EVALUATING A GLEN CANYON DAM TEMPERATURE CONTROL DEVICE TO ENHANCE NATIVE FISH HABITAT IN THE COLORADO RIVER: A RISK ASSESSMENT BY ADAPTIVE MANAGEMENT PROGRAM SCIENCE ADVISORS

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CHAPTER 1: SCIENCE ADVISOR CHARGE AND TCD HISTORY

Section 1.1: Review Charge to Adaptive Management Program Science Advisors

In the summer 2002 Grand Canyon Adaptive Management Program Meeting, the Adaptive Management Work Group (AMWG) decided to solicit a review of the Glen Canyon Dam Temperature Control Device Proposal from the Adaptive Management Program Science Advisors.

In November 2003, the Science Advisors were formally requested by the AMWG to review risks associated with the Bureau of Reclamation proposal to place a Temperature Control Device on Glen Canyon Dam. The review process was to be coordinated by the Grand Canyon Monitoring Research Center and Upper Colorado Region of the US Bureau of Reclamation, working cooperatively with the Adaptive Management Program Science Advisors. The Adaptive Management Program Science Advisors, a competitively selected group of 12 U.S. scientists, provide ongoing reviews of GCMRC and AMWG programs as requested by the GCMRC, AMWG and/or Secretary of Interior.

The US Bureau of Reclamation proposed in 1999, through an Environmental Assessment, to place a Temperature Control Device (TCD) on Glen Canyon Dam to enhance downstream habitat for the endangered humpback chub (HBC), a native fish. The primary goal of the TCD Project, is to elevate water temperature in the river at critical periods in the life cycle of the HBC.

The proposal to place a TCD at Glen Canyon Dam and warm water in the Colorado River has been in an evaluation and planning process since the early 1990s, as reviewed in the following section. One of the final steps in this process is to evaluate the risks of installation and operation of the apparatus.

The Science Advisors are charged to conduct a risk assessment of potential impacts of installing and operating a TCD at Glen Canyon Dam. The specific tasks in the assessment are as follows:

1. Conduct a Risk Assessment of TCD installation and operation on Glen Canyon Dam. The assessment is to be complete by fall 2003.
2. Characterize associated risks in four primary resource areas; operational, social/economic, physical, and biological.
3. Evaluate physical environments where risks might occur; i.e. Lake Powell, Glen Canyon Dam, Colorado River below Glen Canyon Dam, and Lake Mead.

4. Conduct a risk assessment of potential resource impacts expected to occur in response to placement and operation of the TCD.
5. Provide a written report and formal presentation to the AMWG at or before the August 2003 meeting of the AMWG.

Section 1.2 TCD History and PROJECT Approach

TCD installations have proven to be effective in accomplishing ecological objectives at Flaming Gorge and other downstream (Bestgen and Crist. 2000, USDI 1999, USDI 2003). However, both the management objectives and ecological context are importantly different for the Grand Canyon system, as opposed to Flaming George and other systems. Thorough review and two previous workshops have developed the logic and scenarios for TCD uses and management alternatives at Glen Canyon Dam (USDI 1999). However, these differ depending on apparatus selected.

Unlike previous exercises, the Adaptive Management Program Science Advisors were asked to develop an evaluation of risks associated with development of a TCD at Glen Canyon dam, and its likely effects on the Colorado River ecosystem and resources in the Grand Canyon.

Based on a consensus of previous workshops, our central assumption is that the TCD can be used to elevate temperatures at the dam to 15ºC. The logic of maintaining 15ºC is a compromise assumed to improve conditions for both the important coldwater species (rainbow trout) and native species, specifically humpback chub.

Alternative operational scenarios have been developed for TCD use (USDI 1999). Some propose a short period of summer warming (May – September) that would correspond with the spawning of native fishes and their emigration into the mainstem (particularly the humpback chub). Others proposed to sustain the warmer conditions for as long as possible (May-December) to encourage greater growth and recruitment for native fishes.

Our report focuses on a general conceptual approach that accounts for the ecological effects of releasing water from the Glen Canyon Dam as close to 15º C for as long as possible and additional warming as water proceeds downstream during spring through fall. The magnitude of those effects would be generally proportional to the level and duration of warming. This scenario is selected because it permits the least confounding in evaluating risks.

We evaluated a number of ecological, economic and operational risks associated with the operation of a TCD. Although our assessment was independent of that conducted by others (USDI 1999) we reach similar conclusions about the direct effects of thermal enhancement. We differ from that report in four important ways:

1. We gave greater consideration to effects of warming on the prospect of upstream migrations throughout the Grand Canyon system.

2. We recognize that thermal optima may be exceeded for some coldwater species, causing negative effects on their distribution and abundance.
3. We emphasize the role of indirect ecological effects and the consequent increase in uncertainty.
4. We explicitly considered the potential for multiple, potentially interactive impacts on the humpback chub

Given the complexity of direct and indirect effects, we believe that expectation of precise and accurate quantitative predictions is neither likely nor appropriate. A similar position was advocated by the USDI (1999) report. Neither we, nor any other group of scientists have evidence or experience that would assure absolute certainty in outcomes, although existing knowledge does permit general assessments of resource change. In keeping with the most effective scientific basis for environmental decision-making in managed river ecosystems (Poff et al. 2003), we present our collective effort as qualitative and conceptual assessments offered as advice to the policy making process.

Section 1.3 Report Context

This report focuses on the prospect that change in the thermal environment of the Colorado River in Grand Canyon could facilitate recovery of threatened and endangered native fishes, especially the humpback chub (HBC) (*Gila cypha*). Some context for that concern is an important consideration.

The decline of native fishes owes to a sequence of habitat losses, environment change and interactions with non-native species (Fagan and Unmack 2003; Appendix A). Dam construction and operation have reduced both the amount and connection of river habitats, creating isolated population units, as well as altering the flow, temperature, and sediment regimes. Habitat quality changed significantly owing to temperature and variable flow effects derived from dam operations. Exotic species that prey upon and/or compete with native species entered the system by accident or intent. New parasites accompanied the exotic fishes. In short, a complex set of changes, their interactions and cumulative impacts account for the decline and current low abundance of many native fishes.

Thus, while this report focuses on altered temperature regimes as the impact agent to fish, the Science Advisors would like to emphasize that this is but one of four major changes to the Grand Canyon ecosystems that create impact. The three other components that have changed dramatically and require management attention are: 1) biotic relationships including food web, species interactions and predation, 2) flow regimes, and 3) sediment input.

Experiments relating to the flow regime and the deposition of sediments within the canyon have been done, or are currently underway as have more recent experiments at predator control. Direct experiments related to the effect of turbidity (suspended sediment and organic matter) on native fish populations have not been conducted and may be important. The Science Advisors agree that historical flow, temperature and turbidity most certainly interacted to influence native chub survival. These three impactors may be particularly important to chub survival now, given the current biological community in the canyon with a large population of non-native predators.

All of these factors; temperature, flow, suspended sediment, and predators can be and are being addressed through management actions, and using an adaptive management process. The Science Advisors encourage that this continue in a more integrated venue, and become more aggressive as possible. There are feasible ways of using these factors to help learn how to restore lost environmental values and meet statutory requirements. Indeed, there is a growing experience in other large scale resource systems that integrated solutions are needed, not piecemeal ones.

As such, the Science Advisors strongly advise against assuming that the TCD can be considered in isolation from the other factors. Thus, as part of our recommendations with respect to the TCD, we emphasize if the TCD is implemented, there must be a well-organized long-term, adaptive management experimental program including all impactors integration and interactions in the system. A plan for the TCD should not be considered in isolation.

If feasible, the long term adaptive management program should be designed to understand both the single and interactive effects of flow, predator removals, and temperature on humpback chub, acknowledging also the possibility that turbidity experiments should be the next aspect to consider. With this "context statement" in mind, the remainder of the report will focus on risks associated with TCD implementation.

CHAPTER 2: RISK ASSESSMENT APPROACH

Section 2.1 Temperature as a Master Variable

Virtually all ecological production processes are temperature-dependent. As currently operated, the Glen Canyon Dam creates a thermal environment viewed as unfavorable for many of the native species. The pre-dam annual temperature cycle of 4-27º C was typical of their evolutionary history, including a range of cold winter conditions and warm summer conditions. The hypolimnetic releases designed into current Glen Canyon Dam operations produces an annual range of 8-10º C at the outlets. Hence, there are warmer winter temperatures and colder summer temperatures than prior to dam construction. The changes in thermal environment provides excellent habitat for the introduced trout species, and their populations have flourished, resulting in an important recreational fishery, and also expanded predators for native fishes.

Native fishes find thermal refugia or the equivalent of typical historical Colorado River summer conditions only in tributaries where warm summer flows are sustained (e.g., Little Colorado River (LCR)). For example, the confluence of the LCR has become the primary focus of HBC spawning and recruitment processes in the River. Following summer spawning, larval and juvenile fishes reared in the tributaries emigrate into the mainstem and experience a thermal shock of as much as 10-15º C. That shock can severely alter swimming ability, which increases immediate vulnerability to predators. Sustained low temperature conditions can also reduce competitive ability. The resultant depression in growth rates prolongs the period of vulnerability to predators (Childs and Clarkson 1996). Conventional wisdom derived from expert scientists, holds that reducing the magnitude of the thermal shock and sustained low temperature conditions, would improve survival rates of juvenile native fishes (USDI 1999). This reasoning in part motivates the proposal for a Temperature Control Device (TCD) as a management measure.

Fish biologists employ a general classification of three thermal guilds (warmwater, coolwater and coldwater) based on temperature tolerances and optima for individual fish species. Based on the estimates of optimal temperatures for growth, temperatures that provide for spawning behavior, and upper lethal temperature tolerances (USDI 1999), most of the native fishes in the Grand Canyon reach would be considered members of the warmwater fish guild.

Three native warmwater species are now considered extirpated from the Canyon, Colorado River pikeminnow, bonytail chub and roundtail chub. Among those that remain are the humpback chub, bluehead sucker, flannelmouth sucker, razorback sucker and speckled dace. The humpback chub and razorback sucker are listed as endangered species. The flannelmouth sucker is a candidate for listing. Razorback suckers are rarely encountered in current sampling.

High extinction risks for fishes native to the Colorado Basin are not unique to the Canyon. The lower and upper basins have experienced a decline in the abundance and spatial extent of most species (Fagan and Unmack 2003).

In general, the humpback chub and its life history strategy serve as representative of management measures intended to reverse the current status of native species. Some significant exotic fishes (e.g., common carp, channel catfish, fathead minnow) are members of the warmwater guild. Other significant exotics include the rainbow trout and brown trout that are members of the coldwater guild.

Because of the profound influence of temperature, our conceptual model, which is developed in Chapter 3, uses temperature-dependent processes to represent the likely ecological effects of change in the thermal environment related to use of a TCD at Glen Canyon Dam.

Section 2.2 Identifying Sources of Uncertainty

Uncertainty is pervasive in resource issues. The complexity of the physical/ecological systems, from a biotic to biotic variables and their key relationships is immense. The scales over which resource issues occur add to this complexity. The operational and social dimensions associated with TCD use add to the complexity as well.

In this assessment we attempt to winnow this complexity. For example, one objective in this assessment is to identify the key variables in the ecosystem (and relationships among them) that have associated risks when influenced by temperature changes. That is, not all variables and relationships have equal importance, but rather subsets of these are important and are addressed. The scales of these variables and issues are also identified and help to simplify the complexity. Even though this sorting has occurred, there is still substantial uncertainty in terms of how these variables interact and are parameterized.

In general, we see four strategies for dealing with these types of uncertainties. The first is to ignore what we don't know and continue to approach resource management as a trial and error process using haphazard learning. The second strategy is to use the uncertainty of resource issues as an excuse to do nothing. The motivation for this strategy may involve the price of knowledge (witness the tobacco company strategy of disputing carcinogenic claims), or that key stakeholders benefit from existing policies and fear that those benefits would disappear with knowledge. A good example for this is development of alternative explanation for vegetation changes in the Everglades by farming interests, who sought to create alternatives to an explanation that involved nutrient runoff from their farms. The third strategy is to attempt to plan away uncertainty. This strategy is inherent in NEPA type assessments that presume to understand and anticipate impacts prior to actions. The historical limitation to this approach suggests that alternative strategies should be pursued. The fourth strategy is adaptive management where we articulate a set of hypotheses of expected results, then test those hypotheses or predictions through a structured set of management actions. The adaptive management approach is the context of this assessment.

The approach to risk assessment that is used herein constrains the value of the outcomes. However, it is critical to match the approach to the requirements of the analysis. This analysis is designed to guide the decision process on implementation of a TCD on Glen Canyon Dam, not to offer specific proofs on outcomes. It provides a characterization of hypothesized risks of a TCD on aquatic habitat in general and specifically on humpback chubs and other native fishes. It is based on professional assessments (advisors and other specialists) of how the TCD can be implemented to elevate water temperature and expected impacts.

This assessment is not intended to provide specific research designs for actual implementation of the apparatus, except to propose that its operation should permit the maximum flexibility to managers and scientists (within cost constraints), to assess its full utility in enhancing humpback chub and other fish habitat.

Section 2.3 Risk Associated with Doing Nothing

The risks associated with not proceeding with a TCD can be described as resource risks and social risks. The resource risks include continued deterioration of habitat requirements for native aquatic species, especially the HBC, and potential issues of hypoxia associated with discharges from Lake Powell. The social risks include the continued inability to learn about temperature effects on the system, lack of fulfillment of prior legal commitments and the potential for significant prescriptive resource management processes. Each of these issues is described below.

The most pressing resource issue associated with not implementing a TCD is a continued and perhaps increased endangerment to the HBC and native fishes. Prior work, including the Glen Canyon Dam EIS, environmental assessment of the TCD and the draft science plan for the EA all suggest that continued declines in HBC populations and other native fishes are related to temperature stresses. As young are flushed into the river with runoff pulses from the LCR, they are immediately subjected to thermal shock and stress. This trend will continue without the implementation of a TCD. In addition, due to the cold water regime, trout predations on HBC are hypothesized to be significant.

Eutrophication is a common process in lakes and reservoirs; however, the process can be accelerated in reservoirs such as Lake Powell. One of the products of eutrophication is the increased rate of oxygen depletion below the thermocline. Summary data from the monitoring program in Lake Powell by the GCMRC indicate that the extent of oxygen depletion in the hypolimnion has increased significantly since the reservoir has filled. At present, dissolved oxygen concentrations in the hypolimnion of Lake Powell occasionally decrease to below 4 mg/l, with concentrations occasionally below 6 mg/l being released through the penstocks. The rate of oxygen depletion in the hypolimnion is expected to continue and may soon result in the discharge of water with low (< 5 mg/l) oxygen. Release of water with low dissolved oxygen concentrations will impact the fishery immediately below the GCD. As long as the intake structures on GCD are fixed, there is no opportunity to adjust for very low dissolved oxygen concentrations that will occur in the hypolimnion of Lake Powell.

The risk of failure to meet legal requirements could become paramount in a no-action alternative on the TCD. Assessment of TCD as a habitat enhancement factor is called for in the biological opinion and GCD EIS. Further delays could result in potential litigation.

Perhaps the largest social risk associated with maintaining the status quo is the loss of opportunity to test how to restore lost environmental values downstream of the Glen Canyon Dam. One of the most positive benefits of installing a TCD is the ability to manipulate temperature of discharge waters at the base of the dam. Once installed, the device can be used to test hypotheses generated in this report and the TCD science plan. The simple way of saying this is that we won't know the effects of changing water temperatures on restoring HBC populations or any of the other hypothesized effects of the TCD, until we actually try it. The lost opportunity for learning is large and increasing. As such, it is critical to pursue an action alternative.

CHAPTER 3: IDENTIFICATION OF THE RISKS OF TCD

Section 3.1 Categories of Risk

The Science Advisors (SAs) developed a list of risks/effects in operating a TCD at GCD based on the draft EA produced by the Bureau of Reclamation (USDI 1999), results from the TCD workshops in 1999 and 2001, and presentations to the SAs during March 21-22 2003, TCD workshops in Page, Arizona. During the meetings in March, 2003, presentations of the operational, physical and biological effects were made by Bureau of Reclamation and GCMRC scientists, as well as other scientists who have worked in Lake Powell and the Grand Canyon. The list of risks was expanded and further refined by the SAs during meetings in Denver on April 27th and May 21-22nd.

The risks/effects were organized into operational, physical/chemical, biological, economic and administrative categories (Appendix B). Within each of these categories there are different risks/effects depending on the area of the system being considered, including Lake Powell, GCD, areas immediately downstream of GCD, and various reaches in Glen and Grand Canyons.

Operational risks include GCD management issues of the TCD, such as the added complexity of operating and maintaining equipment at GCD. These risks are primarily associated with areas immediately adjacent to the GCD. Installing a TCD above the turbines will increase the likelihood of mechanical outages of the turbines, which in turn could alter the effectiveness of the TCD system in attaining downstream temperature increases (1) (Appendix B). Planned outage of the turbines for maintenance also raises the possibility that for some years or some times of the year, temperature goals might not be met unless a more flexible TCD system is installed (2). Having TCD's on a subset of the eight turbines creates operational complexity in running GCD (3). There are already several constraints on operation of the dam and individual turbines (e.g., water supply to Page, Arizona). There is also a risk that sustained drought could lower Lake Powell below the lowest level of the TCD (4). While this would make the TCD inoperable, such low lake levels may result in releasing warmer water from Lake Powell, and might partially offset the need for the TCD to increase temperatures. Yet, the risk exists that the target temperature may not be met when Lake Powell is below the lowest intake of the TCD. Finally, at GCD there will be risks to BOR associated with stronger near-surface currents and a potential vortex near the TCD intakes (5). This will require the BOR to keep boats away from this area. This could have risks of life and property to boaters.

Physical/chemical risks are concerned with the effects of the TCD on the temperatures and chemistry in Lake Powell and downstream of the GCD. We concur with past findings of the BOR that the operation of the TCD will have minimal impact on the thermal structure and chemistry of Lake Powell (USDI, 1999). However, the TCD, by design, affects the thermal structure downstream of the GCD and will slightly alter the water chemistry. The goal of the TCD considered here, is to maintain release temperatures near 15º C as early in the spring and as long in the fall as possible. Use of a TCD to release water temperatures near 15º C will probably not be possible throughout April, but can be used to increase temperatures from that presently being released (6). From May through December, proper operation of the TCD should enable water to be released near 15º C (7). The TCD can also be used to maintain release temperatures near 15º C for only part of the time between May through December, which may enable control of other warm-water species (USDI 1999). Past models and monitoring data indicate that water temperatures generally increase about 1º C for every 30 river miles; therefore, water temperatures should be about 17-18º C at the LCR reach and about 20º C at the Diamond Creek reach. However, if the TCD is not operated properly due to managerial or other constraints, there is a risk that these temperatures will not be achieved.

Operation of the TCD will likely change the dissolved oxygen and nutrient concentrations in the water downstream of GCD due to water being withdrawn from shallower depths in Lake Powell that have slightly higher dissolved oxygen concentrations and lower nutrient concentrations (8). These changes may impact the productivity in the areas immediately downstream of the GCD and further downstream. Increased water temperatures in the Colorado River will result in warmer water entering Lake Mead that may mix to a shallower depth. We do not feel that this will significantly affect the thermal structure or productivity of Lake Mead.

There are risks that increased temperature will alter the density and viscosity of water that in turn influences turbidity (9) and export of sediment (11). Because temperature may affect sediment properties, the increased temperature may also affect riverbed configuration and hence modify physical habitat for trout (10). Most of these effects are expected to occur downstream of sources of new sediment to the river.

Biological risks include subcategories of basic primary and secondary production processes, warm-water non-native fish species, diseases, humpback chub and other native fishes, and non-native coldwater fishes. We concur with past findings that the operation of the TCD will have minimal impact on the biology of Lake Powell (USDI, 1999). However, higher temperatures downstream of the GCD will alter the production at the bottom of the food web, change in rate of primary production (18), and change in the composition of the periphyton (17). These changes may change the amount of nutrients (8.5) and dissolved and particulate carbon transported downstream (15). Temperature is hypothesized to have direct effects on primary consumers of those resources such as macroinvertebrates (17) and invertebrates (18), as well as indirect effects owing to feedback through trophic interactions. We are uncertain how it will affect species like mud snails (19).

Some of the most significant indirect risks of increased water temperatures are the potential changes to habitat areas and the suitability of these areas to non-native warmwater fish species. These include the entrainment and release of warmwater fish into the tailwater of the dam (20), upstream movement of non-native warmwater fish in the river, especially into spawning areas of the HBC near the LCR (21), upstream movement of warmwater fish from Lake Mead (24), and possibly establishment of new exotic species (23). Increased populations of non-native warm water fish throughout the river may result in increased predation on native warmwater fish as well as an increase in the competition for limited resources (25).

Increased water temperatures are quite likely to increase the risk of several water borne diseases such as bacterial or fungal infections (26), whirling disease (27) and the incidence of parasitism (e.g., Asian tapeworm (28)). Certain species of fish are susceptible to specific diseases; therefore, the extent of disease is expected to vary throughout the river. For example, whirling disease only affects rainbow trout; therefore, it is only expected to be a significant issue directly downstream of the GCD where it could impact sports fishing.

Increased water temperature is expected to increase spawning success of native warmwater fish in the mainstem of the Colorado River, especially in downstream areas with the most warming (29). For example, increased catfish and carp populations would likely increase predation on HBC. Warmer temperatures in the mainstem of the river will also reduce the thermal shock of fish spawning in the warm tributaries (e.g., Little Colorado River) and young fish entering the mainstem. Collectively, these changes should result in improvements in juvenile survival and recruitment to adult populations (30).

In the Glen Canyon reach, increased temperatures may increase the habitat suitability for trout spawning (31) and trout growth (33), and possibly increased trout populations (32). If trout populations increase, emigration may lead to increased predation and competition effects on native fishes in downstream reaches, especially during certain seasons of the year (35, 36). Brown trout are primarily found downstream of the LCR; however warmer water temperatures are likely to increase brown trout numbers in the LCR reach (34). Brown trout are much more predacious than rainbow trout and may impact HBC populations near the LCR.

Economic risks include issues associated with hydropower losses from the operation of the TCD, reducing operating efficiency of the turbines (37), as well as lost hydropower due to additional downtime associated with maintenance or repair of the TCD (38). Construction costs of the TCD are not known with certainty and will depend on the final design and number of units to be installed (39). However, presented designs are expected to exceed $100 million. The potential for a temporary low-tech TCD design would significantly reduce costs and if effective would have great merit. The permanent design TCD will increase operating and maintenance costs at GCD (40). The operation of the TCD will involve greater monitoring of water temperature and adjustments to the TCD as required to attain and maintain the target temperatures (42). There is also an increased cost to GCMRC for monitoring additional variables to better understand the interactions identified in this and past documents. Additional monitoring is essential to insure that the TCD is having the desired, intended effect and to document development of indirect, undesirable effects (41). Additional costs of monitoring adds an additional risk that other core monitoring may not be conducted or budgets to GCMRC must be correspondingly increased to maintain critical program elements. Finally, higher water temperature may enhance trout populations in the Glen Canyon reach (31, 32, 33), which may increase the economic value of recreational fishing and fishing guides.

CHAPTER 4: QUALITATIVE RISK ASSESSMENT

In developing this risk assessment, the Science Advisors, as a group, realized that limited time and incomplete knowledge would severely constrain any formal analysis. Initially we focused on a summary of professional judgment. Our desire to frame our assessment in some integrated concept led us to use of a conceptual ecological model as a science tool for our analysis. In the following sections we provide our argument for the approach selected, and an overview of the modeling concepts used. We then use the modeling approach to characterize the impacts of various biological risks that have been introduced in chapter 3. Only biological risks are addressed using the models. Various figures are used to illustrate linkages and interactions associated with these biological impacts. In our final section of this chapter we again address operational, economic and physical risks presented earlier, but outside of the modeling framework. Additional time would be needed to address all risks presented using the modeling approach.

Section 4.1 The Conceptual Ecological Model as a Science Tool.

Implementation of the TCD may entail an array of both positive and negative consequences for biota within the river. The response of the chub population will be the result of both the direct effect of increased temperature and the many indirect effects that are expected under a change in thermal regime (e.g., changes in food availability, predation, parasitism, etc.). Further, complex and interactive effects are likely (e.g., food availability may increase but competition for that resource may also increase if other consumer populations e.g., non-native fish, New Zealand mud snail increase).

Given the potential complexity of the ecosystem-wide response, we took the most prudent approach to assess the possible ramifications of the TCD, given the time-sensitive nature of the issue. Prior approaches have mostly acknowledged that biological and physical interactions were complex.

Using a conceptual modeling approach we attempted to identify the most important interactions and the most probable response of these interactions to increased temperature. The SAs emphasize that the conceptual model(s) is used as an organizing framework and not for specific analysis. That framework helps identify key variables and knowledge about relationships among variables (functional forms, rates and parameters, degrees of influences, among others). As such, the model(s) becomes a tool for communication and to foster discussions that help articulate key plausible hypotheses that should be tested with a TCD, and identify what should be monitored to evaluate the outcomes of future proposed experiments involving the TCD.

Section 4.2 Conceptual Model Framework

Our approach was to develop general conceptual models using an ecosystem modeling framework (i.e., stocks or abundances of different groups of biota shown in boxes with linkages or flows between stocks shown by arrows) combined with a bioenergetics approach (i.e., species-specific physiological responses to temperature). The conceptual models are qualitative, but illustrate well the factors needed to evaluate the major impacts of the TCD, the major linkages between factors that need to be evaluated empirically, the hypothesized direction and magnitude of the effects that need to be tested experimentally and the current level of information we have regarding each effect.

What the conceptual model illustrates:

1. **The expected *biological response* to increased temperature for each major "group" of biota in the river as physiological curves (Fig 1).** These curves represent species 'suitability' over a range of temperatures, where suitability represents how factors such as growth and reproduction respond to temperature. Biologists, to illustrate the optimum 'performance' of a species as a function of temperature, commonly use these curves. The shaded vertical regions within each curve show the expected temperatures in the river once the TCD is in operation. If the shaded region falls to the left of the peak of the suitability curve, this would suggest that the species may respond positively to the increased temperature (i.e., increased growth and reproduction). If the shaded portion reaches the peak, then a maximum positive response is likely. If the shaded portion extends beyond the peak, then negative effects should be expected. These curves are based on the literature, data from various GCMRC reports and expert opinions. They are analogous to those used in constructing bioenergetics models (Hanson et al. 1997), which are widely adopted in applications where fish growth rates are employed as the indicator of habitat suitability and trophic interactions. Although specific parameters for many of the native fishes are not available, models are available for a total of 47 fishes including their ecological equivalents elsewhere as well as specific models for many of the important non-native species. Regardless of that, the general estimates of curve shapes and temperature optima present a valuable picture of likely temperature responses. In addition, GCMRC staff members are currently working on developing bioenergetics models for both native and non-native fishes.

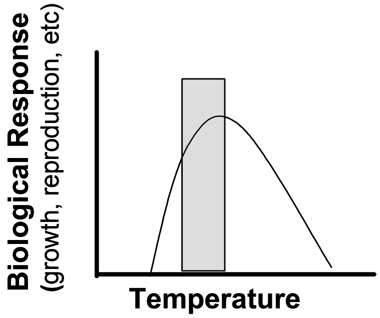

Fig. 1 Schematic of the effect of temperature on physiological processes. The curve represents a species performance as a function of temperature with optimal performance at the peak. Gray bar represents the current temperature in the river (left 'end' of bar) and the temperature expected post TCD installation (right 'end' of bar).

2. **the *major linkages* between these groups in need of empirical evaluation (Fig. 2, arrows)**

3. **the hypothesized direction & magnitude of the effects (Fig. 2, sold vs. dashed arrows)**

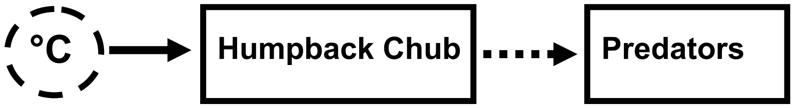

Fig. 2 Schematic of linkages in models. Boxes are stocks such as a population of fish; arrows indicate flows. Solid arrows are inflows to stocks (i.e., arrows pointing toward a stock are increases or positive effects such as temperature increasing the growth or reproduction of chub). Dashed arrows are outflows from stocks (e.g., decreases in the size of the chub population due to predation)

4. **The current level of information regarding each effect (i.e., which aspects are in greatest need of study).** Those effects where we have limited empirical information (i.e., a higher uncertainty for the hypothesize effect) (Figures 3,4,5; Appendix C).

Section 4.3 Underlying Sub-models

The general conceptual models provided for each of three locations along the river: Glen Canyon reach, Little Colorado River reach, and Diamond Creek reach (Figs 3, 4, 5) have been simplified to show the main effects on humpback chub. For each of the stocks (e.g., chub, trout, tapeworms, etc.) detailed sub-models would have to be constructed to assess both the effects of temperature on the growth and reproduction of these biota and the interactive effects of other physical and biological factors on the growth and reproduction of these biota. We illustrate such an approach using Stella© modeling software (Fig. 6, 7, 8, 9;Appendix C), however, we made no attempt to parameterize these models nor include all possible effects and interactions. The latter is a significant undertaking that would require much research, new data from the Canyon, and new experiments. Serious development of these submodels (and their linkage into a larger ecosystem model) would be more suitably approached using other programming software. Stella was used here because it is easy to visualize flows and interactions.

The SAs also suggest that future development of these submodels are outside the scope of this assessment and are not recommended as planning tools to determine impacts. An enormous amount of work is required to develop credible, validated models. Even if such an investment is made, the utility of this investment is questionable in the context of using models to predict outcomes of a TCD prior to implementation. There are many examples of large investments in these types of models as predictive *a priori* assessment tools. That history suggests little success or efficacy of such investments. Instead such model development should focus on their use as integrative tools and to develop more robust hypotheses to test through an adaptive management process.

Section 4.4 Hypothesized Responses.

Species have specific ranges of temperature tolerance and temperature optima set by their evolutionary history, by the timing of their life cycles, and by their strategies of resource acquisition and predator avoidance. Some species may increase dramatically while others may change little or even potentially decrease if the temperature optimum is exceeded. Unlike previous reviews (UDSI 1999), we recognize that optimum growth is a function of food availability and directly related to temperature. Density increases by consumers can offset the effects of increased prey resource production. Because higher temperatures increase metabolic costs, optimum temperatures and growth rates can decline if food resources are increasingly limited by intensified competition (Hanson et al. 1997). Thus, the balance of energy budgeting can develop different responses to thermal enhancement at the scales of individual fishes, populations and predator-prey systems.

We present in the next section hypotheses about expected impacts and briefly outline/discuss the uncertainties involved. The hypotheses and the underlying complexities should be used to guide the science that GCMRC should undertake prior to and during operation of the TCD.

Section 4.5 Hypotheses and Uncertainties

Primary Producers: Because the life processes of many aquatic organisms are temperature-dependent, warmer water can increase growth rates and stimulate reproduction at the basic levels of primary and secondary production. That is the central assumption presented in our conceptual framework and is comparable to results derived from studies elsewhere (Vannote and Sweeney 1980, Hogg and Williams 1996). While compensatory processes may develop that produce strong indirect effects on primary and secondary production that could limit an increase in primary and invertebrate production (e.g., invertebrates may reproduce more frequently and mature more rapidly, but to a smaller size, it is our view that the most realistic hypothesis at this time is that there will be a net increase in primary production and in invertebrate production. In this case, commensurate increases in nutrient availability appear to derive from increased recycling rates. We assume similar responses will occur in canyon reaches. Based on reservoir modeling studies (USDI 1999), some nutrient increase and increase in allochthonous carbon inputs will occur as a consequence of entraining epilimnetic waters. That will be most apparent during summer uses of the TCD.

Although individual species may have different thermal optima, temperature-mediated succession of algae (including periphyton) will probably occur. The important filamentous alga, Cladophora, has temperature tolerances well within the range of the expected increases and so we expect it to remain the dominant macroalgae.

Primary Consumers (invertebrates): As in the primary producers, we expect that adjustments in life history characteristics and/or temperature-mediated species replacement processes will cause the invertebrate community to change production rates in proportion to the temperature increases. This group includes the basic prey resources of many fishes. However, we are uncertain about thermal effects on the exotic New

Zealand mud snail, which is a competitor of other herbivores and appears to not be vulnerable to predation by secondary consumers such as fishes. There is the prospect that black fly abundance may increase due to their competitive ability and rapid population level responses to temperature. With respect to potential extirpations, even for those with limited dispersal abilities, it is unlikely that we will see local extinctions of whole groups of invertebrates (e.g., crustaceans, larval midges, etc.), but it is quite possible we will see changes in the species composition within these groups.

Humpback Chub and other native fishes: Given that much of current reproduction occurs in the thermal refugia of tributary streams, we expect that spawning success of native fishes will increase. Warming of the mainstem may also allow greater spawning success in backwater and eddy habitats in downstream reaches of the Canyon. As specified in the motivation for developing the TCD, thermal shock effects will be reduced for larval and juvenile fishes emigrating from tributaries. Recruitment success should increase. There is an important caveat, increased predation rates by trout and warmwater fishes may offset the enhanced production of native fishes. While others have argued that the TCD need be used only during chub spawning and emigration periods because "humpback chub do very well in cold water" and that "cold water releases would be used to control competitors", we believe that shorter periods of warming have only shorter-term effects. Reverting to lower temperatures would cause continued reduction in growth rates for juvenile and adult chub. Thus, a well-designed assessment program is essential to learning about the magnitude of thermal effects.

Trout at the LCR: Thermal effects at the LCR should produce greater rainbow trout growth rates and abundance at the LCR. The magnitude of those responses will depend on indirect effects to the food base and increased intensity of interaction with warmwater fishes. Perhaps most important, the new thermal regime will probably increase the likelihood of outbreaks of whirling disease which could produce devastating effects on naturally reproducing rainbow trout populations. Although not known to be in the Grand Canyon system at this time, whirling disease continues to spread throughout the West and is increasingly likely to appear.

Rainbow trout: We are fairly certain that the temperature increase will put rainbow trout at or beyond their optimum temperature in the lower reaches of the Canyon. High temperature pulses have the potential for creating bottlenecks for those species that are already at or near their thermal optima. Further, warm water episodes reduce dissolved oxygen and may interact with siltation events to further reduce oxygen available at gill respiratory surfaces and for eggs. This combination of high temperature, low dissolved oxygen, siltation, and exposure to elevated pathogen levels have increasingly negative consequences for trout further downstream from the dam.

Brown Trout at LCR: We are very certain that the increase in temperature will put brown trout at or near their optimum temperature. Although broadly distributed, they are much less abundant than rainbow trout and their current distribution is centered near Bright Angel Creek which probably corresponds to their slightly higher thermal optima than that for rainbow trout. Thus, higher temperatures will increase their relative abundance upstream from Bright Angel. Previous summaries (USDI 1999) did not consider brown trout to be a significant threat to native fishes. We believe that brown trout are among the most potent piscivores in the system. They will probably become more abundant in the LCR reach and, therefore, a potential major source of mortality to juvenile native and non-native fishes.

Non Native Warmwater Fishes: We are very certain that non-native warmwater fishes will exhibit increased growth rates and production. Of equivalent or greater concern is the prospect that their abundances will increase owing to enhanced production and greater rates of upstream migration. This will intensify interactions with native species. Among these non-native warmwater fishes are potential competitors (e.g., common carp) and, perhaps more important, several potential predators on larval and juvenile chubs (e.g., smallmouth bass, striped bass and channel catfish). Monitoring for changes in distribution, abundances, growth rates and diets will be an essential component of pre- and post-TCD studies. Bioenergetics models are available for many of these non-native species and can be used to directly estimate the change in balance between positive thermal effects on native species and negative effects owing to compensatory responses by non-natives.

Asian Tapeworm: Asian tapeworm entered the system with the introduction of warmwater fishes such as carp and other members of the Cyprinidae. It has appeared in humpback chub at levels that cause concern among GCMRC biologists. The life history of this parasite is constrained at temperatures below 15º C. Thus we are very certain that its frequency and abundance will increase as a consequence of warming due to the TCD. Although most tapeworms have some adverse effects on their hosts, we do not know the magnitude of negative effect on populations of this group of native fishes. Control through temperature manipulations is unlikely because the Asian tapeworm is well established among fishes resident in tributary streams.

Section 4.6 Synthesis of Biological Risk

Increased temperatures will increase the intensity of biological processes. A stronger gradient of thermal effects will develop below the dam. For river reaches between the dam and the LCR, conditions will improve for coldwater species and, to some extent, for the native species. At the LCR, increased recruitment success of native fishes will derive from the positive effects of reduced thermal shock, but that benefit may be offset by the increased abundance and interaction rates with competitors and predators such as rainbow trout, brown trout and upstream migrants. Mitigation strategies may be necessary. Lower in the Canyon, increased populations of native fishes may develop from newly available spawning and rearing habitat in the mainstem. Trout populations may experience thermal constraints. The net balance is unknown and difficult to forecast because much of the numerical response by non-native species includes the magnitude of upstream migration by warmwater fishes now limited to the lower reaches of the Canyon. Effects of parasites and pathogens will intensify in proportion to warming. Again, the net negative effects or positive effects of those are of unknown magnitude.

Previous reviews have considered TCD effects on other endangered and special status species such as peregrine falcon, southwestern willow flycatcher and Kanab ambersnail (USDI 1999). We agree with their assessment, that the expected pattern of uses of the TCD is not likely to have negative effects on these species. Much the same is likely for other resident species and migrants. They will probably respond in proportion to the extent that the system exhibits increased productivity of aquatic components.

Much of the Canyon fauna and flora is not native. Many of the most abundant and ecologically significant species are not native. Given that history, we should expect that new exotics will appear. We cannot forecast which and how many new species might appear. Changes in the thermal regime may or may not support new invaders, but we would expect that warming in ways more akin to the pre-dam temperature conditions may make those invasions more likely.

Section 4.7 Operational Risks

It is clear that installation and operation of the TCD will add complexity to operation of GCD. The effectiveness of the TCD device in meeting temperature increases is influenced by unexpected mechanical outages of the turbines or the TCD itself, planned outages of the turbines for maintenance and the number of TCD units that can be installed. Further, having TCD's on a subset of the eight turbines creates operational complexity in running GCD. There is also the possibility that the temperature target may not be hit because the TCD can only be used within other operating criteria. There are already several constraints on operation of the Dam and, even individual turbines (e.g., water supply to Page, Arizona). Sustained drought could lower Lake Powell below the lowest level of the TCD, in which case the TCD is inoperable. Finally, at GCD there will be risks to US BOR to keep boats away from the TCD due to current and potential vortex. This could have risks of life and property to boaters.

Overall, the information we have had access to suggest that operational risks are higher the fewer the turbines the TCD's are installed upon. The more turbines the TCD is installed upon, the lower the risk of not meeting the temperature target, the less complexity in managing the dam and the less likely that other constraints will result in failing to meet the temperature target. This perspective does not obviate the SAs support for a small (1 or 2 turbines) temporary, inexpensive TCD pilot project. If available, such a pilot should be implemented while the primary TCD is in planning.

Section 4.8 Economic Risks

While the operational risks are lower with installation of more turbines with TCD's, the economic risks go up with additional TCD's. The construction costs increase and hydropower losses increase with more turbines with TCD's installed on them. According to Harpman (2003), the hydropower losses are relatively minor (less than 1% loss in hydropower value) even with all eight turbines outfitted with TCD's. Thus, the hydropower loss is relatively minor. Construction costs increase substantially with the number of TCD's. The maintenance costs increase with the number of TCD's. There are economic costs associated with increased monitoring of the TCD performance and attainment of the temperature target. There are costs to GCMRC of monitoring all the key variables necessary to insure that the desired, intended direct effects are occurring and the negative, unintended effects are not overwhelming the desired outcomes. Additional monitoring needs may induce a risk to existing monitoring programs unless additional funding is obtained. New information on potential engineering capability to construct a temporary (three year projected life), but operational TCD for GCD for under $5 million could offer significant hypothesis testing capability. However, information to the SAs on this system was insufficient for evaluation.

Section 4.9 Physical Risks

Changes in water temperature affect the density and viscosity of water that in turn influence the rate of sediment transport within the Colorado River, and, in particular, the inventory of fine sediment stored in the channel bed and banks. The strongest effects are through changes in water viscosity. For temperatures centering on 55º Fahrenheit, an increase in water temperature of 10º F decreases viscosity by about 7%. These changes in viscosity primarily affect the settling velocity in the fine sand range and finer, and also affect the thickness of the laminar sublayer at the sediment-water interface and the properties of bedforms (ripples and dunes). Theoretical and empirical studies of temperature effects on bedload sediment transport rates (e.g., Colby and Scott, 1965) indicate that increase in water temperature by 40º F reduces sediment transport rates by about 75%. Thus expected maximum temperature change from the TCD of about 10º F could reduce bedload sediment transport rates by approximately 18% and thus modestly increase short-term sediment storage on the channel bed after floods on the Paria and Little Colorado Rivers and smaller tributaries below the dam. Water turbidity after tributary floods may be slightly reduced as well as sand grains settle more rapidly to the bed, but effects on silt and clay sized sediment should be minimal. The overall effects of the TCD on long-term sediment storage are likely to be inconsequential.

CHAPTER 5: SUMMARY OF RISKS OF TCD AND RECOMMENDATIONS

Section 5. 1 Summary

The Adaptive Management Program Science Advisors agreed in November 2002, to a charge to conduct a risk assessment of installation of a Temperature Control Device (TCD) on Glen Canyon Dam. The six month project involved identification of risks related to installation and operation of a TCD on the Dam, and assessment of potential direct and indirect resource impacts associated with the TCD.

Four general areas of resource risks are identified; operational, socioeconomic, physical and biological. Further, differing risks are associated with four different geographic areas; Lake Powell, Glen Canyon Dam, the Colorado River corridors from Glen Canyon Dam to Lake Mead, and Lake Mead itself.

Operational risks are associated primarily with using a TCD design that can overcome maintenance, power production, water demand, equipment failure and other operational constraints, and still provide the increased temperature regimes at times needed to enhance HBC habitat. Providing maximum assurance to overcome these risks will generally require TCD installation on most turbines, a project that could range between $80 and $120 million in construction costs and cost additional millions for effective monitoring. This can create significant socio-economic risks to other US BOR water programs and GCMRC monitoring programs. Conversely, not creating a management capability to modify water temperature to potentially enhance HBC habitat could result in continued jeopardy decision, lawsuits or both. The resulting social/legal outcomes could create even greater negative risks to all program areas and resources of concern, including the HBC.

Physical resource risks (water, sediment) appear minor and in most TCD operational scenarios would not pose any major impacts in the system. TCD related changes in water quality are of minor concern as are changes in sediment. Not pursuing the TCD could create higher associated risk of low oxygen water being pulled from the reservoir.

Biological risks and related impacts are the most robust set of risks identified, and include negative links associated with potential increasing predation, parasitism and competition. However, a TCD could also be used to potentially remove cold water fish predation (rainbow trout). A conceptual model approach permitted development and synthesis of various hypotheses that relate to TCD induced impacts. Selected statements of hypothesis include:

- A net increase in primary production and invertebrate production is expected.
- Temperature mediated species replacement processes will likely cause the invertebrate community to change production rates in proportion to temperature increases.
- It is unlikely that extinctions of invertebrates would occur (e.g. crustaceans, larval midges, etc.), but it is probable that changes in species composition will occur.

- Overall, spawning success of native fish (HBC) will increase, as will impacts to the population.
- Recruitment success of native fish (HBC) should increase, even though predation is expected to increase. Predation mitigation may be required and is expected to be effective.
- Overall thermal effects on rainbow trout are expected to be positive in the Lees Ferry reach and negative in lower reaches toward Lake Mead. Overall effects at LCR may be positive and require mitigation due to expected increased HBC predation. Should whirling disease occur, thermal regimes would increase its impact.
- Effect on brown trout would be positive in most upper reaches of the system, including the LCR. HBC predation mitigation may be necessary.
- Effects on warmwater predator fish (catfish, carp, etc) is expected to be positive with expected movement into upper reaches of the river. HBC predation mitigation may be necessary.
- Incidences of parasites such as the Asian tapeworm are expected to increase. This factor would require focused monitoring due to high risk and uncertainty.

In evaluating all TCD risks and potential resource impacts, some geographical areas were identified as low potential risk areas, including Lake Mead and Lake Powell. The greatest geographic areas of concern are the riverine corridor below the Dam and further downstream at the Little Colorado River and beyond.

The assessment identified significant complex interactions and integrated risks and both negative and positive impacts that are associated with use of the TCD. These occurred in all key areas of biological risk, i.e. predation, food base, competition etc.

In balance, the TCD offers a potentially potent management tool to address issues linked to declining populations of HBC. When one considers the general health of the HBC population and the strong influence water temperature has on HBC habitat and other related resources, the option of not pursuing a TCD appears unacceptable. Many of the increased risk factors due to TCD (i.e., predation, parasites etc.) may be mitigated through management strategies.

Section 5.2 Recommendations

As noted in the report, this assessment is constrained by both Advisors time in the six month assessment period and explicit scientific knowledge of critical physical/biological interactions relating to warming of the river with a TCD.

The Advisors think sufficient knowledge exists to make an informed policy decision about proceeding or not proceeding with this adaptive management option. That decision would be for the AMWG to move forward as rapidly as possible with an Adaptive Management Program that incorporates construction and operation of a TCD at Glen Canyon Dam. Several TCD program options exist. The adopted program must permit maximum science and management flexibility to enhance habitat requirements for the humpback chub and other native fish.

Although there are many unknowns associated with use of a TCD at Glen Canyon Dam, the proposed thermal enhancement plan is a well-reasoned approach to rehabilitation of threatened and endangered fishes. TCD applications elsewhere have produced generally positive ecological outcomes. We should expect the same in this case. It is essential, however, that adopting the use of the TCD as a management policy be accompanied by commitment to a comprehensive long-term level of research and monitoring that provides timely results in evaluating its value as a management tool.

The position of the Science Advisors is predicated on the premise that long-lived native fish are being lost from western rivers, and law, policy and public will support reasonable efforts to maintain and improve appropriate habitats for viable populations of the fish.

There are several subparts to this recommendation. We provide these in the following text in hopes that they will be referenced in development of the adaptive management program for the TCD.

1. Commitment to a TCD Adaptive Management Program at GCD is both long term (10 years for planning, construction, testing etc.) and expensive, possibly approaching $200,000,000 (planning assessment, construction, operation, testing, and monitoring costs) over the 10 year period. Possible lower cost pilot efforts may exist and should be evaluated. A policy decision to proceed must parallel development of a comprehensive Adaptive Management Experimental Program (i.e.10 years plus) for the Dam and River resources. The TCD affords a primary management tool to potentially mitigate native fish adverse habitat impacts in western rivers while maintaining Dam structures and the extensive benefits they provide. The costs of the program could be overshadowed in a ten year period by power and water revenue disruptions from environmental litigation, should the effort not be pursued. One only needs to evaluate the environmental conflict over the endangered Spotted Owl, and the demise of the western wood products industry, to realize the potential social costs of environmental litigation.
2. The policy decision to proceed has complex associated risks to resources related to Glen Canyon Dam operations, social and economic issues, and physical and biological resource interactions. All associated risks need to be considered and mitigated as possible with a robust TCD Adaptive Management Program appropriately merged with the Long Term Comprehensive Adaptive Management Experimental Program.
3. In evaluating risks to proceed, major effectors to the HBC habitat were considered; Dam operations (flow regimes, including warming and timing), predation energetics, and sediment. With TCD and the proposed long term experimental program, significant capability exists to improve habitat needs of the HBC. What cannot be affected is sediment, a factor that should be considered as part of the comprehensive Adaptive Management Experimental Program.

4. Risks exist in operation management to effective implementation of TCD. Dam management personnel must be intimately involved in development of the TCD design and the annual operation plan. Maximum effectiveness is gained by their involvement in development of the overall TCD Adaptive Management strategy.
5. Operation of a TCD at GCD, as noted above, can be a critical Adaptive Management tool for HBC habitat enhancement in the Colorado River. However, because of lengthy planning and construction requirements, time may no longer be on the side of management, regarding a TCD Adaptive Management Strategy. The Science Advisors propose a special task force be appointed by AMWG and chaired by GCMRC to expedite development of the proposed Long Term Comprehensive Adaptive Management Program, with the TCD as one critical element. Even an aggressive administrative effort will require five or more years before a TCD can be in place for tests. It is, therefore, critical that all alternative TCD construction strategies be evaluated. The team should consider a TCD Pilot Project, to begin to develop Adaptive Management strategies for the final TCD Structure. A plan should be made for a temporary pilot experimental system to provide warm water below the Dam. This should be drafted and implemented in the next 12-24 months, as the primary TCD effort proceeds.

An effective adaptive management program including TCD requires commitment to effective design and assessment of experimental management approaches. Too many adaptive management programs have failed (Walters 2000). Most often failures were not due to inappropriate research design, but occurred because of interruption and compromise of the research cycle in the Adaptive Management process. If we are to use an adaptive management approach based in science, then we must make sure the science is not compromised in the process.

Management leadership is critical to guiding the adaptive management process. The most appropriate position for management groups is to adopt a rigorous role in the designation and planning of research needs, committing resources required for its pursuit, assuring uninterrupted support for the duration of study, and use the consequent results for design of follow-up management actions and studies.

As such AMWG, TWG and GCMRC, as the leadership for this program should refocus their roles and commitment as they design the TCD into the Long Term Comprehensive Adaptive Management Program. If a decision is made to proceed, then all should commit to a comprehensive approach.

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APPENDIX A:

RESEARCH PAPER ON COLORADO RIVER NATIVE FISH EXTRIPATION

Fagen and Unmark, 2003

Change in Spatial Distribution of the Humpback Chub (*Gila cypha*) in the Lower Basin of the Colorado River: An Analysis of Data from the SONFISHES Database

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Abstract

This document provides an analysis of the contents of a spatially delimited biodiversity database of occurrence records for fishes native to the Sonoran Desert. Of particular interest are changes in the spatial distribution of humpback chub (*Gila cypha*) in the Lower Basin of the Colorado River and whether the distribution of this species has been affected by the construction of Glen Canyon Dam or by the release of hypolimnetic water from the dam. Analysis of the database indicated that 1) the rate range collapse of *G. cypha* (i.e., the rate at which its spatial distribution has shrunk) has increased in the time since construction of the dam and 2) this rate is in the top third of losses for native Sonoran fishes but clearly not an outlier. Results are consistent across each of three spatial scales of analysis (5km, 25km, and 100km or river reach) suggesting that the observed patterns are biologically accurate and not simply the consequence of heterogeneity in database structure.

Introduction

What follows is an analysis of the spatial distribution of the humpback chub (*Gila cypha*) in the Colorado River below Glen Canyon Dam. The starting place for the analysis is the SONFISHES database of species occurrence records for fishes of the Sonoran Desert (Fagan et al. 2002). The database provides the most comprehensive summary available of the historic and current distributions of all 50+ native fish species in the Sonoran ecoregion, which is defined here as the "Lower Basin" of the Colorado River and several drainages in northwestern Mexico. Professor W.L. Minckley, late of Arizona State University, originally conceived of and developed the database. Peter Unmack, a Ph.D. student at Arizona State University, has added recent records (i.e., post 1990) to the database after consultation with species experts.

At issue is how the spatial distribution of humpback chub has changed over the few decades since its original discovery and whether these changes may have been coincident with major changes to its habitat including the construction of Glen Canyon Dam (completed 1963) and the release of cold, hypolimnetic water from the base of that dam (initiated 1970). Using the SONFISHES database, we address two major questions

1) What is the apparent rate of range collapse (i.e., spatial rate of extinction) of humpback chub and has this rate changed within the last few decades ?
2) How does the rate of range collapse of humpback chub compare with comparable measures for other fish species native to the Sonoran ecoregion ?

The SONFISHES database is a resource for spatial analysis.

Although data on numbers of fish collected or seen on a particular survey are often included with individual records within the database, these count data are so heterogeneous with respect to effort and/or detail as to prevent their use in analyses of population abundance via techniques like population viability analysis. In contrast, attributes defining spatial location of records are of a consistent high quality and provide an excellent resource for understanding changes in spatial distributions. Individual records are georeferenced to within ~1 km of a collecting site, and routes of early collectors have been retraced (e.g., Minckley 1999), matching outdated place names with present-day equivalents and excluding all suspicious records.

The validity of conclusions drawn from analyses of spatial datasets depends very much on the characteristics of those databases. Foremost among these is the issue of dataset completeness, but completeness is actually a multi-faceted concept. For example, a dataset can be incomplete if it suffers from an insufficiently large scope (i.e., it does not cover a large enough area). Alternatively, a dataset can be incomplete if, for a given scope, its contents have arisen from sparse sampling.

Researchers can compensate for insufficient scope by ensuring datasets are well-matched to the questions being asked of them. In the context of this analysis for the humpback chub, the SONFISHES database has the appropriate scope for testing ideas about extinction dynamics of humpback chub below Glen Canyon Dam. First, the database details what is known about the spatial distribution of the humpback chub in the entire area of interest. Second, the database contains comprehensive data on a biogeographically defined fauna that provides a context for comparative analyses of extinction risk across species. On the other hand, because of its limited scope the database can offer no insights into differences in fish extinction dynamics between the Upper and Lower Basins.

Other approaches must be adopted to deal with potential concerns about data sparseness. Even though SONFISHES affords spatial coverage that is unusually complete and finely resolved (e.g., occurrence data accurate to within 1 km), users cannot avoid the fact that it is heterogeneous in important respects. For example some survey parties may have taken multiple samples in a region so that we have multiple occurrence records within a relatively small length of river, whereas other survey teams may have covered larger regions but made fewer collections within a local area. A good strategy to deal with such spatial heterogeneity is to analyze spatial patterns at each of several spatial scales. By this use of scale, we mean what geographer's call "grain size," or the degree to which a landscape is subdivided for analysis purposes. Scale is an important consideration because a dataset may indicate that a species is present at certain specific localities within a river but not at others. Nevertheless, by shifting to a larger scale, one could say that the species was present within the river. The gaps in distribution may be real (perhaps reflecting a high level of habitat specificity for the species) or they may be a consequence of the sampling history captured by the database. With historical datasets, distinguishing between these alternative possibilities is difficult at best. However, analyzing changes in spatial patterns at each of several spatial scales provides a means of dealing with such contingencies in biodiversity databases.

Analyzing spatial data at multiple scales provides a means of gauging whether patterns are the result of incompleteness of some kind (i.e., are the result of details of database structure) or whether the patterns are consistently replicated across the landscape and thus may have a biological underpinning. We first partitioned the landscape into units of 100 km of river reach (starting at the foot of Glen Canyon Dam and working downstream), starting from a digital basemap of the region (ESRI 1993). We then subdivided each 100km segment into four units each 25km in length. The 25km units were then each subdivided into five 5km reaches.

To analyze range collapse of the humpback chub from a multi-scale perspective, we have to define, for each time period of interest, the species' occurrence pattern on each of the three scales. To do this, each occurrence record of humpback chub in the SONFISHES database was assigned to a particular 5km reach. By virtue of our hierarchically nested map structure, this assignment process also associated each record with a particular 25km reach and with a 100km reach. On each scale, we can characterize "occupied" reaches as those with at least one occurrence record assigned there during a particular time period. A reach switches from occupied to empty status when no future occurrence records are known from that reach. Our assumptions about the nature of decline in the distribution of humpback chub mean that a reach is treated as occupied during the time before its first known record. Because we focus on presence-absence only, duplicate records (i.e., two or more occurrence records from a reach within a given time period) do not affect our assessments.

Because smaller scale reaches are nested within larger scale reaches, considering distributions at larger scales actually "fills in" gaps in distributions at smaller scales. For example, if records exist for only 7 out of the 20 possible 5 km reaches within one 100km reach, analyses at the 5 km scale treat the empty cells as real gaps in the distribution but analyses at the 100km scale treat the entire 100km as occupied. Thus, this multi-scale approach is advantageous because it facilitates alternative perspectives on the same dataset. For example, analyses may be conducted even when there is concern about the degree to which spatial surveys are locally complete or when there is concern that coarse scale analyses may ignore crucial, habitat-specific disjunctions in a species' distribution.

The SONFISHES database affords a long-term perspective on range collapse.

SONFISHES details the distributions of native freshwater fishes in the Sonoran Desert ecoregion over ~160 years, including records from the Mexican-American Boundary Survey of the 1840s to the present. The database contains incidence, identity, and collecting data for the complete holdings of the major museum collections of Sonoran fishes (ANSP, AMNH, ASU, BYU, MCZ, MSW, UANM, UANL, UMMZ, UNLV, USNM [abbreviations adopted from Leviton et al. 1985]), numerous lesser collections, plus records from peer-reviewed and "gray" literature sources. In total, SONFISHES comprises 20,000+ locality records (representing millions of specimens) for all 52 native freshwater fish taxa in the Sonoran ecoregion; 204 of these occurrence records are for *Gila cypha.*

To interpret the contents of SONFISHES, we adopt a conceptual framework in which changes in species distributions are underlain by an ecological model of "range collapse." In this context, spatial data, in which only a portion of the region is likely to be sampled in a given year, are cumulated over a series of years to obtain the total distribution for that time frame. When a total distribution is available for two or more such time frames, changes in distribution can be assessed. Fagan et al (2002) used this range collapse approach to examine changes in distribution of native Sonoran fishes, comparing historic distributions (pre-1980) with modern distributions (post-1980). A unique strength of this approach is its ability to avoid pitfalls associated with differential sampling efforts between periods. Provided one has confidence in the completeness of the more recent of any two total distributions losses in distribution can be assessed without concern for the differential duration of time frames. The key assumption here is that if a species was observed present in a reach at time t, then the species is assumed to have also occupied that reach for all preceding times. Note that because of this assumption concerning temporal occurrence patterns, the range collapse framework provides a striking contrast with the more familiar "metapopulation model" of species' distributions in which local extinctions are counterbalanced by colonization from occupied areas.

Analysis 1: The apparent rate of range collapse of humpback chub

The 204 occurrences that SONFISHES records for *Gila cypha* within the Lower Basin of the Colorado River fall into 27 distinct 5 km reaches (Fig. 1). This distribution, which translates into 15 reaches at the 25 km scale and 6 reaches at the 100km scale, is interpreted as the maximum historical distribution of the species within the study area. The record that occurs most down river is from an archeological source (dated ~1000 AD), and is included here to provide a portrait of distributional change that is as complete as possible. Only 7 occurrence records are known between the time of this prehistoric record and the completion of the Glen Canyon Dam.

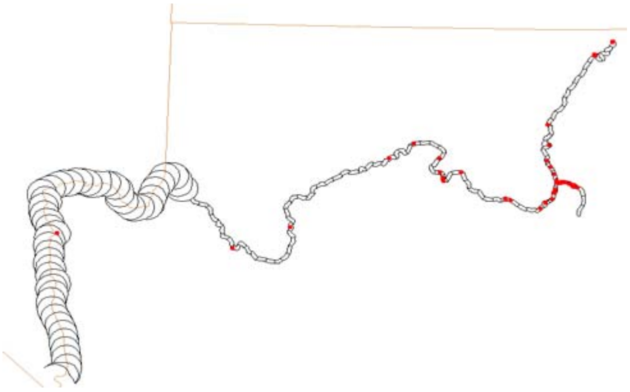

Figure 1. Distribution of *Gila cypha* within the Lower Basin of the Colorado River. Segments bounded by thin black lines are 5 km reach segments (different widths have no meaning in the context of this analysis). Red dots are occurrence records. Brown lines are state boundaries.

Adopting the range collapse perspective described above, analysis of the SONFISHES database suggests that by far the majority of distributional change for *Gila cypha* has occurred in the last decade. Figure 2 summarizes the stepwise loss of reach occupancy at each of the three scales.

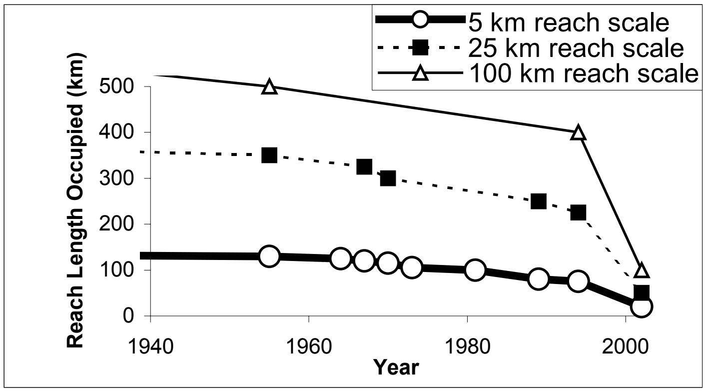

Figure 2. Stepwise loss of reach occupancy for *Gila cypha* within the Lower Basin of the Colorado River. Symbols indicate years when the species distribution shrank based on an analysis of the last known date occupied for each reach (at each scale).

Currently, self-sustaining populations of *Gila cypha* are only known to occur in the lower ~15-20 km of the Little Colorado River, and most other fish found in the Colorado are strays from this population. These changes in spatial distribution can also be examined in terms of apparent spatial rates of extinction (i.e., losses in km/yr based on the distributional information available for each scale). This perspective suggests that the rate of range collapse since the initiation of hypolimnetic releases from Glen Canyon Dam in 1970 exceeded the comparable rate for the period between completion of the dam in 1963 and 1970, and that both of these rates exceeded the "background" rate calculable using the few data that preceded the dam (Table 1).

Table 1. Apparent changes in spatial distribution and rate of range collapse for *Gila cypha* in the Lower Basin of the Colorado River. Data for the pre-1963 time frame assume that *Gila cypha* persisted at the downriver archaeological locality into the 20th century. If it did not than the spatial extinction rate for that time frame is an overestimate of actual loss. Unassigned reaches represent a change in distribution that could not be assigned to a time frame because the date of extinction fell on the boundary of two time frames.

	Reach Length Lost (km)			Spatial Extinction Rate (km/yr)		
Time Frame	5 km	25km	100km	5 km	25km	100km
Pre 1963	5	25	100	0.1	0.4	1.6
1964-1970	10	25	0	1.4	3.6	0.0
1971+	95	250	300	3.0	7.8	9.4
Unassigned	5	25	100			

Analysis 2: The apparent rate of range collapse of humpback chub relative to other fish species

Fagan et al. (2002) used data from SONFISHES to examine the degree to which a species' historic distribution predisposed it to local extinction risk during modern times. Among the data presented in that paper is a table of extinction risk (calculated at the 5km scale) for each of 25 fish species native to the Lower Basin of the Colorado River. The analysis uses 1980 as a cutoff point between "historic" and "modern" because that time corresponds to a switch in the source of distributional data within SONFISHES. Prior to 1980, distributional data came primarily from academic ichthyologists. After 1980, almost all of the records come from resource management sources such as the Arizona Game and Fish Department. The modern records in the SONFISHES database are almost exclusively by-products of intensive efforts by federal or state agencies to determine species' complete distributions prior to listing decisions under the US or Mexican Endangered Species Acts. This change in rationale for the collecting is reflected in a substantial increase in record-density (i.e., records per year) in the database. *Gila cypha* has been extensively studied since ~1970 by several independent workers/agencies (Suttkus et al. 1976, Carothers and Minckley 1981, Kubly 1990, Valdez and Ryel 1995, Douglas and Marsh 1996). Consequently, the spatial distribution of this species is among the best understood of all native fish species in the Lower Basin.

We use this 1980 breakpoint to assess the spatial losses of *Gila cypha* relative to the losses of other fish species native to the Lower Basin at each of three spatial scales using 5km, 25km, and 100km reach segments. Spatial losses of *Gila cypha* are substantial, exceeding 50% on each of the three scales of analysis (Figure 3). On the 5km scale, *Gila cypha* ranks 10th among 25 native fishes of the Lower Basin in terms of proportion of range lost by 1980. On the 25 km scale, it ranks 7th, and on the 100 km scale it ranks 9th. Losses to the distribution of *Gila cypha* have continued since 1980, but we lack some key data that would enable us to place those additional losses in context relative to the losses of other native species. With only 50-100 km of reach occupied (depending on the scale of analysis; Fig. 2), the current distribution of *Gila cypha* is the fourth most restricted of 25 native fish species in the Lower Basin on the 25km and 100km scales and is the sixth most restricted on the 5km scale.

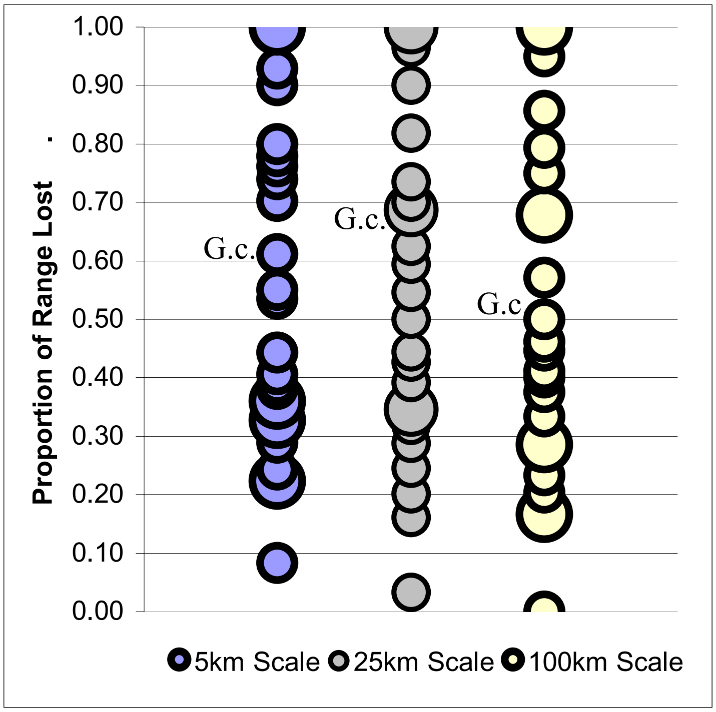

Figure 3. Range losses of *Gila cypha* (denoted G.c.) relative to those of 24 other native fishes of the Lower Basin of the Colorado River at each of three spatial scales of analysis. Small circles give the proportion of range lost for individual species; large symbols indicate when two species exhibited the same degree of loss. For each species range, reaches for which no occurrences were observed from 1981 to the present were considered extirpated. With even a single record post-1980 a species was considered extant in a given reach.

Some Caveats to the Interpretation of these Data

Analyses of species' spatial distributions are only useful if the underlying data are accurate and complete relative to the spatial scale of the analysis. We believe these criteria are met for *Gila cypha,* and the consistency of results from each of the three spatial scales of analysis suggests that the distributional patterns are not artifacts of database structure. Nevertheless, there are some potential concerns that should be recognized. First, any analysis of spatial collapse like those in Fig. 2 and Table 1 have the potential to bias upwards estimates of rates of loss during the most recent time periods. This is because new distributional records found any time in the future could switch river reaches currently classified as "empty" to "occupied", and thereby decrease the apparent rate of spatial extinction. In statistical terms, the occurrence data are "right-censored." The thoroughness with which the remnant populations of *Gila cypha* have been studied in recent decades suggests this kind of situation will be very unlikely. Second, estimates of the background rate of range collapse during the pre-1963 period are limited by the paucity of data from that time period. Nothing in the SONFISHES database suggests that *Gila cypha* was undergoing any kind of spatial collapse before the construction of the dam, but data to test that idea in any truly rigorous way are not available. Third, because *Gila cypha* is a long-lived species (at least 20 years), its population dynamics may exhibit time lags in response to changes in its habitat or environmental conditions. This is especially true with regard to spatial attributes of its populations (e.g., distributional extent), and even today extensive mark-recapture efforts are necessary to disentangle the difference between total spatial distribution and breeding spatial distribution for the species.

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APPENDIX B

RISKS CONSIDERED IN THE QUALITATIVE RISK ANALYSIS

APPENDIX B

RISKS CONSIDERED IN THE QUALITATIVE RISK ANALYSIS

OPERATIONAL

1. Mechanical Outages of Turbines
2. Maintenance Scheduling at Glen Canyon Dam
3. Increased operational complexity if less than 6-8 TCD units
4. Drought below lower intake of TCD
5. Greater need to keep people and boats away from GCD

PHYSICAL/CHEMICAL

6. Attainment of 15º Temp at GCD mainstem April
7. Attainment of 15º Temp at GLD mainstem May-Dec
8. Dissolved oxygen downstream
9. Suspended sediments (turbidity)
10. Entrainment & bed re-working
11. Sediment Budget (export)

BIOLOGICAL

Basal Resources

12. Export of nutrients (N,P)
13. Export of C (POC, DOC) = allochthonous resources
14. Change in (Marco algae species composition)
15. Change in taxonomic composition of periphyton
16. Change in primary production (periphyton+macroalgae)

Invertebrates

17. Change in composition of macroinvertebrates
18. SecondarypProduction of invertebrates
19. Mud Snails

Warmwater Non Native Species

20. WW Reservoir Fish (shad, st. bass) entrainment and release into tailwater
21. Number of warmwater fish (channel catfish, common carp) at LCR
22. Number of warmwater fish migrating up from Lake Mead
23. Establishment of new exotic species populations
24. Predation effects of warmwater alien fish on HBC in LCR reach
25. Competition effects of warmwater alien fish with HBC in LCR reach

Diseases

26. Water diseases (bacteria)
27. Likelihood of whirling disease
28. Water parasites (Asian tapeworm)

Humpback Chub

29. Humpback chub spawning
30. Direct Humpback Chub Recruitment in mainriver

Non Native Coldwater

31. Effects on trout spawning in Glen Canyon reach
32. Direct effects on trout numbers in Glen Canyon reach
33. Effects on trout size in Glen Canyon reach
34. Effects on brown trout numbers in LCR reach
35. Predation effects of trout on HBC in LCR reach
36. Competition effects of trout & HBC in LCR reach

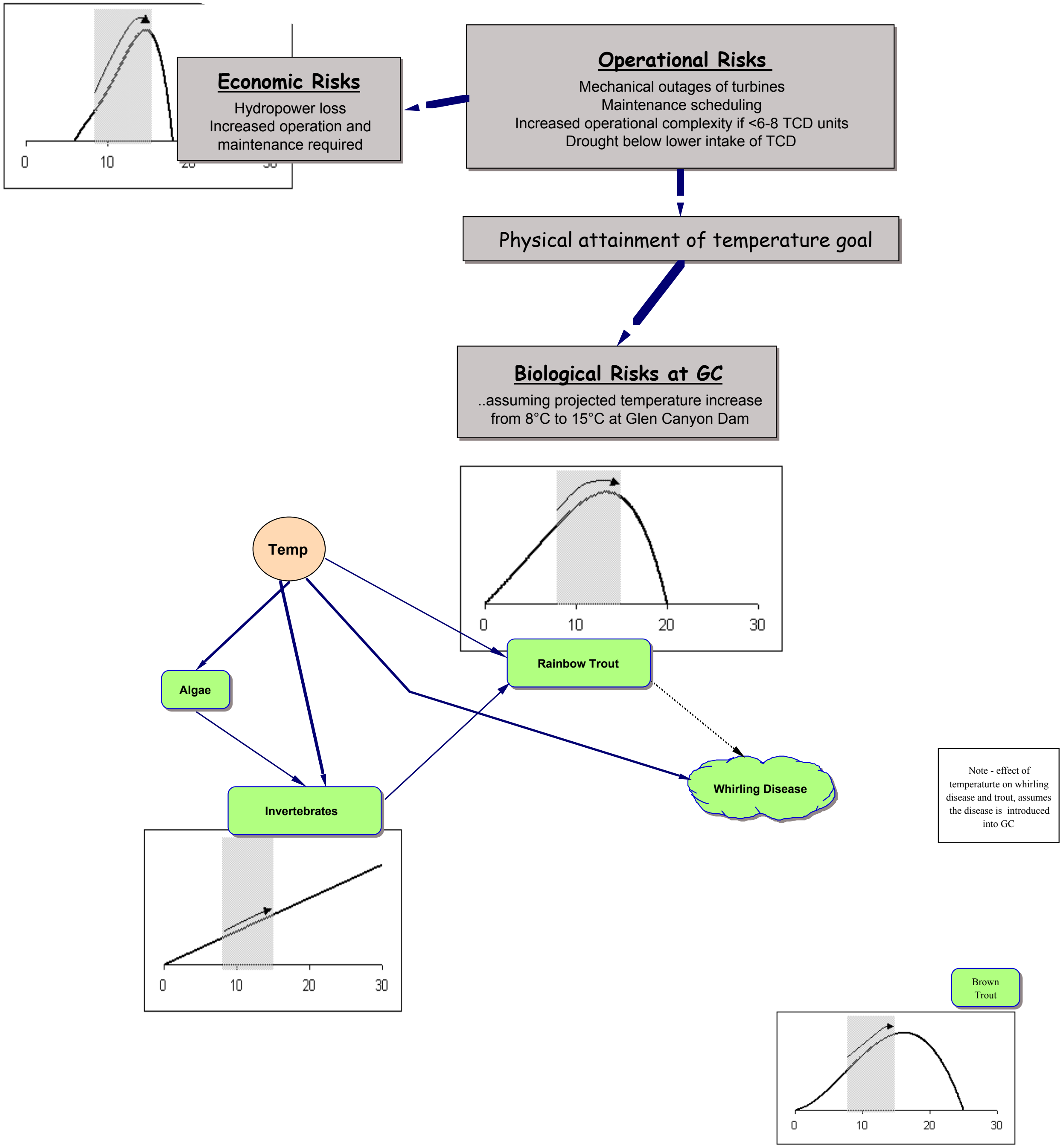
ECONOMIC

37. Hydropower losses (most likely reduced when operating)
38. Hydropower losses due to increased maintenance downtime
39. Construction costs
40. Increased O&M Costs at Glen Canyon Dam
41. Increased GCMRC monitoring, research costs of physical, bio, cultural, social
42. Monitoring TCD operation w/adaptive management to optimize resource benefits
43. Recreational trout fisheries

APPENDIX C

CONCEPTIONAL MODEL FIGURES

Glen Canyon Dam and Glen Canyon Reach



Economic Risks

Hydropower loss
Increased operation and
maintenance required

Operational Risks

Mechanical outages of turbines
Maintenance scheduling
Increased operational complexity if <6-8 TCD units
Drought below lower intake of TCD

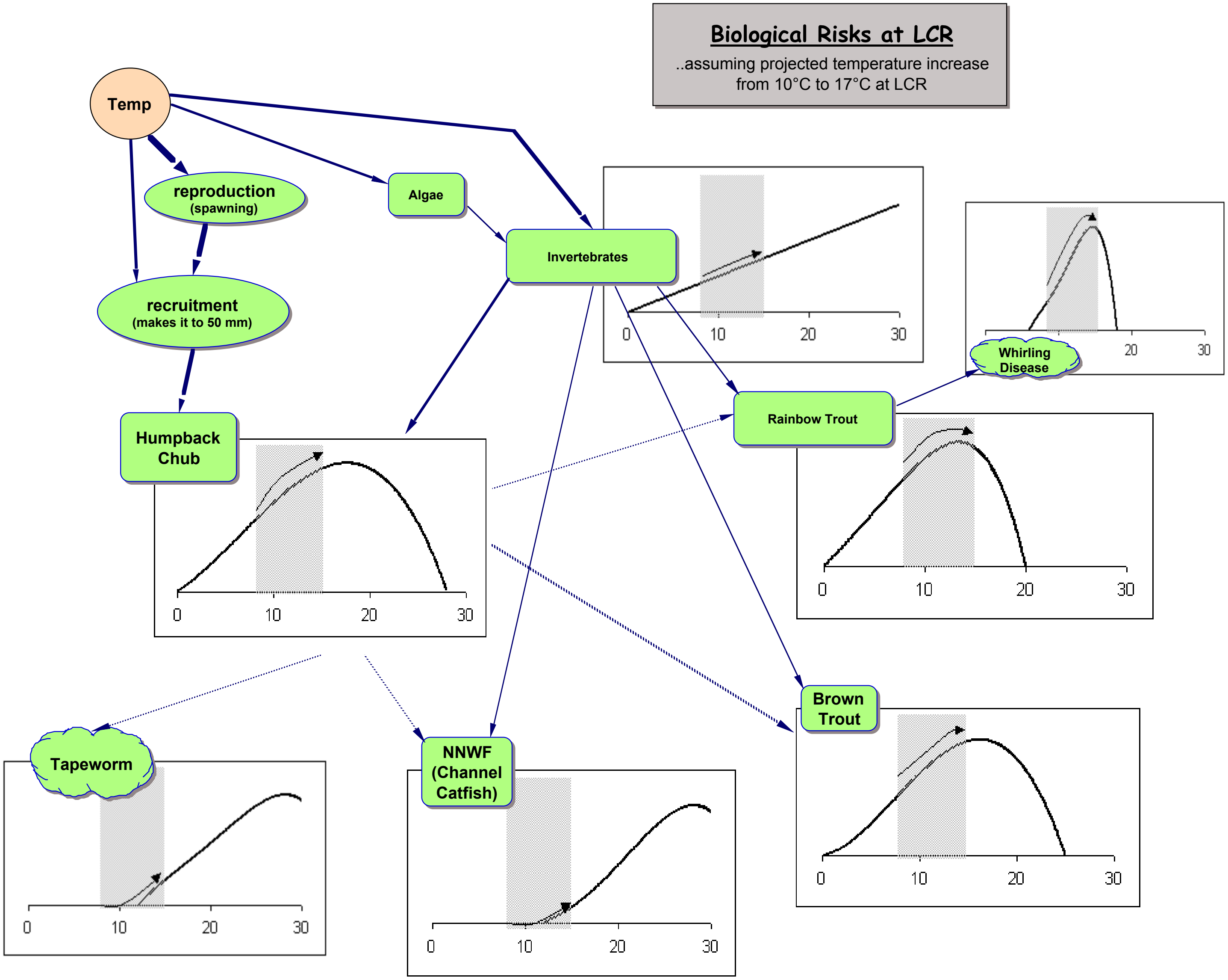
Physical attainment of temperature goal

Biological Risks at GC

..assuming projected temperature increase
from 8°C to 15°C at Glen Canyon Dam

Note - effect of temperaturte on whirling disease and trout, assumes the disease is introduced into GC

Lower Colorado River Reach

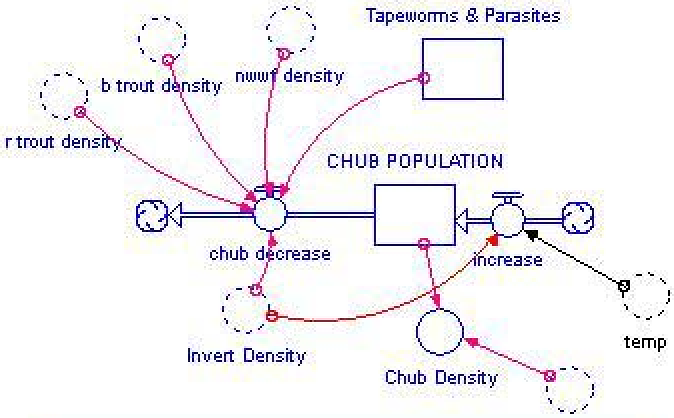


Biological Risks at LCR

..assuming projected temperature increase
from 10°C to 17°C at LCR

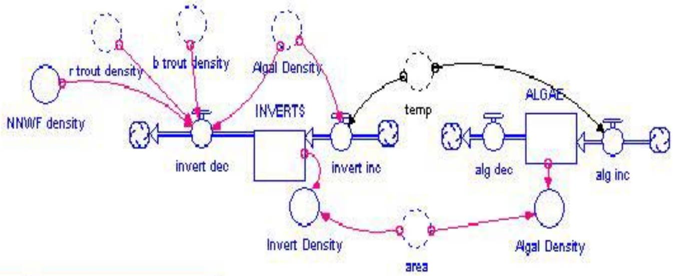
Assumptions:16-22C optimal for chub spawning and larval survival; for brown trout 13- 19C; for rainbow trout 10-16C with upper limit of 20C; for channel catfish 26-30C; whirling begins infections at 9C, peaks at 14.5C and declines to zero at 18.5C; for tapeworm maturation of eggs 25-30C; algae and invertebrates assumed to increase (productivity) with temperature increase as thermal tolerances for all not expected to be exceeded (note NZ mud snail has ca. zero growth at 0C and max tolerance ca. 33C. References in literature cited.

HUMPBACK
CHUB



See larger schematic for fuller view. Note - dashed lines around some compartments indicate there is a submodel to describe that compartments dynamics, so for e.g., temperature effects on all compartments except chub not shown here

FOOD RESOURCES

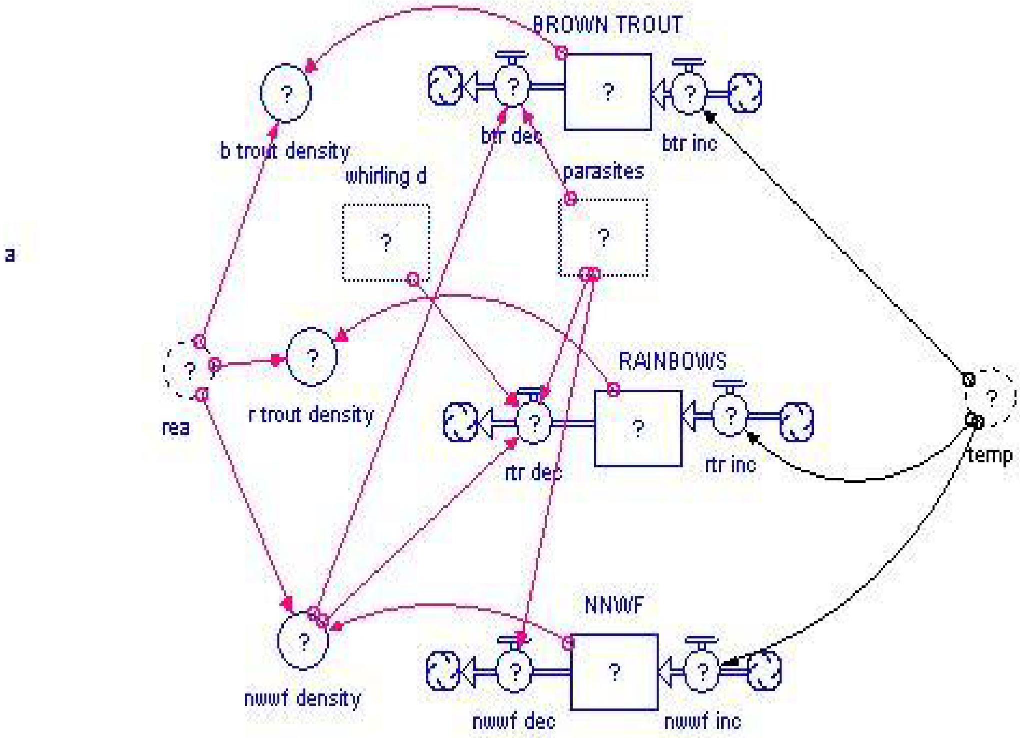


Algae (=Cladophora) - affected by Temp, inverts

Inverts - affected byTemp, Algae, Chub, NNWF

Question: Is standing stock algae affected by fish?
(we assumed it is incidental ingestion of Cladophora
...could split off periphyton.)

PREDATORS

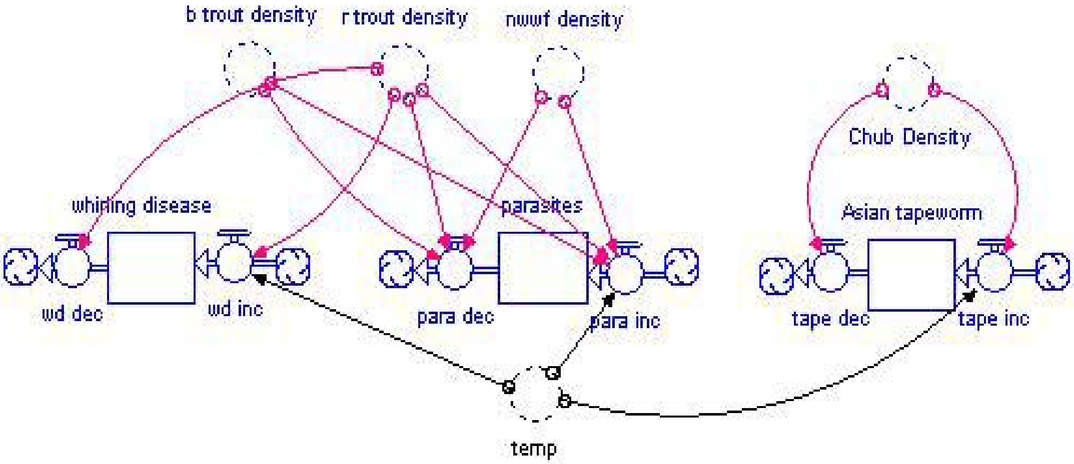


Brown Trout - affected by temp, Chub, NNWF, parasites, Inverts

Rainbow Trout - affected by temp, Chub, NNWF, whirling disease, parasites, inverts

Non-native warm water fish - affected by Temp, Chub, trout , parasites, Inverts

PARASITES and DISEASES
(%) INFECTED



Whirling disease - affected by trout, nonnative warm
water fish (note - assume fish can not only incr wd,
but dcr if fish host pop gets too low)
Parasites - affected by trout, nonnative warm
fish (note - same assumption as for wd)
Tapeworm -affected by chub (note - same