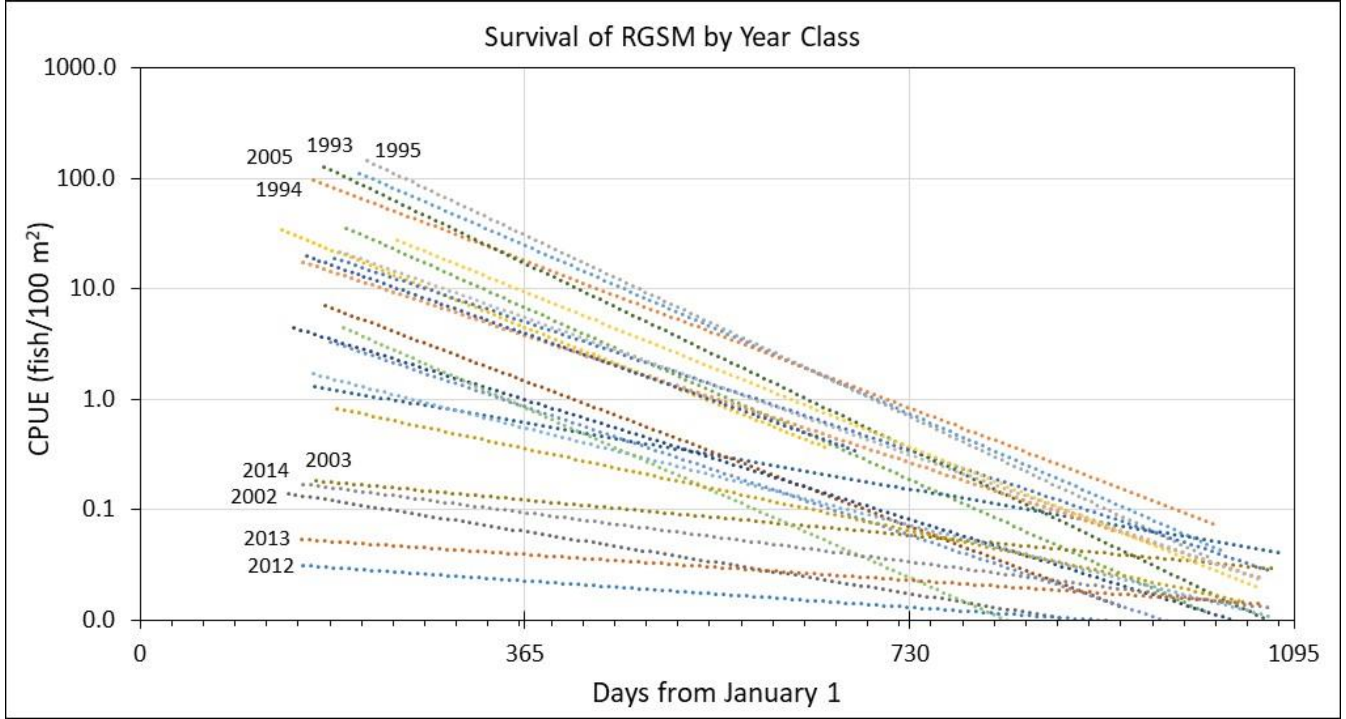
Age-2 Survival = Jan 1 – Dec 31

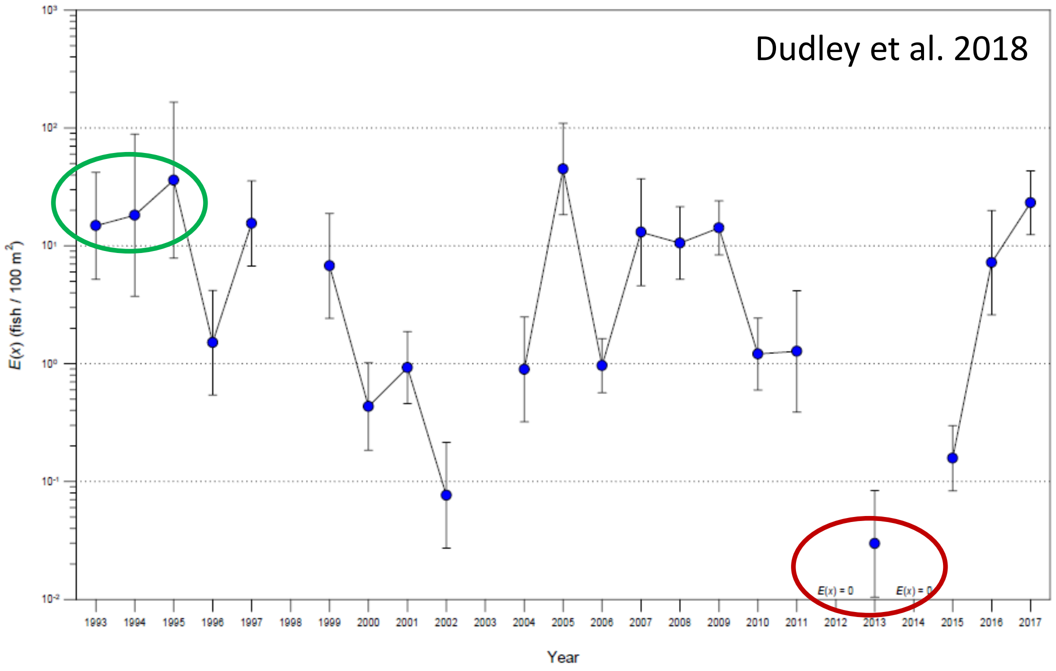
Survival by Year Class (Cohort)


Survival of RGSM by Year Class

High Density—Low Survival

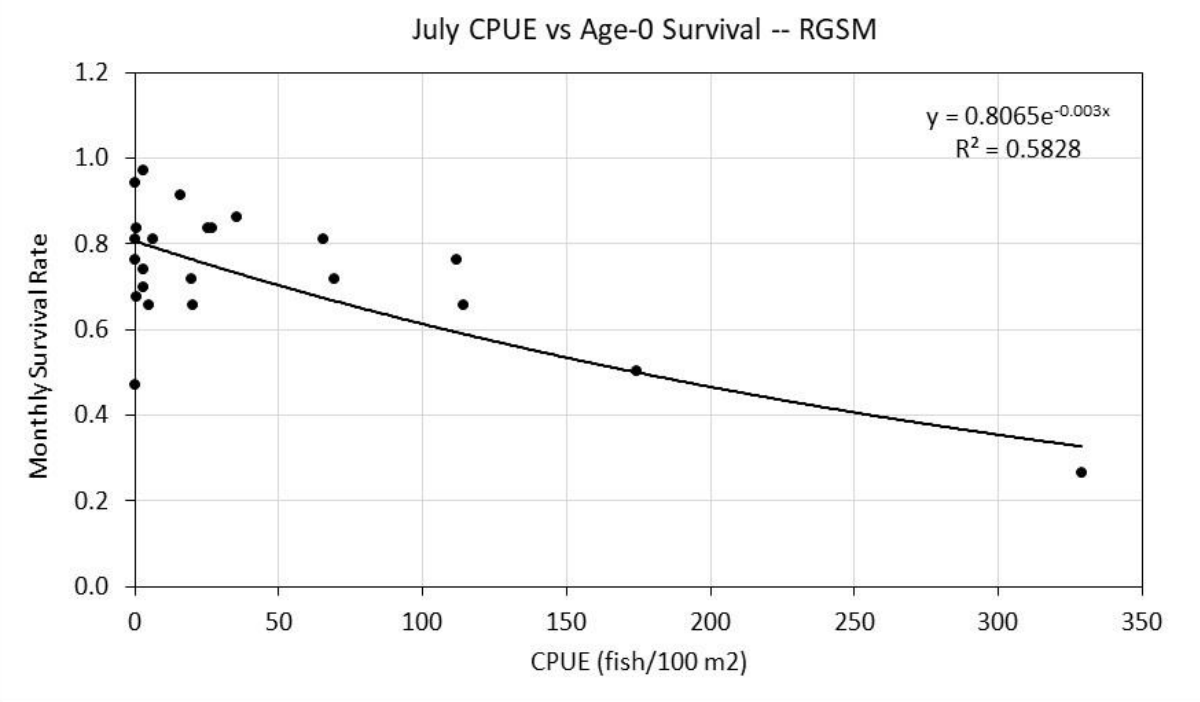
Low Density—High Survival

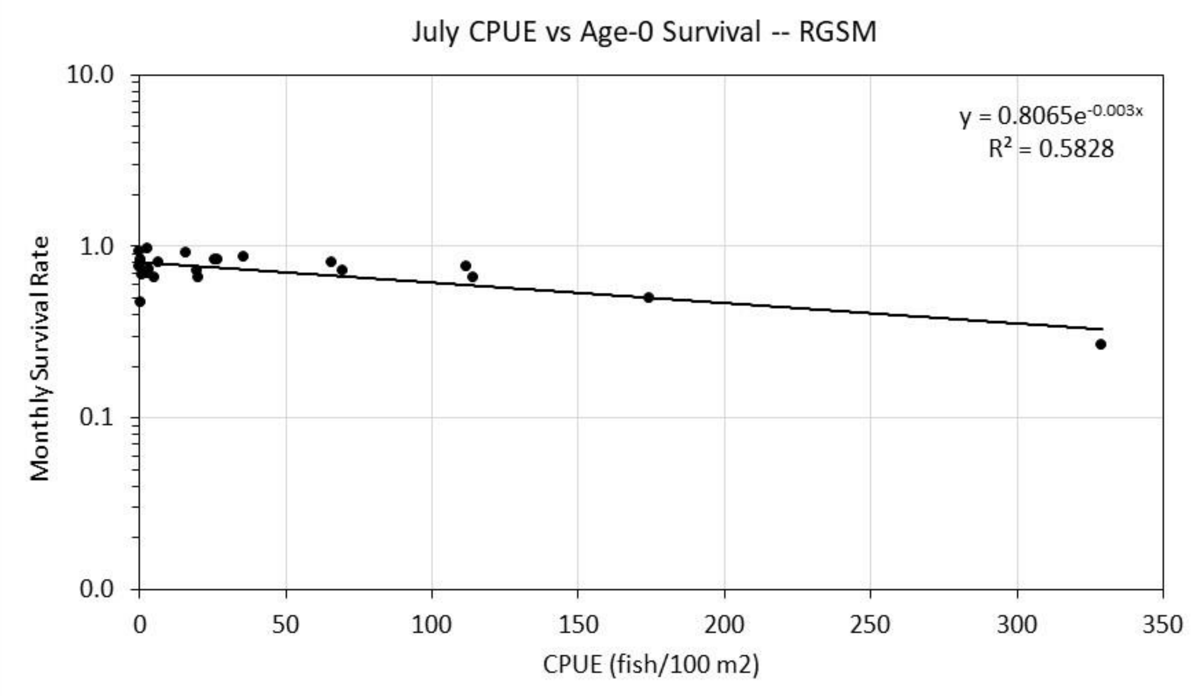

Survival of RGSM by Year Class


Dudley et al. 2018

Is There Density Dependence?

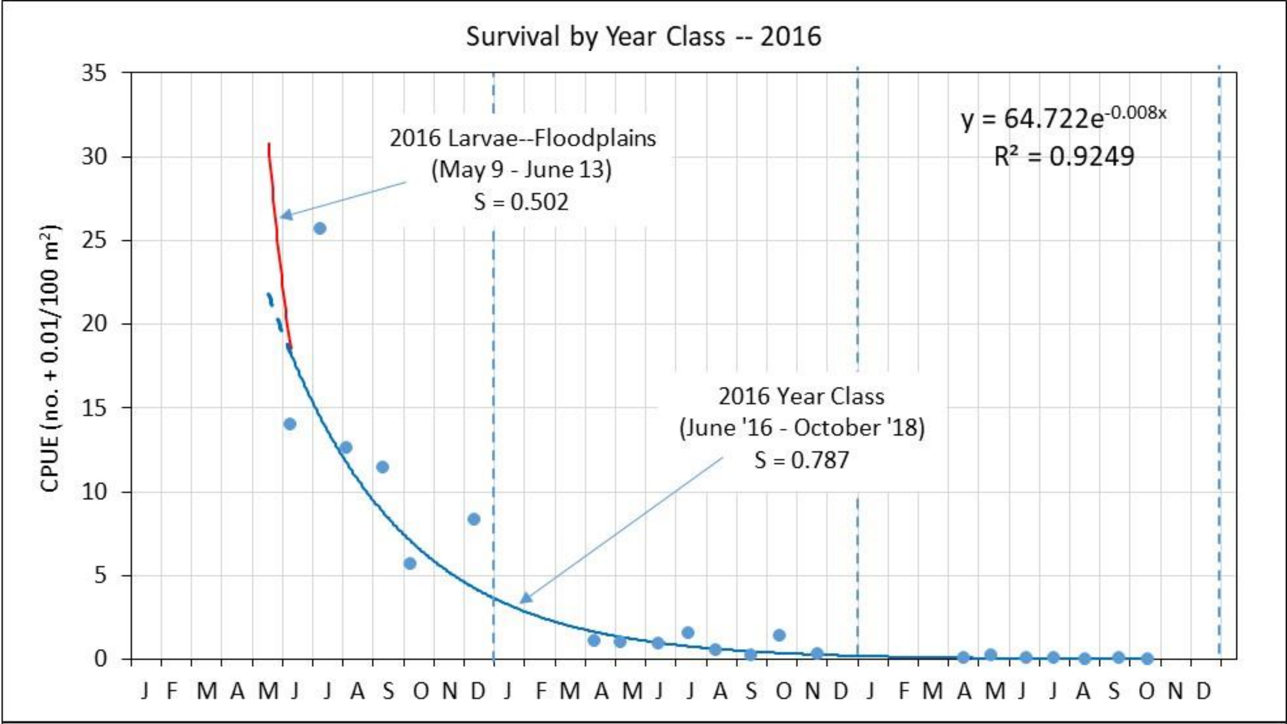
- Density-dependence can significantly impact population abundance.
- Miller (2012): *“We are not able to accurately measure the nature and extent of density dependence in recruitment in our data, and therefore cannot unequivocally parameterize the mode of density dependence in our models.”*
- *Goodman (2009, 2010) believed that there was density-dependence as a complex interaction of inter-annual variability in reproductive success, habitat availability, and carry capacity.*
- Relationship of mean July CPUE and annual Age-0 survival indicates high but variable survival at low density and low survival at high density.

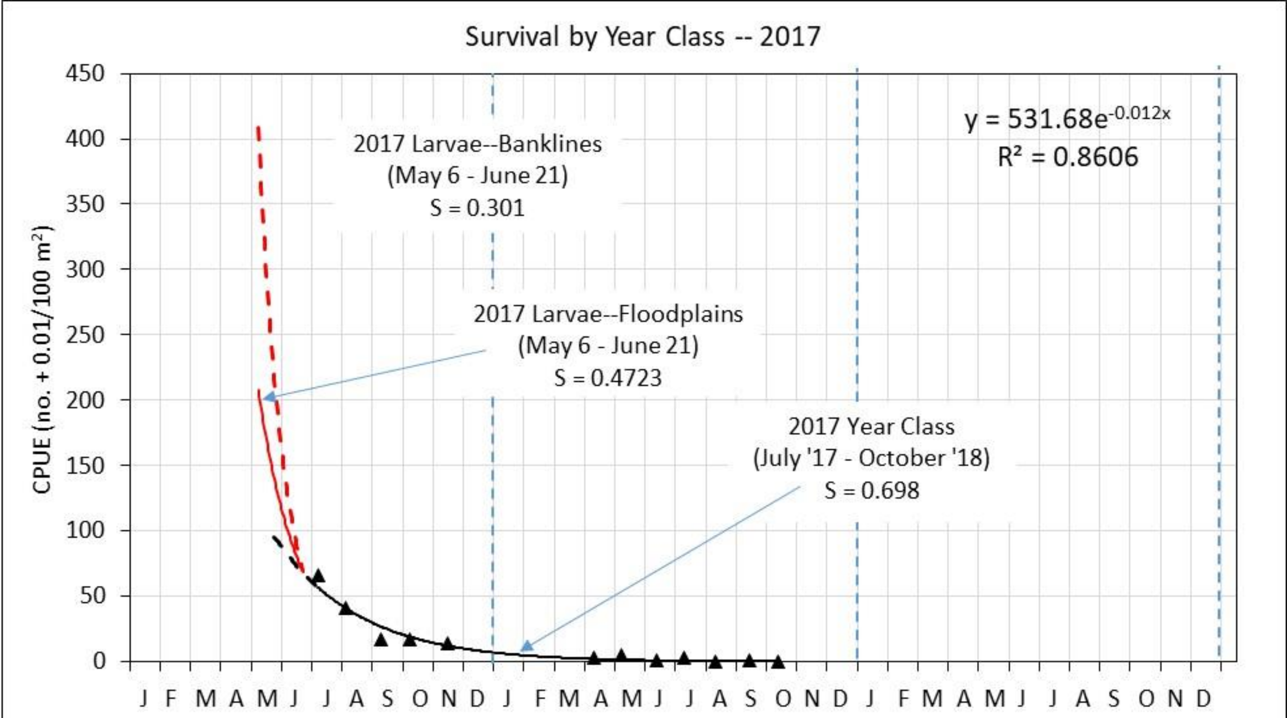




Integrated Survival 2016 and 2017

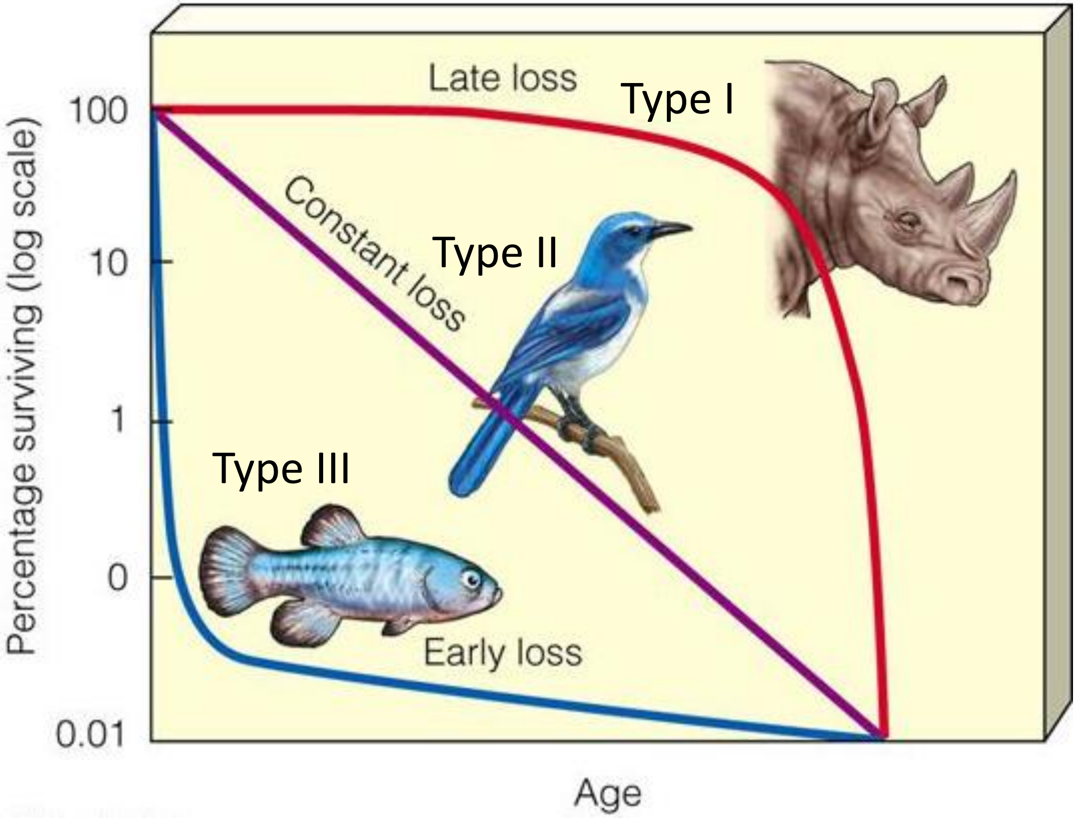
- Survival of larvae is very low.
- Larval survival in mainstem appears lower than in floodplains.
- Survival in first 40-50 days cannot be determined from Pop Mon.
- Year Class Strength largely determined by larval survival.
- Survival rate asymptotes in spring of second year of life.



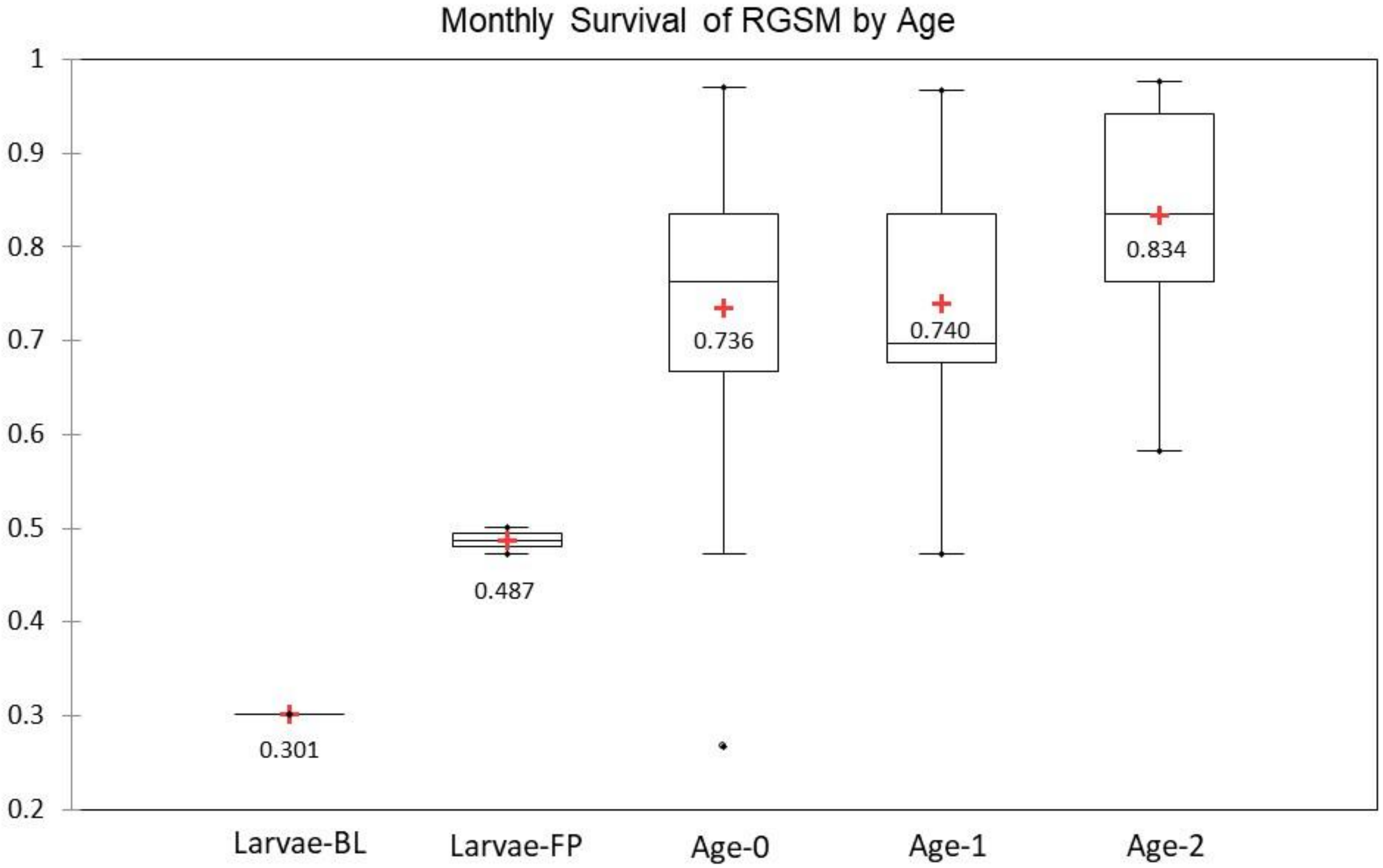


Survivorship Curves

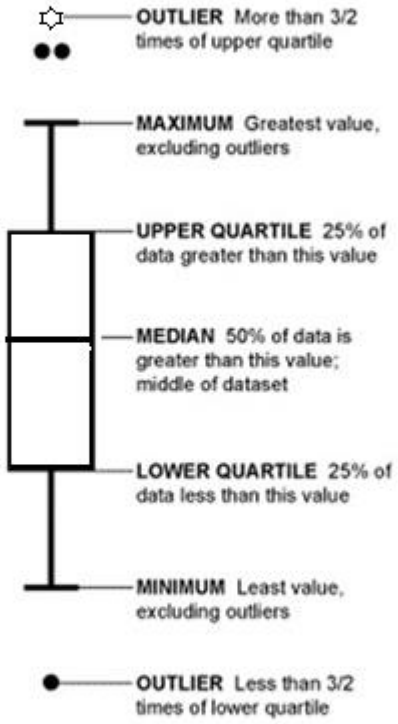
- Type III or concave curves have the greatest mortality (lowest age-specific survival) early in life,
- With relatively low rates of death (high probability of survival) for those surviving this bottleneck.
- This type of curve is characteristic of species that produce a large number of offspring (r selection).
- Enhancing survival of early life stage(s) helps to support populations with Type III survivorship.



Summary of Survival Rates (1993-2017)



Explanation



OUTLIER More than 3/2 times of upper quartile

MAXIMUM Greatest value, excluding outliers

UPPER QUARTILE 25% of data greater than this value

MEDIAN 50% of data is greater than this value; middle of dataset

LOWER QUARTILE 25% of data less than this value

MINIMUM Least value, excluding outliers

OUTLIER Less than 3/2 times of lower quartile

Estimates of Survival for RGSM

Citation	Larvae	Age-0	Age-1	Age-2	Hatchery Age-?
Remshardt (2007)	--	--	--	--	0.662 (mo)
Valdez (2010)	--	0.763 (mo)			--
Miller (2012)	0.15 (mo, assumed)	0.662^{11} x 0.15 = 0.0016 (an)	0.662^{12} = 0.007 (an)	0.05 (an, assumed)	
Goodman (2009a)	--	0.0580 (an) (0.03-0.30)			--
Hatch (2009)	--	0.09 (annual from salvaged fish)			--
Valdez (this report)	0.502 (mo, 2016, floodplains) 0.472 (mo, 2017, floodplains) 0.301 (mo, 2017, mainstem)	0.736 (mo) (0.267-0.970)	0.740 (mo) (0.472-0.968)	0.834 (mo) (0.583-0.976)	--

DOCUMENT REVIEW COMMENTS

PROJECT TITLE:

REPORT DATE:

PAGE	LINE #	Section, Table#, or Figure#	COMMENT	Type of Concern (readability, consistency, inaccurate, etc.)	Significance of the Concern (Low, Medium, High)	Specific Action Needed to Resolve the Concern

Reviewer's Name	FINAL DOCUMENT ACTION	COMMENT

Draft I: Review of the “Analytical framework for evaluating the proposed water management and maintenance actions on Rio Grande silvery minnow, southwestern willow flycatcher, and yellow-billed cuckoo and their critical habitats” with recommendations for future analytical considerations

by

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Draft I Report to:

U.S. Department of the Interior, Bureau of Reclamation, Albuquerque Area Office

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** Note: Figures presented at the November meeting with Albuquerque Bureau of Reclamation – Albuquerque Office may be included in the final version of this report*

Background and Impetus for Review

Rio Grande silvery minnow (*Hybognathus amarus*; *hereafter* RGSM) was listed as endangered under the US Endangered Species Act in 1994 and remains at extremely low abundances in a very restricted portion of its historical distribution. The Middle Rio Grande, from Cochiti Dam to Elephant Butte Reservoir in New Mexico is the only stretch of the Rio Grande River basin where RGSM are consistently present. This portion of the Rio Grande is intensively managed for off-stream water uses, presenting conflicts over limited water sources between off-stream users and attempts to satisfy legal requirements under the ESA.

To achieve the goals of transparent and repeatable analyses and documentation for the potential effects of water management on populations of RGSM, the US Fish and Wildlife Service (*hereafter* Service) completed Appendix A to the 2016 Biological Opinion (*hereafter* BiOp): "Analytical framework for evaluating the proposed water management and maintenance actions on the Rio Grande silvery minnow, southwestern willow flycatcher, and yellow-billed cuckoo and their critical habitats". This appendix summarized the analytical framework, data structure, statistical approach and assumptions used to evaluate the proposed actions' impacts to the river environment and the subsequent effects to the listed species and their habitats, focusing primarily on RGSM.

The framework used to evaluate these impacts is termed the Hydrobiological Objectives (HBO) and is intended to provide water managers with potential strategies to maintain RGSM production and survival. The HBO is comprised of simple linear relationships between RGSM densities or occupancy (measured as the proportion of sampled sited in which RGSM were captured – these analyses are hereafter referred to as "presence") and several hydrologic metrics, including spring flood flows, summer low flows, and floodplain inundation. These relationships are then used to inform semi-quantitative assessments of the potential impacts of various actions on the RGSM population, including the potential impacts of altered hydrology under changing climate conditions. At the time the Appendix to the BiOp was completed, it was based on the best available knowledge with the understanding that it would provide a starting point for future refinements as part of an adaptive management process to continually learn and improve management actions to provide the listed species with the best opportunity for persistence and recovery.

This review was initiated to support the refinement of analyses and recommendations from the HBO, as new information has continued to be collected and the report and analyses in the Appendix had yet to be externally reviewed. The overall goal of this assessment is to review the HBO analyses and associated spreadsheet models to provide recommendations for refining the analyses and identifying data gaps. This review comprises the first of three potential phases, where the second phase may involve refining the models used to assess the impacts of hydrology on RGSM, and the third phase may involve providing tools for adaptive management. Of specific interest to this initial assessment are data that were not included in the HBO analyses (i.e., drying metrics), the assumption of spatial homogeneity (i.e., minnows in all reaches respond equally to the same flow metric) and the analytical framework used to assess relationships between the many flow metrics identified in the HBO and populations of RGSM.

<u>Strengths of the Original HBO Analyses</u>

An inherent challenge associated with analyzing the impacts of environmental conditions on the population dynamics of any species is identifying, gathering, and organizing the available data from multiple sources to account for many potential driving factors. The Service has completed a substantial amount of work in the HBO analyses, identifying the myriad potential hydrologic metrics that may impact RGSM, determining which data are available, gathering and organizing those data and executing analyses of each individual metric gathered. This is no small feat and deserves commendation. The collection and organization of these data provide the starting point for any analysis (past or future) of the impact of hydrologic conditions on RGSM populations. Additionally, the regression analyses executed for each of the hydrologic metrics identified in the HBO against either RGSM density or presence provide a valuable initial step for identifying general patterns and understanding the distributions and limitations of the data available.

The analysis of both historic and potential future hydrologic scenarios for the Middle Rio Grande provides valuable information about the conditions under which RGSM populations existed in the past, as well as how it may respond to future changes in hydrology resulting from climate change and altered land use. By estimating flows through the Middle Rio Grande from tree rings for the past 600 years, the Service is able to better understand the distribution of historic flow conditions present in the river, beyond what has been experienced in the 70 years since the installation of in-river gaging stations. By using this distribution of historic flows to bracket simulated future conditions into very wet, normal and very dry conditions, the Service can provide a range of potential outcomes given the uncertainty in future hydrologic conditions.

Opportunities for Improvement

Treatment of Uncertainty

Inherent in all models are multiple sources of uncertainty and error, including measurement or observation error and errors in the structure of the model describing the system (process errors). For simple models describing complex systems with many interacting components, accounting for and presenting estimates of uncertainty is critically important for model interpretation, particularly if model predictions are to be used for management decisions in the system.

The HBO analyses do not fully present the uncertainty in either the data being analyzed, nor in the model estimates of relationships. There are no measures of uncertainty provided for the annual RGSM density estimates. As these estimates are derived from many individual seine hauls, and are not census data, there will be variation in the density of RGSM sampled in each seine haul, in each site, and in each reach. Without incorporating this uncertainty into the models, estimates of model fit (e.g., R^2) will be inflated, presenting greater than deserved trust in model predictions.

While the HBO presents confidence intervals for the regressions on the figures, these intervals only measure how well the mean relationship is captured by the model. This is certainly an important characteristic to present, but for the management of species with highly variable population dynamics, understanding the <u>range</u> of potential responses to a given condition can be as important as understanding the average response. For example, if the species is managed to maintain populations above a threshold density (e.g., 1 RGSM per m2), it would be highly beneficial for managers and stakeholders to understand the probability of the population falling under the threshold at any given condition of the system. Confidence intervals alone do not allow for this type of analysis.

Problems with zero values: Mathematical

Estimating abundances and densities of populations presents some numeric challenges for model fitting, namely, that neither abundance nor density can drop below zero. As such, data transformations that do not allow predictions to fall below zero are required for these analyses. The HBO addressed this issue by log-transforming density estimates, a suitable and widely-used approach. However, log-transformations present a challenge of their own in that the log of zero is undefined. As there are several zero values for RGSM density in the data set, this is a pertinent issue for the HBO analyses. The Service addressed this issue by adding 1 to all density estimates, a common approach to alleviate this limitation of log-transformed data, but one which has a greater impact on low densities than high densities (e.g., adding 1 to a value of 0.1 changes its value in log-space from approximately -2.3 to 0.95, while adding 1 to a value of 25 changes its value in log-space from 3.22 to 3.26). There are more robust approaches to accounting for zero values that may simultaneously address another important issue with the data and model interpretations (*see below*).

Problems with zero values: Functional

One of the limitations of the RGSM density data is that a density estimate of zero does not indicate that there are actually zero RGSM individuals remaining in the MRG, only that no individuals were captured during fall sampling events. As the entire MRG is not sampled and the probability of capturing the available individuals is not 100%, there is a chance that RGSM are present in the system, but not in the samples. This causes model fitting issues and difficulties with predicting the effects of hydrologic conditions during low density years. As a density estimate of zero can only indicate low abundance, there is limited contrast in the response variable during these low-density periods.

The estimates of zero density present in the data also highlight another opportunity for improving the models in the HBO. The fact there are years with estimates of RGSM fall densities of zero, which are followed by years with non-zero densities suggest that there need not be RGSM in the river in one year for there to be RGSM in the river the following year. The apparent lack of relationship between population abundance in one year and the next does not make ecological sense, as the offspring in one year must have been produced by individuals that were present the previous year. Part of this incongruence can be explained by the previously discussed fact that density estimates of zero do not actually indicate zero abundance, only lack of capture and/or detection. Additionally, the productivity of the remaining spawners may be so greatly impacted by environmental conditions that any relationship between spawners and recruits may be completely masked by environmental variability. Finally, the production of offspring from zero adults may be explained by the stocking of hatchery-reared individuals after the fall density sampling has taken place. Regardless of how this is occurring, this pattern in the data highlights issues with the assumption of temporal independence in the model that provides an opportunity for improvement in future analyses (*see below*).

Extrapolation of models beyond observed conditions

Predictions of ecological responses made beyond the bounds of experienced conditions should always be treated very carefully, as non-linear and threshold dynamics are common in ecological systems. The use of polynomial regressions in the HBO to predict both density and presence requires care, particularly when there is little evidence of curvature in the response to changes in the predictor variable. Polynomial relationships can change direction as the value of a predictor variable is increased or decreased (e.g., Fig. A20). Unless there is an *a priori* reason for such a change in the direction of a relationship between RGSM density or presence and the hydrologic predictor, polynomial regressions should be avoided, particularly if they are going to be extrapolated. The pitfalls of the polynomial regression are evident in Fig. A10, wherein negative proportional presence is predicted when flow volumes are extrapolated to higher levels than have been measured in the period of record. The HBO then attributes these negative values to the RGSM being unable to cope with high-flow velocities. This response is not supported by the analysis, as flow velocities are not included in the analysis, and the negative proportional presence at high flows is entirely attributable to the polynomial relationship being extrapolated beyond the bounds of the observed data. The negative downturn at high flow volumes is driven entirely by a single data point and the assumption of a polynomial relationship.

Extrapolation of population status estimates reveals another structural limitation of the current models. Examination of the output from the linear regressions in the HBO reveals the model is predicting exponentially increasing RGSM densities as flow increases (due to the densities being log-transformed in the model). This suggests that the abundance of RGSM in the MRG would continue to increase to infinite abundance if, for example, spring peak flows could continually be increased. Such a prediction assumes there is no carrying capacity for RGSM populations in the MRG and that they are capable of increasing abundance indefinitely. As they are endangered and thus assumedly at reduced densities relative to historic values, RGSM densities may not have approached carrying capacity during the period of record. However, it remains important to include this ubiquitous ecological condition in the models, such that expectations are based in reality.

Inappropriate model structure: Predicting impossible probabilities of presence and densities

A subset of the regression analyses in the HBO could incorporate more appropriate assumptions about the data structure, an issue most apparent in the presence analyses. As they are proportional values, the response values of the presence analyses are inherently limited between zero (no sites are occupied) and one (all sites are occupied). Therefore, the relationship fit against the predictor variables should only be able to produce predictions between zero and one. The confidence intervals shown in Figs. A20-A22 all include values outside of this interval, and extrapolation of the lines of best fit result in predictions greater than 1 and less than zero, indicating an inappropriate model structure.

Similarly, the model predictions of RGSM densities include negative density values among the predictions for the linear model. Only models that can produce estimates limited to values greater than or equal to zero should be considered. Unlike the polynomial regressions examining log-transformed data, the accompanying linear models of un-transformed data (Tables A3-A12) are inappropriate as they can produce negative densities and should not be presented.

Assumption of temporal independence

As the response variable (RGSM density or presence) represents a time-series of an index of the status of a biological population, it should be assumed that the state of the population in one year should be influenced by the state of the population in the previous year. The number of adults present in the population in one year is going to be a function of the number surviving from the previous year and the number of juveniles recruiting to the population. As such, individual samples cannot be treated as independent of each other. The current regression models do just this, treating the densities and presence in one year solely as a function of hydrologic variables. Even if the RGSM population dynamics are primarily driven by annual hydrologic variation, the temporal autocorrelation needs to be accounted for in the model structure.

Indicators of low flow conditions and spatial homogeneity

The Middle Rio Grande is divided into four distinct reaches (though only three are regularly sampled for RGSM). These reaches are separated from each other by diversion dams impassable to RGSM in an upstream direction and, frequently, in both directions. In addition to being partially disconnected from each other, each has unique hydrologic conditions due to the many diversion structures in place from the intensive water development in the region. As conditions at the Central Gage will covary to different degrees with the conditions in the river below subsequent diversion structures, it should be assumed the RGSM sub-populations in each of these reaches will respond differently to the hydrologic conditions being measured at the Central Gage, though the available data may not be able to detect these differences. In particular, metrics of low flow are likely to be very different among the reaches. Currently, low flow periods are being measured by the number of days that the Central Gage is measuring discharge below 200 cfs or 100 cfs. These values were selected as they correlate with conditions of drying in the Isleta and San Acacia reaches. However, this correlation is going to be dependent upon the operations at the individual diversion structures, and the amount of drying in any individual reach will likely vary beyond that which can be estimated from the discharge at the Central Gage alone. Additionally, metrics of flow conditions at the Central Gage provide no information regarding the extent of any drying that may be occurring (e.g., kilometers of river without water).

Correlated Predictor Variables

While the large number of regression analyses examined in the HBO are an excellent and necessary first step in the analysis of how hydrology impacts RGSM populations, the simple, single predictor regressions are limited in several ways. First, single predictor regressions likely oversimplify the relationship between RGSM and their environment, as it is highly unlikely a single environmental condition determines the dynamics of a population across twenty years.

Associated with the limitation presented by the single predictor approach is the fact that nearly all the metrics examined are highly correlated with each other (Figure 1). Thus, the same general relationship is found across all the metrics examined. Years in which there were more days of flow over 2000 cfs also tended to have higher spring peak flows, and higher average spring flows, etc. Years with large spring flows generally have higher summer base flows, fewer days under low flow thresholds, etc. This high degree of correlation between the different flow metrics makes it very difficult to determine which (if any) of the metrics are influencing RGSM density or presence.

Due to this difficulty, many of the specific recommendations made in the discussion section rely on highly correlated metrics. Listing all the predictors and thresholds as if they are all important determinants of RGSM population condition when they are all highly correlated, while serving as a starting point for identifying relationships, does not yet fully allow for distinguishing the specific contribution of individual hydrologic metrics to the RGSM population. Perhaps the minnows are responding to only a single condition, but that condition is highly correlated with each of the other predictor variables. The sections where specific combinations of conditions are highlighted as important would benefit from specifically analyzing those (and additional) interactions. What would likely occur if they were tested, is that only one of the metrics would come out as significant (or none of them), as the metrics are so highly correlated all of the contrast in conditions experienced by RGSM populations could be gleaned from a single metric.

Minimum viable population

The Appendix describes threshold densities deemed critical for the persistence of RGSM in the MRG, derived from an analysis of the Minimum Viable Population (MVP). The Service explains that these density thresholds protect against lost haplotypes, but do not present data on the number of haplotypes or how haplotype diversity responds to the density of RGSM. Further, these threshold values seem odd to present as MVP sizes, given that the population has dropped below these thresholds repeatedly, and indeed remained below these thresholds for extended periods, before recovering to densities well above the thresholds. Perhaps, additional description and clarification of the MVP analyses that informed these values would improve understanding.

Occupancy and Detection

The current estimates of presence, the proportion of sites at which RGSM was captured, does not account for the probability of detection and are thus negatively biased and underestimate uncertainty. At any given site, capturing a RGSM indicates that they are truly present at the site. However, not capturing one does not indicate that they were truly absent. True absence cannot be proved without perfect sampling efficiency, as there is always the possibility that RGSM were present at the site but not captured during sampling. We are aware that a proportional occupancy analysis has been completed and is updated annually (Dudley et al. 2018), providing proper metrics for occupancy and probability of detection. Each of these metrics could be used for further exploration of the conditions driving RGSM distribution and abundance.

<u>Suggested Approaches</u>

Here, we provide suggestions for approaches that could address the issues presented above, as well as select examples of the suggested analyses. Any figures and analyses provided herein are preliminary, intended as examples only, and should not be considered comprehensive and complete analyses.

Treatment of Uncertainty

To address the limitations of models fit without incorporation of uncertainty, we suggest two initial measures. As multiple sites are sampled each year, simple approach to account for uncertainty in annual RGSM density estimates, would be to calculate the standard deviation of densities among sampling sites each year. Incorporation of data uncertainty into the models would provide a more complete estimate of the uncertainty in the regression relationships.

A more comprehensive approach to estimating uncertainty would be to estimate density hierarchically (Gelman and Hill 2006). In this approach, a global mean density would be estimated, from which densities in individual sites or seine hauls would be drawn. A hierarchical model of this type assumes that there is an average density across the entire MRG, and the densities in each reach are normally (or log-normally) distributed around this mean density (i.e., some have lower density, some have higher density). This hierarchical modeling approach would further assume that the density at each site within each reach was distributed around the reach-level mean value (i.e., some sites have higher densities than the reach average, and some have lower densities than the reach average). In addition to estimates of mean densities at the different scales, this approach would provide estimates of uncertainty at the MRG scale, as well as the reach and site scales.

While the confidence intervals for the regressions are presented on the figures of Appendix A, it would be beneficial to the reader and ultimately any manager interested in using the model outputs to present the prediction intervals for these regressions as well as, or in place of, the confidence intervals. The prediction interval captures the range across which one would predict individual samples or observations to occur. Prediction intervals will be much broader than the confidence intervals and provide a better approximation of the uncertainty in how RGSM populations can be expected to respond to changes in hydrologic conditions (for an example, see top right panel of Figure 3 in this review). Accounting for the prediction uncertainty is particularly important for systems being managed for threshold values (e.g., RGSM densities being managed for 1 individual per m^2). With the prediction interval, the percentage of future observations predicted to fall below the conservation threshold at a given state of the system can be estimated. Managers and stakeholders can then better assess the risk of poor RGSM performance for any chosen management strategy (e.g., minimum flow value, spring flood duration).

Problems with zero values: Mathematical and Functional

One approach that would alleviate the issues presented by zero-values from both a mathematical and functional perspective, and simultaneously treat zero-values as an indicator of occupancy as well as low densities would be to use zero-inflated regression or hurdle models (e.g., Martin et al. 2005; Potts and Elith 2006). These approaches model the density of RGSM through a two-stage process, where the detection of RGSM is first modeled (i.e., is measured density greater than zero?), and then, if the model predicts RGSM were detected, the second stage models the density of RGSM as a function of selected predictor variables. The log-transformation of zero values would remain an issue, but the nonlinear effect of adding 1 to all densities could be mediated by adding a smaller value (e.g., add 0.001 to all values). By adding a smaller value, the change in values relative to each other will be much smaller, better maintaining contrasts among annual density estimates.

Extrapolating regressions beyond observed conditions

While it is always necessary to be cautious when extrapolating model predictions beyond the bounds of observed conditions, the dangers of doing so can be alleviated somewhat by selecting model structures which do not change direction with continually increasing predictor values. The negative downturn of predicted RGSM presence at high flow volumes (Figure A20 in Appendix A) is driven entirely by a single data point. If an alternative model structure (e.g., a generalized linear model with logit-link, which limits predictions to values between 0 and 1) were fit to these data, the downturn in predicted proportional presence at high flows would not occur. Then, the proportional presence would be predicted to be at or near 1 in these high flow years. For all the models examined, selecting models that increase or decrease monotonically across the range of observed conditions would provide more reasonable predictions when extrapolating beyond the bounds of the data. If there is an *a priori* reason to include a model that changes the direction of the response across the range of observed conditions (e.g., obvious unimodal-shape to the data), then a polynomial could be appropriate. However, none of the relationships presented in the appendix demonstrate a clear pattern indicating changing directions of the relationship. Nonetheless, even with a statistically appropriate model structure, much care needs to be taken when extrapolating beyond the bounds of observed data as directional relationship can change beyond unknown threshold values.

Density-dependence can be incorporated by modeling RGSM densities with a saturating relationship (e.g., a modified Gompertz function, see Figure 3) as flow conditions improve:

$$ln\left(D_y\right) = \alpha e^{-\beta e^{-cH_y}} - .5\alpha \tag{1}$$

where D_y is the estimated RGSM density in year y, H_y is the habitat condition in year y, and α, β, and c are estimated parameters. The subtraction of 0.5α centers the log-density predictions on zero. If RGSM have not approached their carrying capacity during the period of record, fitting such a model would still predict increasing densities as flow is increased and have large estimates of uncertainty around RGSM carrying capacity and the flow conditions at which density-dependence begins to act upon the population (see top right panel of Figure 3). These models would also provide estimates of the hydrologic state at which one would expect to stop seeing increases in local densities of RGSM. Interpretation of such values would need to be cognizant of the potentially valuable spillover benefits to other reaches of the river. If the RGSM populations in the MRG reached their carrying capacity (perhaps after an extended period of optimal conditions), additional individuals produced by the population each year would not be able to survive on the limited resources locally and should attempt to move to locations with lower densities and thus lower competition for resources. Movement to other reaches could also occur as a function of larval drift. In such situations, while maintaining optimal conditions would likely not produce further increases in the densities of RGSM locally in the MRG, there should be spillover benefits to adjacent accessible reaches.

Inappropriate model structure: Predicting impossible probabilities of presence and densities

The regressions examining how presence responds to hydrologic variation should be reanalyzed using a generalized linear model with a logit-link. This approach limits the response (i.e., predicted proportional presence) to values between zero and one, while still allowing for continuous linear regression. For the analyses of density, as densities are inherently limited to values greater than or equal to zero, only models that can produce estimates limited to values greater than or equal to zero should be considered. Log-transformation of density observations and predictions would account for this limit. Predicted densities would be exponentiated after the analysis to convert them to real values for interpretation.

Temporal independence

Even if the RGSM population dynamics are primarily driven by annual hydrologic variation, the temporal autocorrelation should be assessed in the model structure. A simple approach would be to incorporate an autoregressive error structure (AR1) to the model, where residuals in one year are influenced by the residuals in the previous year (e.g., Fieberg and Ditmer 2012) . For example, if the model predicts lower than observed densities in year 1, it would be more (or less, depending on autoregressive parameter estimate) likely to predict lower than observed densities again in year 2.

A more complex approach to accounting for temporal autocorrelation would be to build a state-space model, in which a latent (unmeasured) variable describing the state of the system (e.g., supporting high densities vs. supporting low densities) is estimated using a random walk process (Figure 4). The random walk process would be added to the linear or saturating relationship being used to model RGSM response to flow, producing autocorrelated predictions. The random walk process can also demonstrate temporal changes in the relationship between RGSM populations and the flow condition being examined. For example, if the random walk process demonstrates negative values for the first ten years and then positive values for the next ten, this could indicate that something in the system changed at the ten-year mark, altering the way RGSM populations respond to that particular flow metric.

Finally, a model structure incorporating spawner-recruitment relationships along with hydrologic impacts could potentially highlight how the number of spawning adults influences the abundance of age-0 RGSM in the fall sampling period. There are several spawner-recruitment relationships that could be examined, including a Beverton-Holt function, Ricker function (Hilborn and Walters 1992), Shepherd function (Shepherd 1982), linear function or no relationship with stock size (i.e., recruitment is only a function of hydrologic variables). The hydrologic variables would be included in these analyses as factors influencing the residuals off the spawner-recruit relationship. Such an analysis of spawner-recruitment would also need to account for the number of RGSM stocked into the MRG from conservation hatcheries each fall. The impacts of the stocking program need to be examined in more detail, in general and for these analyses of spawner-recruitment specifically. Each of these approaches provides an opportunity for accounting for the temporal autocorrelation inherent in biological time-series.

Indicators of low flow conditions and spatial homogeneity

To account for the spatial heterogeneity in hydrologic conditions and RGSM population dynamics, the RGSM density and presence should be modeled at the reach scale (i.e., Angostura, Isleta, and San Acacia densities should be modeled as unique indices, though not necessarily independently). This reach-based approach could be accomplished with hierarchical approaches (Gelman and Hill 2006), where an MRG mean density is modeled as a function of hydrologic conditions and other predictors, and the reach specific densities are modeled as random deviations from the MRG mean value. This random variation can be due to variance in the slope parameters fit to hydrologic predictors (i.e., reach-specific RGSM densities respond differently to changes in flow), or reach-specific intercept values, for example (i.e., reaches have different baseline densities).

Alternatively, reach-specific hydrologic variables could be used to predict reach-specific responses to conditions. None of the metrics that have been assessed thus far directly measure the extent of drying conditions experienced by RGSM populations. Therefore, the low flow metrics that have been assessed thus far should be supplemented with additional metrics such as the number of days with full channel drying in each reach, the maximum number of river miles dry in each reach annually, or, better yet, a combination of timing and extent of drying experienced in each reach in each year (e.g., kilometer-days dry). Such metrics would more explicitly capture the extent and impact of local drying conditions on RGSM population dynamics.

Correlated Predictor Variables

There are methods available that could address the issues presented by the correlated predictor variables. Dimension reduction techniques, such as principal components analysis (PCA) can be applied to find the primary axes of variation among the many correlated predictor variables being examined (e.g., Figure 2). The resulting axes of variation can then be used as composite predictor variables in subsequent regressions (e.g., Figures 3 and 4; Lisi et al. 2013). As the axes produced from the PCA are inherently orthogonal (perpendicular to each other with zero correlation in multidimensional variable space), predictor variable correlation will not be an issue. However, the resultant axes will not be as readily interpretable in terms of providing specific management advice. For example, when examining the bottom panel in Figure 2, it is not immediately obvious what a value of 1 on the x-axis translates to in terms of spring flow conditions. However, this approach may be beneficial in that it will restrict the likelihood of attributing a response to a single metric out of a potential pool of many highly correlated metrics. The results could be used to develop a more conceptual and easier to interpret diagram for non-scientist stakeholders.

Occupancy and Detection

The point and uncertainty estimates in the presence analysis require the use of a more complex, though still widely used, modeling approach, which we understand is already available and completed for the RGSM in the MRG (Dudley et al. 2018). Occupancy analyses (e.g., Mackenzie et. al. 2002; Budy et al. 2015) use multiple sampling events at the same location to estimate not only whether the site is occupied, but also the probability of detection. For example, if RGSM are not detected on the first sampling event, but are on the second sampling event, it can be assumed that they were present but not detected. After accounting for the probability of detection, a more accurate estimate of the probability of occupancy can be calculated. Further, occupancy analyses provide estimates of the probability of local extinction (i.e., probability an occupied site in the last time step is unoccupied in the current time step) and local colonization (i.e., probability a site unoccupied in the last time step is occupied in the current time step). These estimates could subsequently be related to flow variables to examine how hydrologic conditions impact the distribution of RGSM in the MRG.

Hypotheses examined and those suggested for future examination

In addition to the individual hypotheses presented in Table 1, interactions between the hypotheses should also be examined (e.g., through multiple regression, hurdle models, etc.).

Table 1. Hypotheses already examined and (*) those suggested for future examination. All hypotheses have example recommended analyses and model structures, as well as the data requirements for the suggested analyses (continued on next two pages).

Hypothesis	Analysis or Model Structure(s)	Data Requirements
1. RGSM October density increases with increasing spring flood conditions	Regression analysis of natural logarithm of RGSM October density as a function of principal components (from PCA) describing major axes of hydrologic variation, examining a number of functional model forms including: - Linear - Saturating (e.g., Gompertz)	- October RGSM Densities (mean and sd) - Annual hydrograph for Central Gage
2. RGSM October site proportional presence increases with greater summer low flow conditions (i.e. higher minimum flows).	Generalized linear model (with logit-link) of RGSM October occupancy as a function of principal components (from PCA) describing major axes of hydrologic variation.	- October RGSM site occupancy estimates (with uncertainty; from Dudley et al. 2018) - Annual hydrograph for Central Gage
3. * RGSM densities and occupancy in different reaches respond differently to the same environmental drivers.	Mixed-effects model of the natural logarithm of RGSM October density as a function of principal components describing major axes of hydrologic variation, examining a number of functional model forms, including: - Linear - Saturating Analysis of reach-specific occupancy (or extinction/colonization) would require a generalized linear mixed effects model (with logit-link) estimating October occupancy/extinction/colonization as a function of principal components describing the major axes of variation. Each model structure would include estimates of reach-specific responses to hydrologic variation, drawn from a distribution around the MRG mean response to hydrologic variation.	- Reach-specific October RGSM density estimates (mean and sd) - Reach-specific October RGSM occupancy/extinction/colonization probabilities - Annual hydrograph for Central Gage
4. * RGSM October occupancy is reduced in reaches experiencing a greater extent of channel drying in summer.	Generalized linear model (with logit-link) of reach-specific RGSM October occupancy as a function of reach-specific drying extent.	- Reach-specific October RGSM density estimates (mean and sd) - Reach-specific estimates of drying extent (i.e., km-days dry)

Table 1 (continued).

Hypothesis	Analysis or Model Structure(s)	Data Requirements
5. * RGSM October density is a function of the interaction between spring flood conditions, summer drying extent and the previous year’s density.	Hurdle or delta model simultaneously estimating occupancy and density of RGSM in October. A generalized linear model (with logit-link) estimates the probability of occupancy given hydrologic conditions (e.g., PCA axis of drying conditions, reach-specific extent of drying), while a separate model estiamtes the density of RGSM (provided they are present) as a function of hydrologic conditions. Multiple functional model forms can be examined (i.e., linear, saturating), and temporal autocorrelation can be included with either a random-walk component or autocorrelated residuals. Additionally, reach-specific responses to hydrologic change can be incorporated in a mixed-effects framework.	- October RGSM density estimates (mean and sd, reach-specific if using mixed-effects framework) - Annual hydrograph from Central Gage - Reach-specific estimates of drying
6. * RGSM October density is related to the density of RGSM in the previous October/April (i.e., there is a significant relationship between spawning abundance and recruitment).	Spawner-recruitment analysis in which October age-0 RGSM densities are predicted from either the preceding April RGSM densities or the previous October RGSM density. Multiple structural model forms can be analyzed, including: - Beverton-Holt - Ricker - Shepherd - Linear Additionally, reach-specific spawner-recruitment relationships can be examined in a mixed-effects framework.	- October Age-0 RGSM densities (mean and sd) - October or April RGSM densities (all ages; mean and sd) - Reach-specific values of the above if using a mixed-effects framework
7. * RGSM hatchery stocking efforts increase RGSM densities in the following October.	Regression analysis of natural logarithm of age-1 RGSM October density as a function of principal components (from PCA) describing major axes of hydrologic variation and the number of age-0 RGSM stocked in the MRG in the previous November, examining a number of functional model forms including: - Linear - Saturating (e.g., Gompertz)	- October RGSM density estimates (mean and sd) by age-class - Annual hydrograph for Central Gage - Annual RGSM stocking abundance

Table 1 (continued).

	Hypothesis	Analysis or Model Structure(s)	Data Requirements
8.	* RGSM Age-0 production increases with the number of acre-days the floodplain is inundated in the spring.	Regression analysis of natural logarithm of RGSM October density as a function of the number of acre-days the floodplain is inundated in spring, examining a number of functional model forms including: - Linear - Saturating (e.g., Gompertz) Reach-specific responses to floodplain inundation could be examined in either a mixed-effects framework or with reach-specific estimates of floodplain inundation.	- October RGSM density estimates (mean and sd; reach-specific if necessary) - Estimates of annual floodplain inundation (acre-days; reach-specific if necessary)

Highlights of preliminary analyses

Accounting for Correlated Predictor Variables

Nearly all the predictor variables examined in the analyses of Appendix A are highly correlated with each other (Figure 1). As such, the regressions of RGSM density against each of the predictors show very similar results and it is impossible to determine from the analyses to which condition RGSM are responding. Principal components analysis (PCA) offers an approach to reduce the dimensionality of the predictor data into the primary axes of variation across all predictors.

Figure 1. Pairwise correlations between the predictor variables used in the HBO analyses of Appendix A. The upper-right triangle of figures shows the relationship between predictor variables, while the value in the lower-left triangle of panels indicates the correlation between predictor variables. All predictor variables are highly correlated with each other, except for Summer Minimum Flows at San Acacia.

When the predictor variables used in Appendix A are analyzed by PCA, two primary axes of variation are identified. The first principal component explains 78.7% of the variance in the data (Figure 2a) and is an index of how much water was in the MRG in each year (Figure 2b). All the predictor variables load positively on this axis (i.e., larger values for the predictor variable correspond to larger values of the principal component axis). This indicates that all the variables are highly correlated and most of the information contained in the individual predictor variables cannot be separated from the information contained in the other predictor variables. The only exception to this pattern is the predictor variable describing the summer minimum flow at the San Acacia gage. While this variable still loads positively on the first axis, it has a much weaker loading (indicated by the shorter distance along the x-axis that the vector points on Figure 2b).

The second principal component explains a further 13.6% of the variance in the data (Figure 2a). This component primarily separates years with higher and lower summer minimum flow conditions, as the only predictor variables that load substantially on this axis are the San Acacia summer minimum flow, the Central gage summer minimum flow, and the Summer channel acres inundated. More negative values on this axis actually indicate higher water conditions during the summer low flow period. It is important to realize that the direction of the principal component values is unimportant and can be reversed without losing information if it will help interpretation (e.g., it may be beneficial to multiply all the principal component 2 scores by -1 such that years with better summer low flow conditions had positive values).

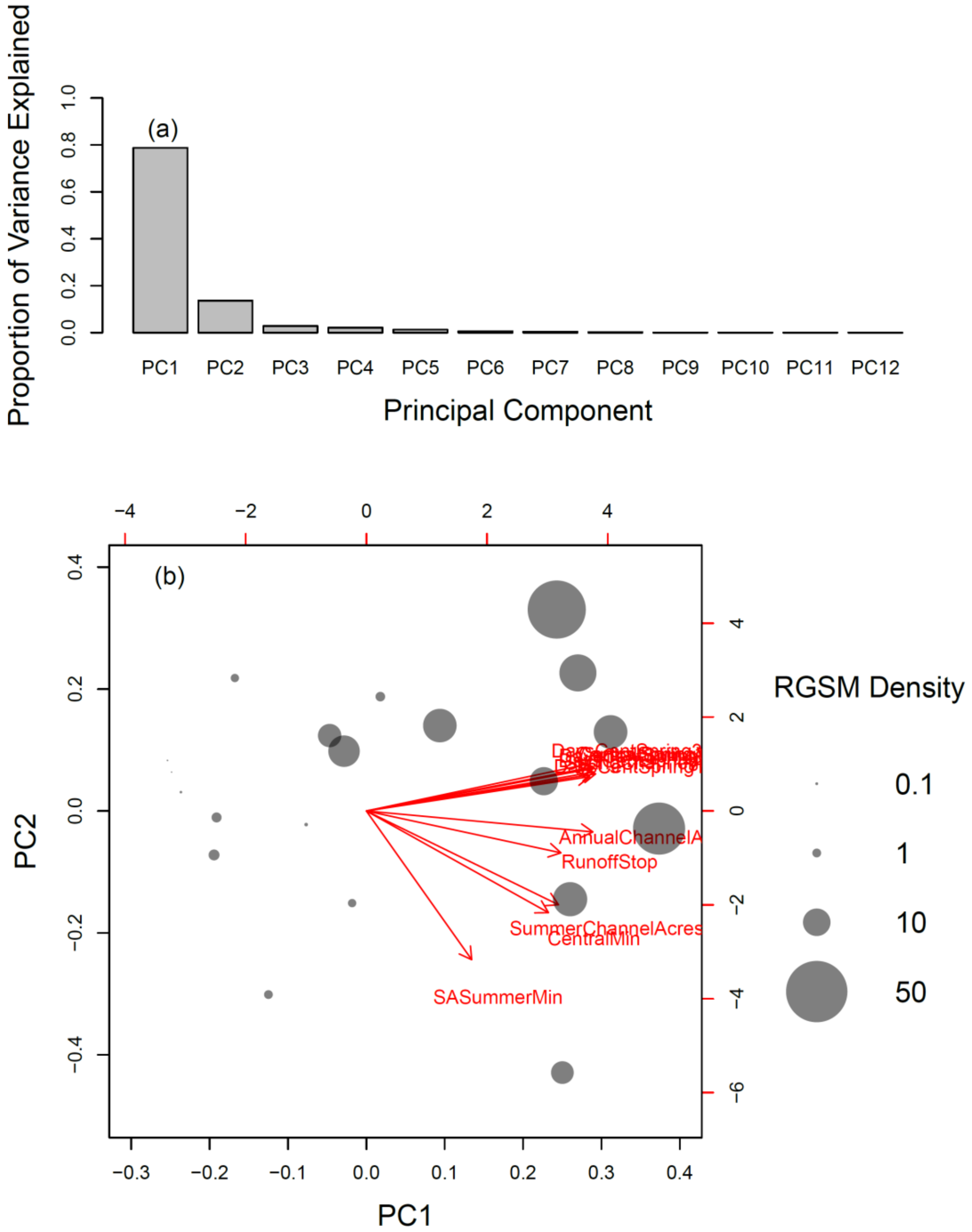

Figure 2. Principal components analysis of the predictor variables used in Appendix A of the Biological Opinion. (a) The proportion of total variation in the predictor variables described by each principal component. PC1 explains 78.7% of the variance and PC2 explains 13.6%. (b) PC1 primarily separates wet springs (more positive values) from dry springs (more negative values). PC2 primarily separates years with lower summer minimum flows (more negative values) from those with higher summer minimum flows (more positive values), particularly for the San Acacia Reach. These two axes can be used to examine the impacts of spring flows and summer low flows, as well their interactions on densities or occupancy of RGSM in the Middle Rio Grande. The point size on the lower panel indicates the estimated RGSM October density.

Together the first two principal components explain over 90% of the variance in all the predictor variable data. These two components can be used in place of the individual predictor variables without losing much explanatory power, and without repeating analyses using correlated predictor variables which cannot be teased apart in simple regression analyses. Examining the relationship between RGSM October density and the first two principal components reveals an obvious positive relationship with principal component 1, but no obvious relationship with principal component 2 (Figure 2b). We thus focused on the first principal component as a predictor of the October density of RGSM for example preliminary analyses, and generically identify this principal component as “Habitat Quality” in subsequent figure labels.

Accounting for carrying capacity

Animal populations are inherently limited in their ability to increase abundance by the availability of resources in their habitat. Even with habitat improvements, there will be some limiting factor that will prevent further increases in local abundance. Accounting for such a carrying capacity in models of population response to changing conditions can inform managers approximately how much of an increase they can expect in local population abundances before further habitat improvements present diminishing returns. One approach to modeling this relationship is to fit a saturating response to the predictor variables of interest.

For the RGSM October density data presented in Appendix A, there is some evidence that increases in density were slowing at high values of the spring flood condition indices examined. As a preliminary test of the insights offered by fitting a saturating relationship to these data, we examined how RGSM October density responded to increases in habitat quality (i.e., principal component 1) by fitting a modified Gompertz function (Eq. 1; Figure 3a). Both the saturating and linear models fit the data well in log-scale. However, the saturating function tends to follow the trend in RGSM densities better, increasing rapidly before flattening out at high habitat quality values.

When examined in real space (as opposed to log-space), the major difference between the two models becomes apparent (Figure 3b). As predictions of RGSM density are extrapolated to habitat conditions beyond what has been experienced in the period of record, the linear model prediction increase exponentially. However, the predictions from the saturating model flatten out at an estimated carrying capacity. As there are no data in this extrapolated region, there is great uncertainty in what the carrying capacity is, and the prediction interval for expected RGSM density under high habitat quality conditions is very wide. Informing these relationships as to how the populations will respond to increased habitat quality would require an adaptive management approach, where the system is deliberately pushed into the conditions beyond what have been experienced since 1993, or serendipitous conditions provided by a very large snowpack that cannot be controlled fully by infrastructure on the Rio Grande.

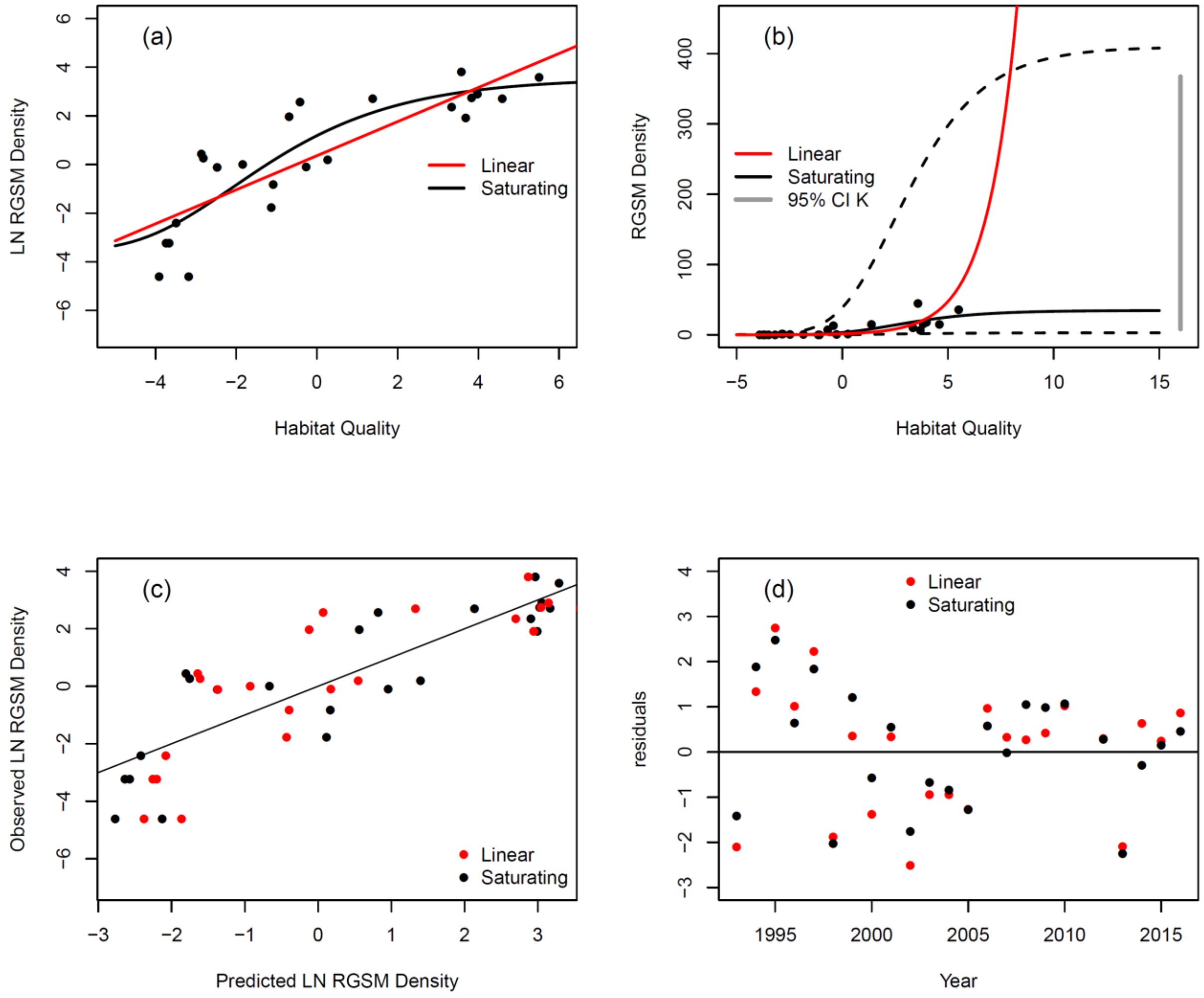

Figure 3. (a) Example fits of a linear model fit to log-transformed RGSM densities as predicted by habitat quality (PC1 from Figure 2) compared to a saturating relationship with the same predictor variables. The saturating relationship assumes that there is a carrying capacity for the RGSM population in the MRG. The dashed lines in (b) present the prediction interval for the saturating relationship, indicating large uncertainty in predictions of RGSM densities during high water years (high "habitat quality" years), but still maintaining that there is a predicted maximum density possible in the MRG. The vertical grey line in (b) indicates the 95% confidence interval for the carrying capacity density for RGSM in the MRG. (c) Predicted vs. observed RGSM densities for the saturating and linear models. (d) Time-series of residuals for the saturating and linear models.

Accounting for temporal dependence

We can account for temporal dependence by multiple methods. One approach that may help identify additional driving forces on RGSM densities is to include a latent (unobserved) time-series variable in the model. For example, if we want to examine the linear relationship between the log of RGSM densities and habitat quality, we can add a random walk process as the latent trend (*Z*) to the model:

$$\begin{gathered} ln(D_y) = \alpha + \beta h_y + Z_y + \varepsilon_y, \\ Z_y \sim N(Z_{y-1}, \sigma_z), \\ \varepsilon_y \sim N(0, \sigma_r) \end{gathered} \tag{2}$$

where D_y is the October density of RGSM in year *y*, h_y is the habitat quality index for year *y*, Z_y is the latent time-series trend value in year *y*, which is drawn from a normal distribution centered on the previous year's value, and ε is residual error.

The predicted densities from the linear model with the random walk component are much more similar to the observed values than the standard linear model predictions, particularly for low predicted densities. (Figure 4a). Additionally, the time-series of residuals is much less variable for the random walk model than the standard linear regression (Figure 4b). The random walk trend (Figure 4c) demonstrates that there is a latent trend where the densities are lower than would be predicted by the model in the early years of the time series, followed by a period where densities are higher than would be predicted by the linear relationship, followed by a period where the linear relationship predicts densities well (i.e., little trend after about 2006, with the exception of 2013). This random walk trend can be examined further for correlation with as yet unexplored predictor variables and may highlight unanticipated drivers or influences of RGSM densities in the MRG. Further, a random-walk component can be added to more complex model structures, such as those incorporating a carrying capacity (Figure 5).

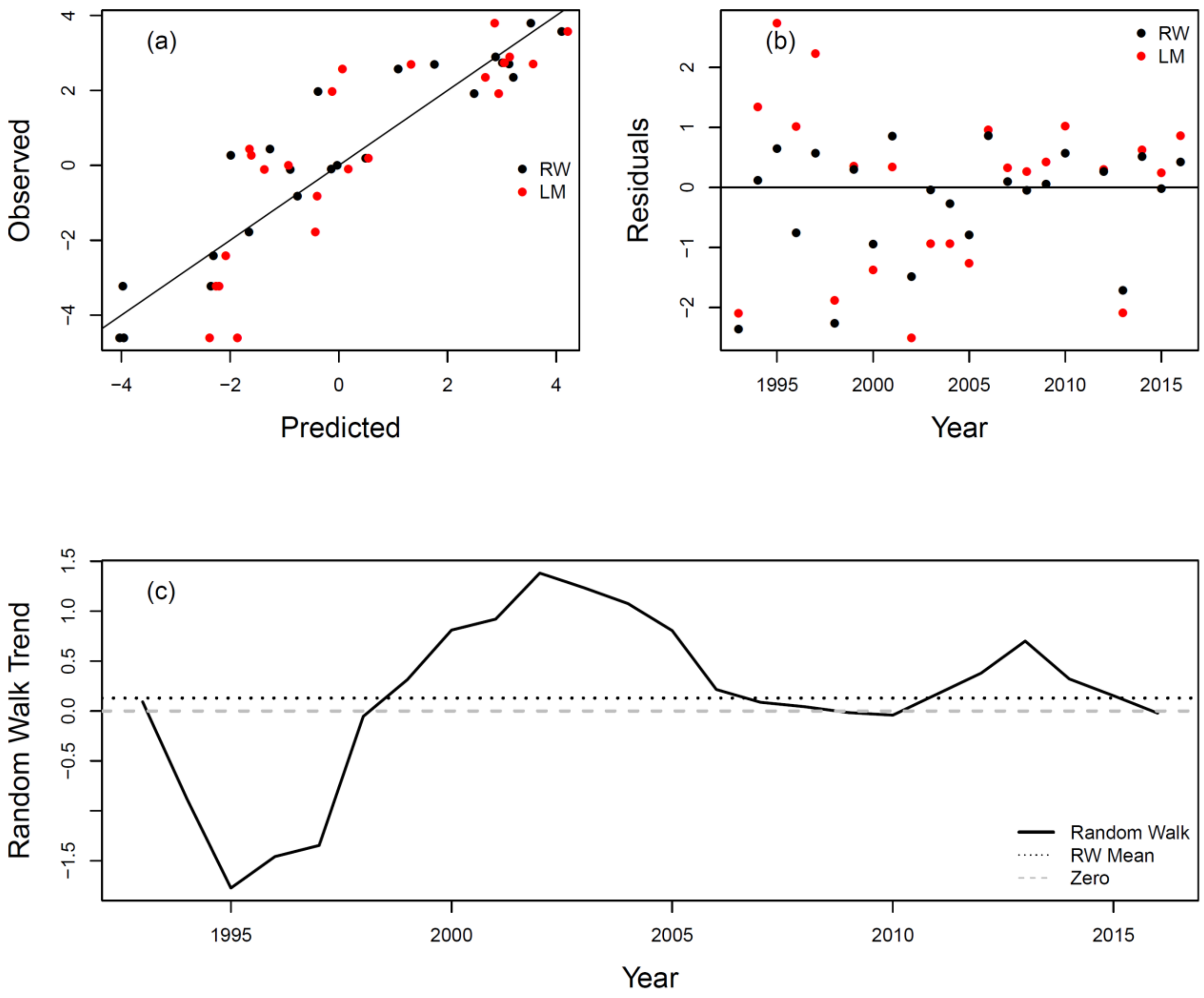

Figure 4. Model fits of a time-series analysis of RGSM density as a function of habitat quality (i.e. PC1 from Figure 2). (a) Predicted vs. observed values for both the standard linear model (red dots) and the random-walk time series model. (b) Time-series of model residuals for the two models (note that nearly all the random walk model estimates are closer to zero than the linear model fits, indicating a better fit). (c) Model estimated random walk process. This random walk trend can subsequently be compared to time series of other potential predictors of RGSM density to determine what may be driving this pattern.

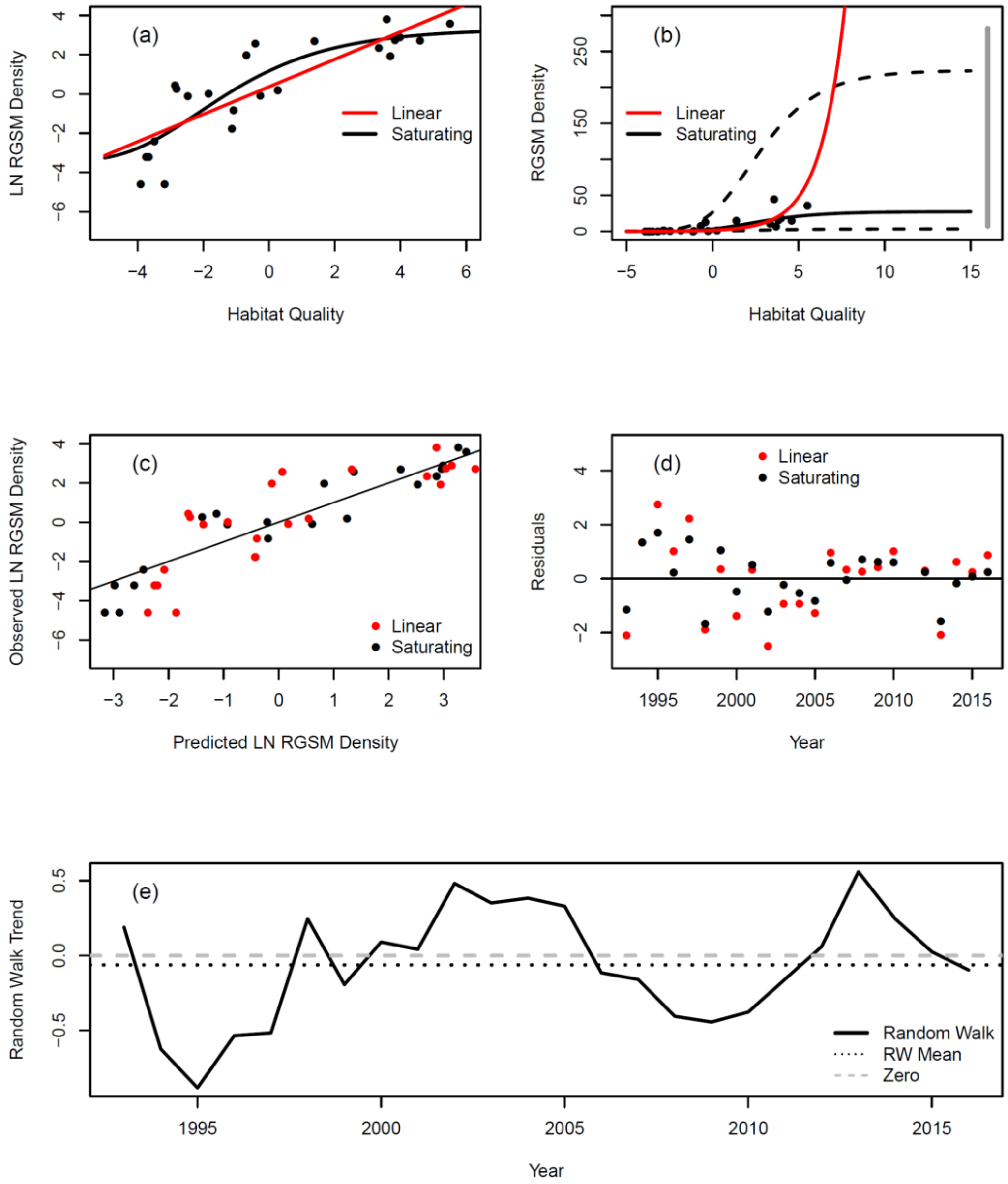

Figure 5. (a) Model fits of a time-series analysis of log-RGSM density as a function of habitat quality (i.e. PC1 from Figure 2) for both a standard linear model and a saturating model with a random-walk component. (b) Real value predictions of RGSM densities as a function of habitat quality. The dashed lines indicate the 95% prediction interval for RGSM densities from the saturating model with random walk, and the vertical grey line is the 95% confidence interval for the estimate of carrying capacity. (c) Predicted vs. observed values for both the standard linear model (red dots) and the saturating model with random-walk component. (d) Time-series of model residuals for the two models (note that nearly all the random walk model estimates are closer to zero than the linear model residuals, indicating a better fit). (e) Model estimated random walk process. This random walk trend can subsequently be compared to time series of other potential predictors of RGSM density to determine what may be driving this pattern.

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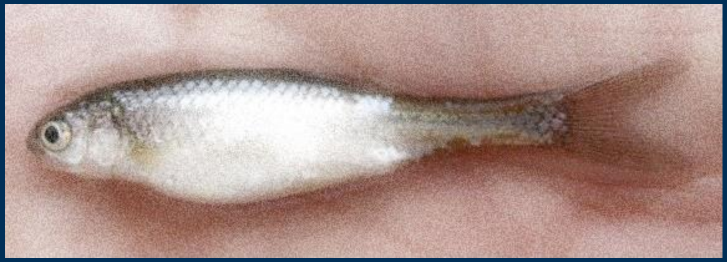
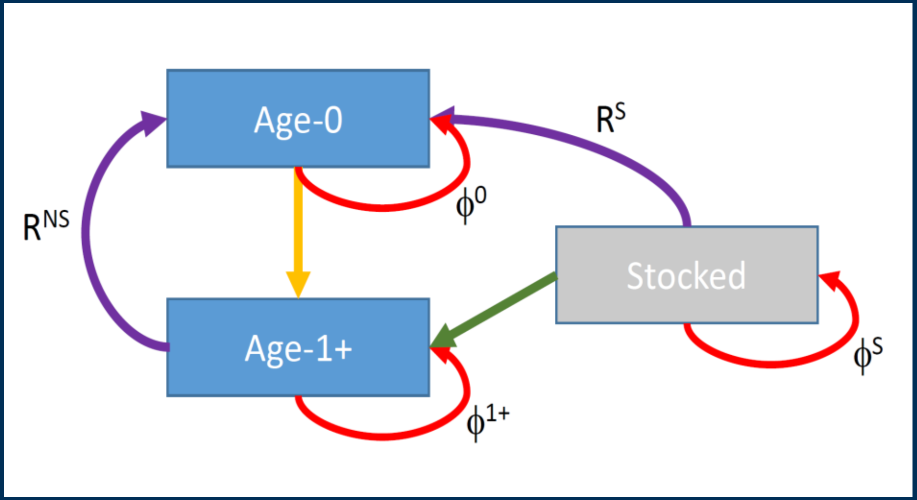


Developing an integrated population model for Rio Grande Silvery Minnow

December 12, 2018



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U.S. Department of the Interior
U.S. Geological Survey

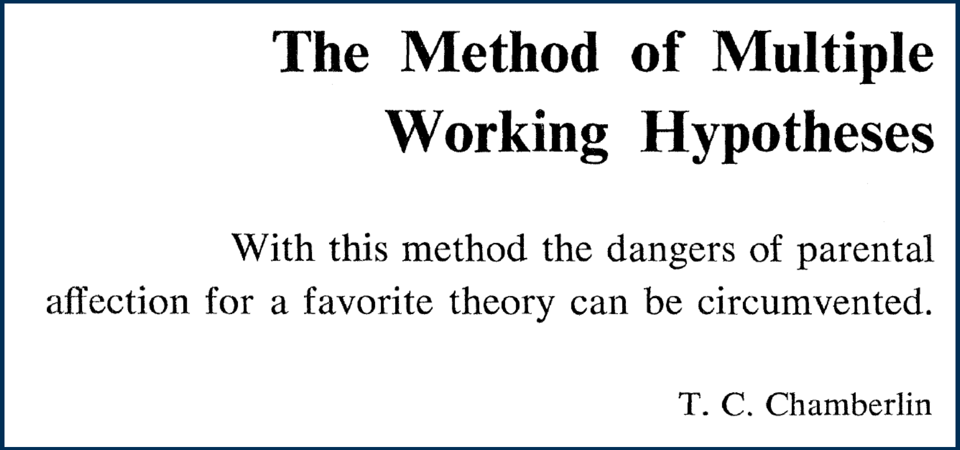
Outline

- Why model?
- An example: Brown trout
- RGSM proposal

Why build a model?

- Predict outcomes of management and associated uncertainty.
- Evaluate multiple competing hypotheses.
- Determine monitoring, and research to reduce uncertainty / discriminate amongst competing hypotheses.

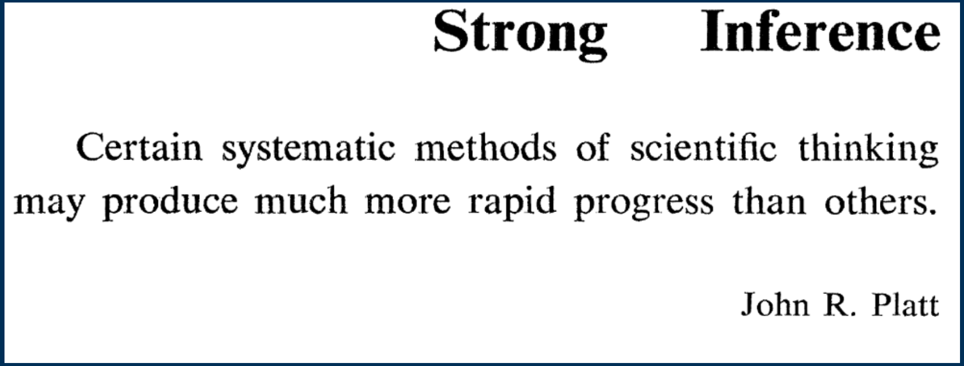
A little philosophy of science



The Method of Multiple Working Hypotheses

With this method the dangers of parental affection for a favorite theory can be circumvented.

T. C. Chamberlin



Strong Inference

Certain systematic methods of scientific thinking may produce much more rapid progress than others.

John R. Platt

- Multiple competing hypotheses
- A priori hypotheses and predictions
- Hierarchy of inference
  - Fits past observations
  - Predicts new observations
  - Responds to an experimental manipulation
- May not need to resolve all uncertainties to guide management.

Why build a model collaboratively?

- A group can develop and operationalize multiple competing hypotheses better (but maybe not quicker) than one person.

- Increase transparency and minimize unintended assumptions.

Outline

- Why model?
- An example: Brown trout
- RGSM proposal

Background

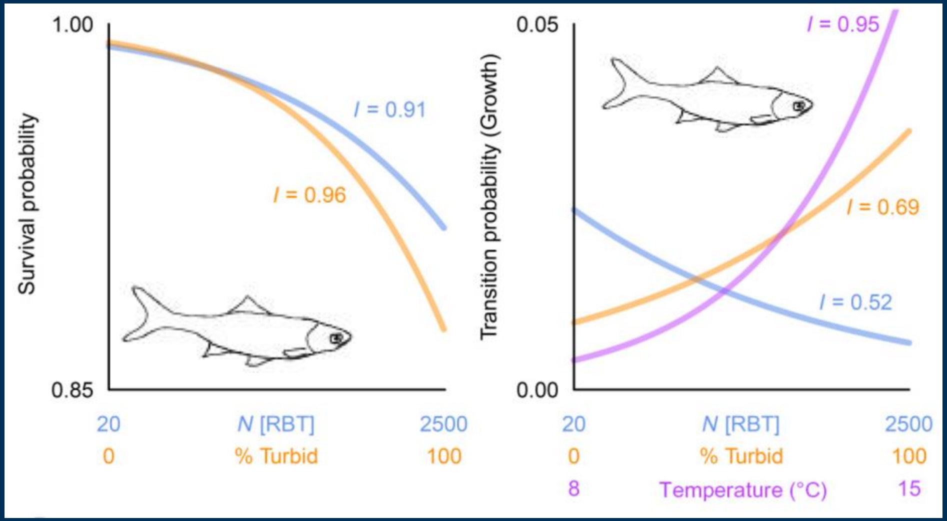
- Main focus for HBC in GC:
  Rainbow trout vs. temperature

- Brown trout known to be more
  piscivorous, but also rarer.

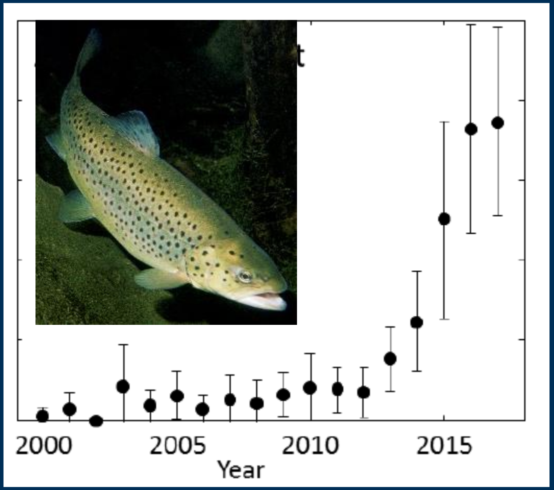
- Rapid increased in Brown trout in tailwater

- No consensus on cause of increase or best management action to respond.

- NPS beginning an EIS.
  - Other stakeholders (especially anglers) requested an independent analysis.



Yackulic et al. (2018)



Runge et al. (2018)

Brown Trout in Lees Ferry—Evaluation of Causal Hypotheses and Potential Interventions

By Michael C. Runge,[1] Charles B. Yackulic,[1] Lucas S. Bair,[1] Theodore A. Kennedy,[1] Richard A. Valdez,[2] Craig Ellsworth,[3] Jeffrey L. Kershner,[1] R. Scott Rogers,[4] Melissa A. Trammell,[5] and Kirk L. Young[6]

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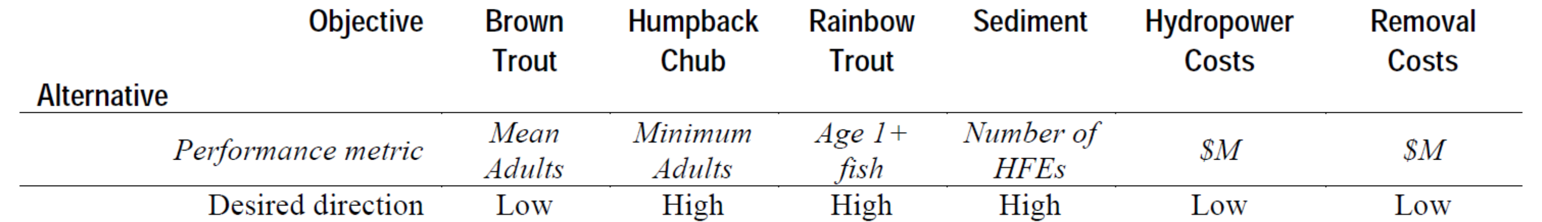
[2]SWCA Environmental Consultants.
[3]Western Area Power Administration.
[4]Arizona Game and Fish Department.
[5]National Park Service.
[6]U.S. Fish and Wildlife Service.

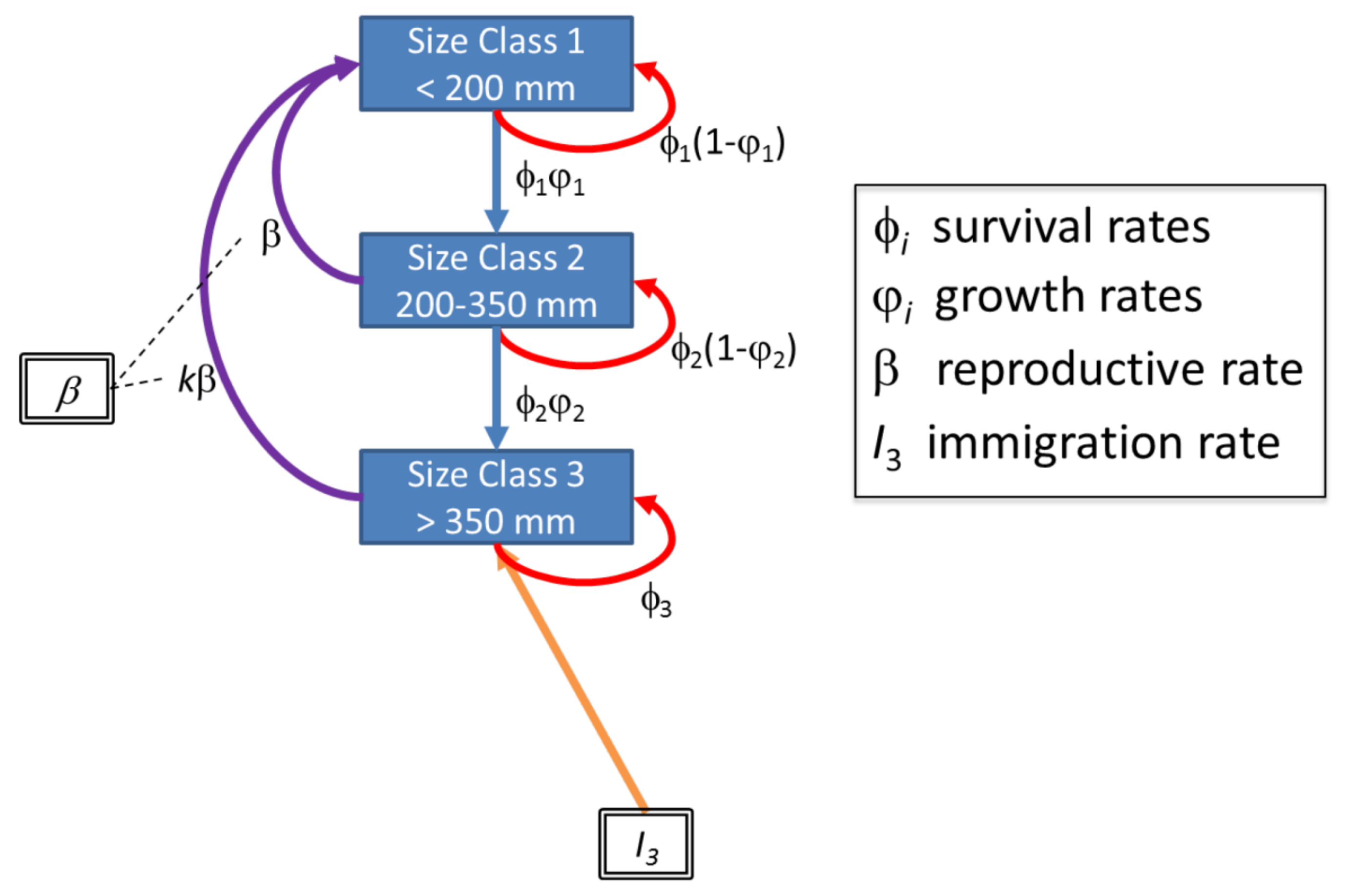
Step 1: Identify management objectives



Objective Alternative	Brown Trout	Humpback Chub	Rainbow Trout	Sediment	Hydropower Costs	Removal Costs
Performance metric	*Mean Adults*	*Minimum Adults*	*Age 1+ fish*	*Number of HFEs*	*$M*	*$M*
Desired direction	Low	High	High	High	Low	Low

Step 2: Agree on a general model structure

(*ideally one that is easily updated with monitoring data)



ϕ_i survival rates

φ_i growth rates

β reproductive rate

I_3 immigration rate

Step 3: Identify a set of contrasting and competing hypotheses

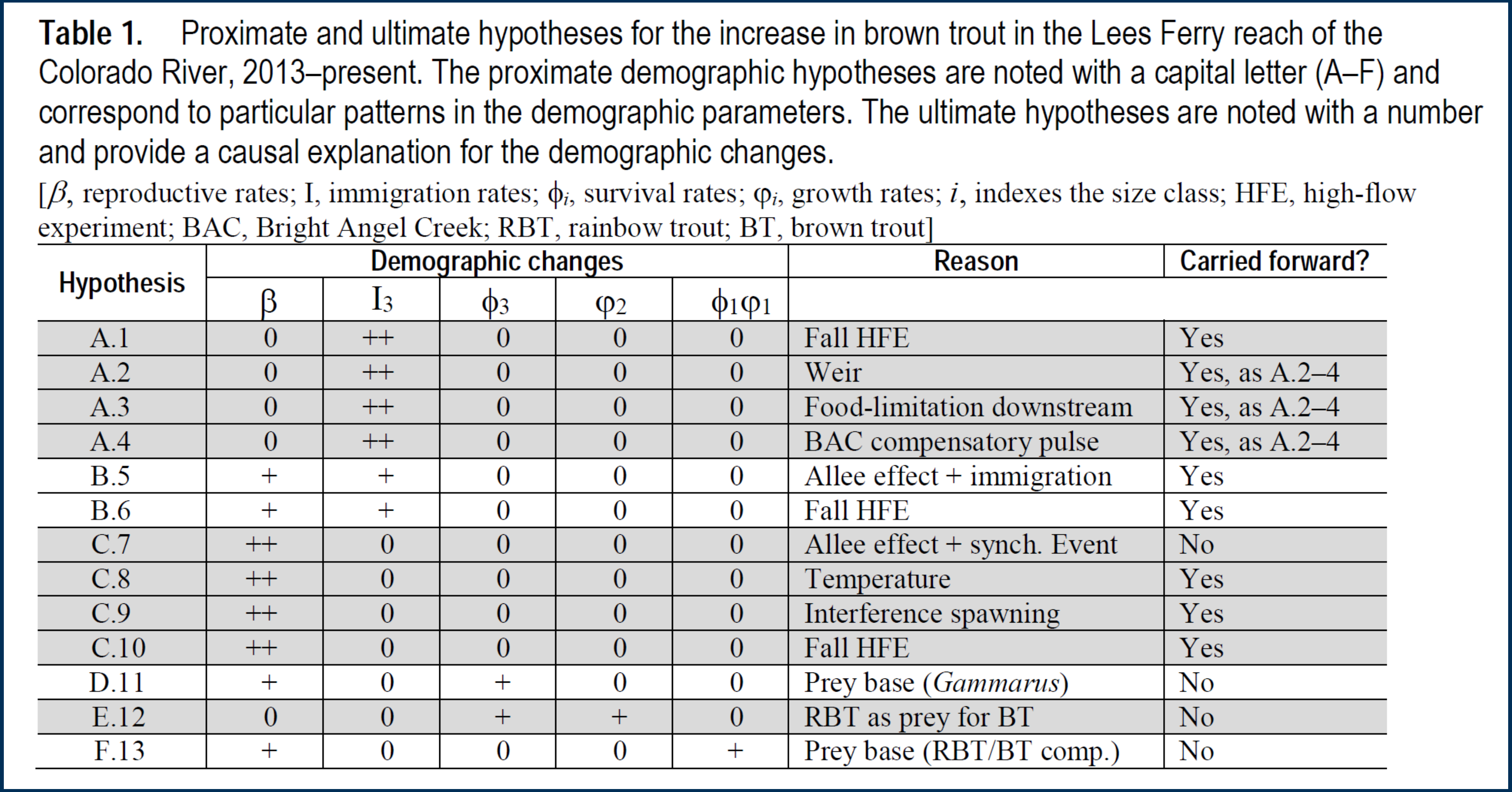
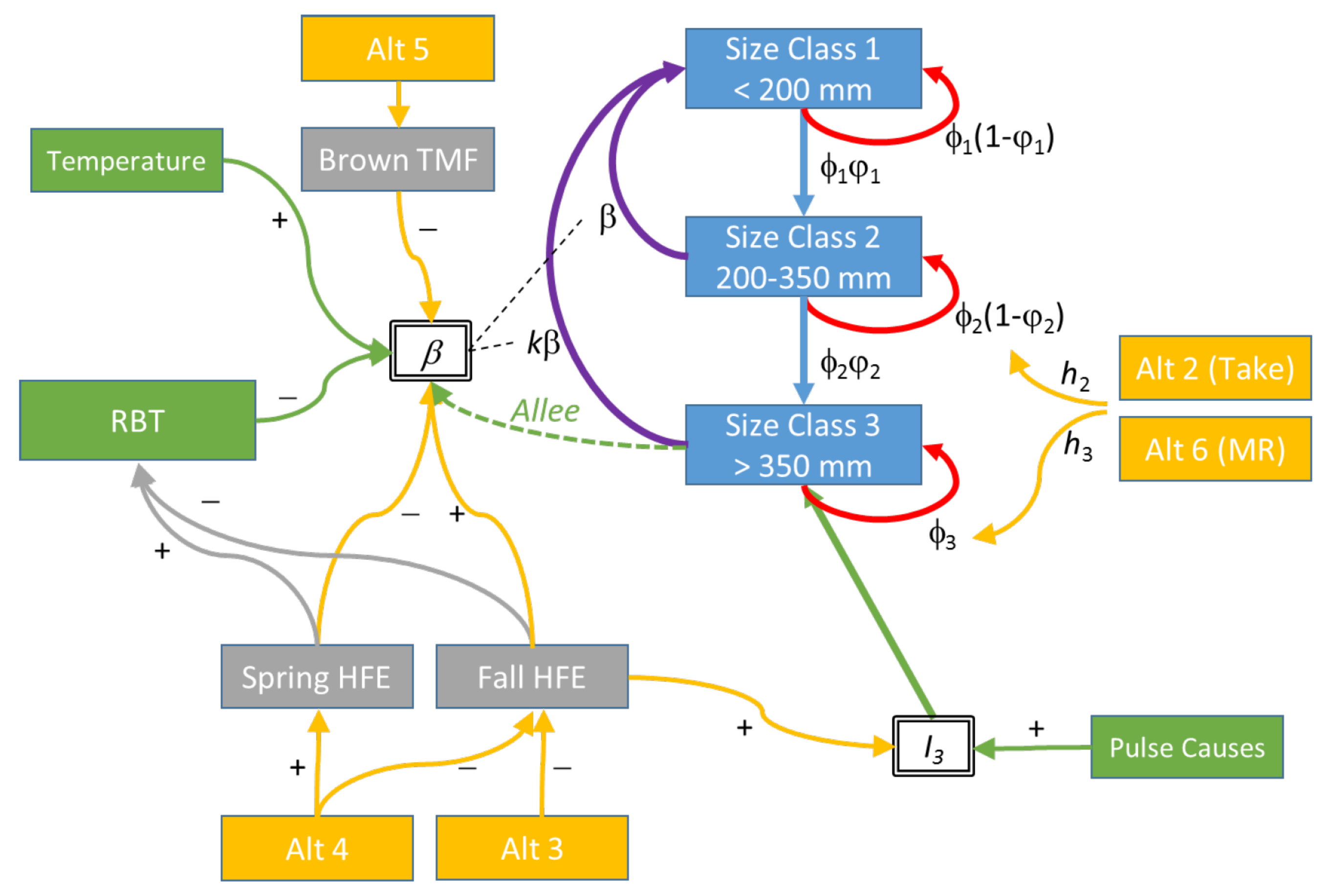


Table 1. Proximate and ultimate hypotheses for the increase in brown trout in the Lees Ferry reach of the Colorado River, 2013–present. The proximate demographic hypotheses are noted with a capital letter (A–F) and correspond to particular patterns in the demographic parameters. The ultimate hypotheses are noted with a number and provide a causal explanation for the demographic changes.

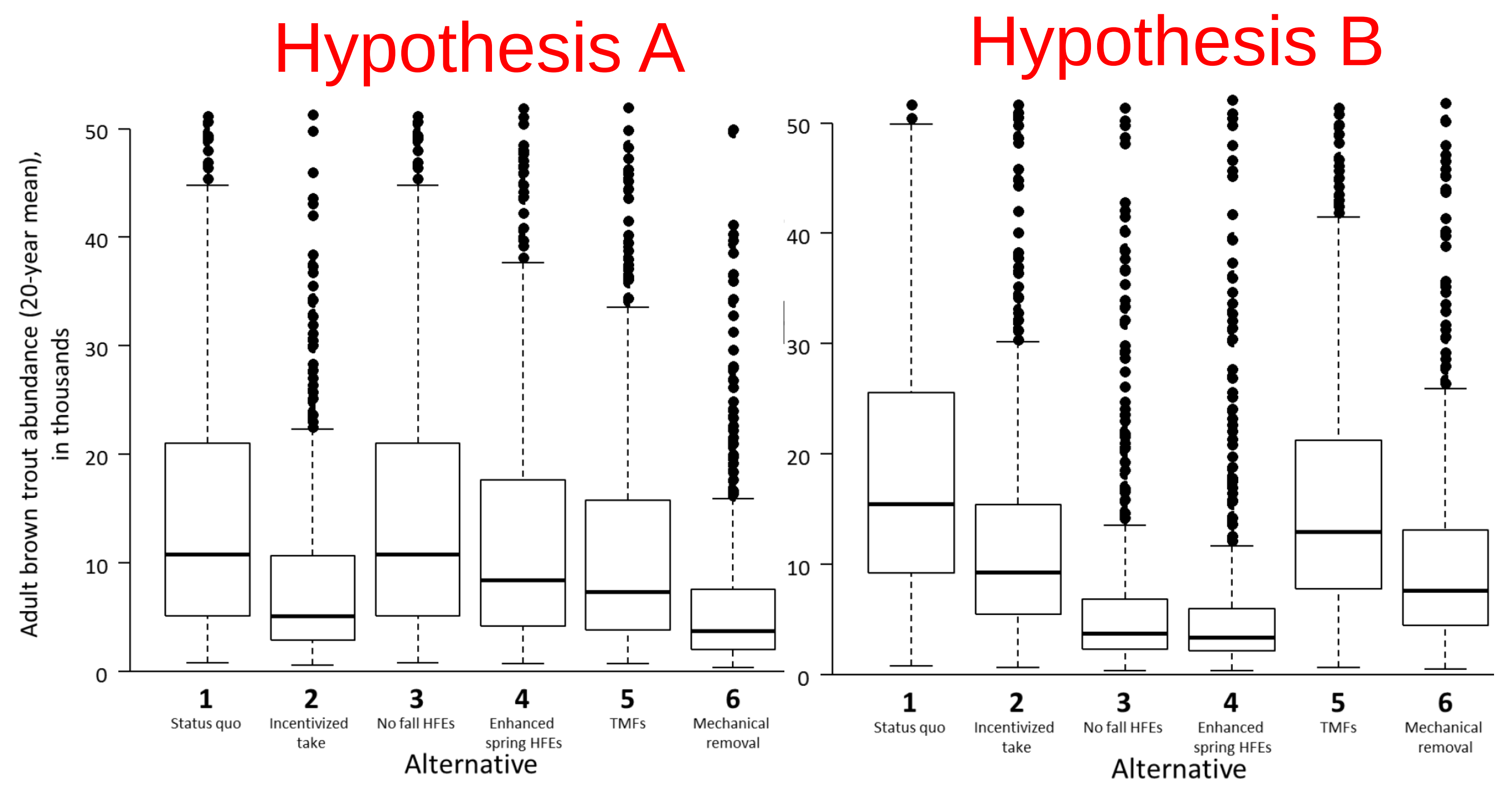
[β, reproductive rates; I, immigration rates; ϕ_i, survival rates; φ_i, growth rates; i, indexes the size class; HFE, high-flow experiment; BAC, Bright Angel Creek; RBT, rainbow trout; BT, brown trout]

Hypothesis	Demographic changes					Reason	Carried forward?
	β	I_3	ϕ_3	φ_2	$\phi_1\varphi_1$		
A.1	0	++	0	0	0	Fall HFE	Yes
A.2	0	++	0	0	0	Weir	Yes, as A.2–4
A.3	0	++	0	0	0	Food-limitation downstream	Yes, as A.2–4
A.4	0	++	0	0	0	BAC compensatory pulse	Yes, as A.2–4
B.5	+	+	0	0	0	Allee effect + immigration	Yes
B.6	+	+	0	0	0	Fall HFE	Yes
C.7	++	0	0	0	0	Allee effect + synch. Event	No
C.8	++	0	0	0	0	Temperature	Yes
C.9	++	0	0	0	0	Interference spawning	Yes
C.10	++	0	0	0	0	Fall HFE	Yes
D.11	+	0	+	0	0	Prey base (*Gammarus*)	No
E.12	0	0	+	+	0	RBT as prey for BT	No
F.13	+	0	0	0	+	Prey base (RBT/BT comp.)	No

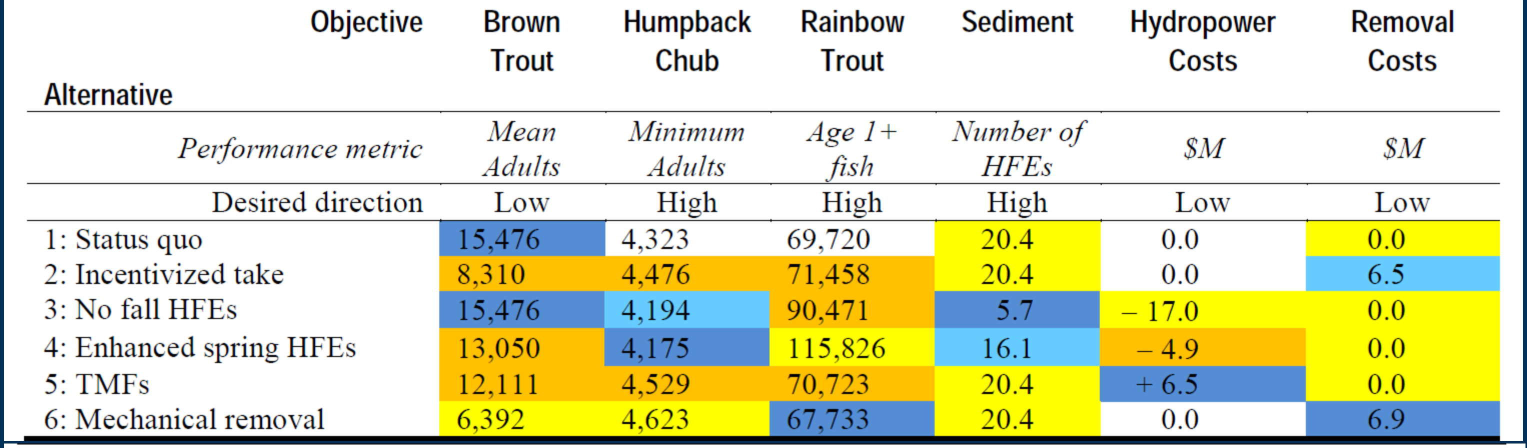
Step 4: Describe a set of management alternatives



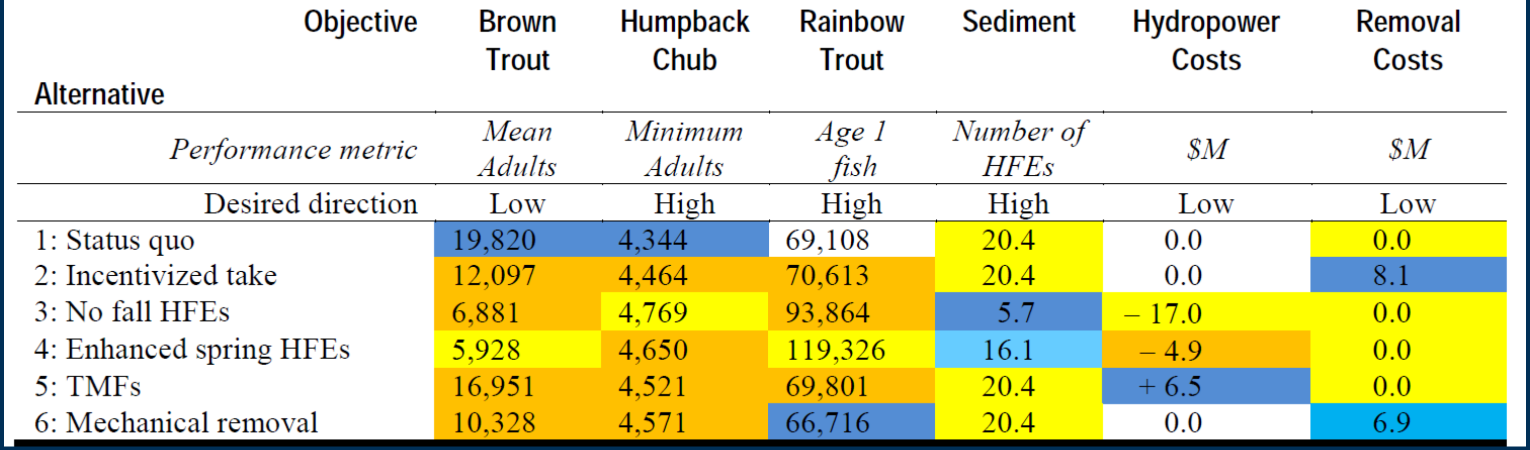
Step 5a: Evaluate management alternatives under different hypotheses



Step 5b: Evaluate tradeoffs among resources



Objective Alternative	Brown Trout	Humpback Chub	Rainbow Trout	Sediment	Hydropower Costs	Removal Costs
Performance metric	*Mean Adults*	*Minimum Adults*	*Age 1+ fish*	*Number of HFEs*	*$M*	*$M*
Desired direction	Low	High	High	High	Low	Low
1: Status quo	15,476	4,323	69,720	20.4	0.0	0.0
2: Incentivized take	8,310	4,476	71,458	20.4	0.0	6.5
3: No fall HFEs	15,476	4,194	90,471	5.7	– 17.0	0.0
4: Enhanced spring HFEs	13,050	4,175	115,826	16.1	– 4.9	0.0
5: TMFs	12,111	4,529	70,723	20.4	+ 6.5	0.0
6: Mechanical removal	6,392	4,623	67,733	20.4	0.0	6.9

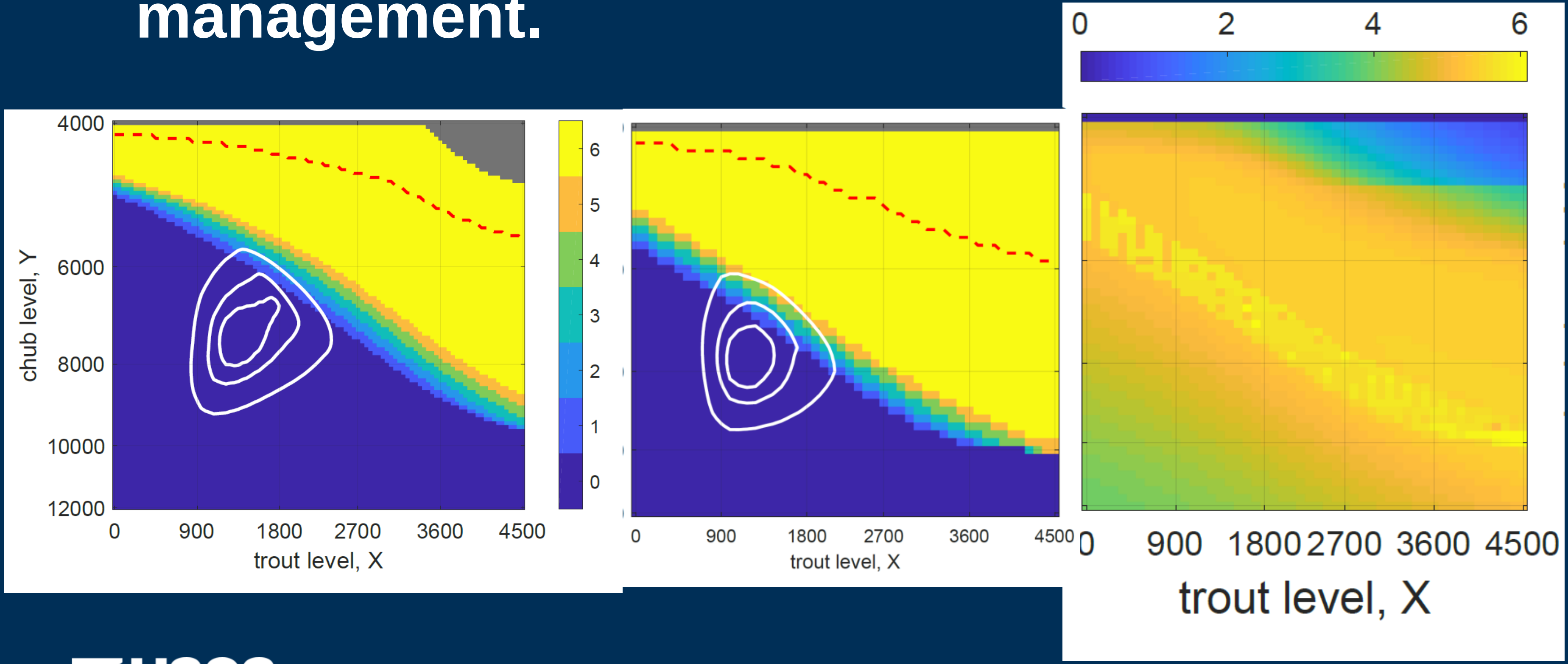


Objective Alternative	Brown Trout	Humpback Chub	Rainbow Trout	Sediment	Hydropower Costs	Removal Costs
Performance metric	*Mean Adults*	*Minimum Adults*	*Age 1 fish*	*Number of HFEs*	*$M*	*$M*
Desired direction	Low	High	High	High	Low	Low
1: Status quo	19,820	4,344	69,108	20.4	0.0	0.0
2: Incentivized take	12,097	4,464	70,613	20.4	0.0	8.1
3: No fall HFEs	6,881	4,769	93,864	5.7	– 17.0	0.0
4: Enhanced spring HFEs	5,928	4,650	119,326	16.1	– 4.9	0.0
5: TMFs	16,951	4,521	69,801	20.4	+ 6.5	0.0
6: Mechanical removal	10,328	4,571	66,716	20.4	0.0	6.9

USGS

Other potential steps

- Formally evaluate research & monitoring programs in terms of how they inform management.



Outline

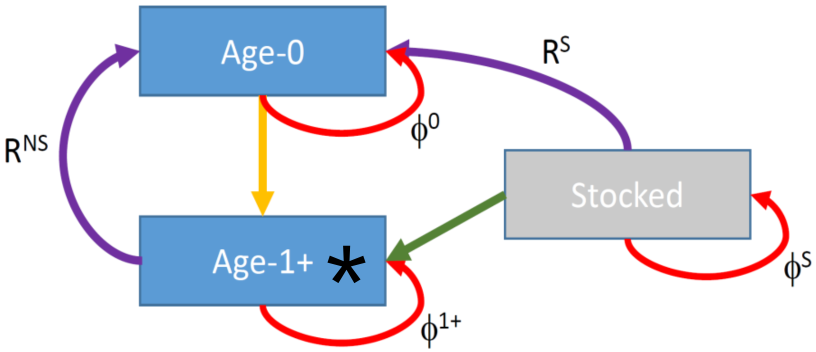
- Why model?
- An example: Brown trout
- RGSM proposal

Proposal – develop a tool for decision support

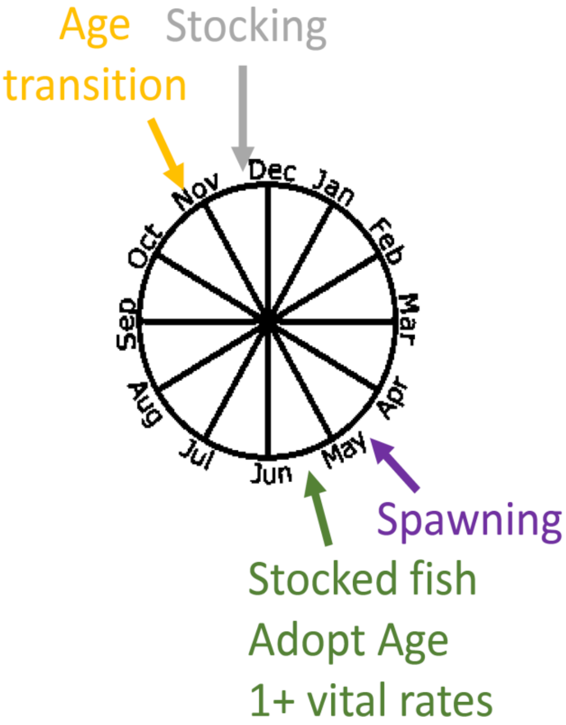
- Develop and fit a general model structure
- Identify (and operationalize) a set of competing hypotheses
- Identify research or monitoring that can discriminate among hypotheses

Proposed starting point

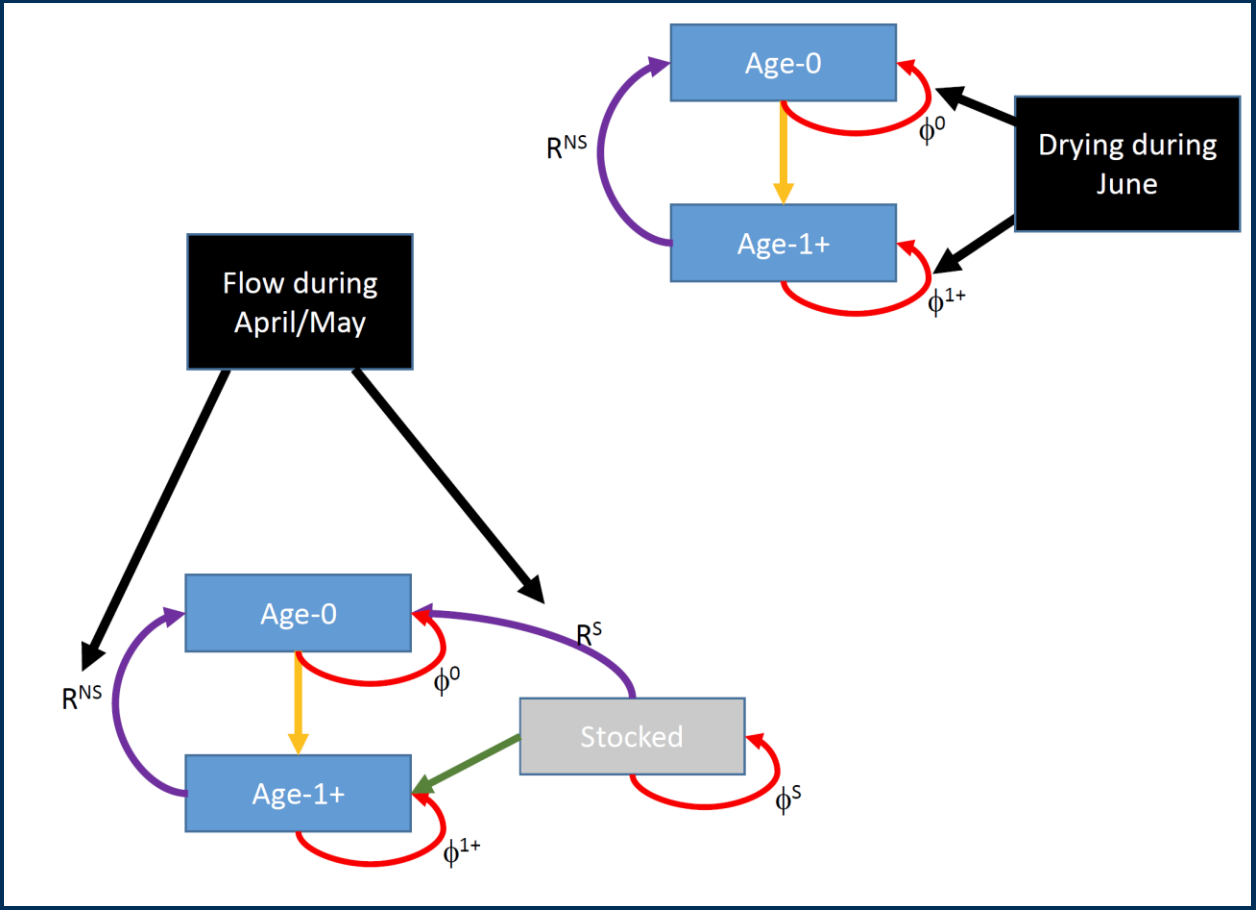
ϕ^{0}	Age-0 monthly survival
ϕ^{1+}	Age-1+ monthly survival
ϕ^{S}	Stocked monthly survival
R^{S}	reproductive rate - stocked
R^{NS}	reproductive rate - not stocked



Timing of key events



Operationalizing hypotheses as covariates.



Some outstanding issues for discussion

- Age – 1+
  - Seems like there is interest from many folks in adding ages classes – that's fine with me, will probably have to assume same survival across ages 1+. Question for group, what is the longest known surviving stocked fish?
- How much spatial realism to include?

Potential sub-groups

- Habitat availability – need to think about this to scale from catch to abundance. Some sources of info, but probably need a group to think about how availability should vary with discharge.

- Going to need continued help getting various bits of data together and in right format, but am already getting great help from various folks.

- Identifying competing hypotheses

Questions?