U.S. Bureau of Reclamation | Upper Colorado Region

Benefits and Risks of Temperature Modification at Glen Canyon Dam to Aquatic Resources of the Colorado River in the Grand Canyon

Salt Lake City, Utah | Final Review – September 2013

Cover Photo:

Glen Canyon Dam in 1983 with releases through the four bypass valves and the spillway (Bureau of Reclamation photo). Highest release was 92,600 cfs on June 29, 1983.

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Benefits and Risks of Temperature Modification at Glen Canyon Dam to Aquatic Resources of the Colorado River in Grand Canyon

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EXECUTIVE SUMMARY

1. The Colorado River through the Grand Canyon was transformed from a seasonally-warmed river to one with less variable and colder temperature following completion of Glen Canyon Dam in 1963. Pre-dam river temperature ranged from 0°C to 30°C and post-dam temperature ranged from 7°C to 12°C as Lake Powell filled and the reservoir remained full during 1974–2003. From 2004 to 2011, reservoir elevation dropped, the penstocks began to entrain warm surface water, and dam release temperatures reached a high of 16°C in October and November.
2. The recent and ongoing drought in the Colorado River Region and the prospect of future but unpredictable low reservoir elevations introduces a level of uncertainty for managers and raises questions about the need and efficacy of thermal modification. It also introduces the possibility that temperature modification may need to be designed to withdraw water from a range of elevations, including deeper cold levels to offset a prolonged period of warm releases that may cause undesirable effects on cold-adapted species, such as trout.
3. Cold dam release temperatures have affected the aquatic communities downstream of the dam, and a temperature control device (TCD) has been identified to provide warmer temperatures that are more suitable for key aquatic species. Warmer water may benefit desirable species, but may also promote populations of undesirable species that are predators, competitors, and parasites of native fishes.
4. A TCD at the dam penstocks would allow warmer water to be taken from the surface of Lake Powell, and seasonal air temperatures would warm the water with distance downstream from the dam. The effects of modifying 2, 4, and 8 penstocks were evaluated at five locations on available temperature degree-days for 46 aquatic species, including 35 fishes, 4 fish parasites, and 7 aquatic invertebrates.
5. Post-dam cold-water releases (i.e., No Action) favor primarily reproduction and growth of brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*), and walleye (*Sander vitreus*) for about 250 miles downstream to Separation Canyon.
6. A 2-unit TCD would provide suitable temperatures for all life stages of the five cold-water fish species; brown trout, rainbow trout, walleye, redside shiner (*Richardsonius balteaus*), and smallmouth bass (*Micropterus dolomieu*) at all

locations, and would provide suitable growth temperatures for up to 13 other nonnative and native warm-water species.

7. A 4-unit TCD would provide suitable temperatures for all life stages of brown trout, rainbow trout, walleye, redside shiner, and smallmouth bass, as well as striped bass (*Morone saxatilis*), razorback sucker (*Xyrauchen texanus*), roundtail chub (*Gila robusta*), flannelmouth sucker (*Catostomus latipinnis*), and gizzard shad (*Dorosoma cepedianum*) as far downstream as Havasu Creek; a 4-unit TCD would also provide suitable growth temperatures for 16 other nonnative and native species.
8. An 8-unit TCD would provide suitable temperatures for all life stages of 10 fish species below the dam and at RM 30, including brown trout, rainbow trout, walleye, striped bass, razorback sucker, roundtail chub, flannelmouth sucker, gizzard shad, Colorado pikeminnow (*Ptychocheilus lucius*), bonytail (*Gila elegans*), and red shiner (*Cyprinella lutrensis*); an 8-unit TCD would also provide suitable growth temperatures for 16 other nonnative and native species. Downstream of the LCR, an 8-unit TCD would provide suitable temperatures for spawning by 18 to 21 fish species, including the 11 species named above as well as native bluehead sucker (*Catostomus discobolus*), humpback chub (*Gila cypha*), and speckled dace (*Rhinichthys osculus*); and nonnative golden shiner (*Notemigonus crysoleucas*), sand shiner (*Notropis stramineus*), largemouth bass (*Micropterus salmoides*), mosquitofish (*Gambusia affinis*), blue tilapia (*Oreochromis aureus*), common carp (*Cyprinus carpio*), and channel catfish (Ictalurus punctatus).
9. The call for a selective withdrawal program for Lake Powell waters in the 1995 BO was prompted by the perceived need to provide warmer water primarily to allow the endangered humpback chub to complete all of its life cycle in the mainstem Colorado River in Grand Canyon. The thermal regime of the post-dam Colorado River is too altered for the completion of all life stages of the humpback chub. Temperatures are not sufficiently warm for mainstem reproduction (16–22ºC), except for a short time in late summer in the most downstream reaches of the lower Grand Canyon, and suitable temperatures for growth (14–25ºC) are available for only a short time in summer. The implementation of a 2-unit TCD would provide limited benefit for humpback chub, and the greatest benefit for spawning and growth would be provided with a 4 or 8-unit TCD.

10. Predicted temperatures were suitable for tubifex worms, which are the host of whirling disease, at all locations under No Action, 2, 4, and 8-unit TCDs. Temperatures were not suitable under No Action for parasitic copepods (*Lernaea cyprinacea*) and host activity of the Asian tapeworm (*Bothriocephalus acheilognathi*) and trout nematode (*Dactnitis truttae*) at any of the five locations. With a 2-unit TCD, temperatures were suitable for host activity and infestation of whirling disease (*Myxobolus cerebralis*) at all locations, but suitable only for infestation by trout nematodes, except at the downstream-most location (i.e., Separation Canyon, RM 240), where trout do not occur. With 4 and 8 units, temperatures would be suitable for both life stages of only for whirling disease, whereas temperatures would continue to be too cold for host activity of the Asian tapeworm, parasitic copepod, or trout nematode; the exception is that temperatures would be suitable at Separation Canyon for completion of life stages of the parasitic copepod. Without warming, conditions are generally not suitable for these parasites, except for whirling disease.
11. Modifying 2 or 4 penstocks would provide greater temperature degree-days for some common beneficial invertebrates, such as the freshwater amphipod (*Gammarus lacustris*), midges (*Chironomus* sp.), and blackflies (*Simulium arcticum*), although other stenothermic invertebrates species may not be able to adjust to a wider range of temperatures. Warming would also improve temperature conditions for the New Zealand mudsnail (*Potamopyrgus antipodarum*), currently found in large numbers in Grand Canyon and for the quagga mussel (*Dreissena bugensis*), not currently found in Grand Canyon. However, warming would not likely provide suitable mainstem temperatures for reproduction and growth of the red swamp crayfish (*Procambarus clarkii*) or the northern crayfish (*Orconectes virilis*), although these species may prosper in isolated off-channel habitats.
12. The water temperatures of the Colorado River downstream from Glen Canyon Dam lack strong seasonal variability, which may prevent successful colonization by native insects that historically lived in this river. Such variability would be desirable for returning certain invertebrate species to the system. However, it is important to note that attaining this variability through any known strategy or dam modification is not currently possible.

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1.0 INTRODUCTION

1.1 Background

The Colorado River is a seasonally-warmed river that was impounded near the Utah/Arizona state line by Glen Canyon Dam in 1963 (see cover photo and Figure 1). The dam draws cold clear water from the depths of Lake Powell and releases it downstream, where it is affected by seasonal air temperatures over nearly 300 miles to Lake Mead. The river flows through Glen Canyon National Recreation Area and Grand Canyon National Park and supports a variety of important and valued resources (Gloss et al. 2005). These resources are monitored and managed by the Glen Canyon Dam Adaptive Management Program (GCDAMP), a Federal Advisory Committee established under the Grand Canyon Protection Act of 1992 (Public Law 102-575, GCPA) that provides for dam operations *"in such a manner as to protect, mitigate adverse impacts to, and improve the values for which Grand Canyon National Park and Glen Canyon National Recreation Area were established, including, but not limited to natural and cultural resources and visitor use."*

The natural resources of the Colorado River are supported by a complex aquatic ecosystem comprised of many temperature-sensitive species (Walters et al. 2000). These include the endangered humpback chub (*Gila cypha*), found as nine aggregations in the Grand Canyon (Figure 1); and the endangered razorback sucker (*Xyrauchen texanus*) that occurs in the lower Grand Canyon and Lake Mead inflow (Valdez and Ryel 1995; Valdez et al. 2012a). Three additional native fish species occur in the region, and there is a blue-ribbon trout fishery in the dam tailwater. A suite of nonnative fish species also inhabits the region; many are predators of native fish and competitors for habitat. The river supports a thermally-modified food base consisting of native and introduced invertebrates that transition toward native forms with distance downstream from the dam and increasing influence of tributaries.

Thermal modification of dam has been proposed to provide more suitable water temperature for key aquatic resources, but the effects of a modified thermal regime are not well known. This document assesses the benefits and risks associated with modifying dam release temperatures on 48 selected aquatic species of the Colorado River through Grand Canyon, including 35 fishes, 4 fish parasites, and 7 invertebrates.

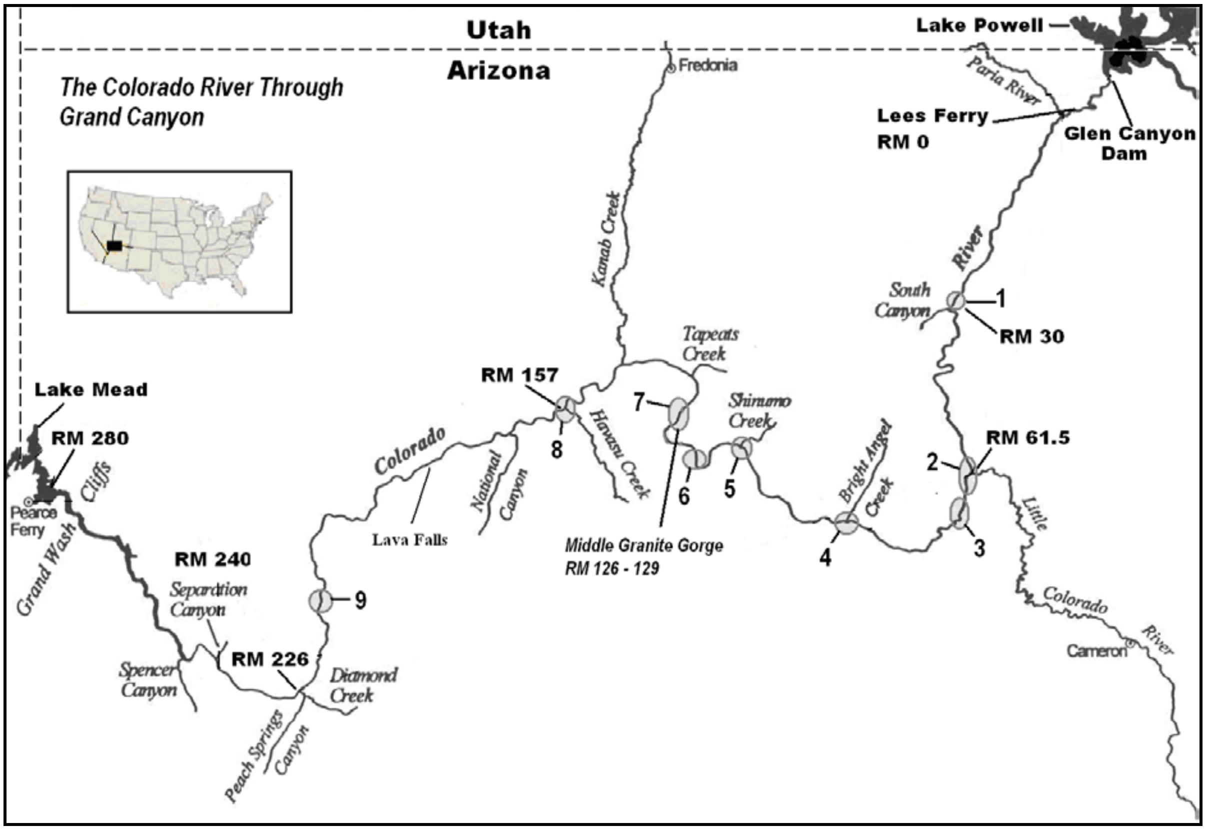

Figure 1. Map of the Colorado River from Glen Canyon Dam to Lake Mead, a distance of about 300 miles. The nine aggregations of humpback chub are shown in numbered grey ovals. River Miles (RM) are distance downstream from Lees Ferry, which is 15 miles downstream from Glen Canyon Dam.

1.2 Genesis of Temperature Modification at Glen Canyon Dam

The effect of cold-water releases on downstream aquatic resources through the Grand Canyon has long been a concern (U.S. Fish and Wildlife Service 1978; U.S. Department of the Interior 1988; Carothers and Brown 1991). Further study of temperature modification was identified as a common element of the 1995 Glen Canyon Dam Environmental Impact Statement (U.S. Department of the Interior 1995, 1996), and in the 1995 Final Biological Opinion (Opinion) that directed the Bureau of Reclamation (Reclamation) to *"…implement a selective withdrawal program for Lake Powell waters…"* and to determine effects of temperature modification on the reservoir and on downstream resources, especially native and endangered fishes.

Following the 1995 Opinion, Reclamation investigated the feasibility of modifying the dam to release warmer water, and in January 1999, released a Draft Environmental

Assessment (EA) for a temperature control device (TCD) on Glen Canyon Dam (U.S. Bureau of Reclamation 1999). The 1999 EA identified a valve planning study that was conducted in 1997 to screen various design alternatives that could modify the intakes of the dam (i.e., penstocks for the eight power generators) for desired temperature releases and to develop appraisal level costs. The planning study identified five design proposals that included: (1) use the existing spillway structure to release warm surface water from the reservoir; (2) remove the top of the trashrack structure and install a gate at the penstock intake; (3) control overdraw through the existing trashrack structure; (4) install an external frame structure with flat gates for variable level withdrawal; and (5) install a curtain to direct warm surface water from the forebay. The cost of the structural proposals ranged from $15,000,000 to $148,500,000.

A review of the EA expressed concern for unintended negative effects (i.e., nonnative fish proliferation) as a result of the operation of a TCD, as well as the lack of a detailed science plan to measure those effects (Mueller 1999). The EA was withdrawn before being finalized, and in 1999 and 2001, Reclamation convened workshops of scientists and managers to evaluate the feasibility of a TCD and to further develop a research and monitoring program that would evaluate ecosystem responses to warmer dam releases. A study with a hydraulic model was conducted in 1999 to collect hydraulic design data; and to develop modifications, as necessary, to improve hydraulic performance (Vermeyen 1999). This study used data for head losses, submergence criteria, near-field velocities, vortex formation potential, and qualitative water hammer pressures.

An assessment by the Glen Canyon Dam Adaptive Management Program (GCDAMP) Science Advisors (Garrett et al. 2003) recommended the installation of a TCD on Glen Canyon Dam as soon as possible and the construction of a pilot TCD in the interim, but resource agencies, especially the U.S. Fish and Wildlife Service (Service), continued to express concern over possible nonnative fish proliferation. Reclamation continued to work on assessing a TCD by utilizing the U.S. Army Corps of Engineers' CE-QUAL-W2 model to predict dam release temperatures (Cole and Wells 2008). The 1-D Generalized Environmental Modeling System for Surface Waters (GEMSS; Kolluru and Fichera 2003) was used to model temperatures from Glen Canyon Dam to Separation Canyon; and the 3-D GEMSS model was used to predict backwater temperatures below the confluence of the Little Colorado River (LCR).

In 2007, Reclamation completed a preliminary risk assessment to evaluate responses of aquatic resources in Grand Canyon to the construction and implementation of a 2-unit and a 4-unit TCD (Valdez and Speas 2007). That risk assessment used a categorical approach for quantifying life history parameters similar to risk assessment protocols used by the U.S. Environmental Protection Agency (CENR 1999; Nico et al. 2005; NRC 1983; RAM 1998; USEPA 1985, 2000, 2005, 2006). Reviewers of that document (Andersen et al. 2007) requested an analysis based on species temperature requirements; i.e., temperature degree-days. This document addresses that need and uses required temperature magnitude and duration (expressed as temperature degree-days) for species and life history stages as a comparison with available predicted dam releases temperatures. A subsequent review of the revised document recommended a more comprehensive evaluation that could be used by managers in deliberation on whether to construct a TCD (Budy et al. 2011).

This document evaluates temperature changes that would take place with 0, 2, 4, or all 8 of the dam penstocks modified to entrain warmer surface water from the reservoir. Modifications of 2, 4, or 8 penstocks are represented as a 2-unit, 4-unit, or 8-unit TCD, respectively, which represents the number of penstocks that would withdraw water from the warmer near-surface layers of the reservoir. These dam release temperatures also provide insight into the effect of temperature modification that might be achieved by other means, such as large impellers or a curtain in the forebay of the dam.

2.0 EFFECT OF DAM ON THERMAL REGIME

2.1 Overview of Dam Design and Operation

Glen Canyon Dam was completed in 1963 as a concrete archway dam with a structural height of 710 feet (ft) and a crest elevation of 3715 ft (Figure 2). At its full pool elevation of 3700 ft, Lake Powell holds 27 million acre feet (maf) of water and is 560 ft deep at the dam. Water is released from the dam at three elevations through right and left spillways (3648 ft), eight power penstocks (centerline of 3470 ft), and four bypass valves (3374 ft). Each penstock is 15 ft in diameter with a combined capacity of about 33,100 cfs, and the combined capacity of the bypass valves is about 15,000 cfs. Water is generally not released through the bypass valves except for emergencies or special releases. Water is released through the spillway only when the reservoir is high and only for emergency or test purposes. Neither the bypass valves nor the spillways are equipped with power generators (see U.S. Department of the Interior 1995, 1999 for additional information on dam operations).

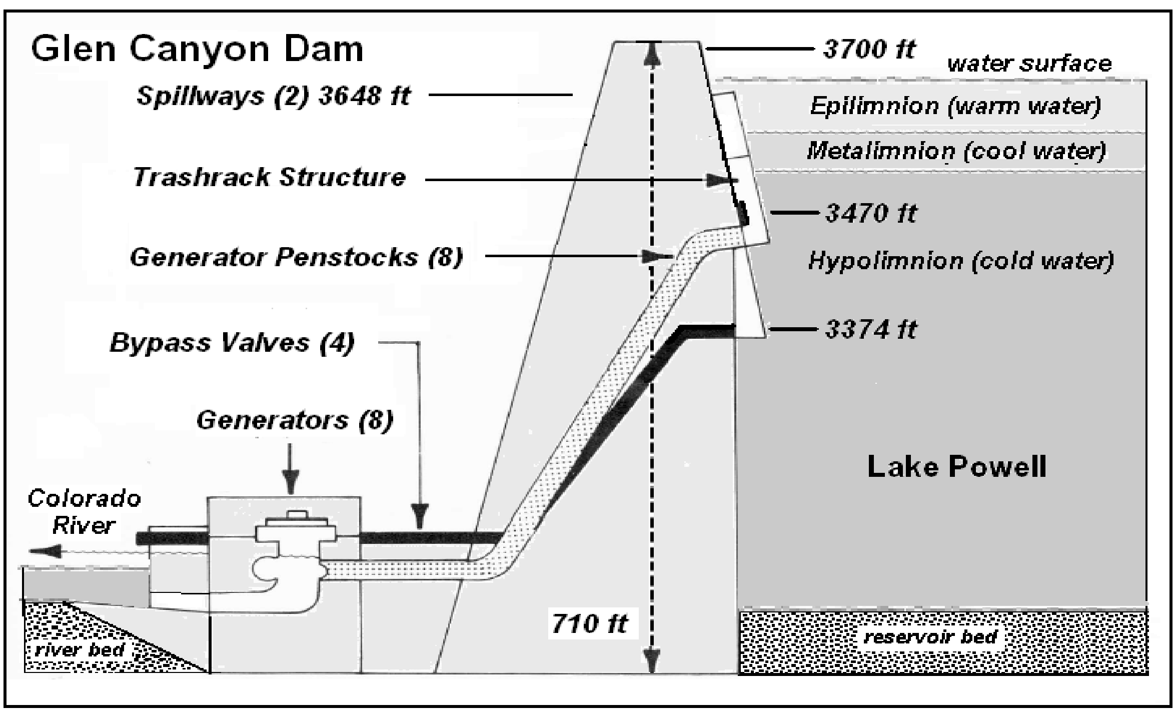

Figure 2. Cross-section of Glen Canyon Dam with spillway elevation, trashrack structure, generator penstocks, bypass valves, and generators. Lake Powell stratifies in summer with a warm water surface layer (epilimnion), a mid-level cool mixed layer (metalimnion), and a deep cold layer (hypolimnion).

2.2 History and Background of Dam Release Temperature

For about the first 10 years that Lake Powell was filling (i.e., 1963-1972), water released from Glen Canyon Dam underwent a seasonal variation in temperature as had been seen in the Colorado River prior to dam construction, but with an annual decrease in temperature range as the reservoir deepened (Figure 3; see also Voichick and Wright 2007). Starting in about 1973, as the reservoir rose to an elevation of about 3600 ft, the temperature of water released from the dam began to vary less, and by 1974 release temperature was generally in the range of only 7°C to 12°C. From 1974 to 2003, dam release temperature remained in this range because the elevation of the reservoir stayed high and the power intakes continued to draw water from the deep cold layer (i.e., hypolimnion; see Figure 2). Water from the warmest surface layer (i.e., epilimnion) and the middle layer (i.e., metalimnion) was not withdrawn from these intakes during the high reservoir elevations.

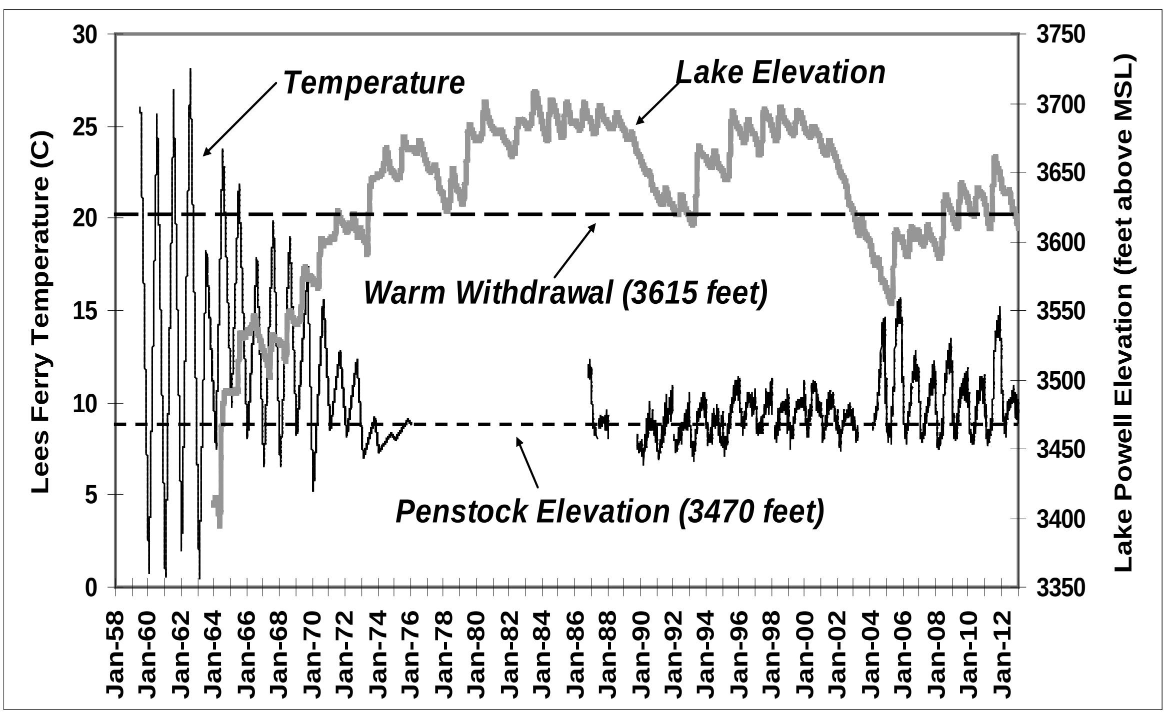

Figure 3. Elevation of Lake Powell and mean daily water temperature of the Colorado River at Less Ferry. Temperature data from July 1959 through December 1975 were compiled from USGS Water Supply Papers. Data from October 1986 through December 2012 are from the USGS gage at Lees Ferry (09380000), which was used as the primary source of temperature data because of its long period of record (1986-present); the gage is about 15 miles downstream of Glen Canyon Dam and water temperature differs from releases <0.5°C. Lake Powell elevation data are from Bureau of Reclamation, Upper Colorado Region Reservoir Operations, http://www.usbr.gov/uc/crsp/GetDataSet?.

2.3 Reservoir Elevation and Temperature

In February of 2003, the elevation of Lake Powell dropped to an historic low of 3615 ft and by April 2005, the reservoir reached its lowest level since filling of 3555 ft during an extended period of drought in the Colorado River Region (see Figure 3). For the first time in 30 years (1974-2003), average daily summer and fall temperature at Lees Ferry exceeded 12°C, and continued to do so from 2004 to 2011.

Mean daily temperature of the Colorado River at Lees Ferry is shown in Figure 4 for a 12-year period, including the 9 years of warm releases, 2004-2011. There was little difference in daily temperature among years between January and mid-May, but differences in temperature became apparent in June and July and exceeded 14°C between mid-July and late November of 2005 and from September through November of 2004, 2005, and 2011. Warmest temperature for the 9-year period occurred during the months of September, October, and November. Temperature recorded at 20-minute intervals below the dam showed maximums of 15.75°C on November 2, 2004; 16.39°C on October 14, 2005; and 15.41°C on November 12, 2011 (Grand Canyon Monitoring and Research Center [GCMRC], http://www.gcmrc.gov/dasa/tabdata/).

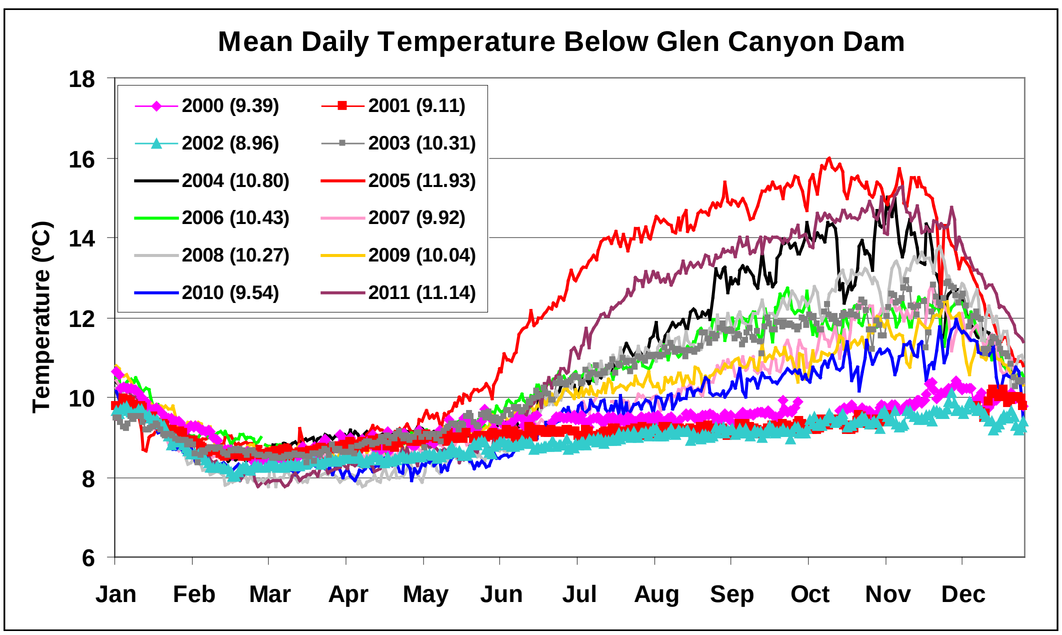

Figure 4. Mean daily temperature of releases from Glen Canyon Dam for the period 2000–2011. Mean annual water temperature is shown in parentheses after each year. Temperature data from Grand Canyon Monitoring and Research Center, http://www.gcmrc.gov/dasa/tabdata/.

For the period 2000 through 2004, it appeared that dam release temperature was directly related to reservoir elevation, among and within years, as indicated by annual temperature/elevation signatures (Figure 5), with releases of >14°C occurring at a reservoir elevation of <3570 ft. However, warm releases at higher elevations in 2005 and especially in 2011, made it apparent that release temperature was not related to lake elevation alone (also reported by Vernieu et al. 2005). The warmest release temperature of 16.4°C on October 14, 2005, occurred at a reservoir elevation of 3602 ft, about the same elevation as 2003, 2006, and 2007 (i.e., 3600-3615 ft), when maximum release temperatures were 3-4°C cooler.

Warmest dam release temperatures also did not occur at lowest elevations because of seasonal temperature differences. In 2008, minimum reservoir elevation of 3588 ft occurred in March, but warmest temperature of 13.5°C occurred in November at a higher elevation of 3624 ft. Similarly, in 2011, minimum reservoir elevation of 3610 ft occurred in April, but maximum temperature of 15.4°C occurred in November when the reservoir was much higher at 3650 ft. The variable temperature of reservoir elevation among years indicates that a fixed level withdrawal system may not produce an expected or desired dam release temperature, as the temperature in the forebay may differ for the same elevation among years.

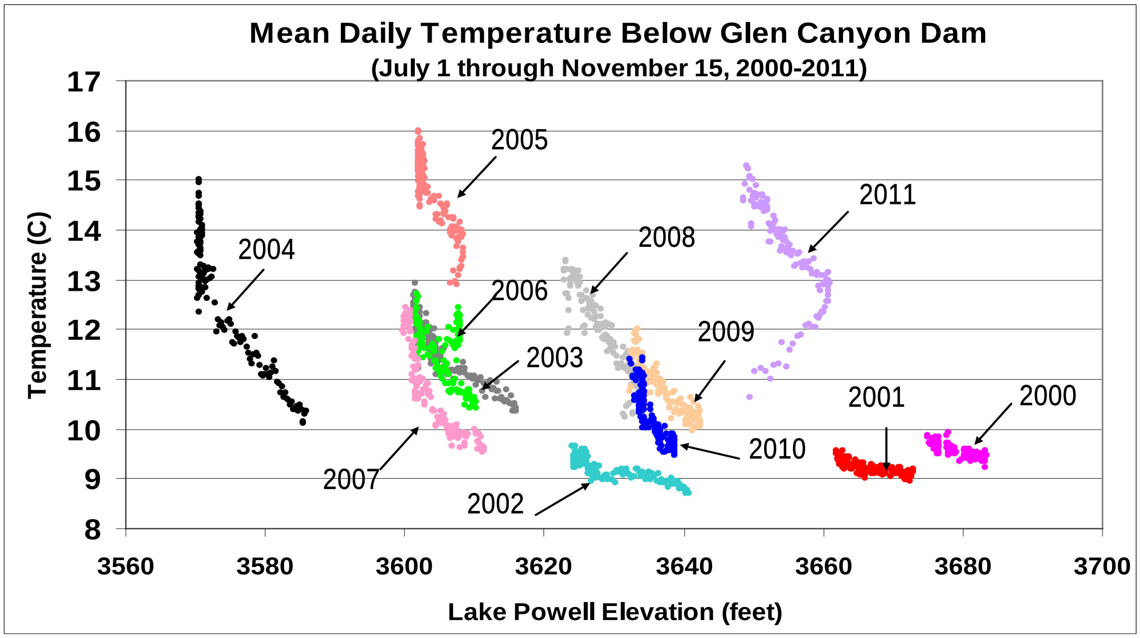

Figure 5. Annual signatures of mean daily temperature of the Colorado River below Glen Canyon Dam at corresponding reservoir elevation for July 1 through November 15, 2000-2011. Temperature data from Grand Canyon Monitoring and Research Center, http://www.gcmrc.gov/dasa/tabdata/. Lake Powell elevation data from Bureau of Reclamation, Upper Colorado Region Reservoir Operations, http://www.usbr.gov/uc/crsp/GetDataSet?.

Dam release temperature can vary among years, depending on several factors, including reservoir elevation, time of year, wind, thickness of thermal stratification (especially the epilimnion and metalimnion), volume and temperature of reservoir inflow, and volume and timing of dam releases (Vernieu et al. 2005). One of the most immediate and influential factors is reservoir elevation and the proximity of the metalimnion and epilimnion layers to the penstock intakes, combined with the effect of fall overturn (i.e., destratification) when these warm layers mix into the colder underlying hypolimnion near the penstocks. Water temperature of Lake Powell in the dam forebay for 2008-2009 (U.S. Department of the Interior 2012) showed a maximum surface temperature of 28°C in July, but water at the 50-m depth (164 ft) did not reach a maximum temperature of 11°C until October and November (Figure 6). For the same time period (June 2008-June 2009), the water depth above the centerline of the penstock intakes (3470 ft) ranged from about 43 m (140 ft) to 50 m (164 ft). Dam release temperature for the same time period followed the same pattern as temperature at the 50-m depth, but up to 2°C warmer, indicating that water was being drawn at and above the 50-m level and from a mixed zone during destratification and mixing. This phenomenon of delayed warming of water down to about 50 m below the reservoir surface helps to explain the later seasonal warming pattern of dam releases with peaks in September, October, and November (see Figure 4), and is an important factor when evaluating thermal modification as a benefit to key species with temperature-sensitive life stages that are seasonal.

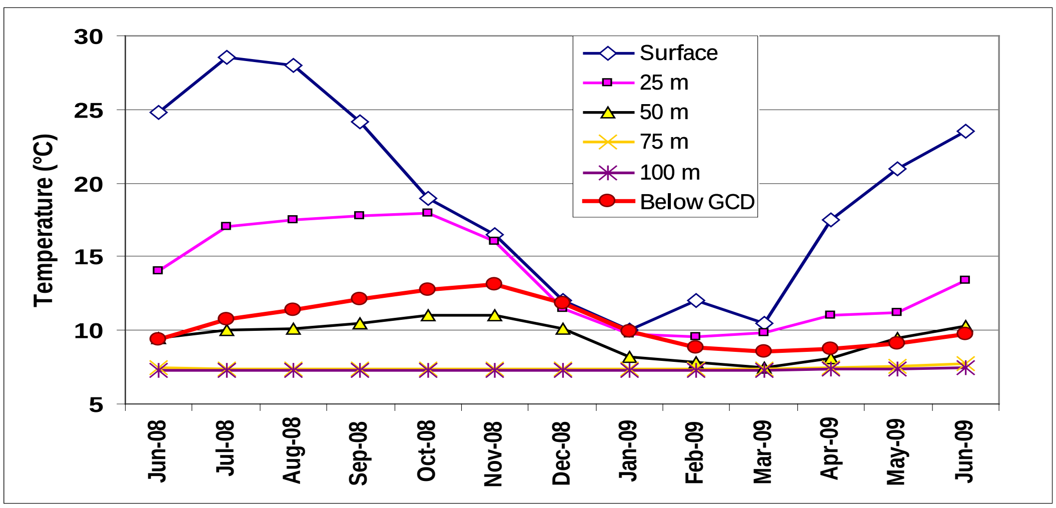

Figure 6. Water temperature at five depths in the Glen Canyon Dam forebay and below Glen Canyon Dam, June 2008 to June 2009. Note the 75 and 100-m temperatures are virtually the same. Data for five depths from U.S. Department of the Interior (2012); temperature data below Glen Canyon Dam from Grand Canyon Monitoring and Research Center, http://www.gcmrc.gov/dasa/tabdata/.

The phenomenon of large western reservoirs warming later with increasing depth to about 50 m is illustrated with mean daily temperatures at depths of 2 m to 140 m for Lake Mead during 2010-11 (Figure 7). Although the temperature at depths of 2 m and 5 m was greatest in July, temperature at 35 m to 50 m was warmest in late October and early November. This phenomenon of delayed warming with depth is attributed primarily to the fall turn over in which the warm surface water mixes with the underlying layers starting in about September. The mixing continues until temperatures cool sufficiently to produce nearly isothermal condition through winter. Lake Powell has a similar vertical temperature profile to Lake Mead and Figure 7 illustrates how warmer water can be withdrawn into the Glen Canyon Dam penstocks when the reservoir is low and the penstocks withdrawal creates sufficient current to entrain the warmer water during the fall turn over.

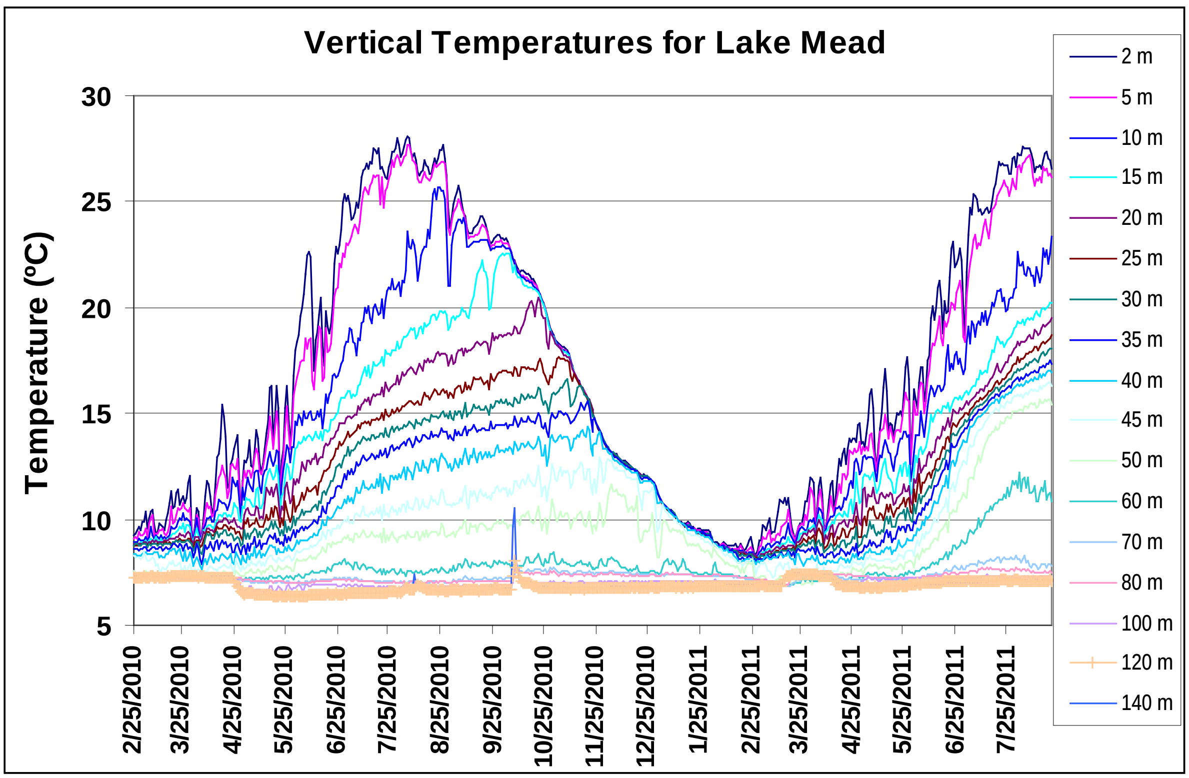

Figure 7. Mean daily temperatures for Lake Mead at depths of 2 m to 140 m for February 25, 2010 to August 20, 2011. Temperature data from: http://nevada.usgs.gov/water/lmqw/index.htm.

2.4 Future Projected Reservoir Elevation

The low reservoir elevations and resulting warm releases seen in 2004–2011 are likely to reoccur. The long-term projection for Lake Powell shows a high probability of low reservoir elevation in the next 15 years, whereby 8 of 11 traces (73%) drop below 3615 ft elevation (Figure 8); an elevation at which warm releases were first seen during 2004-2007. Given the pattern of annual historic and projected hydrological events (U.S. Department of the Interior 2011a, 2011b), low reservoir elevation is likely to occur for several consecutive years.

The recent and ongoing drought in the Colorado River Region and the prospect of future but unpredictable low reservoir elevations introduces a level of uncertainty for managers and raises questions about the need and efficacy of thermal modification. It also introduces the possibility that temperature modification may need to be designed to withdraw water from a range of elevations, including deeper cold levels to offset a prolonged period of warm releases that may cause undesirable effects on cold-adapted species, such as trout.

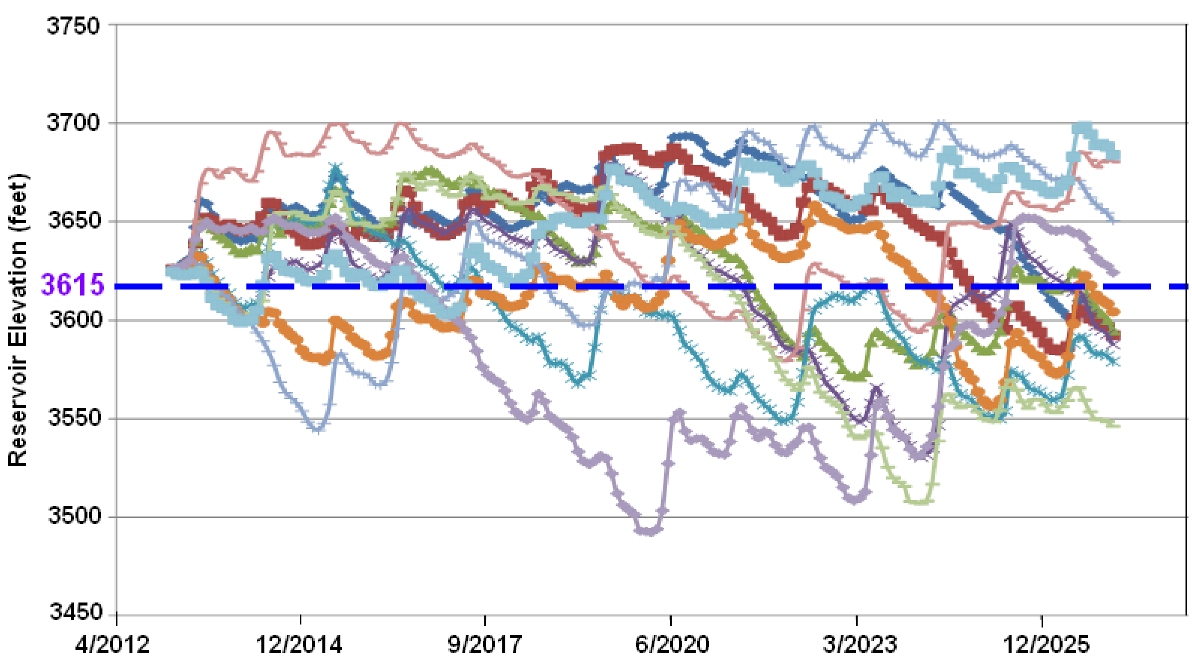

Figure 8. Eleven traces for Lake Powell elevation for 2012 to 2027. The traces show a high probability of lower reservoir elevation and warm releases in the next 15 years; warm releases generally occur when the reservoir drops below about 3615 ft elevation (horizontal dashed blue line). Traces from Bureau of Reclamation, CRSS results April 2012, unpublished data.

3.0 METHODS TO EVALUATE TEMPERATURE

3.1 Temperature Requirements of Aquatic Species

Forty-eight aquatic species from the Colorado River were evaluated including 35 fishes, 4 fish parasites, and 7 aquatic invertebrates (Table 1). Temperature information was assimilated (Valdez and Speas 2013; see Appendix A: Sources of Temperature Data) and requirements were identified for ovulation, incubation, and growth of 35 fish species (Table 2; Valdez and Ryel 1995; Gloss and Coggins 2005). Temperature requirements were also identified for infestation and host activity of four species of fish parasites, including the Asian tapeworm, parasitic copepod, trout nematode, and whirling disease (Table 3). The Asian tapeworm was first reported from minnows and suckers of Grand Canyon in 1990 (Clarkson et al. 1997; Brouder and Hoffnagle 1997) and the parasitic copepod was first found on fish in 1979 (Carothers et al. 1981). The trout nematode is found in the intestines of rainbow trout and brown trout in the tailwater fishery, and whirling disease was reported in rainbow trout in the tailwater in June of 2007 (U.S. Fish and Wildlife Service 2008).

Seven selected invertebrate species were also evaluated (Table 4), including three common forms that are important to the aquatic food web (i.e., amphipods, midges, and blackflies) and four invasive species that could complete their life cycles with warmer river temperatures, including the New Zealand mudsnail, quagga mussel, red swamp crayfish, and northern crayfish. The New Zealand mudsnail was first identified from samples collected in Grand Canyon in March 2002, and analysis of archived collections revealed that mudsnails were present as early as May 1995 (Kennedy and Gloss 2005). The mudsnails now dominate the biomass and production of the tailwater invertebrate assemblage below Glen Canyon Dam (Rosi-Marshall et al. 2010). The quagga mussel has not been found below the dam, but was found in Lake Powell in 2013 and in Lake Mead in 2007, as well as further downstream in Lakes Mohave and Havasu and in the Colorado River Aqueduct. Although the risk for quagga mussels or zebra mussels (*Dreissena polymorpha*) establishing in the Colorado River is low, these could become established in the Lees Ferry tailwater where water clarity, temperature, and nutrient concentrations are suitable (Kennedy 2007). The red swamp crayfish was recently discovered in Grand Canyon (Personal communication, Emile Omana, Grand Canyon National Park), and the northern crayfish is common in Arizona.

Table 1. Common and scientific names and status of aquatic species evaluated.

Common Name	Scientific Name	Status in Grand Canyon
Fishes (35)		
Black bullhead	*Ameiurus melas*	Uncommon, found in tributaries and backwaters
Black crappie	*Pomoxis nigromaculatus*	Rare, originates from Lakes Powell or Mead
Blue tilapia	*Oreochromis aureus*	Not present; found in Lake Mead
Bluegill	*Lepomis macrochirus*	Rare, originates from Lakes Powell or Mead
Bluehead sucker	*Catostomus discobolus*	Native, common in mainstem and tributaries
Bonytail	*Gila elegans*	Endemic, extirpated from Grand Canyon
Brown trout	*Salmo trutta*	Locally abundant in and near cold tributaries
Burbot	*Lota lota*	Not present, found in Green River and reservoirs
Channel catfish	*Ictalurus punctatus*	Uncommon in mainstem, common in tributaries
Colorado pikeminnow	*Ptychocheilus lucius*	Endemic, extirpated from Grand Canyon
Common Carp	*Cyprinus carpio*	Common in mainstem and tributaries
Fathead minnow	*Pimephales promelas*	Locally common in backwaters and tributaries
Flannelmouth sucker	*Catostomus latipinnis*	Endemic, common in mainstem and tributaries
Flathead catfish	*Pylodictis olivaris*	Not present; found in downstream warm waters
Gizzard shad	*Dorosoma cepedianum*	Rare, originates from Lakes Powell or Mead
Golden shiner	*Notemigonus crysoleucas*	Rare in mainstem and tributaries
Grass carp	*Ctenopharyngodon idella*	Not present; found in Arizona ponds
Green sunfish	*Lepomis cyanellus*	Uncommon in backwaters and tributaries
Humpback chub	*Gila cypha*	Endemic, present as nine aggregations
Largemouth bass	*Micropterus salmoides*	Uncommon in backwaters and tributaries
Mosquitofish	*Gambusia affinis*	Locally common in backwaters and tributaries
Plains killifish	*Fundulus zebrinus*	Locally common in backwaters and tributaries
Rainbow trout	*Oncorhynchus mykiss*	Locally abundant in tailwater, mainstem, tribs
Razorback sucker	*Xyrauchen texanus*	Endemic, not present; population in Lake Mead
Red shiner	*Cyprinella lutrensis*	Common along shorelines and tributaries
Redside shiner	*Richardsonius balteatus*	Rare along shorelines and tributaries
Roundtail chub	*Gila robusta*	Endemic, extirpated
Sand shiner	*Notropis stramineus*	Not present, abundant in upper basin
Smallmouth bass	*Micropterus dolomieu*	Uncommon, found in Grand Canyon in 2004
Speckled dace	*Rhinichthys osculus*	Native, abundant along talus slopes and debris fans
Striped bass	*Morone saxatilis*	Uncommon, originates from Lakes Powell or Mead
Threadfin shad	*Dorosoma petenense*	Rare, originates from Lakes Powell or Mead
Utah chub	*Gila atraria*	Not present, locally abundant in upper basin
Walleye	*Sander vitreus*	Uncommon, originates from Lakes Powell or Mead
Yellow bullhead	*Ameiurus natalis*	Uncommon, found in lakes Mead and Powell
Fish Parasites (4)		
Asian tapeworm	*Bothriocephalus acheilognathi*	Present in minnows and suckers since 1990
Parasitic copepod	*Lernaea cyprinacea*	Present since 1979; common in warm tributaries
Trout nematode	*Dactnitis truttae*	Present in rainbow trout and brown trout
Whirling disease	*Myxobolus cerebralis*	Found in rainbow trout at Lees Ferry in 2007
Invertebrates (7)		
Freshwater amphipod	*Gammarus lacustris*	Introduced in 1970's as food source after dam
Midges	*Chironomus* sp.	Most common invertebrate species
Blackflies	*Simulium arcticum*	Common in mainstem and tributaries
New Zealand mudsnail	*Potamopyrgus antipodarum*	Present since 1995; abundant since mid-2000

Common Name	Scientific Name	Status in Grand Canyon
Quagga mussel	*Dreissena bugensis*	Not present; found in Lakes Mohave and Havasu
Red swamp crayfish	*Procambarus clarkii*	Uncommon in mainstem
Northern crayfish	*Orconectes virilis*	Probably not present; common in Arizona waters

Table 2. Temperature requirements for ovulation, incubation, and growth of 35 fish species that are found in or near the Colorado River in Grand Canyon (Valdez 2008). Minimum (Min.), Maximum (Max.), and Optimum (Opt.) temperatures are in degrees centigrade.

Common Name	Code	Ovulation			Incubation			Growth		
		Min.	Max.	Opt.	Min.	Max.	Opt.	Min.	Max.	Opt.
Black bullhead[1]	BB	20	25	21	20	27	20	22	34	25
Black crappie[1]	BC	14	18	16	15	22	17	16	30	27
Blue tilapia[1]	TL	16	29	27	20	30	27	21	30	28
Bluegill[1]	BG	19	22	20	21	24	23	18	22	21
Bluehead sucker[2]	BH	16	25	18	16	20	18	16	30	27
Bonytail[2]	BT	15	27	20	17	27	24	16	26	21
Brown trout[3]	BR	7	14	10	8	20	10	8	20	15
Burbot[3]	BU	1	4	2	1	7	4	4	12	10
Channel catfish[1]	CH	16	26	19	18	24	19	14	22	20
Colorado pikeminnow[2]	CP	15	30	23	15	25	24	14	28	24
Common Carp[1]	CC	16	28	20	19	22	21	18	28	24
Fathead minnow[1]	FH	16	25	20	18	23	20	12	22	20
Flannelmouth sucker[2]	FM	14	25	19	14	23	18	14	22	20
Flathead catfish[1]	FC	22	29	26	22	29	27	24	30	26
Gizzard shad[1]	GZ	14	24	20	18	28	21	14	24	20
Golden shiner[1]	GD	16	30	24	18	26	24	16	28	24
Grass carp[1]	GP	19	24	20	21	24	23	18	23	22
Green sunfish[1]	GS	19	27	20	20	26	20	15	25	23
Humpback chub[2]	HB	16	25	22	19	25	22	14	25	22
Largemouth bass[1]	LM	16	30	25	16	29	25	16	27	25
Mosquitofish[1]	MF	16	28	23	20	30	24	14	30	27
Plains killifish[1]	PK	21	28	23	21	28	26	25	32	27
Rainbow trout[3]	RB	6	13	10	7	15	10	8	21	16
Razorback sucker[2]	RZ	14	22	18	14	25	19	14	24	20
Red shiner[1]	RS	15	25	18	17	23	20	15	21	18
Redside shiner[3]	RD	10	18	15	12	20	18	12	22	18
Roundtail chub[2]	RT	14	22	16	16	22	18	14	24	18
Sand shiner[1]	SS	16	26	18	16	27	19	14	22	18

Common Name	Code	Ovulation			Incubation			Growth		
		Min.	Max.	Opt.	Min.	Max.	Opt.	Min.	Max.	Opt.
Smallmouth bass[3]	SM	12	18	16	14	18	15	14	26	23
Speckled dace[2]	SD	16	30	22	20	24	22	14	28	22
Striped bass[1]	SB	14	24	18	16	26	18	16	30	24
Threadfin shad[1]	TS	20	30	28	20	30	28	20	30	25
Utah chub[1]	UC	14	20	16	14	20	18	16	30	23
Walleye[3]	WE	6	13	7	6	14	13	7	23	21
Yellow bullhead[1]	YB	19	31	22	19	24	23	22	31	30

[1]Fishes grouped as nonnative, warm-water species (21)
[2]Fishes grouped as native, warm-water species (8)
[3]Fishes grouped as nonnative, cold-water species (6)

Table 3. Temperature requirements for host activity and infestation of four fish parasite species of the Colorado River in Grand Canyon. Minimum (Min.), Maximum (Max.), and Optimum (Opt.) temperatures are in degrees centigrade. Sources of temperature data are provided in footnotes.

Common Name	Code	Host Activity			Infestation		
		Min.	Max.	Opt.	Min.	Max.	Opt.
Asian tapeworm[1]	AT	18	20	19	20	30	25
Parasitic copepod[2]	LC	20	30	25	18	30	25
Trout nematode[2]	TN	16	20	18	16	20	18
Whirling disease[3]	WD	5	10	8	11	18	14

[1]Granath and Esch (1983)
[2]Hoffman (1967)
[3]Gilbert and Granath (2003)

Table 4. Temperature requirements for life functions of seven selected aquatic invertebrate species of the Colorado River. Minimum (Min.), Maximum (Max.), and Optimum (Opt.) temperatures are in degrees centigrade. Sources of temperature data are provided in footnotes.

Common Name	Code	All Life Functions		
		Min.	Max.	Opt.
Freshwater amphipod[1]	GA	5	26	18
Midges[2]	MI	10	30	15
Blackflies[3]	BF	11	28	20
New Zealand mudsnail[4]	NZ	2	28	19
Quagga mussel[6]	QM	4	20	12
Northern crayfish[5]	NC	10	30	24
Red swamp crayfish[5]	RC	16	30	25

[1]Smith (1973)
[2]Nebeker (1973)
[3]Shipp et al. (1988)
[4]Aquatic Nuisance Species Task Force (http://www.anstaskforce.gov/spoc/nzms.php)
[5]http://el.erdc.usace.army.mil/ansrp/ANSIS/html/orconectes_virilis_northern_crayfish
[6]Huner and Barr (1981)

3.2 Computation of Temperature Degree-Days

A temperature degree-day is a useful metric for standardizing the effect of temperature on life-history events of poikilothermic organisms that may be differentially affected by a given temperature regime. Degree-days combine temperature and time in computing total heat requirement for a variety of processes. A degree-day is defined as an average of 1°C above a certain threshold temperature for one day (Neuheimer & Taggart 2007). The threshold temperature used in this analysis was the species-specific minimum temperature required for a given life process or life stage; i.e., ovulation, incubation, or growth. The minimum temperature is a biological threshold below which development of the life process is negligible (Hempel 1979). For example, if the temperature for 3 consecutive days was 16, 19, and 23°C for a species with a minimum ovulation temperature of 16°C and a maximum of 22°C, total degree days = 1 + 4 + 0 = 5.

Temperature degree-days (TDDs) were computed for each life stage of 35 fish species using a TDD calculator developed in Microsoft Excel® using the following steps:

1. Minimum, maximum, and optimum temperature requirements were derived for each species and life stage (i.e., ovulation, incubation, and growth) through a literature search (Valdez and Speas 2013) and stored on an individual worksheet (Table 2).
2. Predicted mean daily temperature for each of the five locations (see section 3.3) for 0, 2, 4, or 8 unit TCDs was stored on a separate worksheet. A "Test Temp" worksheet was established for input of mean daily water temperature to be evaluated.
3. Minimum temperature degree days (MTDDs) required each for ovulation, incubation, and growth was computed for each fish species as a product of minimum temperature and duration for each life stage in days (Table 5). This metric provided an estimate of the minimum number of temperature degree-days needed by a species to initiate a given life stage.
4. The total temperature degree-days less than the maximum temperature requirement for each species and life stage (Max TDD) was determined from the mean daily temperature in the "Test Temp" worksheet.
5. The total temperature degree-days less than the minimum temperature requirement for each species and life stage (Min TDD) was also determined from the mean daily temperature in the "Test Temp" worksheet.
6. Net temperature degree-days (NTDDs) were computed as the number of degree-days from minimum to maximum temperature requirements, Max TDD – Min TDD.
7. Suitable temperature degree-days (STDDs) were determined by comparing the MTDDs with the NTDDs. If NTDDs < MTDDs, the STDDs was 0; if NTDDs > MTDDs, the STDDs was equal to the NTDDs.

Table 5. Minimum temperature degree-days (MTDDs) required for ovulation, incubation, and growth by each of 35 fish species in the Colorado River in Grand Canyon. MTDDs were computed as the product of minimum temperature (Min.) and minimum days required at that temperature (Days). Species codes are provided in Table 2.

Species Code	Ovulation			Incubation			Growth		
	Min.	Days	MTDDs	Min.	Days	MTDDs	Min.	Days	MTDDs
BB	20	60	1200	20	5	100	22	30	660
BC	14	60	840	15	4	60	16	30	480
TL	16	60	960	20	7	140	21	30	630
BG	19	60	1140	21	6	126	18	30	540
BH	16	60	960	16	6	96	16	30	480
BT	15	60	900	17	4	68	16	30	480
BR	7	60	420	8	41	328	8	30	240
BU	1	60	60	1	80	80	4	30	120
CH	16	60	960	18	1	18	14	30	420
CP	15	60	900	15	4	60	14	30	420
CC	16	60	960	19	3	57	18	30	540
FH	16	60	960	18	6	108	12	30	360
FM	14	60	840	14	6	84	14	30	420
FC	22	60	1320	22	8	176	24	30	720
GZ	14	60	840	18	4	72	14	30	420
GD	16	60	960	18	4	72	16	30	480
GP	19	60	1140	21	7	147	18	30	540
GS	19	60	1140	20	3	60	15	30	450
HB	16	60	960	19	5	95	14	30	420
LM	16	60	960	16	5	80	16	30	480
MF	16	60	960	20	4	80	14	30	420
PK	21	60	1260	21	5	105	25	30	750
RB	6	60	360	7	31	217	8	30	240
RZ	14	60	840	14	7	98	14	30	420
RS	15	60	900	17	7	119	15	30	450
RD	10	60	600	12	6	72	12	30	360
RT	14	60	840	16	5	80	14	30	420
SS	16	60	960	16	3	48	14	30	420
SM	12	60	720	14	8	112	14	30	420
SD	16	60	960	20	25	500	14	30	420
SB	14	60	840	16	3	48	16	30	480
TS	20	60	1200	20	21	420	20	30	600
UC	14	60	840	14	9	126	16	30	480
WE	6	60	360	6	7	42	7	30	210
YB	19	60	1140	19	5	95	22	30	660

3.3 Predicted Temperatures by Location

Dam release temperatures were predicted for No Action, and for a 2, 4, or 8-unit TCD based on design proposals described in the 1999 Plan and Environmental Assessment (U.S. Bureau of Reclamation 1999). Historical mainstem water temperatures for 1990-2003 were used to predict maximum, minimum, and mean daily temperature using Reclamation's GEMSS® (Generalized Environmental Modeling System for Surface Waters) model. The model simulated warming patterns that would be seen when the reservoir volume is greater than about 15 million acre-feet (~3631 ft elevation), or about 65% of capacity. The No Action alternative (0 units) represents dam release temperatures for the period 1990-2003 in which all releases were from the cold hypolimnetic zone of Lake Powell.

River temperatures were predicted for each of the four alternative dam modifications at five locations: (1) below Glen Canyon Dam (GCD, RM -15), (2) Fence Fault Springs (RM 30), (3) below the Little Colorado River (RM 61), (4) below Havasu Creek (RM 157), and (5) Separation Canyon (RM 240) (see Figure 1). In order to relate locations to distance downstream from the dam, 15 miles was added to each river mile location; i.e., the five locations translate to 0, 45, 76, 172, and 255 miles downstream from the dam.

Maximum, minimum, and mean temperatures were predicted for No Action, and a 2, 4, or 8-unit TCD at each of the five locations at and downstream from Glen Canyon Dam (see Appendix B: Predicted River Temperatures). Three factors affect the river temperature at given locations. The first is dam release temperature that is determined by reservoir elevation and a suite of factors described in section 2.3 above. The temperature at the dam determines the base temperature of the river as it flows downstream and is warmed by solar radiation. Maximum release temperatures in September and October reflect the temperature of the water near the penstocks (see section 2.3).

The second factor affecting river temperature at locations is the longitudinal warming that occurs with distance downstream from the dam. This is driven by seasonal aspects, such as sun angle and the degree of solar radiation that warms the river (Yard 2003). The increased temperature at downstream locations reflects the base dam release temperature and the amount of solar warming. Hence, although dam release temperatures are greatest in September and October, longitudinal warming is greatest in July and August. The third factor is river volume, where the rate of warming is exponentially related to volume (Wright et al., 2008), such that the river warms increasingly faster with reduced volume (see section 3.5).

The mean daily predicted temperatures were used for computing temperature degree-days. The 7-day averages of these mean daily temperatures are shown in Figure 9 for each of the five locations and the four alternative modifications. As a reference and for the purpose of comparison, the mean daily temperature of the Colorado River near Cisco, UT (USGS gage 09180500) is included in each graph of Figure 9. The temperature of the Colorado River near Cisco is not influenced by nearby dams and represents a naturalized temperature regime similar to the historical temperature of the river before Glen Canyon Dam.

Because the graphs shown in Figure 9 are 7-day averages of mean daily temperature, maximum and minimum values are dampened, but the seasonal temperature pattern and the effect of longitudinal warming are self-evident. When compared to the Colorado River at Cisco, river temperatures below the dam warm later with a lower maximum temperature until the river reaches Separation Canyon. The biggest difference is that the temperature of the river below the dam does not drop below about 7°C, whereas the naturalized river upstream drops to 0°C—as did the pre-dam Colorado River through Grand Canyon.

The effect of modifying 2, 4, or 8 units has little effect on temperature from about December through April with temperatures ranging from about 7°C to 12°C. An increase in temperature with all modifications is seen from May to November with highest mean temperatures in July, August, and September of about 22°C at the dam and 25°C at Separation Canyon. Clearly, the greatest increase in temperature occurs with the 8-unit modification and the highest temperatures are reached at the downstream-most locations. The effect of this manner of temperature modification, together with longitudinal warming, is not only to the increase in magnitude of temperature, but also to the expanded time or duration in which warmer temperature occurs. A greater number of days at higher temperature translates to more degree-days.

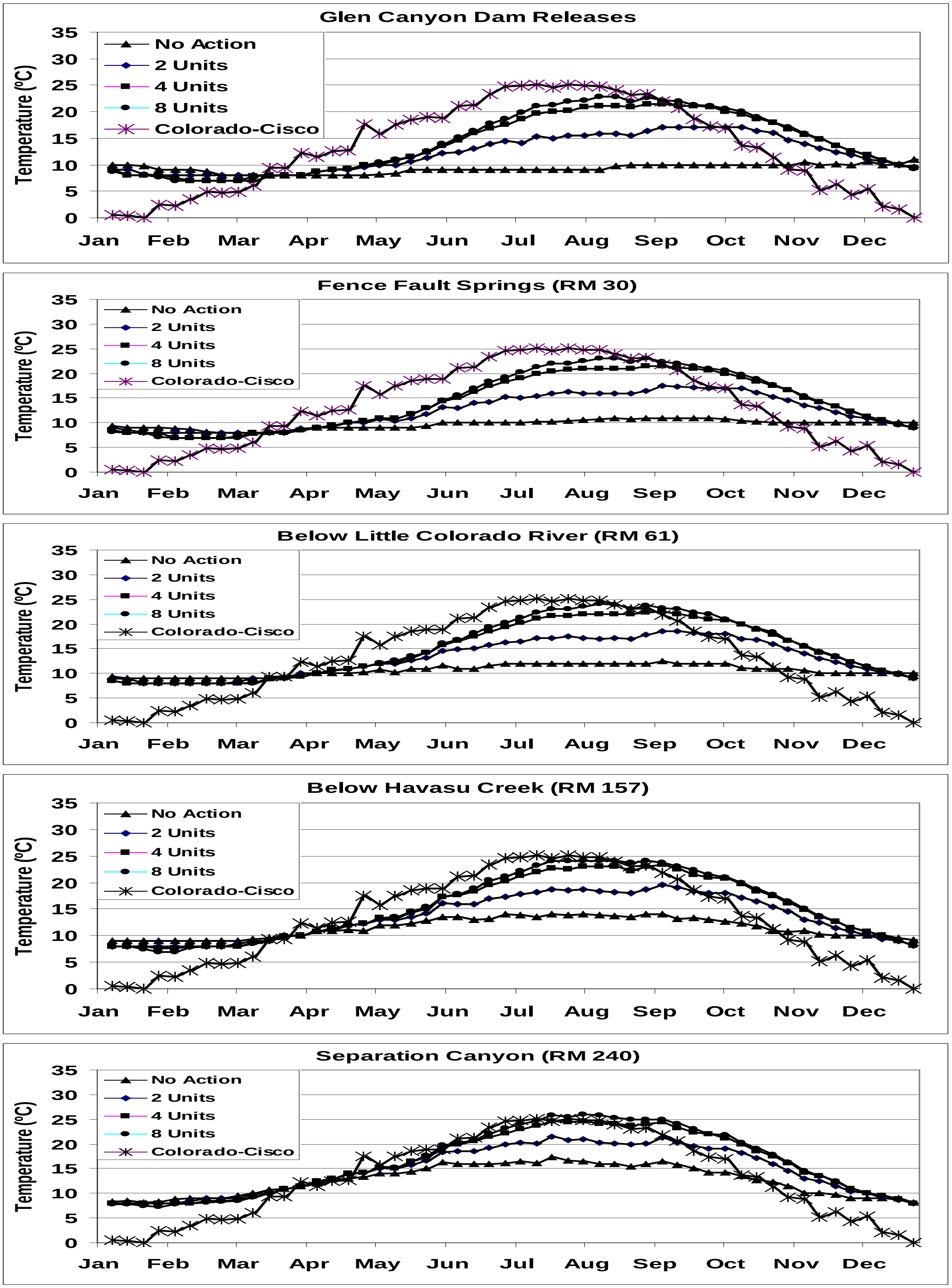

Figure 9. Predicted mean daily water temperature of the Colorado River for five locations downstream from Glen Canyon Dam with No Action and 2, 4, and 8-unit TCDs and the Colorado River at Cisco, UT, for 2012 (USGS 09180500). Data points are 7-day averages. Data generated by GEMSS® model.

3.4 Comparison of Observed and Predicted Temperatures

The performance of the GEMSS model was evaluated by comparing predicted monthly temperatures from the model for 2-unit TCD at RM 30, with predicted temperature using a simplified water temperature model (Wright et al. 2008), and with actual temperature measured at the GCMRC gage in 2005, a year of warm releases (Figure 10). The temperatures predicted by the GEMSS model were not expected to be the same as the actual temperatures for 2005, but the predicted temperatures from the GEMSS model and the simplified model are similar, except during the winter months of January-March and November-December when the GEMSS model consistently under-estimated temperature by about 1°C. These under-estimates occur in winter at lower temperatures and should not affect temperature degree-day computations for the 48 aquatic species evaluated.

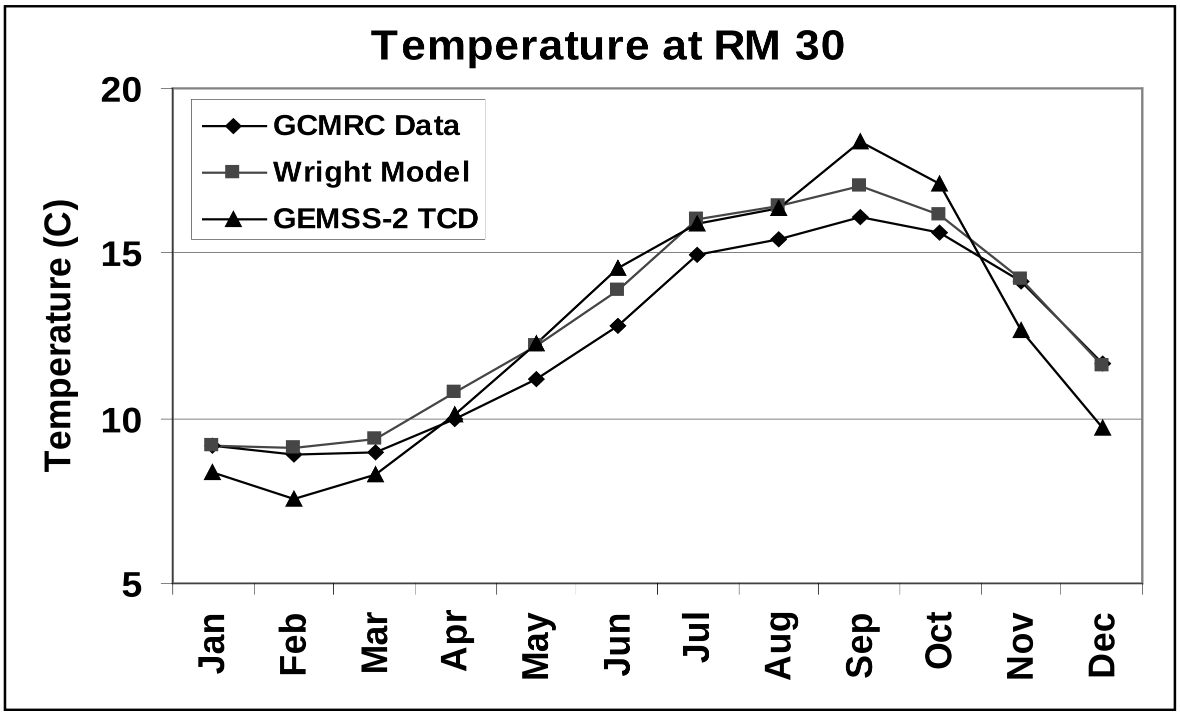

Figure 10. Mean monthly temperature of the Colorado River at RM 30 as measured at the GCMRC gage and as predicted by a simplified water temperature model for 2005 and the GEMSS model for 2-unit TCD. GCMRC data from Grand Canyon Monitoring and Research Center, http://www.gcmrc.gov/dasa/tabdata/.

Figure 11 provides a perspective of the predicted temperatures for a 2, 4, and 8-unit TCD compared to average pre-dam temperatures, a year of cold releases (1976), and a year of warm releases (2005). First, it is important to note that the peak temperatures from 4 and 8-units TCDs occur in August, about 1 month later than with peak pre-dam temperatures. It is also notable that peak temperature with a 2-unit TCD occurs in early October, nearly 3 months after the pre-dam peak. The pre-dam regime also shows how temperature dropped to 0ºC in winter, a temperature that cannot be achieved post-dam because of the large heat content of Lake Powell. Pre-dam temperature also rose to nearly 30ºC in summer; a temperature that can also not be reached even with substantial dam modification. Note also that the warmest annual dam release temperatures on record (2005) followed a similar pattern to a 2-unit TCD.

These comparisons are shown to remind the reader that modifying the dam—even with all 8 units—will not restore the magnitude or timing of the pre-dam thermal regime. The pattern of dam releases is determined by the temperature of the water in the forebay that is a reflection of many factors throughout Lake Powell, and it is not the same as the historical thermal regime of the Colorado River.

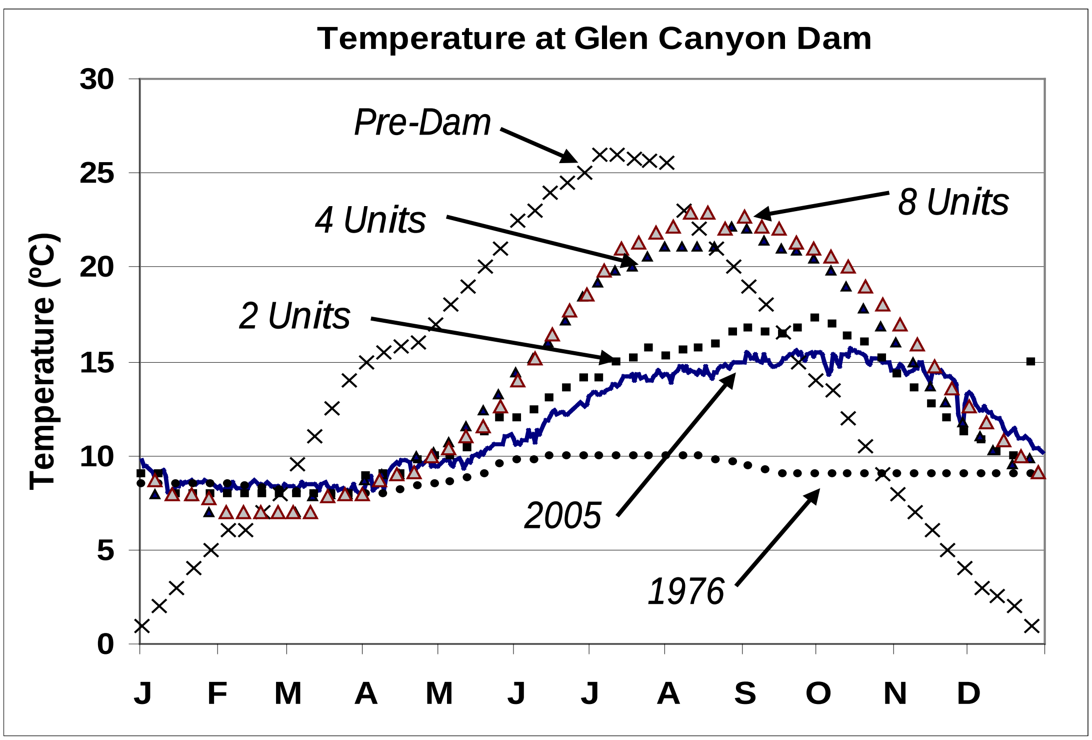

Figure 11. Temperature of dam releases for pre-dam era, 1976 cold-water year, and 2005 warm-water year compared predicted temperatures for 2, 4 and 8-unit TCDs.

4.0 RESULTS OF TEMPERATURE SUITABILITY

4.1 Native and Nonnative Fishes

4.1.1 All Species

Suitable temperature degree-days (STDDs) for ovulation, incubation, and growth by each of 35 fish species were computed for the four TCD alternatives within each of the five locations (see Appendix C: Temperature Degree-Days for Fish). The numbers of species able to complete all three life stages by alternative and location are summarized in Table 6. Under No Action, cold releases provide suitable mainstem temperatures for all life stages of only three species. But by the time the river reaches Separation Canyon, about 255 miles downstream from the dam, temperatures are suitable for all life stages of 5 species and for some life stages of 16 species. Modifying releases with a 2, 4, or 8-unit TCD substantially increases the number of species able to complete all life stages in the mainstem, especially in the more downstream locations. A 2-unit TCD could provide suitable temperatures for 5 species at the LCR (RM 61) and would benefit 20 other species; whereas a 4- or 8-unit TCD could provide suitable temperatures for all life stages of 12 and 18 species, respectively. This analysis shows that, except in the most downstream locations, a 2-unit TCD would have little effect on most fish species. The more dramatic benefits would occur with a 4- or 8-unit TCD.

Table 6. Numbers of fish species that could complete all 3 life stages (ovulation, incubation, and growth) or only 1 or 2 based on STDDs at each of five locations for No Action and 2, 4, and 8-unit TCDs.

Location	Life Stages	No Action	2 units	4 units	8 units
GCD	All 3	3	4	9	11
	1 or 2	1	13	21	22
RM 30	All 3	3	5	9	10
	1 or 2	1	16	21	23
RM 61	All 3	3	5	12	18
	1 or 2	1	20	21	16
RM 157	All 3	4	5	9	19
	1 or 2	2	21	24	16
RM 240	All 3	5	12	19	18
	1 or 2	16	17	16	17

The 35 fish species were divided into three groups to evaluate the potential benefits to: (1) nonnative cold-water, 6 species; (2) native warm-water, 8 species; and (3) nonnative warm-water, 21 species (see Table 2). Cold-water species included: brown trout, burbot, rainbow trout, redside shiner, smallmouth bass, and walleye. Native species included: bluehead sucker, bonytail, Colorado pikeminnow, flannelmouth sucker, humpback chub, razorback sucker, roundtail chub, and speckled dace. Nonnative warm-water species included: black bullhead, black crappie, blue tilapia, bluegill, channel catfish, common carp, fathead minnow, flathead catfish, gizzard shad, golden shiner, grass carp, green sunfish, largemouth bass, mosquitofish, plains killifish, red shiner, sand shiner, striped bass, threadfin shad, Utah chub, and yellow bullhead.

The sum of STDDs for any life stage of each group was taken as a proportion of the total STDDs for all groups and used as an index for the fish group most likely to benefit from river warming with 2, 4, and 8-unit TCDs (Table 7). Clearly, with no thermal modification, temperatures at all locations favor the cold-water species, although at Separation Canyon, about 26% of STDDs are available for warm-water native and nonnative species.

With a greater number of units modified, resulting temperatures could provide slightly greater benefits to nonnative over native warm-water species within each location. A 2-unit TCD would provide some benefit to these two groups of fishes, but temperatures continue to remain most suitable for cold-water species throughout, although other environmental factors (e.g., water clarity, habitat, food, etc.) limit these cold-water fishes. A 2 or 4-unit TCD would provide a substantial increase in suitable temperatures for nonnative and native warm-water species, but tend to favor the former with distance downstream (see also section 4.1.2 for statistical evaluation of STDDs for fish groups).

The proportion of STDDs for any life stage within each fish group illustrate that cold-water species continue to have about the same suitable temperature regimes for all four alternatives at all five locations (Table 8). Suitable temperatures for native species, however, increase substantially with 4 and 8 units. Nonnative warm-water species show a similar pattern, but slightly higher suitable temperatures. A multiple means comparison of STDDs is described in section 4.1.2 for select keystone species. Some of the 35 species evaluated are not currently residents of the Grand Canyon ecosystem and the keystone species were selected to provide a more relevant analysis.

Table 7. Proportion of STDDs suitable for any life stage of 35 species of nonnative cold-water (NN-CW), native warm-water (NA-WW), and nonnative warm-water fishes for No Action and 2, 4, and 8-unit TCDs within each of five locations.

Fish Group	No Action	2 Units	4 Units	8 Units
Glen Canyon Dam (GCD)				
NN-CW	1.00	0.85	0.34	0.28
NA-WW	0.00	0.06	0.29	0.32
NN-WW	0.00	0.08	0.37	0.40
Sums:	1.00	1.00	1.00	1.00
Fence Fault Springs (RM 30)				
NN-CW	1.00	0.72	0.34	0.27
NA-WW	0.00	0.14	0.29	0.32
NN-WW	0.00	0.14	0.37	0.41
Sums:	1.00	1.00	1.00	1.00
Below Little Colorado River (RM 61)				
NN-CW	1.00	0.63	0.29	0.22
NA-WW	0.00	0.18	0.32	0.30
NN-WW	0.00	0.20	0.40	0.48
Sums:	1.00	1.00	1.00	1.00
Below Havasu Creek (RM 157)				
NN-CW	0.98	0.57	0.28	0.21
NA-WW	0.00	0.20	0.30	0.30
NN-WW	0.02	0.23	0.42	0.49
Sums:	1.00	1.00	1.00	1.00
Separation Canyon (RM 240)				
NN-CW	0.74	0.34	0.20	0.19
NA-WW	0.14	0.30	0.30	0.29
NN-WW	0.13	0.36	0.50	0.52
Sums:	1.00	1.00	1.00	1.00
All Locations				
NN-CW	0.96	0.72	0.45	0.39
NA-WW	0.03	0.20	0.36	0.39
NN-WW	0.01	0.09	0.19	0.23
Sums:	1.00	1.00	1.00	1.00

Table 8. Proportion of STDDs suitable for any life stage of nonnative cold-water, native warm-water, and nonnative warm-water fish species for No Action and 2, 4, and 8-unit TCDs for locations within each fish group.

Location	No Action	2 Units	4 Units	8 Units	Sum
Nonnative Cold-Water					
GCD	0.20	0.28	0.27	0.24	1.00
RM 30	0.22	0.29	0.27	0.23	1.00
RM 61	0.25	0.29	0.24	0.21	1.00
RM 157	0.27	0.29	0.23	0.21	1.00
RM 240	0.29	0.29	0.22	0.20	1.00
Native Warm-Water					
GCD	0.00	0.04	0.43	0.53	1.00
RM 30	0.00	0.10	0.41	0.50	1.00
RM 61	0.00	0.13	0.42	0.45	1.00
RM 157	0.00	0.16	0.38	0.46	1.00
RM 240	0.05	0.27	0.35	0.33	1.00
Nonnative Warm-Water					
GCD	0.00	0.04	0.44	0.52	1.00
RM 30	0.00	0.08	0.41	0.51	1.00
RM 61	0.00	0.10	0.38	0.52	1.00
RM 157	0.01	0.12	0.36	0.51	1.00
RM 240	0.04	0.21	0.37	0.38	1.00

The 35 fish species evaluated were ranked according to the sum of STDDs for any life stage at all locations with a 2, 4, and 8-unit TCD (Table 9). The scores represent the sum of STDDs for a species taken as a proportion of the highest STDD value within the stated alternative. Six of the top 10 ranked species are the same for each alternative; i.e., brown trout, walleye, rainbow trout, flannelmouth sucker, razorback sucker, and Colorado pikeminnow. The Colorado pikeminnow is not present in the system, but this analysis shows that temperatures could be quite suitable for all life stages of the species with 2, 4, or 8 units modified; however, other life history requirements, such as persistent warm nursery backwaters are not reliably available. Of the top 10 species overall, four are cold-water forms (walleye, brown trout, rainbow trout, redside shiner), three are native warm-water forms (Colorado pikeminnow, flannelmouth sucker, bonytail), and two are species rarely found in the Grand Canyon ecosystem, but are common downstream in Lake Mead (striped bass, gizzard shad).

Table 9. Relative rankings of 35 fish species evaluated for the sum of STDDs for any life stage at all locations with 2-, 4, and 8-unit TCDs. Scores represent the sum of STDDs for a species taken as a proportion of the highest STDD value; a species with a value of 0.00 has no STDDs at that alternative. Shaded cells: white = nonnative cold-water species; gray = native warm-water species; dark gray = nonnative warm-water species.

Rank	Code	No Action	Code	2 Units	Code	4 Units	Code	8 Units	Code	Sums
1	WE	1.00	BR	1.00	WE	1.00	WE	1.00	WE	1.00
2	RB	0.87	WE	0.90	BR	0.79	CP	0.83	BR	0.89
3	BR	0.82	RB	0.82	RB	0.78	BR	0.76	RB	0.81
4	BU	0.40	RD	0.63	FM	0.69	SB	0.73	CP	0.57
5	RD	0.19	SM	0.33	RZ	0.65	RB	0.73	FM	0.57
6	SM	0.07	FM	0.28	CP	0.63	GZ	0.71	RD	0.56
7	FH	0.05	RZ	0.28	GZ	0.63	FM	0.69	RZ	0.54
8	FM	0.03	CP	0.24	SB	0.62	BT	0.68	GZ	0.51
9	RZ	0.03	FH	0.23	RD	0.56	RZ	0.66	SB	0.50
10	CP	0.03	RT	0.22	RT	0.53	LM	0.61	BT	0.42
11	RT	0.02	BU	0.22	BT	0.48	MF	0.56	RT	0.41
12	SS	0.02	SS	0.18	SS	0.43	SS	0.55	SS	0.39
13	CH	0.02	GZ	0.18	FH	0.43	GD	0.53	FH	0.38
14	GZ	0.02	UC	0.15	LM	0.42	FH	0.48	LM	0.37
15	MF	0.02	RS	0.15	MF	0.37	HB	0.48	MF	0.35
16	SD	0.02	SB	0.14	HB	0.37	RT	0.48	SM	0.34
17	UC	0.02	CH	0.14	RS	0.37	SD	0.46	CH	0.32
18	BC	0.01	BC	0.12	CH	0.36	CH	0.45	HB	0.32
19	BH	0.01	MF	0.12	GD	0.35	BH	0.41	RS	0.31
20	LM	0.01	SD	0.11	BC	0.35	RS	0.40	GD	0.31
21	SB	0.01	HB	0.11	SD	0.31	RD	0.40	SD	0.30
22	BB	0.00	BT	0.10	SM	0.31	BC	0.37	BC	0.28
23	BG	0.00	LM	0.09	BH	0.28	SM	0.35	BH	0.26
24	BT	0.00	BH	0.09	GS	0.28	GS	0.35	UC	0.25
25	CC	0.00	GS	0.08	UC	0.28	CC	0.33	BU	0.25
26	FC	0.00	GD	0.05	BU	0.23	UC	0.31	GS	0.24
27	GD	0.00	CC	0.01	CC	0.17	BU	0.26	CC	0.17
28	GP	0.00	YB	0.01	TL	0.11	TL	0.24	TL	0.12
29	GS	0.00	BB	0.01	YB	0.08	YB	0.10	YB	0.06
30	HB	0.00	BG	0.00	BB	0.06	BB	0.09	BB	0.05
31	PK	0.00	FC	0.00	GP	0.05	TS	0.08	GP	0.04
32	RS	0.00	GP	0.00	PK	0.03	GP	0.08	PK	0.03
33	TL	0.00	PK	0.00	BG	0.03	PK	0.07	TS	0.03
34	TS	0.00	TL	0.00	TS	0.02	BG	0.05	BG	0.03
35	YB	0.00	TS	0.00	FC	0.01	FC	0.03	FC	0.01

The fish species able to complete all three life stages for each alternative are ranked in Table 10. Altogether, temperatures were suitable for all life stages of 23 of the 35 species; in other words, even with temperature augmentation, not all species in or near the GCE would be able to complete their life cycle in the mainstem Colorado River. Temperature degree-days were ranked from highest (1) to lowest (19) based on pooled STDDs for each location and alternative. Species highest in the column under each location and temperature alternative are expected to benefit the most from the predicted temperature changes. All species with temperature suitability for all three life stage are shown and the three temperature-sensitive groups are colored coded to facilitate a visual assessment of species most likely to benefit from temperature change. The three groups are nonnative cold-water species, nonnative warm-water species, and native warm-water species.

Table 10 illustrates visually the number of species that would benefit from warmer temperatures. It also shows that there would likely be no clear distinct benefit to a particular species or group of fishes due to mainstem temperature alone. Warming temperatures of the Colorado River through Grand Canyon would tend to satisfy thermal requirements of a variety of species presently in the system, as well as possible future invaders.

This analysis shows that even with warming, the cold and cool-warm species would tend to benefit more than the warm-water species. For all warming scenarios, rainbow trout, brown trout, walleye, redside shiner, and smallmouth bass would tend to benefit the most. This analysis also shows that at least 4 units would have to be modified to reach sufficiently warm temperatures to benefit the native warm-water species, especially in the upper to middle reaches of the river.

Table 10. Rankings of fish species able to complete all life stages of ovulation, incubation, and growth at five locations with predicted temperatures for No Action and 2, 4, and 8-unit TCDs. Shaded cells: light gray = nonnative cold-water species; medium gray = nonnative warm-water species; dark gray = native warm-water species; blank cells = insufficient degree-days for all life stages. Rankings are based on summed STDDs for all life stages with highest rankings have the greatest number of STDDs. Species codes are provided in Table 2.

Rank	No Action					2 Units					4 Units					8 Units				
	GCD	RM 30	RM 61	RM 157	RM 240	GCD	RM 30	RM 61	RM 157	RM 240	GCD	RM 30	RM 61	RM 157	RM 240	GCD	RM 30	RM 61	RM 157	RM 240
1	WE	WE	WE	WE	BR	BR	BR	BR	BR	BR	WE	WE	WE	WE	CP	WE	WE	WE	WE	CP
2	RB	RB	RB	RB	WE	WE	WE	WE	WE	WE	RB	BR	BR	BR	WE	BR	BR	CP	CP	BT
3	BR	BR	BR	BR	RB	RB	RB	RB	RB	RB	BR	RB	RZ	CP	SB	RB	FM	BR	GZ	LM
4				RD	RD	RD	RD	RD	RD	RD	RD	FM	FM	RB	GZ	FM	RZ	SB	SB	MF
5					SM	SM	SM	SM	SM	FM	RZ	RZ	RT	FM	LM	RZ	CP	GZ	BR	WE
6										RZ	FM	RD	RB	GZ	BT	CP	RB	RB	RB	GD
7										CP	RT	RT	CP	SB	BR	GZ	GZ	FM	BT	SB
8										GZ	GZ	GZ	GZ	BT	FM	RT	SB	BT	LM	SS
9										SB	SB	SB	RD	RD	MF	SB	RT	LM	FM	BR
10										RS			SB		GD	BT	BT	GD	MF	SD
11										BT			BT		RB	RS	RS	MF	GD	RB
12													RS		SS			SS	SS	GZ
13															SD			HB	HB	FM
14															CH			FH	FH	BH
15															HB			SD	SD	HB
16															BH			CC	CH	FH
17															RD			CH	BH	CC
18															CC			BH	RD	CH
19																			CC	
Total	3	3	3	4	5	5	5	5	5	11	9	9	12	9	18	11	11	18	19	18

4.1.2 Keystone Species

Five species each of nonnative cold-water, nonnative warm-water, and native warm-water fishes were selected as keystone species for this evaluation. These are considered keystone species because they are all current residents of the Colorado River through the Grand Canyon, comprise the majority of fish numbers, include potentially dangerous invasive species, and include sensitive and endangered species. The five cold-water species are walleye, rainbow trout, brown trout, redside shiner, and smallmouth bass. The nonnative warm-water species are green sunfish, channel catfish, common carp, fathead minnow, and red shiner. The native warm-water species are speckled dace, humpback chub, bluehead sucker, flannelmouth sucker, razorback sucker.

Suitable temperature degree-days (STDDs) for ovulation, incubation, and growth by each of the 15 keystone species are shown in Figure 12 at each of the five locations with No Action and a 2, 4, and 8-unit TCD. A visual comparison of graphs for each column illustrates the effect of temperature modification, and a comparison of graphs within each row shows the longitudinal effect of downstream warming, irrespective of temperature modification. A visual inspection of Figure 12 shows that there is currently greater temperature benefit for more fish species with distance from the dam, as the river is warmed seasonally, and that an 8-unit TCD will affect the most species.

Ovulation temperatures for native species in the mainstem downstream to Havasu Creek would be suitable only with 4- and 8–unit TCDs, and only for the flannelmouth sucker and razorback sucker. With an 8-unit TCD, temperatures would be suitable for ovulation by all 5 native species downstream of the LCR, although temperatures could be too warm for the razorback sucker.

With respect to other life stages, mainstem temperatures with No Action were suitable for growth for only a few warm-water species even as far downstream as Separation Canyon. However, a 2-unit TCD would make temperatures suitable for growth downstream of the LCR for all native species, except bluehead sucker. The 4- and 8-units TCDs would provide suitable growth temperatures for all native species throughout.

The endangered humpback chub would see little benefit from a 2-unit TCD, except for suitable growth temperatures downstream of the LCR. With 4- and 8-unit TCDs, mainstem temperatures would be suitable only for growth of chubs, and suitable ovulation temperatures would occur with 4-units only at Separation Canyon, where for the species is currently rare. With an 8-unit TCD, mainstem spawning by humpback chub would be possible downstream of the LCR.

Of the nonnative warm-water species, temperatures for all life stages would be suitable only for the red shiner downstream of the LCR with a 4-unit TCD, although an 8-unit TCD would make temperature conditions suitable for this species just downstream of the dam (i.e., Lees Ferry reach). With 8 units, temperatures for all life stages of all nonnative warm-water species would become suitable downstream of the LCR, except for ovulation by green sunfish. Notably, suitable temperatures for all life stages of channel catfish and common carp do not occur at Separation Canyon with a 4-unit TCD and only downstream of the LCR with an 8-unit TCD.

Of the three groups of keystone species, the four alternatives would likely continue to provide the most suitable temperatures for the cold-water species. Mainstem temperatures were suitable for all life stages of rainbow trout, brown trout, and walleye at all five locations and for all four alternatives. The 2- and 4-unit TCDs provide the greatest benefit, in terms of STDDs, to the trout species due primarily to increased temperature suitability for growth. A species of particular concern is the smallmouth bass, which has been found in small numbers throughout the canyon. Suitable temperatures for all life stages of smallmouth bass occur with 2 and 4-unit TCDs, although an 8-unit TCD would provide temperature too warm for ovulation, but suitable for growth.

An additional illustration of the effect of temperature warming as a function of dam modification and longitudinal distance from Glen Canyon Dam is provided in Figure 13. The graphs in this figure show a convergence of pooled TDDs for all 15 keystone species with increased warming. In other words, warmed releases with 2, 4, and 8-unit TCDs provide increasingly more suitable temperatures for all 35 species considered in this evaluation. This convergence of temperature suitability was also evident in Table 10, where separate shaded cells representing the three temperature-sensitive fish groups converged with greatest warming.

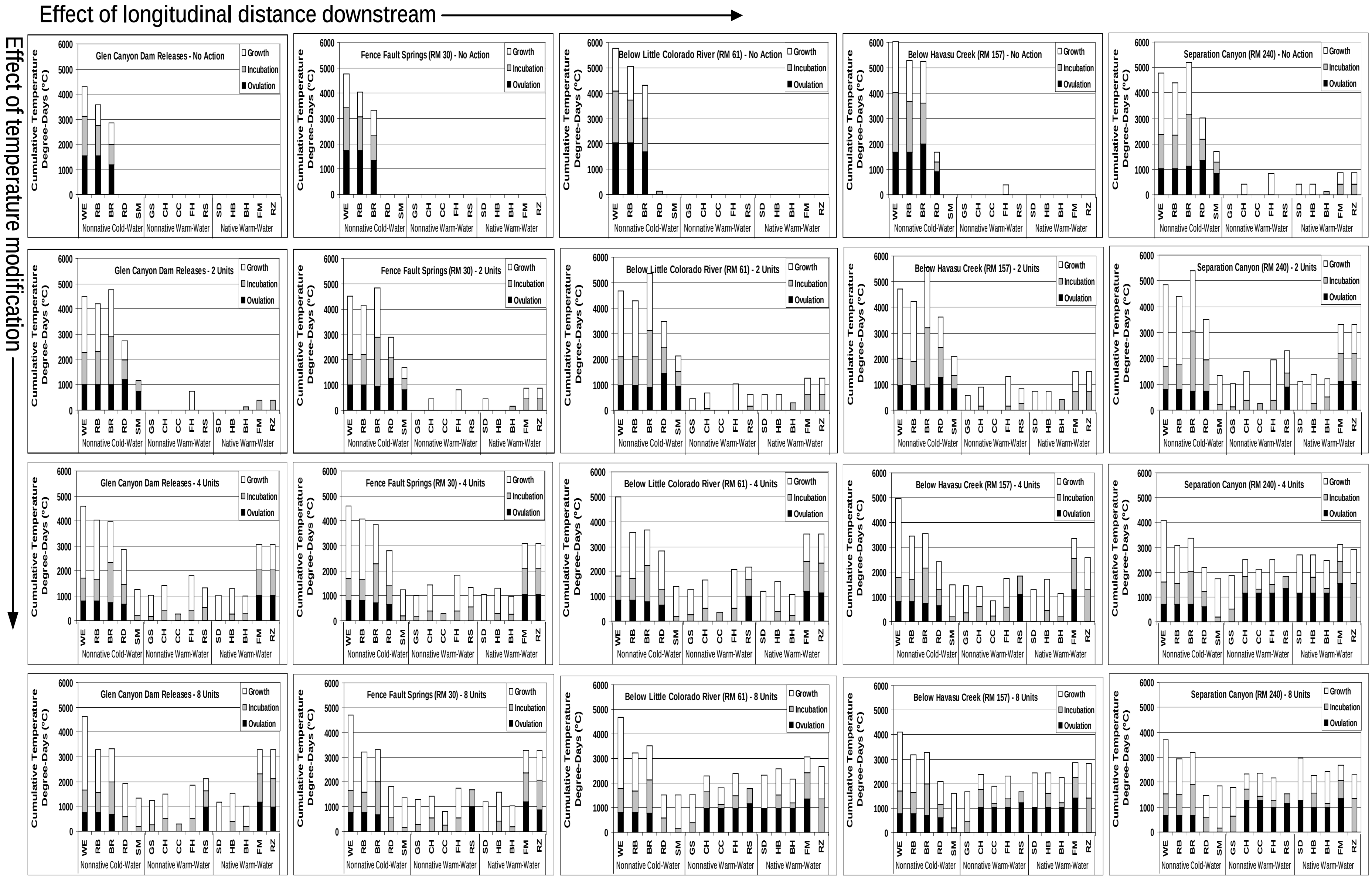

Figure 12. Suitable temperature degree-days (STDDs) for ovulation, incubation, and growth by nonnative cold-water, nonnative warm-water, and native warm-water fish species (5 keystone species per group) at each of five locations with No Action and 2, 4, and 8-unit TCDs. Species codes are provided in Table 2.

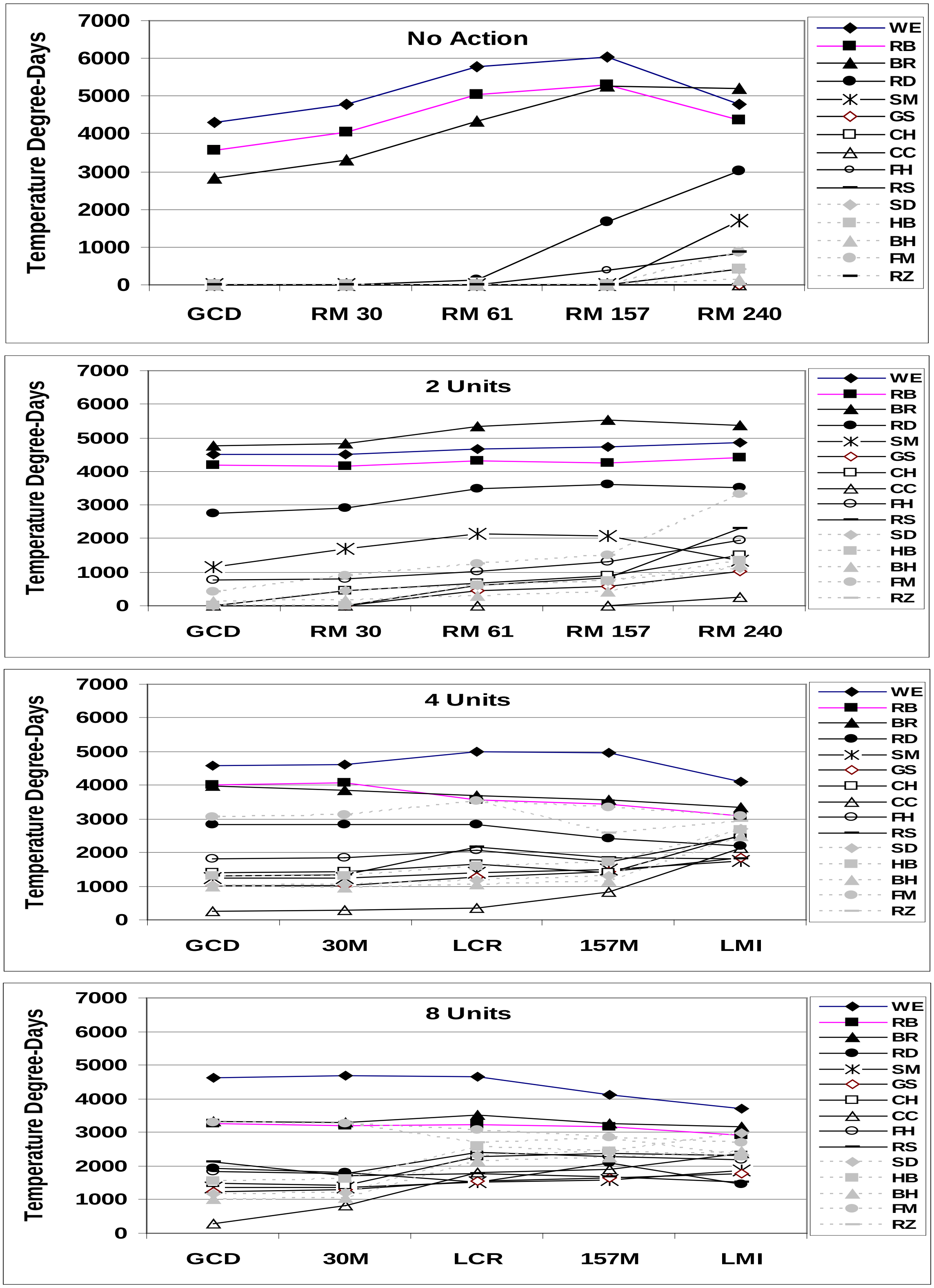

Figure 13. Sums of STDDs for nonnative cold-water, nonnative warm-water, and native warm-water fish species (5 keystone species per group) at five locations downstream from Glen Canyon Dam for No Action and 2, 4, and 8-unit TCDs. Note that the horizontal x-axis is not to scale.

Multiple comparisons were performed for mean STDDs for No Action and 2, 4, and 8-unit TCDs within each fish group and location. Comparisons were done with one-way Analysis of Variance and Bonferroni comparison of means ($p < 0.05$). Only the keystone species were used to standardized sample size and to consider those species currently found in the GCE and most relevant to this analysis. Figures 14–16 show that at all locations there were no significant gains or losses in STDDs for cold-water species with any of the four alternatives. There were however, significantly more suitable temperatures for native and nonnative warm-water species with 4 and 8 units, compared to 2 units. The last column of graphs of Figure 16 shows the mean STDDs for the three fish groups at all locations, and best illustrates the greater temperature benefits of 4 and 8-unit TCDs, compared to a 2-unit modification. The mean STDDs were greater at all locations for native fishes than for nonnative species (although not significant), which indicates that temperature modification could benefit native fishes to a greater degree, but nonnative fish will benefit as well.

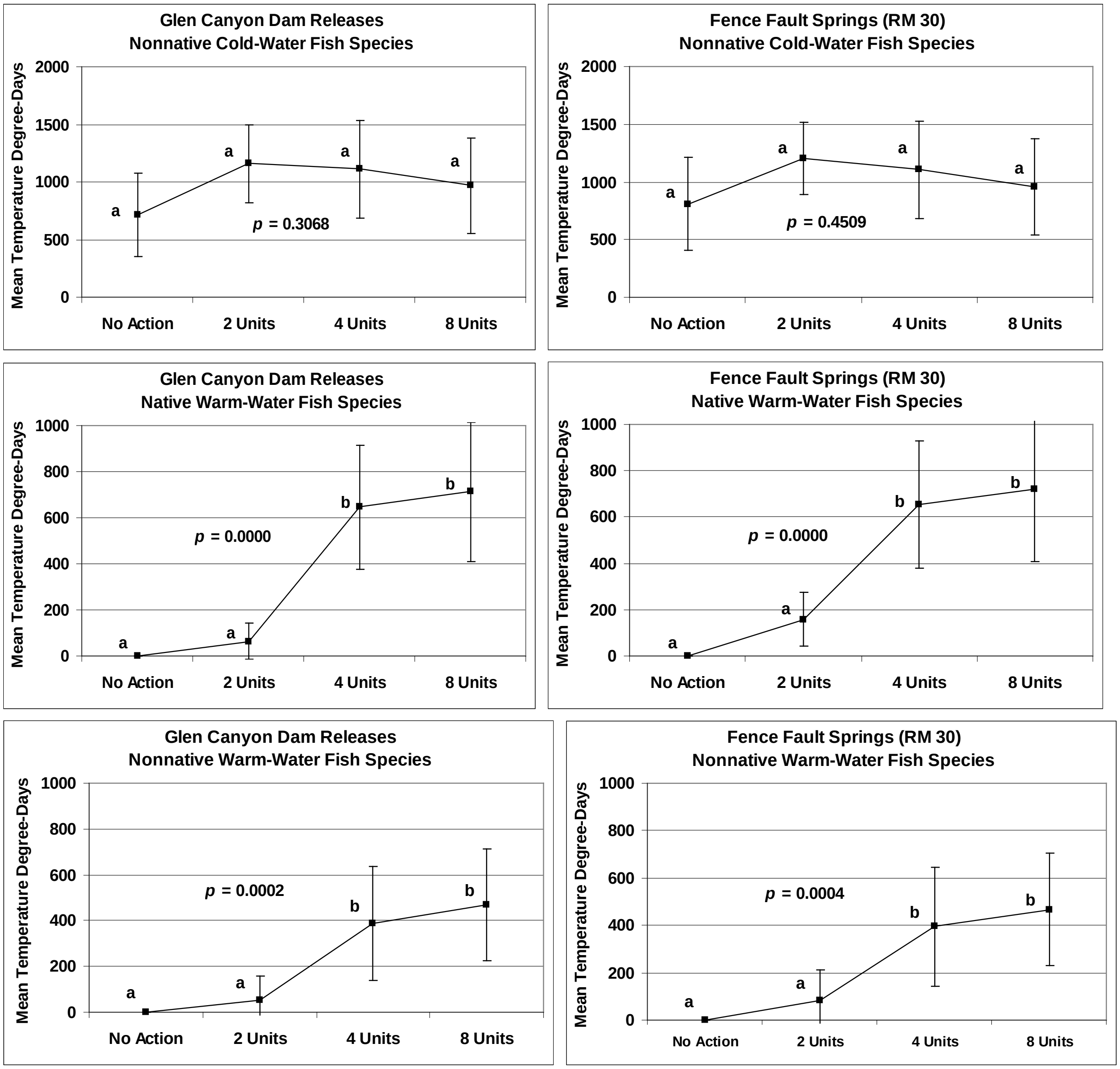

Figure 14. Multiple comparisons of mean STDDs (± 95% C.I.) for No Action and 2, 4, and 8-unit TCDs within each fish group (5 keystone species per group) and location (Glen Canyon Dam and RM 30). STDDs included any of the 3 life stages. Comparisons were done with one-way Analysis of Variance and Bonferroni comparison of means. Different letters next to means show significant differences at the indicated *p*-values.

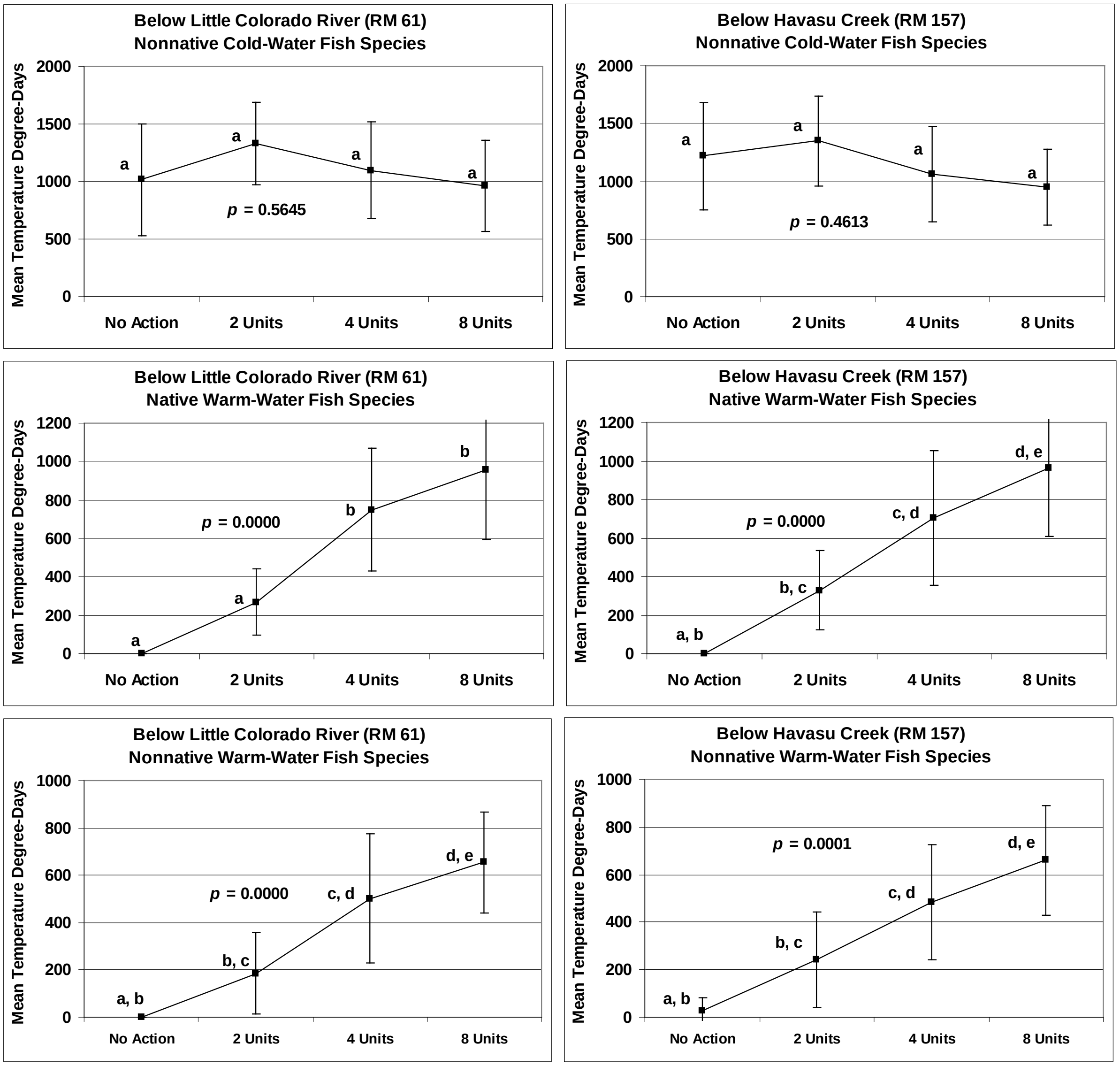

Figure 15. Multiple comparisons of mean STDDs (± 95% C.I.) for No Action and 2, 4, and 8-unit TCDs within each fish group (5 keystone species per group) and location (RM 61 and RM 157). STDDs included any of the 3 life stages. Comparisons were done with One-Way Analysis of Variance and Bonferroni comparison of means. Different letters next to means show significant differences at the indicated *p*-values.

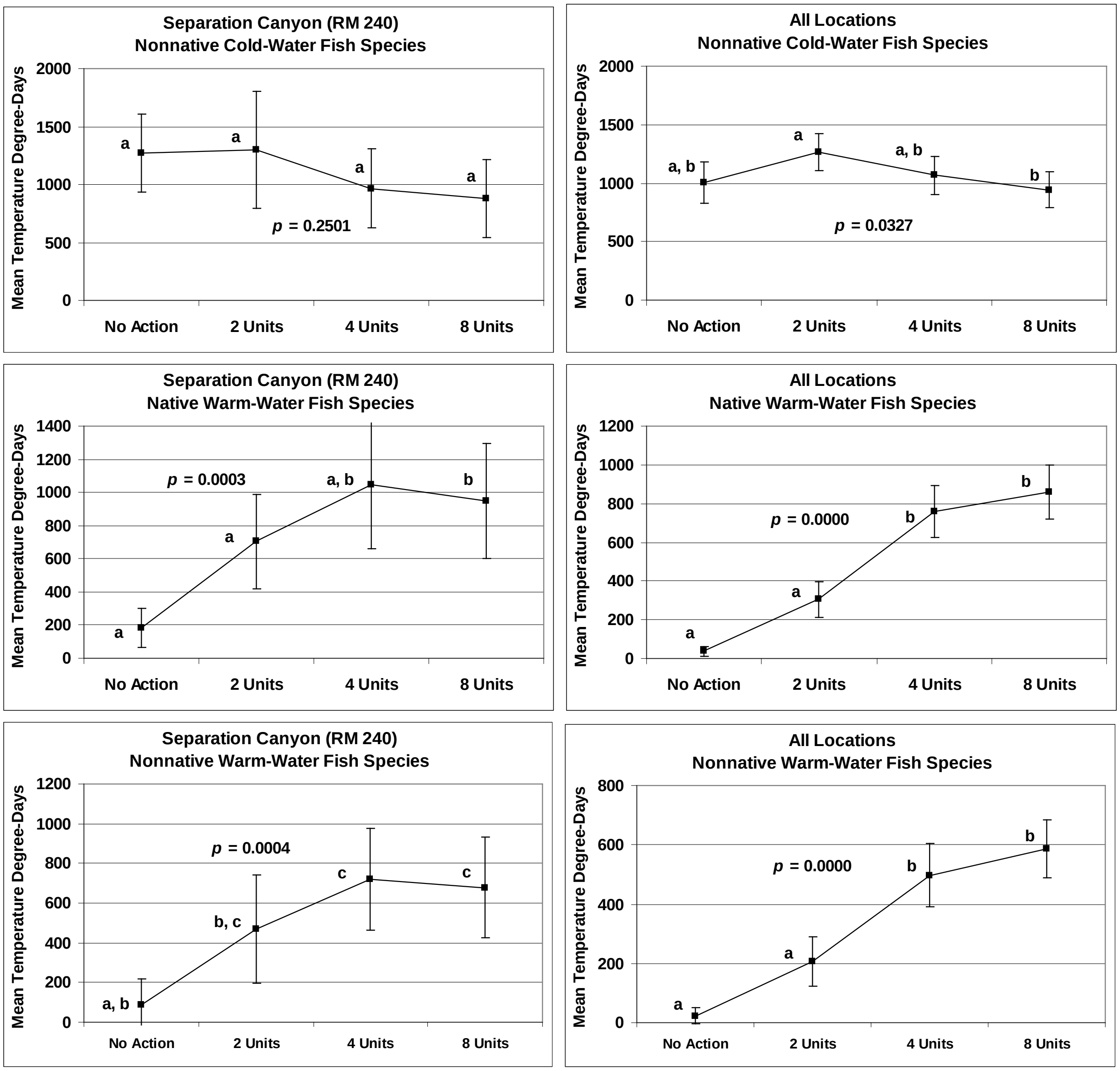

Figure 16. Multiple comparisons of mean STDDs (± 95% C.I.) for No Action and 2, 4, and 8-unit TCDs within each fish group (5 keystone species per group) and location (RM 240 and all locations). STDDs included any of the 3 life stages. Comparisons were done with Analysis of Variance and Bonferroni comparison of means. Different letters next to means show significant differences at the indicated *p*-values.

Multiple means comparisons were also done to determine if one group received significantly more STDDs than the others for a given alternative and location (Figures 17–18). Mean STDDs for native and nonnative warm-water species were not significantly different for any warming alternative at any location. Mean STDDs for cold-water species were significantly greater at all locations for No Action and a 2-unit TCD. However, a 4-unit TCD increased the mean STDDs for warm-water species, and there was no significant difference in mean STDDs for cold-water species and native warm-water species at any location. There was also no significant difference in mean STDDs between native and nonnative warm-water species for any warming alternative and location, although the mean STDDs for the native species were greater, indicating possibly greater benefits to the native warm-water species.

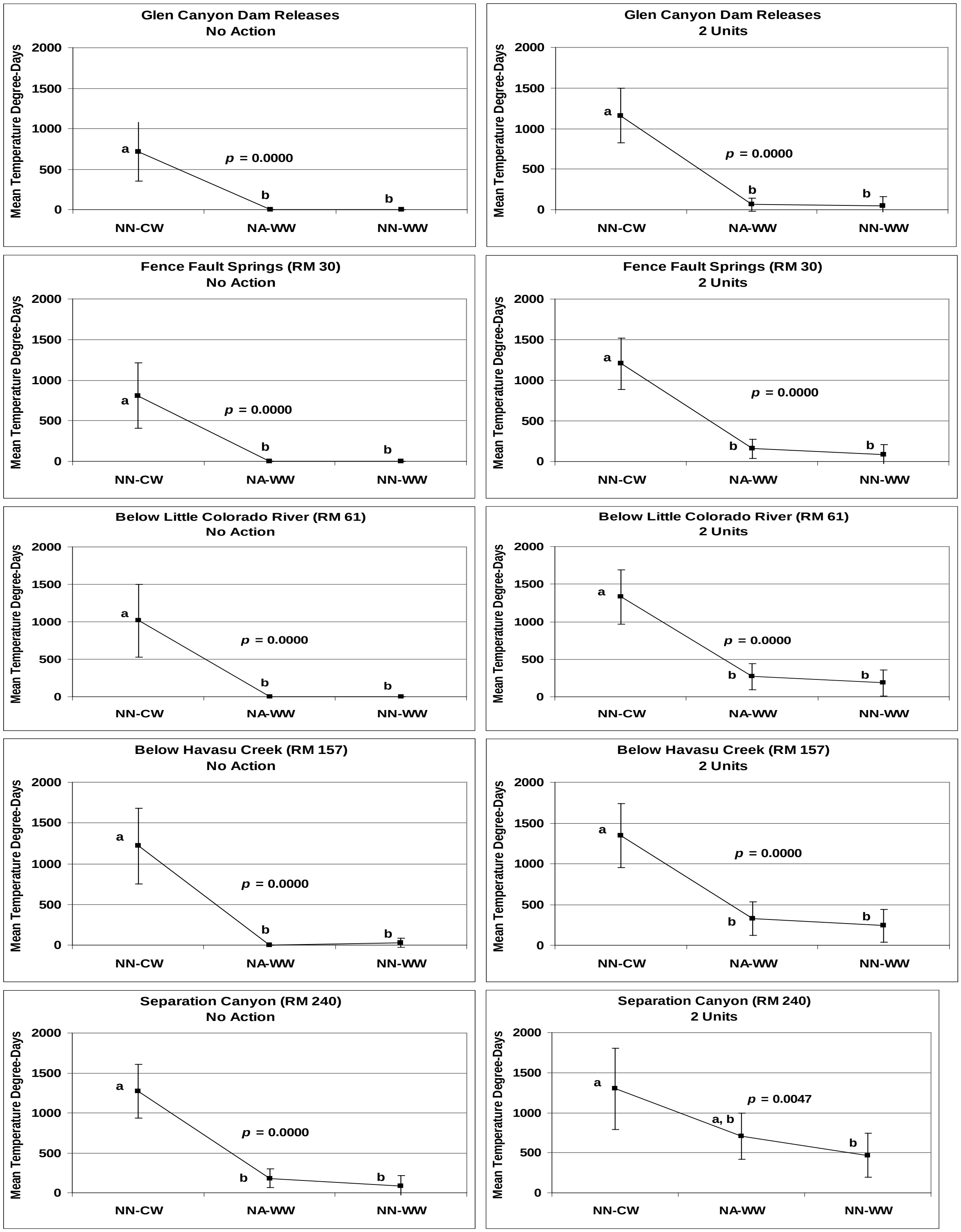

Figure 17. Multiple comparisons of mean STDDs (± 95% C.I.) among fish groups (5 keystone species per group) for No Action and 2--unit TCDs and location. STDDs included any of the 3 life stages. Comparisons were done with one-way Analysis of Variance and Bonferroni comparison of means. Different letters next to means show significant differences at the indicated *p*-values.

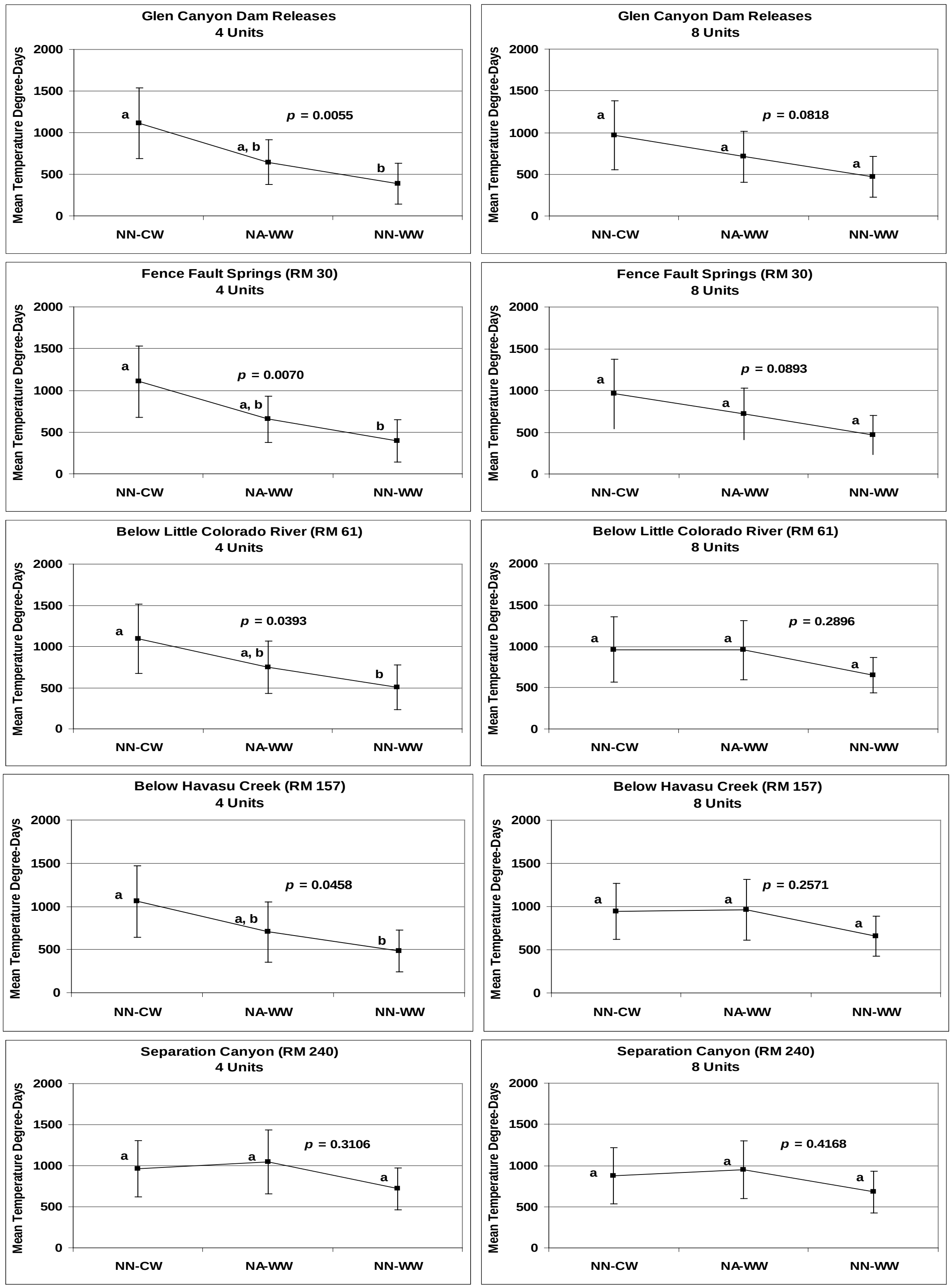

Figure 18. Multiple comparisons of mean STDDs (± 95% C.I.) among fish groups (5 keystone species per group) for 4- and 8--unit TCDs and location. STDDs included any of the 3 life stages. Comparisons were done with one-way Analysis of Variance and Bonferroni comparison of means. Different letters next to means show significant differences at the indicated *p*-values.

4.2 Fish Parasites

The four species of fish parasites considered in this assessment were the Asian tapeworm, parasitic copepod, trout nematode, and whirling disease. Each of these parasites requires either a host or specific developmental conditions to complete its life cycle. The Asian tapeworm requires an intermediate host, a cyclopoid copepod that inhabits quiet, shallow, warm waters usually associated with lake shorelines and riverine backwaters. The parasitic copepod does not have an intermediate host but the free-living ciliated immature stage requires quiet, shallow, warm habitat for infecting host fish. The trout nematode also requires a copepod as an intermediate host. The primary host of whirling disease is a tiny and common aquatic worm, the oligochaete (*Tubifex tubifex*), that is commonly found in mud-bottom streams and lakes and occurs in the Colorado River downstream from Glen Canyon Dam (Rosi-Marshall et al. 2010). In order for these parasites to thrive, habitat and temperatures must be suitable for the host as well as for immature stages that allow for the infestation of a fish host.

Predicted temperatures were suitable for tubifex worms, which are the host of whirling disease, at all locations under No Action, 2, 4, and 8-unit TCDs (Figure 19). However, temperature was not suitable under No Action for parasitic copepods and host activity of the Asian tapeworm and trout nematode at any of the five locations. With a 2-unit TCD, temperatures were suitable for host activity and infestation of whirling disease at all locations, but suitable only for infestation by trout nematodes, except at the downstream-most location (i.e., Separation Canyon, RM 240), where trout do not occur. With a 4-unit TCD, temperatures would be suitable for both life stages of whirling disease, whereas temperatures would continue to be too cold for host activity of the Asian tapeworm, parasitic copepod, or trout nematode. Similar temperature suitability would occur with 8 units as with 4 units, whereby temperatures would be suitable for all life stages of only whirling disease; the exception is that temperatures would be suitable at Separation Canyon for completion of life stages of the parasitic copepod.

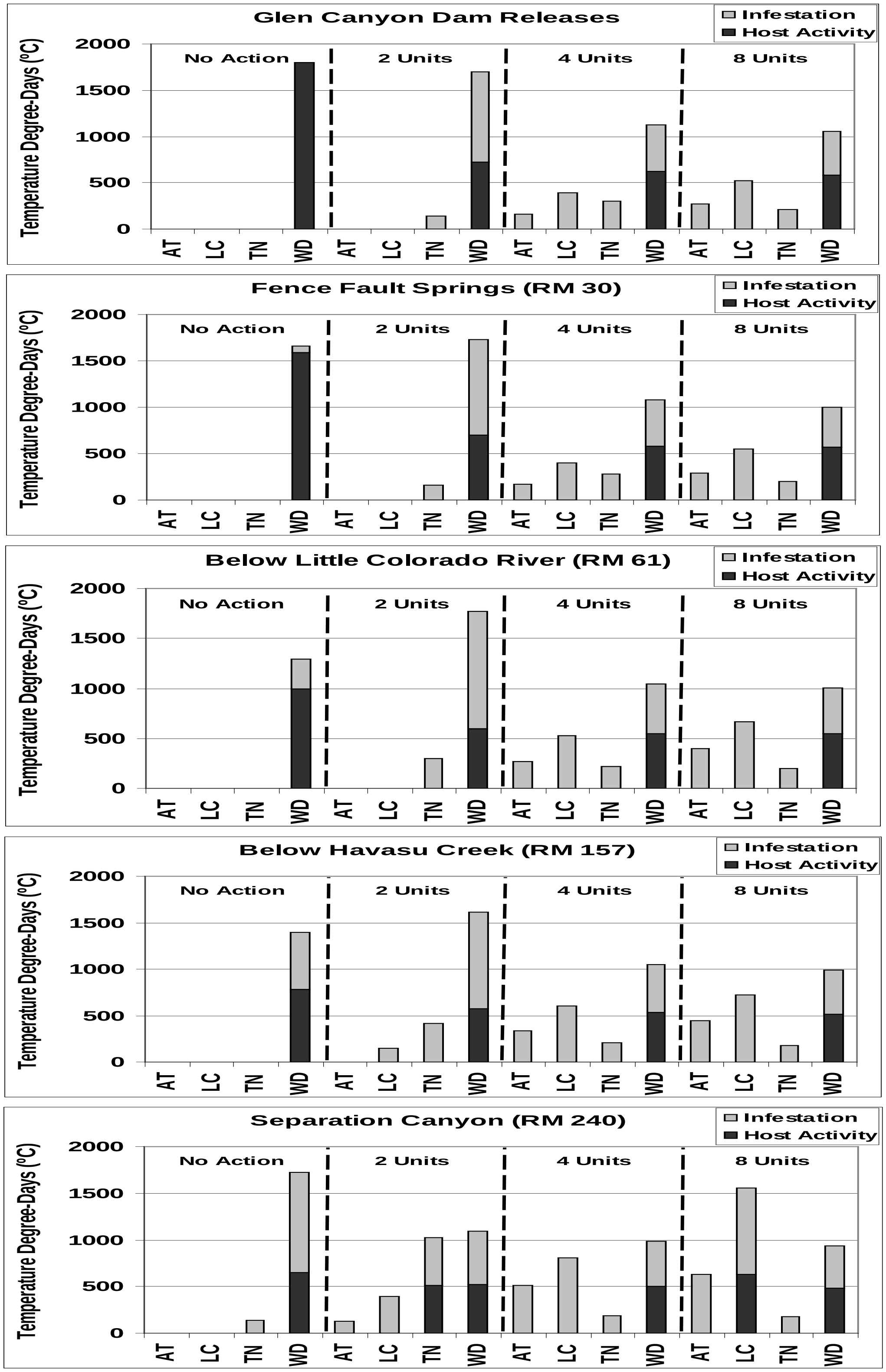

Figure 19. Suitable temperature degree-days (STDDs) for infestation and host activity of four fish parasites under No Action and 2, 4, and 8-unit TCDs for five locations. AT = Asian tapeworm, LC = *Lernaea cyprinacea*, TN = trout nematode, WD = whirling disease.

4.3 Aquatic Invertebrates

Temperatures for the New Zealand mudsnail and quagga mussel were suitable under all three alternatives from Glen Canyon Dam to Separation Canyon (Figure 20). Temperatures for northern crayfish were marginally suitable with all alternatives. Red swamp crayfish, however, require warm temperature and mainstem temperatures were not suitable under No Action and only marginally suitable with the 2, 4 and 8-unit TCDs.

Gammarus lacustris, *Chironomus* sp., and *Simulium arcticum* are common aquatic invertebrates in Grand Canyon that are important components of the aquatic food base for fish. Although mainstem temperatures are suitable for all three species under all three alternatives, the 2 and 4-unit TCD would increase temperature degree-days for these species by 5 to 8 times compared to No Action (Figure 20). Suitable temperatures would also increase gradually downstream.

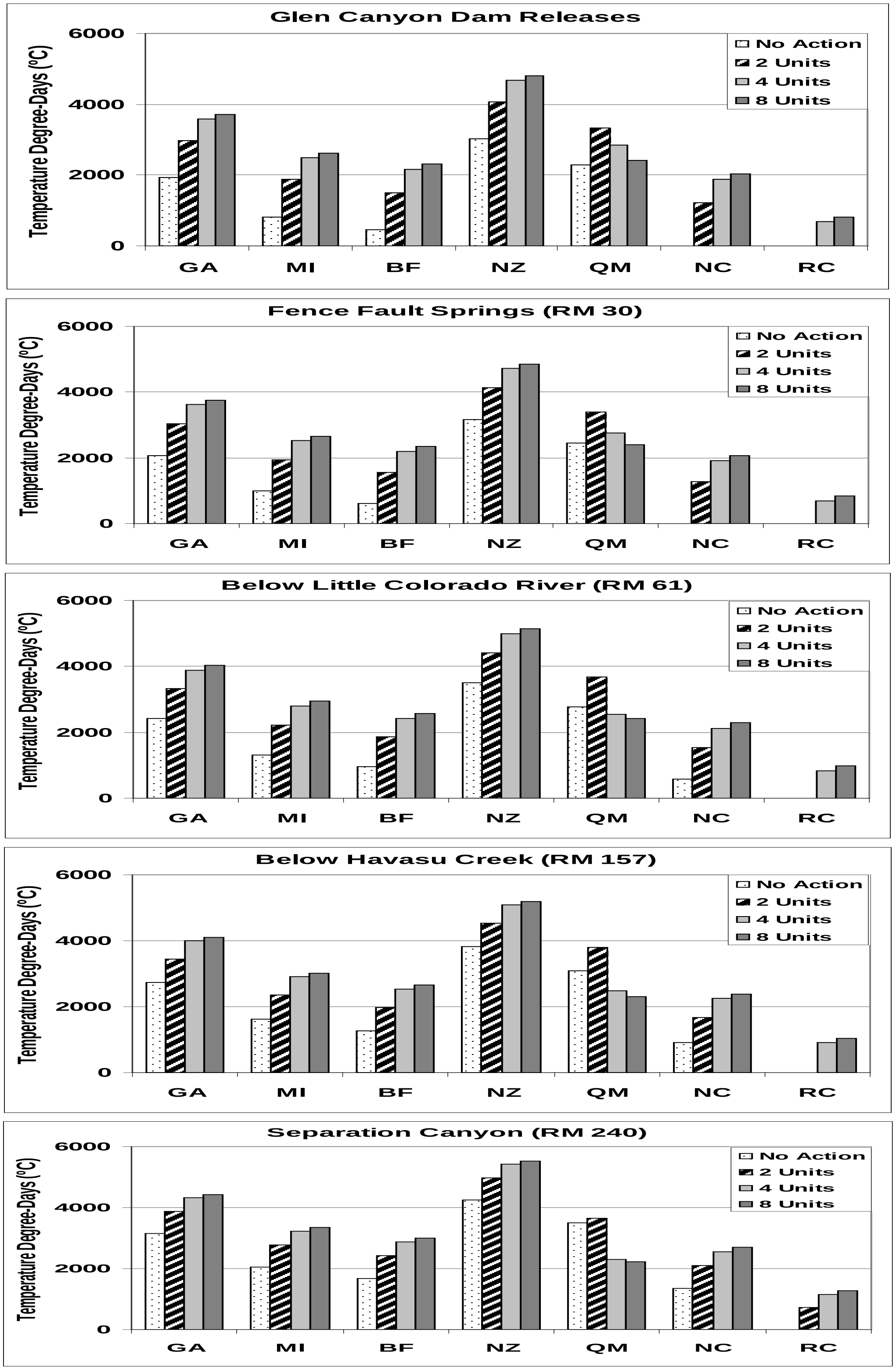

Figure 20. Suitable temperature degree-days (STDDs) for four invasive invertebrate species under No Action and 2, 4, and 8-unit TCDs for five locations. GA = *Gammarus lacustris*, MI = midges, BF = blackflies, NZ = New Zealand mudsnail, QM = quagga mussel, NC = northern crayfish, RC = red swamp crayfish.

5.0 DISCUSSION

5.1 Summary of Temperature Effects

Cold dam releases can limit reproduction and growth of aquatic forms downstream of Glen Canyon Dam and it is hypothesized that warmer releases will benefit native and endangered fishes, as well as trout sportfish. However, warmer water could also enable undesirable nonnative species to complete their life stages, including fish that prey upon or compete with native species. Warmer releases could also enable fish parasites and diseases to complete their life cycles, and allow populations of invasive shellfish and crustaceans to expand and possibly disrupt basic food chains.

Under current dam operations (i.e., No Action), the river temperature is suited primarily for cold-water fish species—principally rainbow trout, brown trout, and walleye—through most of the 300-miles from Glen Canyon Dam to Lake Mead. Trout currently spawn primarily in the Lees Ferry reach and at some locations downstream, mostly in clear, cold-water tributaries and inflows (e.g., Nankoweap Creek, Bright Angel Creek, Shinumo Creek, Tapeats Creek, and Deer Creek). Trout are not uniformly distributed throughout because tributaries such as the Paria River and the LCR deliver increasing amounts of sediment downstream from the dam that limit these sight feeders. Walleye have not been confirmed spawning in the Colorado River through Grand Canyon, but the fact that temperature appears suitable for this species should prompt managers to monitor the system for evidence of reproduction. Temperatures in the lower canyon (i.e., Separation Canyon) appear suitable under No Action for spawning by smallmouth bass, another dangerous predaceous species that should be monitored closely. Otherwise, temperatures throughout are too cold for ovulation, incubation, and growth by most fish species in the Grand Canyon Ecosystem, or likely to access the system.

A temperature control device could be built onto Glen Canyon Dam for warmer dam releases that would increase available temperature degree-days for downstream aquatic resources. This assessment predicts that a 2-unit TCD is likely to continue to benefit cold-water fish species, such as brown trout, rainbow trout, and walleye, but will also make temperatures suitable for spawning by redside shiner and smallmouth bass downstream to below Havasu Creek, as well as for red shiner, flannelmouth sucker and razorback sucker downstream at Separation Canyon. The benefit to native fishes from a 2-unit TCD would be marginal and could be offset by a similar benefit to a large number of predaceous and competing nonnative fish species. Brown trout and rainbow trout are known predators of humpback chub (Marsh and Douglas 1997; Valdez and Ryel 1995) and redside shiners are notorious competitors and predators of small-bodied fish along shorelines (Reeves et al. 1987). Walleye and smallmouth bass are particularly aggressive species that can consume large numbers of native fish. Smallmouth bass have recently become problematic in reaches of the Upper Colorado River Basin (Upper Colorado River Endangered Fish Recovery Program 2008). Although mainstem temperatures may not be entirely suitable for a species, the warmer temperatures provided by a TCD would provide a higher base temperature for added longitudinal warming and for sheltered habitats like backwaters and shorelines.

The greatest predicted benefit to native fishes would occur with a 4 or 8-unit TCD. With 4 and 8 units, temperatures would be suitable for all life stages of flannelmouth sucker and razorback sucker downstream to the LCR. The razorback sucker occurs as four populations in Lake Mead and individuals have been detected with sonic telemetry, PIT tags, and recent captures in the lower Grand Canyon (Valdez et al. 2012b). A 4-unit TCD could make mainstem temperatures suitable for the species to complete its life history from Glen Canyon Dam to Lake Mead. Although a 4-unit TCD could provide suitable mainstem temperature for reproduction by the native fish species, temperatures would also be suitable for growth of 15 nonnative species that are predators or competitors.

Altogether, temperature modification with an 8-unit TCD would make conditions suitable for all life stages of 23 of the 35 species, including 5 native species and 18 nonnative species. Species that are not expected to respond include black crappie, burbot, gizzard shad, mosquitofish, black bullhead, plains killifish, threadfin shad, blue tilapia, and flathead catfish. Most of these species have either rarely been found in Grand Canyon, exist in tributaries, or occur outside of the area, mostly downstream in Lake Mead or in the upper or lower Colorado River. Species such as black bullhead, mosquitofish, and plains killifish could continue to be self-sustaining because they rely on seasonally warmed tributaries or warmed backwaters for sustaining local populations. Warm mainstem temperatures could allow for greater dispersal by these species that are otherwise restricted to certain habitats by surrounding cold mainstem temperatures. This assessment predicts that channel catfish are not likely to benefit from a TCD, except with 8 units below Havasu Creek. This species presently spawns in the LCR and may move upstream from Lake Mead. Warmer temperatures in the mainstem may also allow for greater movement and dispersal by channel catfish throughout the Colorado River and its tributaries in Grand Canyon.

Small cyprinid species, such as fathead minnow and red shiner could benefit from a temperature modification, where nearshore habitat is used as a mainstem nursery by native fishes, including the endangered humpback chub. Fathead minnow and red shiner inhabit shorelines and are highly predaceous on small-bodied fish that use these same habitats (Rupert et al. 1993).

The four species of fish parasites considered in this assessment were the Asian tapeworm, parasitic copepod, trout nematode, and whirling disease. None of these fish parasites has been considered a serious threat to fish populations under current conditions (i.e., No Action), although the effect of a recent invasion of whirling disease in the Lees Ferry trout fishery continues to be evaluated. Temperatures for all life stages of whirling disease are suitable in at all locations with a 2, 4, or 8-unit TCD, and in all locations except Lees Ferry under No Action, where temperature is not sufficient for infestation. When host activity and infestation are considered for these parasites, temperatures are not suitable for the Asian tapeworm and parasitic copepod with a 2, 4, or 8-unit TCD. Conditions for the trout nematode could be suitable with a 2 or 4-unit TCD, but only at the downstream most location, Separation Canyon, where trout are not present.

The Asian tapeworm requires an intermediate cyclopoid copepod that is present in Lake Powell and apparently becomes entrained in penstock withdrawals (Budy et al. 2004). The copepod host inhabits quiet, shallow, warm waters usually associated with lake shorelines and riverine backwaters. These habitats are available in Grand Canyon, although they may be ephemeral or transient, depending on dam operations. The parasitic copepod *Lernaea* is present in the system, but like the Asian tapeworm, cool mainstem temperatures keep infestation at a low level. The parasitic copepod does not have an intermediate host but requires similar quiet, shallow, warm habitat for fish infection. Although a TCD would reduce the heat budget in Lake Powell, the shoreline habitat is not likely to be affected as dramatically and no effect is expected to fish parasites or their hosts in the reservoir as a result of increased host density or other environmental aspects favorable to these parasites.

Whirling disease is a metazoan parasite native to the Eurasian continent. The immature stages penetrate the head and spinal cartilage of fingerling trout where it multiplies rapidly, putting pressure on the organ of equilibrium (Hoffman 1990). This causes the fish to swim erratically (whirl) and to have difficulty feeding and avoiding predators. In severe infestations, the disease can cause high rates of mortality in young fish. Fish that survive until their skeletal cartilage hardens to bone can live a normal life span, but are often marred by structural deformities. Fish can reproduce without passing on the parasite to their offspring. The ingestion of spores by tubifex worms is temperature independent, but the development and release of triactinomyxons (TAMs), the stage infectious to trout, are highly affected by temperature (Hoffman 1990). Individual tubifex worms can shed a maximum of 46,000 TAMs/day and with some worms, TAMs are released in a membrane enclosed packet or "fecal packet." These TAMs are ciliated and motile and infect the gill membrane of fish where they gain entrance to the circulatory system and eventually the nervous system.

Infections in tubifex worms progress slowly at 5°C and 10°C, are optimal at 12°C to 15°C (dam release temperatures with a 2-unit TCD), but are restricted and in fact are rapidly eliminated at temperatures of 25 and 30°C. Possibly, whirling disease can become more serious in waters that remain cool through the year (as may occur with a 2-unit TCD), where the tubifex worms become and stay infected and persistently release TAMs. In contrast, worms in warmer systems may become infected during cool periods and cured during high temperature only to be re-infected later. This cycle of infection, cure, and re-infection could reduce the incidence of high and continuous TAM releases.

Warming may also improve temperature conditions for the New Zealand mudsnail and the quagga mussel. The New Zealand mudsnail is currently found in large numbers in Grand Canyon (Kennedy and Gloss 2005), and the quagga mussel is not currently found in Grand Canyon, but conditions in the tailwater are suitable for the species (Kennedy 2007). However, warming would not likely provide suitable mainstem temperatures for reproduction and growth of the red swamp crayfish and only marginal conditions for the northern crayfish, which require warmer temperatures. Modifying 2 or 4 penstocks would provide greater temperature degree-days for some common beneficial invertebrates, such as the *Gammarus lacustris, Chironomus* sp., and *Simulium arcticum,* although other stenothermic invertebrate species may not be able to adjust to a wider range of temperatures.

This assessment was based on temperature effects to life functions of fishes, fish parasites, and aquatic invertebrates, and did not consider ecological aspects such as habitat suitability and food availability. What would happen to the aquatic food base of the Colorado

River in Grand Canyon if the river was seasonally warmed in the absence of the large amount of allochthonous organic matter that was historically delivered to the region and is now held in Lake Powell? Following construction of Glen Canyon Dam, the Colorado River through Grand Canyon was quickly transformed from an allochthonous system to an autochthonous system dependent largely on autotrophic, photosynthetic production. Large amounts of algae and diatoms are produced in the clear cold waters downstream of the dam, and the amount of this photosynthetic production declines downstream with decreased water clarity (Kennedy and Gloss 2005). Production in the lower reaches of the Colorado River through Grand Canyon tends to be limited because of reduced photosynthesis and a lack of organic matter (Rosi-Marshall et al. 2010). Warming the Colorado River through Grand Canyon will likely replace cold-adapted algal and diatom species with warm-adapted species that rely on input of organic matter rather than photosynthesis. A warm river would likely produce fewer desirable species in the clear dam tailwater, but the warm-adapted species in the more turbid downstream reaches would lack the organic matter to thrive. This could stagnate or suppress the aquatic food base.

The importance of temperature effects on the aquatic food base and thus, on the fish population, is illustrated with a bioenergetics model developed by Petersen and Pauckert (2005) to examine how warmer water temperatures might affect growth rate and food conversion of humpback chub. Consistent with this assessment of temperature degree-days, model simulations indicate that increasing dam release temperature from 9°C to 16°C during summer and fall would have a minimal effect on growth rate unless food availability also increased. Increased food availability and growth of humpback chub would increase survival by reducing their time at a small size that is vulnerable to predation. Because the river in summer and fall warms as it flows downstream from the dam, the effect of warmer temperature on humpback chub and on the food base would depend on the locations of fish. Companion bioenergetics models for humpback chub and rainbow trout (Petersen and Pauckert 2007) predict that consumption by the rainbow trout population is at least 10 times higher than by the smaller humpback chub population, inferring substantial competition where these species co-occur.

Despite the predicted benefits to native fish species in Grand Canyon and the offsetting effects from benefits to nonnative species, the resultant effect to the river ecosystem and the food base are not known, but cannot be ignored. Warming the Colorado

River through Grand Canyon will benefit many fish species, including native forms, but warming could also have a detrimental effect on the aquatic food base (e.g., Cucherousset et al. 2011). Unfortunately, modifying the penstocks of Glen Canyon Dam is an expensive undertaking that cannot be guaranteed to benefit key resources. The only way to know for sure is to build a TCD and implement it in a manner that does not impose long-term damage to the aquatic ecosystem. Evidently, if a TCD is operated continually for years, it could have detrimental effects on the aquatic food base. However, if it was operated selectively to accomplish specific goals (e.g., provide suitable temperatures for mainstem spawning by native fish), a TCD may be a useful tool.

The goal of managers with respect to river temperature downstream of Glen Canyon Dam should be to identify a range of temperatures (i.e., "sweet spot") in which:

- Native fish benefit for growth, recruitment, and spawning;
- Non-native fish do not increase or expand;
- Fish diseases and parasites are kept in check; and
- Aquatic food base diversity is increased.

We conclude from this evaluation that there probably is not a "sweet spot" for a temperature range that would meet all four criteria above. The type of warming seen with a 4 and 8-unit TCD would provide growth benefits to the native fishes, but also the nonnative species as well.

The variable warming pattern relative to reservoir elevation is an important consideration when evaluating the most suitable temperature modification strategy. Although the surface water warms more and earlier than the underlying layers, drawing water from the surface may not be desirable because of air entrainment in the penstocks and the possibility of entraining fish. Water at the 25-m level may be more desirable because of a more prolonged warming (i.e., 17-18°C during July-October), though the risk of fish entrainment may remain.

Another period of warm releases, such as seen in 2004-2011, is likely but the timing and duration is uncertain. Periods of cold releases and warm releases provide the opportunity to monitor and evaluate the responses of various aquatic species to these changing water temperatures of the Colorado River through the Grand Canyon. Warm releases that result from low reservoir elevation are unpredictable and may not have the same thermal regime as directed releases of warmer surface water through designed temperature modification. As seen when annual temperature of 2005 was compared with a 2-unit TCD, the patterns were similar but the latter was about 1ºC warmer. Nevertheless, these periods of warm release provide a natural experiment that simulates a 2-unit TCD giving managers the opportunity to monitor effects on resources.

The predictions contained in the analysis are based on temperature only. The authors recognize that temperature change brought about by a TCD is likely to cause significant, but unpredictable and possibly widespread ecological consequences. Because the interactions are not fully understood and quantified, the present analysis is narrowly focused on the effects of a TCD on temperature degree-days for fish, fish parasites, and selected aquatic invertebrates of the Colorado River in Grand Canyon. This analysis compared predicted river temperatures with temperature degree-days of aquatic species in or near the Grand Canyon region and did not take into account other factors, such as habitat suitability or food availability. Effects of temperature on many aquatic species of Grand Canyon are not well understood and a weight-of-evidence approach is applied in dealing with the uncertainty of response to temperature change.

Aquatic invertebrates are very sensitive to temperature. Egg hatching and emergence of adult insects is often triggered by low and high temperature extremes, respectively. The temperature of the river downstream from Glen Canyon Dam lacks strong seasonal variability, which may prevent successful colonization by native insects that historically lived in this river (Kennedy et al. 2013). Such extreme variability would be desirable for returning certain invertebrate species to the system. However, it is important to note that attaining this extreme variability through any known strategy or dam medication is not currently possible. Neither the upper range of 30ºC nor the lower range of near freezing is achievable through penstock modification or any other strategy.

5.2 Benefits and Risks to Humpback Chub

The call for a selective withdrawal program for Lake Powell waters in the 1995 BO was prompted by the perceived need to provide warmer water primarily to allow the endangered humpback chub to complete all of its life cycle in the mainstem Colorado River in Grand Canyon. The thermal regime of the post-dam Colorado River is too altered for the completion of all life stages of the humpback chub. Temperatures are not sufficiently warm for mainstem reproduction (16–22ºC), except for a short time in late summer in the most downstream reaches of the lower Grand Canyon, and suitable temperatures for growth (14–25ºC) are available for only a short time in summer. The implementation of a 2-unit TCD would provide suitable spawning temperatures downstream of Havasu Creek, and suitable growth temperature starting at about the LCR. The greatest benefit for spawning and growth of humpback chub would be provided with a 4 or 8-unit TCD. Either unit would provide suitable temperature for growth starting at Glen Canyon Dam. A 4-unit TCD would provide suitable spawning temperature in the lower-most reach of the Grand Canyon, and an 8-unit TCD would provide suitable spawning temperatures in the mainstem, starting at about the LCR.

Temperature augmentation is also likely to benefit several species of nonnative warm water fishes that could compete with and prey on the humpback chub, including the green sunfish, channel catfish, common carp, fathead minnow, and red shiner; for every alternative and location where humpback chub benefit from temperature augmentation, at least these species benefit equally. Also, several cold water species, including the walleye, smallmouth bass, and redside shiner would also benefit from temperature modification. The net effect to humpback chub from possible increased numbers and distribution of nonnative fish cannot be determined, but would require contingency plans in case one or more of these species flourished.

Another benefit from warming would be the increased swimming performance by humpback chub in warmer water and a greater ability to escape cold water trout predators. Valdez and Ryel (1995) surmised that rainbow trout and brown trout could collectively nearly eliminate an entire year class of young humpback chub in the mainstem near the LCR, and hypothesized that cold mainstem temperatures were limiting swimming ability of the chub, as demonstrated by Bulkley et al. (1982). Ward (2013) demonstrated in a laboratory that survival of juvenile humpback chub from rainbow trout predation was nearly twice as high at 20ºC as at 10ºC, although the effect was not the same for brown trout. Until a decision is made to modify dam release temperature at Glen Canyon, the effect of warm dam releases during low reservoir elevations (e.g., 2004–2011) should be monitored and evaluated to learn as much as possible in anticipation of negative effects of temperature modification.

The establishment of a second population separate from the LCR is important for the security of the species in the Grand Canyon and for species recovery. In evaluating the feasibility of establishing a second population of humpback chub in Grand Canyon, Valdez et al. (2000) determined that population size necessary for demographic and genetic viability (i.e., population size and structure) are unlikely to be met in a tributary, but may be met in two contiguous mainstem aggregations (Stephen Aisle/Middle Granite Gorge) or in the mainstem taken as a whole or as a metapopulation. The metapopulation concept was thought to present the greatest likelihood for success in establishing a new, demographically and genetically viable population of humpback chub in Grand Canyon. But, it was also acknowledged that suboptimal river temperature precludes spawning by the species in the mainstem and the need for further evaluation of temperature augmentation was identified.

Figures 21 and 22 are presented to illustrate seasonal warming patterns for No Action and 2, 4, and 8-unit TCDs downstream of Glen Canyon Dam and at each of the nine humpback chub aggregations identified by Valdez and Ryel (1995). It should be noted that the temperature patterns represent seasonal means at each location, and do not consider TDDs as presented elsewhere in this report. Nevertheless, temperature patterns are clear for each of the four alternatives and show that in summer and fall, the minimum growth temperature of 14ºC is reached downstream of Havasu Creek and the minimum spawning temperature of 16ºC is not reached at any aggregation.

With a 2-unit TCD, minimum growth temperature is exceeded at all locations in summer and fall, and minimum spawning temperature is exceeded in summer downstream of the LCR and met in the fall. With 4 and 8-unit TCDs, both the minimum growth temperature and the minimum spawning temperature are exceeded at all locations in summer and fall. These results seem inconsistent with the TDD analysis above because the longitudinal temperatures represent seasonal means and do not consider the length of time at a given temperature, as inherent to the determination of TDDs. In other words, although suitable temperature is reached, a particular life stage cannot be successful if that temperature is not sustained for the necessary period of time. Another consideration in this particular analysis is whether a dam release temperature of >20ºC is possible even with an 8-unit TCD. As seen in Figures 6 and 7, to achieve a release temperature of 20ºC, water withdrawal would have to come from about the top 20 m of the reservoir, which could lead to air entrainment in the penstocks as well as entrainment of fish (U.S. Department of the Interior 2012).

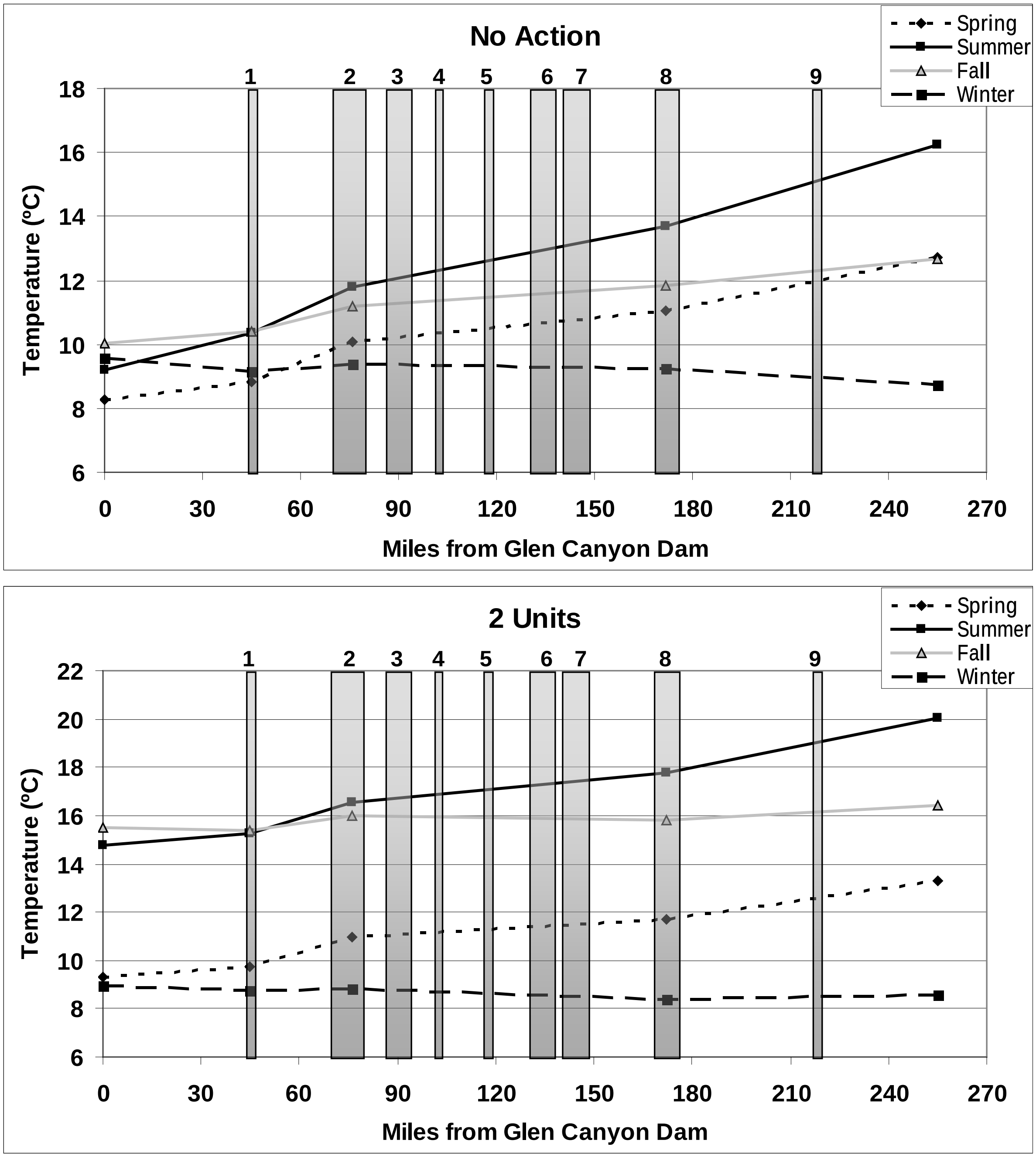

Figure 21. Seasonal longitudinal patterns of river temperature downstream from Glen Canyon Dam for No Action and a 2-unit TCD. Spring = Mar-May, Summer = Jun-Aug, Fall = Sep-Nov, Winter = Dec-Feb. Dark vertical bars represent locations of the nine mainstem humpback chub aggregations: 1 = 30-Mile, 2 = LCR inflow, 3 = Lava Chuar to Hance, 4 = Bright Angel Creek inflow, 5 = Shinumo Creek inflow, 6 = Stephen Aisle, 7 = Middle Granite Gorge, 8 = Havasu Creek inflow, and 9 = Pumpkin Spring (Valdez and Ryel 1995). Minimum growth temperature is 14ºC and minimum incubation/hatching temperature is 16ºC.

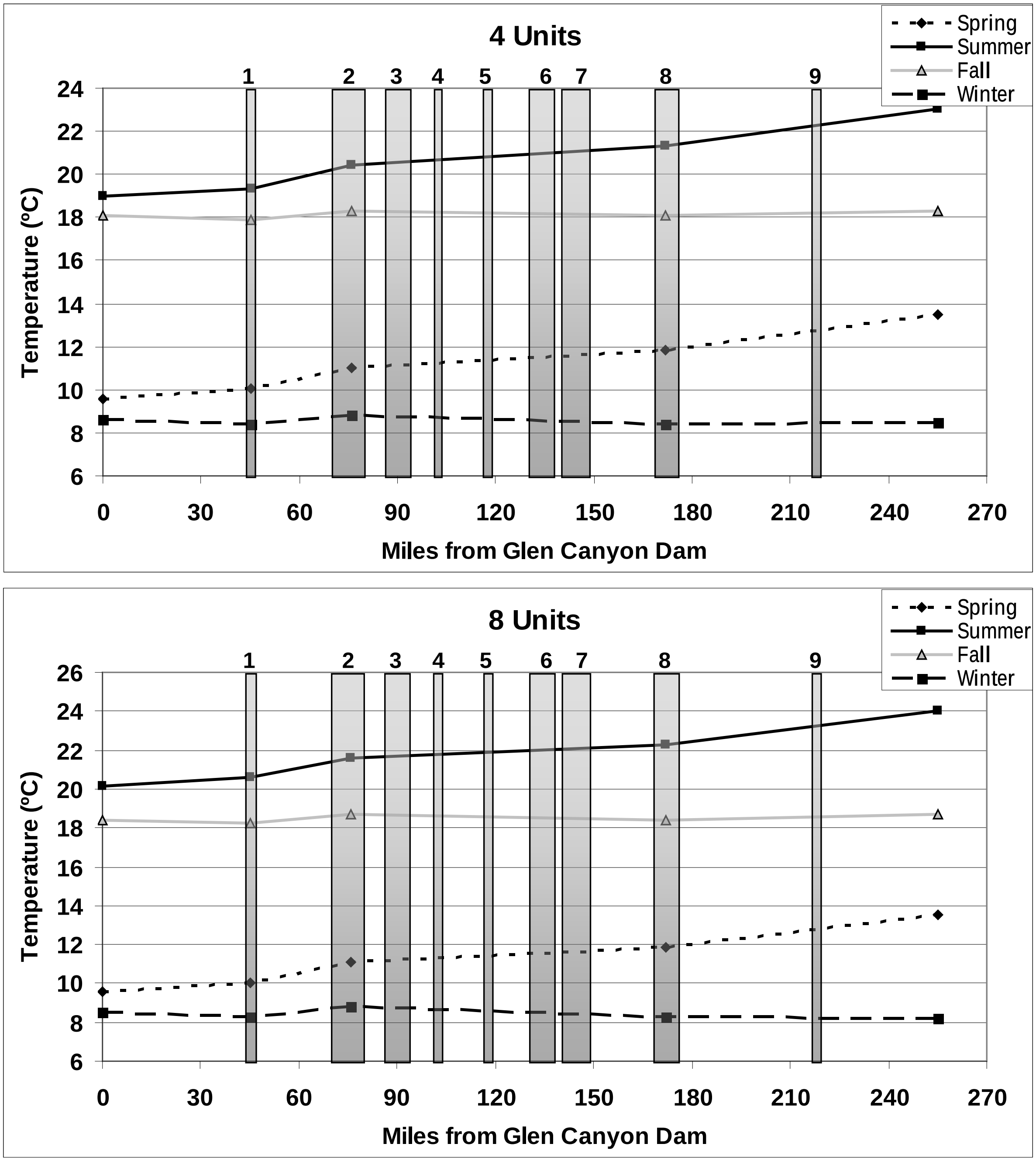

Figure 22. Seasonal longitudinal patterns of river temperature downstream from Glen Canyon Dam for 2 and 4-unit TCDs. Spring = Mar-May, Summer = Jun-Aug, Fall = Sep-Nov, Winter = Dec-Feb. Dark vertical bars represent locations of the nine mainstem humpback chub aggregations: 1 = 30-Mile, 2 = LCR inflow, 3 = Lava Chuar to Hance, 4 = Bright Angel Creek inflow, 5 = Shinumo Creek inflow, 6 = Stephen Aisle, 7 = Middle Granite Gorge, 8 = Havasu Creek inflow, and 9 = Pumpkin Spring (Valdez and Ryel 1995). Minimum growth temperature is 14ºC and minimum incubation/hatching temperature is 16ºC.

5.3 Considerations for Temperature Modification

Changes in the temperature of rivers from dam impoundment are recognized worldwide as having large effects on downstream aquatic ecosystems, particularly fish populations (Castelletti et al. 2009). Where dams are built in historically warm river segments, hypolimnetic releases transform the downstream river into a cold clear stream that reduces available temperature degree-days and displaces warm-water species. Dams built at higher elevations in cold-water habitat used by trout and salmon may alter the seasonal thermal regime and affect spawning cues. Biologists and managers responsible for conserving downstream resources may opt to modify release temperatures to benefit target resources, but these modifications may also pose indirect risks by benefiting competitive or predaceous invasive species.

5.3.1 Examples of Dam Modifications

A number of dams in the Pacific Northwest of the U.S. have disrupted thermal regimes of cold-water trout and salmon, prompting managers to modify dam release temperatures. Shasta Dam, constructed on the Sacramento River, CA, in 1945, disrupted the thermal regime for the endangered winter run Chinook salmon (*Oncorhynchus tshawytscha*), and in 1997, a temperature control device (TCD) was retrofitted on the dam for controlling downstream river temperatures (Bartholow and Heasley 2006). Similarly, Dworshak Dam, built in 1971, controls flow of the Clearwater River to meet the overall flood regulation plan for the Columbia River. The dam was built with temperature control structures capable of controlling the temperature of releases to provide cold water during the summer to benefit the Snake River salmon (*O. nerka*), steelhead (*O. mykiss*), and fall Chinook salmon (Yearsley 2003). In the case of the McKenzie River that supported the largest remaining wild population of Chinook salmon in the upper Willamette River Basin (Good *et al.*, 2005), Cougar Dam in 1964 altered the temperature pattern downstream and disrupted the timing of migration, spawning, and egg hatching. A selective withdrawal tower built in 2005 selects water from a given level or blends warm water from the top of the reservoir with cooler water at deeper levels to match a downstream temperature target (Rounds 2007).

In one of the largest restoration projects in North America, an 83-m high underwater "Selective Water Withdrawal Tower" was constructed in the forebay of Pelton Round Butte Dam on the Deschutes River, Oregon, that adjusts the temperature of releases, changes water currents in the lake, and directs trout and salmon into a sorting facility. Larger fish are returned to the lake, and smaller, migratory fish are tagged and trucked around the dam to be released into the lower river. These Pacific Northwest dams were modified to ensure cold releases year-around to protect salmonid fishes (Higgs and Vermeyen 1999).

In other rivers, dams have been modified to increase the temperature of releases and restore thermal requirements of cold-water species. Hungry Horse Dam, completed on the Flathead River, Montana in 1953, releases water too cold for cutthroat trout (*O. clarkii*) and was retrofitted with a selective withdrawal system in 1995 to increase mid-summer temperature in the tailwater and promote higher growth rates (Vermeyen 2006). Similarly, Flaming Gorge Dam, built on the Green River, Utah in 1963, was retrofitted in 1978 with a selective withdrawal structure that warmed releases from about 4°C to 13.5°C and had an immediate benefit on rainbow trout (*O. mykiss*) growth and production in the tailwater; annual growth of young trout increased from about 45 mm to 150 mm (U.S. Department of the Interior 1999). The river downstream also warmed to nearly 21°C in regions occupied by warm-water fishes, where the endangered Colorado pikeminnow (*Ptychocheilus lucius*) has returned to native habitat (Bestgen et al. 2005). The aquatic invertebrate population in the dam tailwater maintained total abundance and diversity with some increases in amphipods or scuds following the thermal modification (Vinson 2001).

For impounded river segments at middle to low elevations, where the historical fish community consisted of obligate warm-water species, cold releases have virtually eliminated the native fish communities that are often replaced by invasive fish species. Glen Canyon Dam, built in the middle Colorado River in 1963, transformed historical releases of 0–32ºC to a post-dam range of 7–12°C. Cold releases eliminated 4 of the 8 native fish species and allowed a trout fishery to become established and persist, as well as nearly 20 species of non-native fishes (Gloss et al. 2005). The roundtail chub (*Gila robusta*) and endangered Colorado pikeminnow, bonytail (*G. elegans*), and razorback sucker (*Xyrauchen texanus*) were extirpated, and the populations of flannelmouth sucker (*Catostomus latipinnis*), bluehead sucker (*C. discobolus*), speckled dace (*Rhinichthys osculus*) and the endangered humpback chub (*G. cypha*) were reduced.

5.3.1 Forebay Impellers

The large number of dams in Murray-Darling Basin, New South Wales, Australia has raised such concern for riverine warm-water fish species as to coin the term "cold water pollution" (Astles et al. 2003; Preece 2003). Cold releases have altered aquatic communities and disrupted warming patterns that cue spawning of native fishes, such as the imperiled Murray cod (*Maccullochella peelii*), trout cod (*M. macquariensis*), Macquarie perch (*Macquaria australasica*), and river blackfish, (*Gadopsis marmoratus*). These changes have allowed invasive deleterious species such as common carp (*Cyprinus carpio*) that stand to benefit if a warm-water regime is restored.

The problems and the solutions having to do with temperature and dam regulation are not the same for any two systems, and a particular design or strategy may not be appropriate to all situations. Sherman (2000) identified options for mitigating cold water discharges from dams and provided a number of strategies currently in use. Figure 25 provides illustrations as example strategies for releasing warm water from a reservoir. A selective withdrawal removes water from selected strata within the water column. A forebay current forces warm surface water into area of withdrawal, and pumps and impeller send warm surface water downwards into the withdrawal layer. An example of the pumping system was implemented at Googong Dam in New South Wales, Australia. Googong Reservoir is one of five sources supplying Canberra's water. Its waters are mainly used for potable water supply but the reservoir is also used for recreational purposes. The reservoir has a history of low to medium levels of Cyanobacteria, namely *Anabaena*, responsible for taste and odor problems and, at definitely higher concentration levels, for producing neurotoxins. Destratification was thought as a suitable way to solve the problem. This technique involves increasing rates of vertical mixing via mechanical means, with the objective to improve dissolved oxygen conditions at depth which in-turn reduces the likelihood of nutrient and metal release from the sediments under anoxic conditions. Two pairs of 5 m diameter WEARS (brand) surface mounted mixers (Water Engineering and Research Solution; www.wears.com.au) were installed for that purpose in March 2007. These mixers or impellers were installed in the forebay to provide mixing of water of various temperatures, quality, and nutrient load (see bottom graph of Figure 25). The WEARS Resmix System is often used instead of the more expensive bubbling of compressed air to eliminate problems related to stratification and dissolved oxygen, and reduce blooms of Cyanobacteria in lakes and reservoirs.

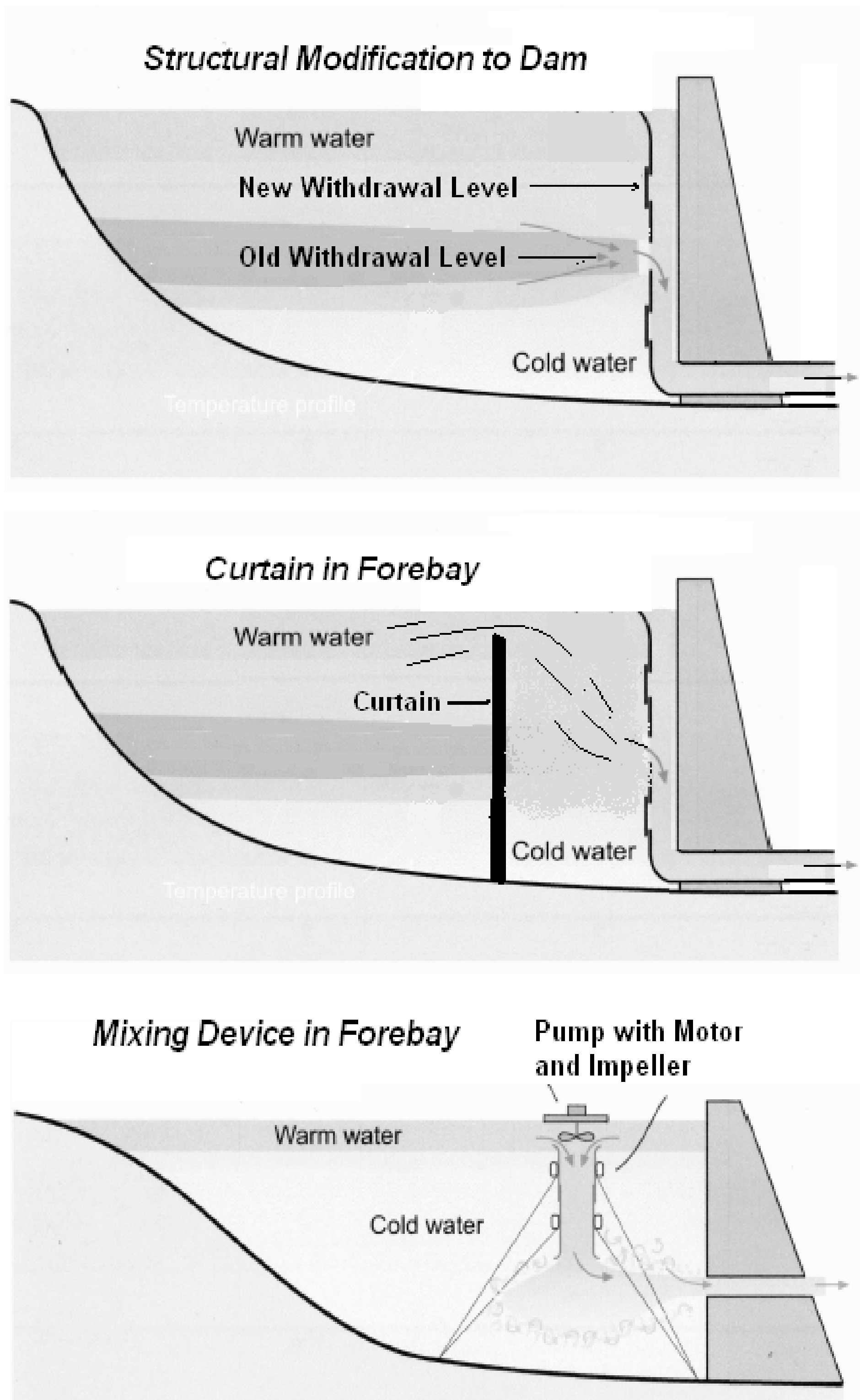

Figure 23. Example strategies for releasing warm water from a reservoir. Selective withdrawal (top) removes water from selected strata within the water column. Forebay current (center) forces warm surface water into area of withdrawal. Pumps and impeller (bottom) send warm surface water downwards into the withdrawal layer.

5.4.1 Reducing Dam Release Volumes

Reducing river volume reduces the mass of water that can be warmed with solar radiation, which theoretically results in higher river temperatures. The relationship of river volume (as cfs) to mainstem temperature is illustrated in Figure 24 with the use of a simplified river temperature model (Wright et al. 2008). This analysis does not involve the predicted temperature data generated by the GEMSS model, but is based on actual dam release temperatures recorded by GCMRC for the given years. This analysis is presented herein to inform the reader of the relationship of river volume to temperature, as dam release temperatures would be affected by temperature modifications at Glen Canyon Dam.

Only the month of August was used, as it represents the warmest month of the year and the highest rate of longitudinal warming. The first thing to notice about these relationships is that, as previously stated, the temperature of dam releases is important as the baseline temperature upon which longitudinal warming occurs. In a year of cold releases (i.e., 2002), average monthly dam release temperature for August was 9ºC, whereas temperature in a moderate year (i.e., 2006) was 11ºC, and for a warm year (2005) was 14ºC (see annual release signatures in Figure 5). After the base dam release temperature is determined, the longitudinal rate of warming is the about same for the different flows (Figure 24).

The rate of warming is greatest at lower volumes. In all years, the predicted increase in temperature at RM 30 when volume is decreased from 15,000 cfs to 5,000 cfs is about 1ºC, but the dam release would have to be reduced from 5,000 cfs to 2,000 cfs for an additional 2.0ºC; current minimum allowable dam release is 5,000 cfs (U.S. Department of the Interior 1996). Further downstream at the LCR (RM 61), predicted temperature increases by about 1.5ºC from 15,000 cfs to 5,000 cfs and by about 3ºC from 5,000 cfs to 2,000 cfs. Temperature increases for these volume changes at Havasu Creek are about 4.5ºC and 7ºC, and about 7ºC and 10ºC at Separation Canyon.

The relationship of river volume to temperature shows the importance of dam release temperatures to achieve some target downstream temperature at normal operating flows (e.g., 8,000-20,000 cfs). Even at flows of 5,000 cfs, the amount of warming is not very great and if a given target temperature is desired at a downstream location, the dam release temperature will need to be factored into the expected rate of warming for river volume to determine if a target temperature is achievable.

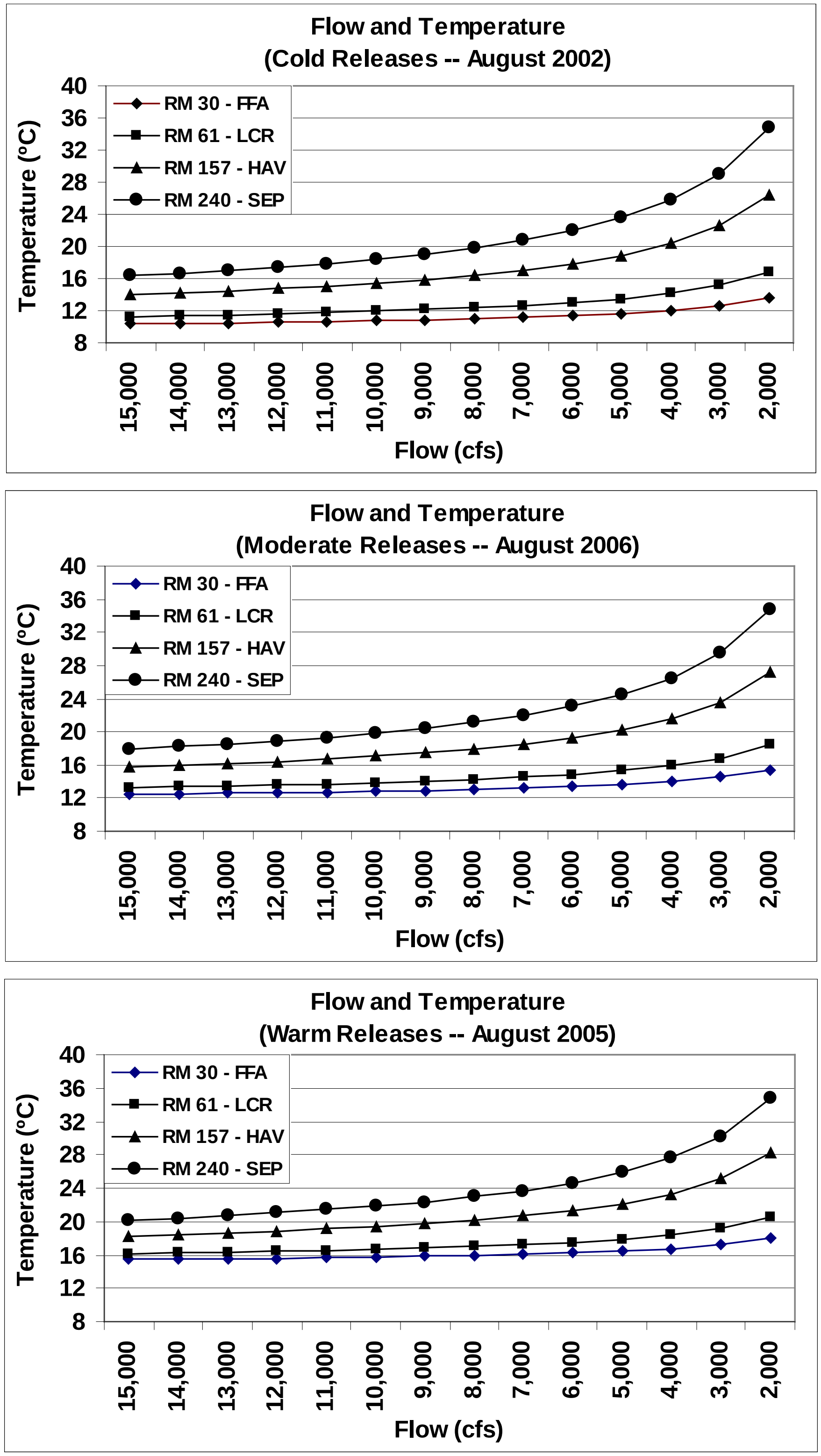

Figure 24. Relationship of river volume (as cfs) to temperature for August of a year of cold releases (2002), moderate releases (2006), and warm releases (2005). Temperatures predicted with a simplified river temperature model (Wright et al. 2008). Dam release temperatures from Grand Canyon Monitoring and Research Center, http://www.gcmrc.gov/dasa/tabdata/.

The relationship of dam release temperature and release volume is further illustrated as predicted temperature of the Colorado River at the nine humpback chub aggregations downstream from Glen Canyon Dam (Figure 25). Dam release temperature was set a 9ºC, 11ºC, and 14ºC, representing years of cold (e.g., 2002), moderate (e.g., 2006), and warm (e.g., 2005) August temperatures, respectively. The warming patterns and differences between release volumes were similar for of 5,000; 10,000; and 15,000 cfs.

At a cold dam release of 9ºC, If it is assumed that minimal growth temperature for humpback chub is about 14ºC and minimum ovulation temperature is 16ºC (see Table 2), the minimum growth temperature of 14ºC is not reached with releases of 10,000 and 15,000 cfs until about Havasu Creek, and the minimum ovulation temperature of 16ºC is not reached until about Diamond Creek. If the volume is reduced to 5,000 cfs, these minima are reached at about Bright Angel and Shinumo Creek, respectively.

At a moderate release temperature of 11ºC, the minimum growth temperature of 14ºC would be exceeded at the LCR with a release volume of <5,000 cfs and the minimum ovulation temperature would be reached at Bright Angel Creek. However, at higher release volumes of 10,000 cfs and 15,000 cfs, these minima would not been seen until about Middle Granite Gorge. At a warm release temperature of 14ºC, minimum growth and ovulation temperatures would be reached or exceeded at all volumes starting at the LCR.

This analysis was performed for only the August temperature, the month of maximum longitudinal warming. The temperature of the river at other months of the summer and fall will warm more slowly with distance from the dam. To perform a realistic evaluation of the potential benefit of warming for humpback chub from the combination of release temperature and release volume, the timing of spawning would have to be considered. Most humpback chub spawn in the LCR during April–June and most adults in the mainstem Colorado River not spawning in the LCR reach peak spawning condition during May–July (Valdez and Ryel 1995). It is unknown if suitable ovulation and spawning temperatures would have to be provided in the May–July period or if the fish would be able to adjust to a later period when dam release temperature is warmest at a slower longitudinal rate of warming (i.e., September–November).

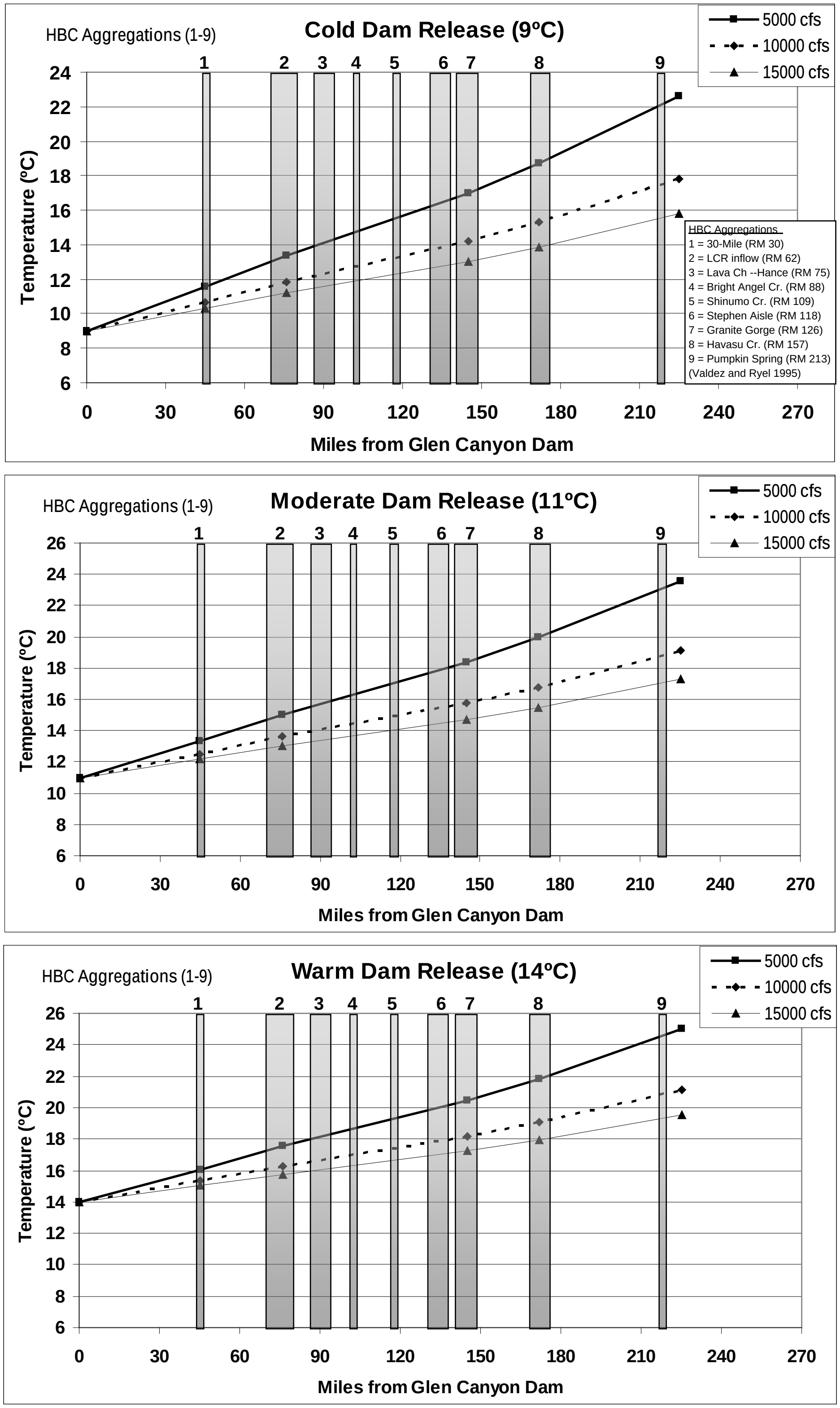

Figure 25. Predicted August temperatures of the Colorado River at nine humpback chub aggregations downstream from Glen Canyon Dam (Mile 0) for releases of 5,000; 10,000; and 15,000 cfs with dam release temperatures of 9ºC, 11ºC, and 14ºC. Temperatures predicted with a simplified river temperature model (Wright et al. 2008).

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Appendix A: Sources of Temperature Data

Table A-11. Literature sources for temperature data for the aquatic species evaluated. Complete citations are provided in Valdez and Speas (2013).

Common Name	Scientific Name	Literature Source
Fishes (35)		
Black bullhead	*Ameiurus melas*	Minckley 1973; Scott and Crossman 1973
Black crappie	*Pomoxis nigromaculatus*	Merriner 1971; Sublette et al. 1990
Blue tilapia	*Oreochromis aureus*	Hauser 1975; Platt and Hauser 1978; Hensley and Courtenay 1980; Bruton and Gophen 1992;
Bluegill	*Lepomis macrochirus*	Morgan 1951
Bluehead sucker	*Catostomus discobolus*	Maddux and Kepner 1988; Minckley 1991
Bonytail	*Gila elegans*	Hamman 1982
Brown trout	*Salmo trutta*	Leitritz and Lewis 1980; Melisky et al. 1980; Jobling 1981; Raleigh et al. 1986; Bell 1990
Burbot	*Lota lota*	McPhail and Paragamian 2000; Roy 2001
Channel catfish	*Ictalurus punctatus*	Shrable et al. 1969; Andrews et al. 1972; ; Andrews and Stickney 1972; Scott and Crossman 1973; Leitritz and Lewis 1980; Jobling 1981; Pawiroredjo 2004
Colorado pikeminnow	*Ptychocheilus lucius*	Hamman 1981; Black and Bulkley 1985a, 1985b; Marsh 1985; Bestgen et al. 1998;
Common Carp	*Cyprinus carpio*	Swee and McCrimmon 1966; Edwards and Twomey 1982; Bell 1990
Fathead minnow	*Pimephales promelas*	McPhail and Lindsey 1970; Scott and Crossman 1973; Melisky et al. 1980; Gale and Buynak 1982; Lechleitner 1992
Flannelmouth sucker	*Catostomus latipinnis*	Lechleitner 1992
Flathead catfish	*Pylodictis olivaris*	Carlander 1969; Sublette et al. 1990; Etnier and Starnes 1993; Mettee et al. 1996
Gizzard shad	*Dorosoma cepedianum*	Zweifel et al. 2009
Golden shiner	*Notemigonus crysoleucas*	Moyle 1976
Grass carp	*Ctenopharyngodon idella*	Etnier and Starnes 1993; Mettee et al. 1996
Green sunfish	*Lepomis cyanellus*	Hunter 1963; Scott and Crossman 1973; Etnier and Starnes 1993
Humpback chub	*Gila cypha*	Hamman 1982; Marsh 1985; Lupher and Clarkson 1994
Largemouth bass	*Micropterus salmoides*	Mettee et al. 1996; Etnier and Starnes 1993
Mosquitofish	*Gambusia affinis*	Krumholz 1948; Medlen 1952
Plains killifish	*Fundulus zebrinus*	Minckley and Klassen 1969; Lee et al. 1980; Haden 1992
Rainbow trout	*Oncorhynchus mykiss*	Scott and Crossman 1973; Hokanson et al. 1973; Leitritz and Lewis 1980; Melisky et al. 1980; Jobling 1981; Sigler and Sigler 1987; Bell 1990; Lechleitner 1992
Razorback sucker	*Xyrauchen texanus*	Toney 1974; McAda and Wydoski 1980; Bulkley and Pimentel 1983a;1983b; Snyder and Muth 1990; Minckley 1991; Schrader 1991; Burke and Mueller

Common Name	Scientific Name	Literature Source
		1993
Red shiner	*Cyprinella lutrensis*	Scott and Crossman 1973; Matthews and Hill 1977;
Redside shiner	*Richardsonius balteatus*	Miller 1951; Sigler and Sigler 1987
Roundtail chub	*Gila robusta*	Sigler and Miller 1963; Vanicek and Kramer 1969; Holden 1973; Muth et al. 1985; Kaeding et al. 1990; Karp and Tyus 1990; Brouder et al. 2000
Sand shiner	*Notropis stramineus*	Carlander 1969; Pflieger 1975; Etnier and Starnes 1993; Sigler and Sigler 1996;
Smallmouth bass	*Micropterus dolomieu*	Sigler and Sigler 1996; Etnier and Starnes 1993
Speckled dace	*Rhinichthys osculus*	Carothers and Minckley 1981; Lechleitner 1992; Weiss 1993; Gorman 1994; Robinson et al. 1996
Striped bass	*Morone saxatilis*	Scott and Crossman 1973; Hill et al. 1989
Threadfin shad	*Dorosoma petenense*	Kimsey and Fisk 1964; Rawstron 1964; Burns 1966; Moyle 1976
Utah chub	*Gila atraria*	McConnell et al. 1957; Graham 1961
Walleye	*Sander vitreus*	Etnier and Starnes 1993
Yellow bullhead	*Ameiurus natalis*	Scott and Grossman 1973; Mettee et al. 1996; Sigler and Sigler 1996
Fish Parasites (4)		
Asian tapeworm	*Bothriocephalus acheilognathi*	Granath and Esch 1983
Parasitic copepod	*Lernaea cyprinacea*	Grabda 1963; Hoffman 1976; Bulow et al. 1979; Stoskopf 1993
Trout nematode	*Dactnitis truttae*	Hoffman 1967
Whirling disease	*Myxobolus cerebralis*	Markiw 1992; El-Matbouli et al. 1999; Blazer et al. 2003; Gilbert and Granath 2003; Elwell et al. 2009
Invertebrates (7)		
Freshwater amphipod	*Gammarus lacustris*	Smith 1973
Midges	*Chironomus* sp.	Nebeker 1973; Merritt and Cummins 1996
Blackflies	*Simulium arcticum*	Shipp et al. 1987
New Zealand mudsnail	*Potamopyrgus antipodarum*	Aquatic Nuisance Species Task Force, http://www.anstaskforce.gov/spoc/nzms.php
Quagga mussel	*Dreissena bugensis*	Aquatic Nuisance Species Task Force, http://www.anstaskforce.gov/spoc/nzms.php
Red swamp crayfish	*Procambarus clarkii*	Huner and Barr 1981; Liua et al. 2013
Northern crayfish	*Orconectes virilis*	http://el.erdc.usace.army.mil/ansrp/ANSIS/html/orconectes_virilis_northern_crayfish

Appendix B: Predicted River Temperatures

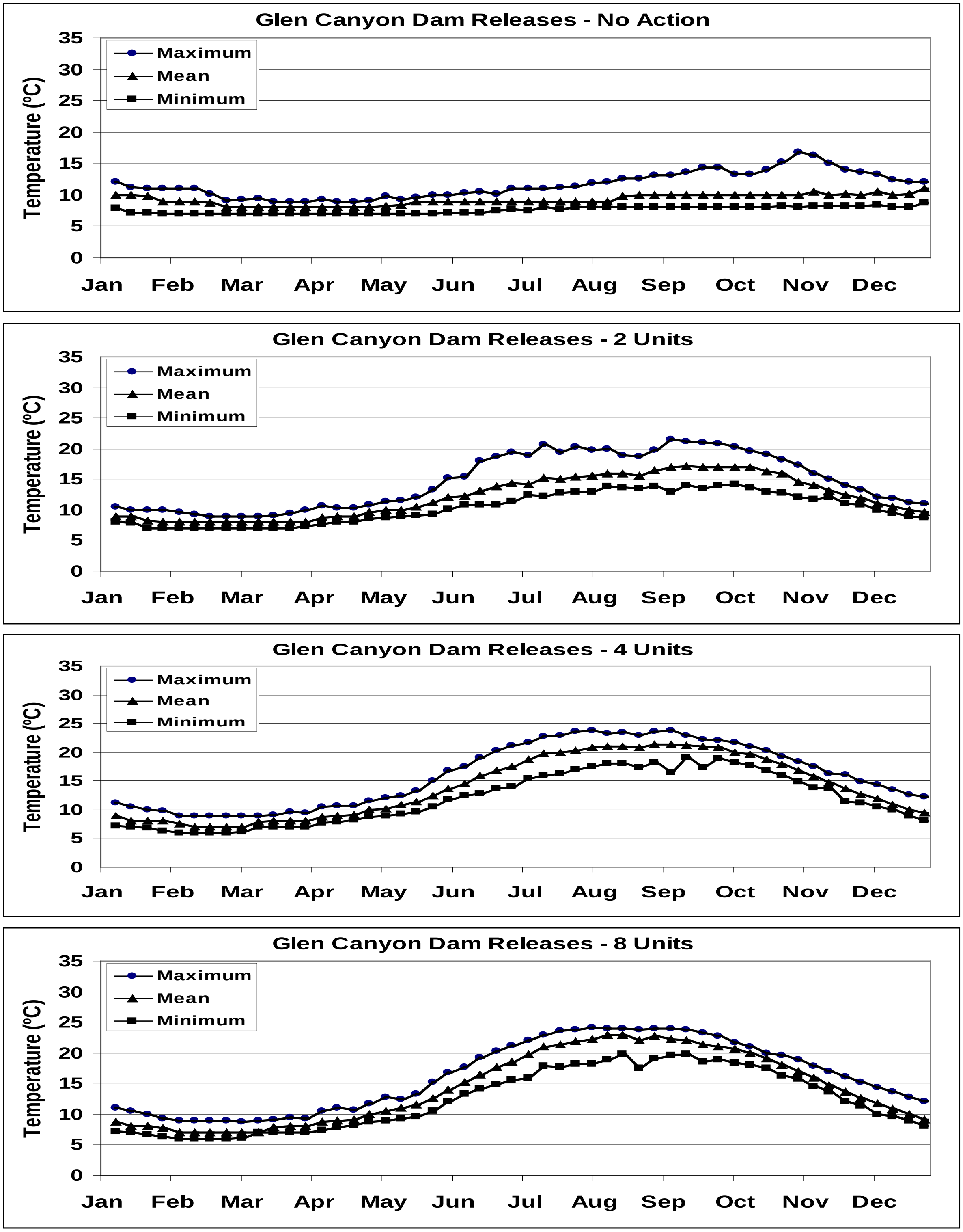

Figure B-26. Predicted maximum, minimum, and mean daily water temperature for Glen Canyon Dam releases with No Action and a 2, 4, and 8-unit TCD. Data points are 7-day averages. Data generated by GEMSS® model.

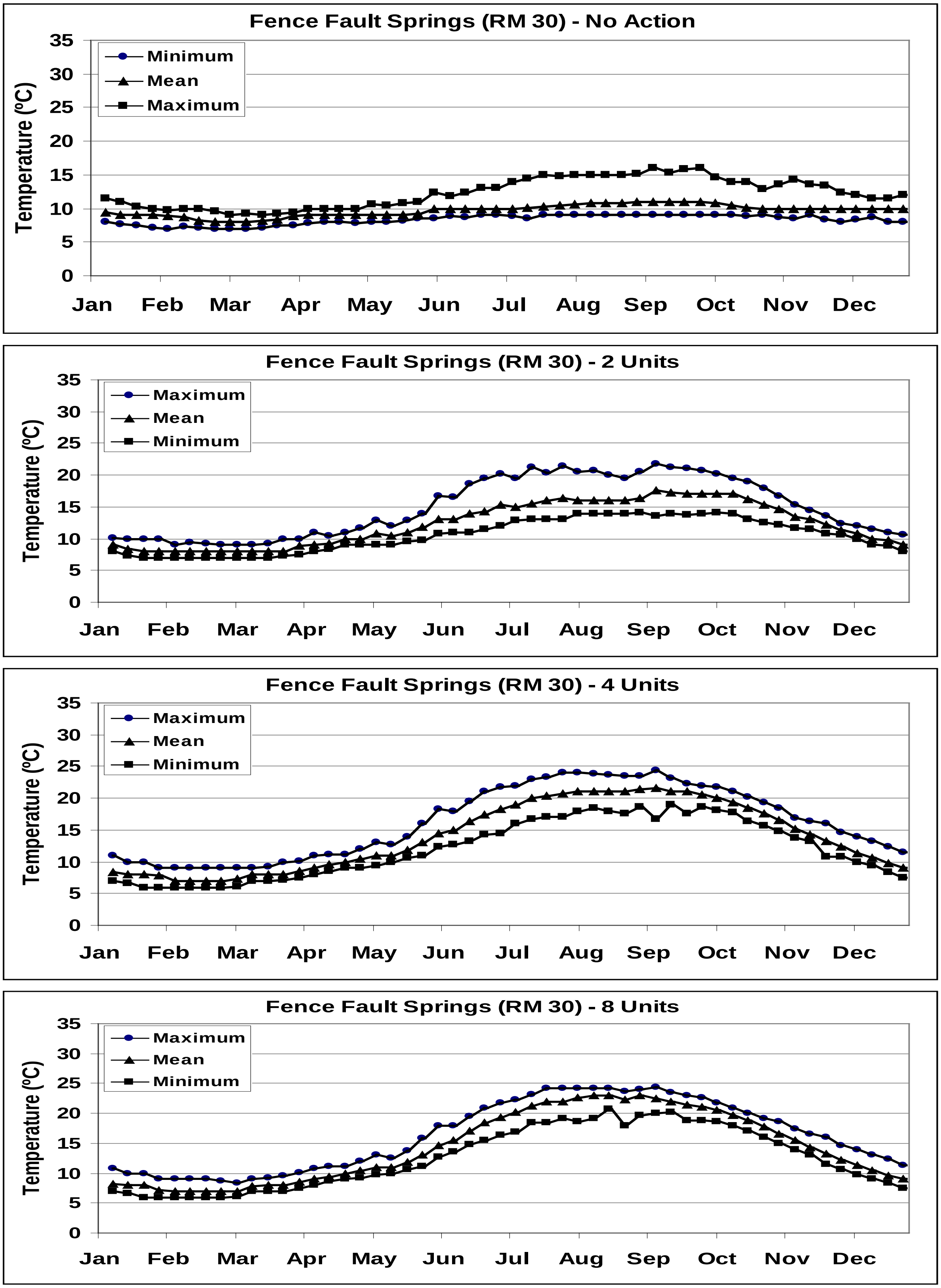

Figure B-27. Predicted maximum, minimum, and mean water temperatures at RM 30 with No Action and a 2, 4, and 8-unit TCD. Data points are 7-day averages. Data generated by GEMSS® model.

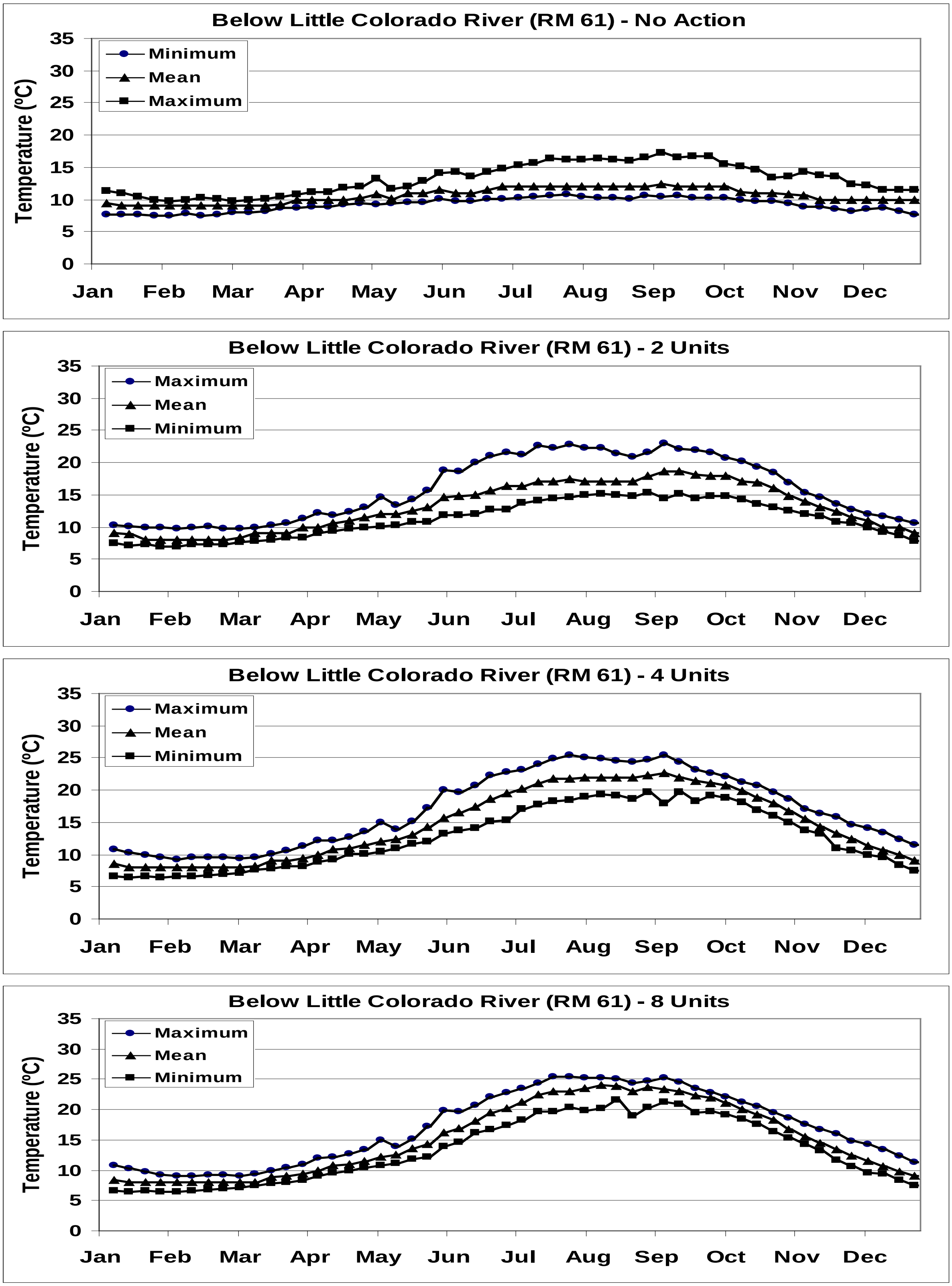

Figure B-28. Predicted maximum, minimum, and mean water temperatures at RM 61 with No Action and a 2, 4, and 8-unit TCD. Data points are 7-day averages. Data generated by GEMSS® model.

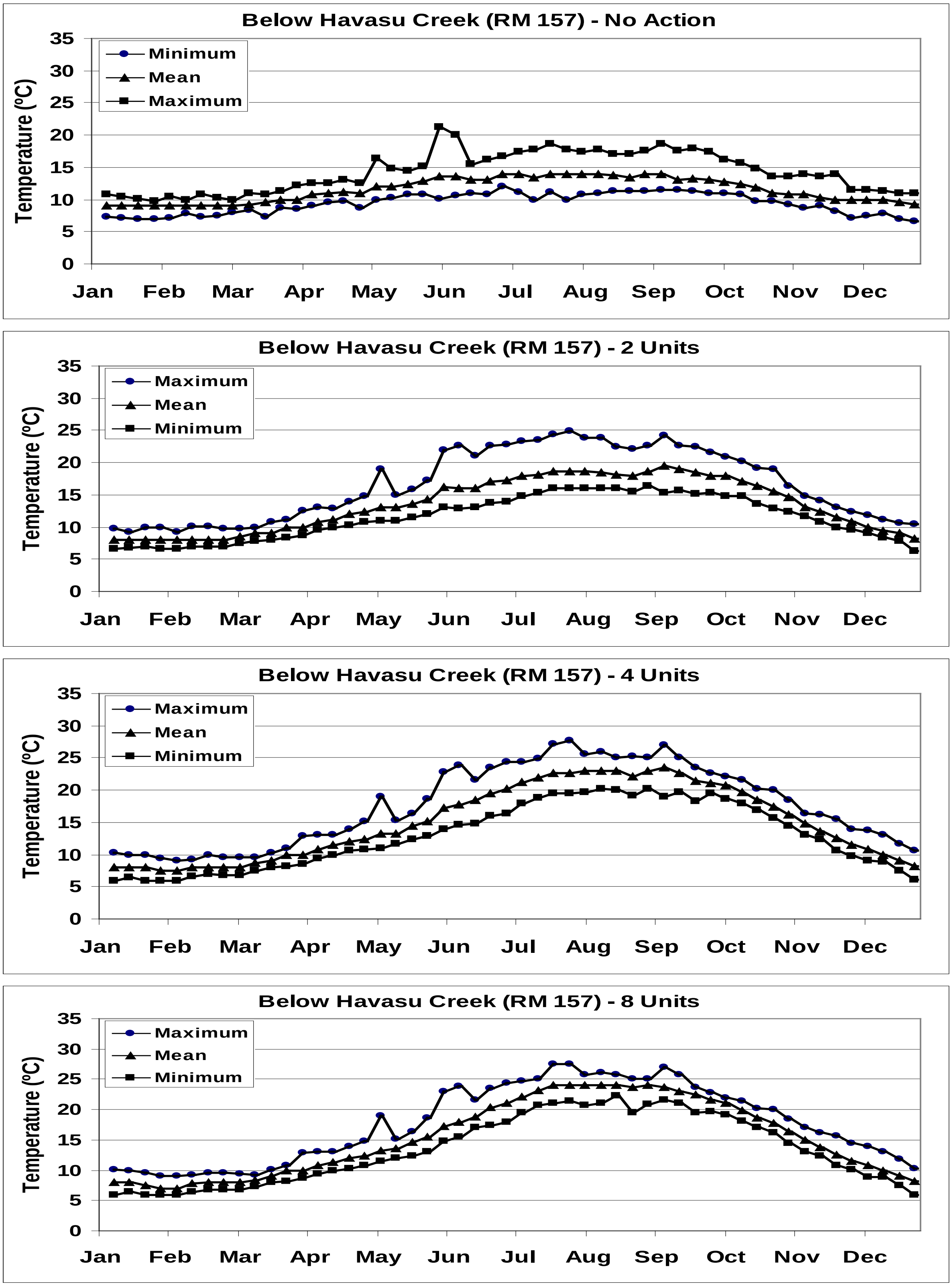

Figure B-29. Predicted maximum, minimum, and median water temperatures at RM 157 with No Action and a 2, 4, and 8-unit TCD. Data points are 7-day averages. Data generated by GEMSS® model.

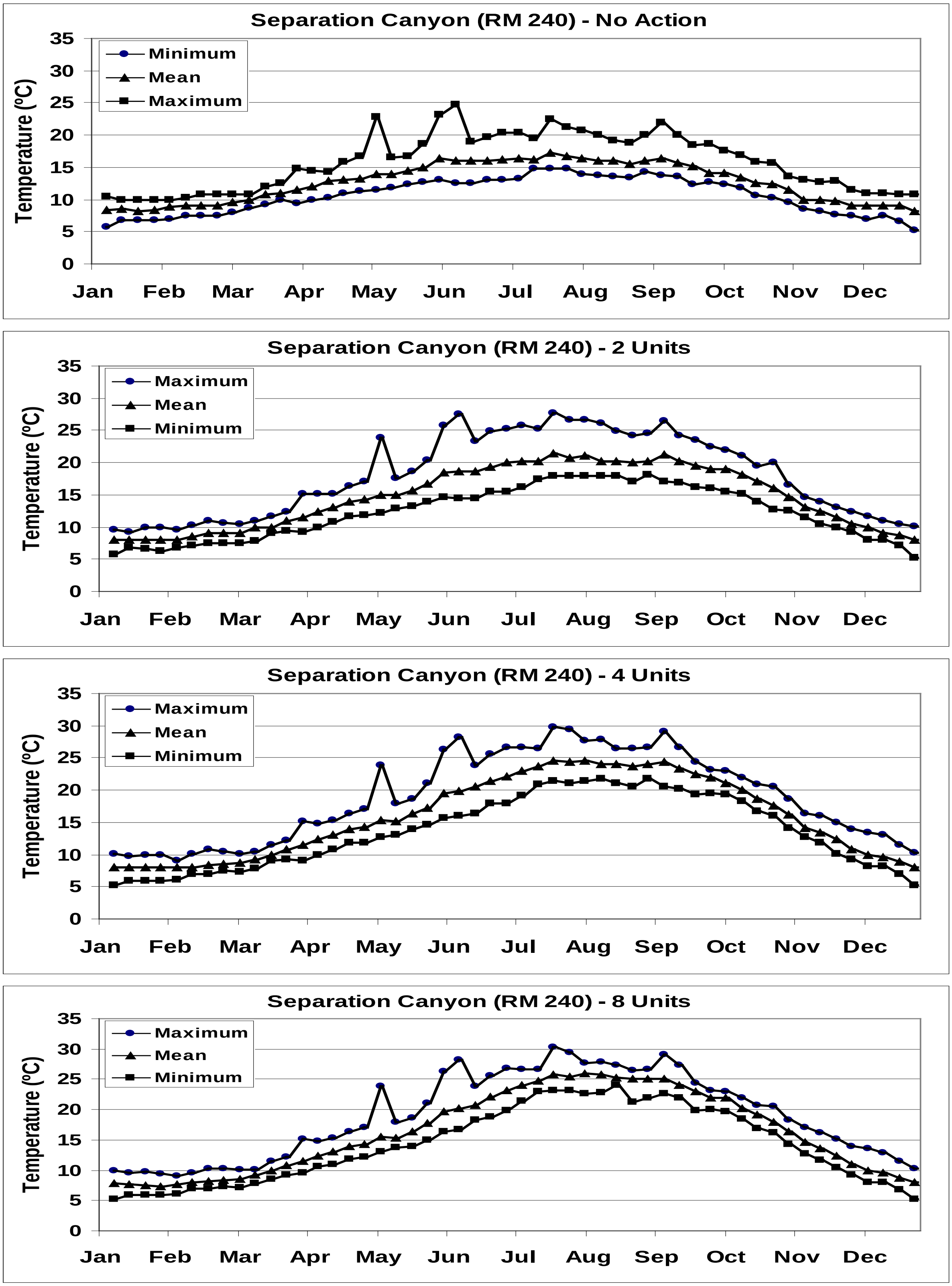

Figure B-30. Predicted maximum, minimum, and median water temperatures at Separation Canyon (RM 240) with No Action and a 2, 4, and 8-unit TCD. Data points are 7-day averages. Data generated by GEMSS® model.

Appendix C: Temperature Degree-Days for Fish

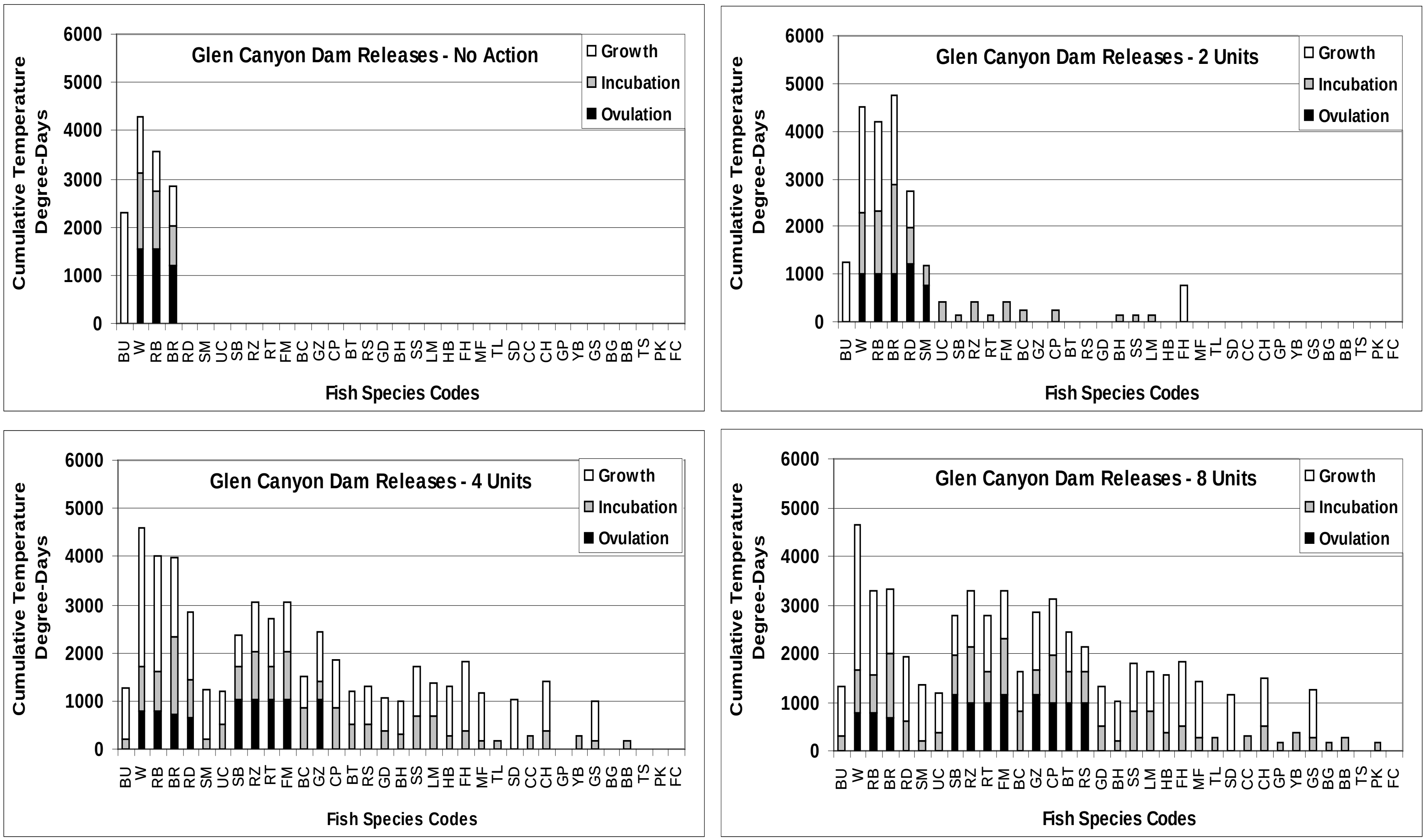

Figure C-31. Suitable temperature degree-days (STDDs) for ovulation, incubation, and growth by 35 fish species for Glen Canyon Dam releases with No Action and a 2, 4, and 8-unit TCD. Species codes are provided in Table 2.

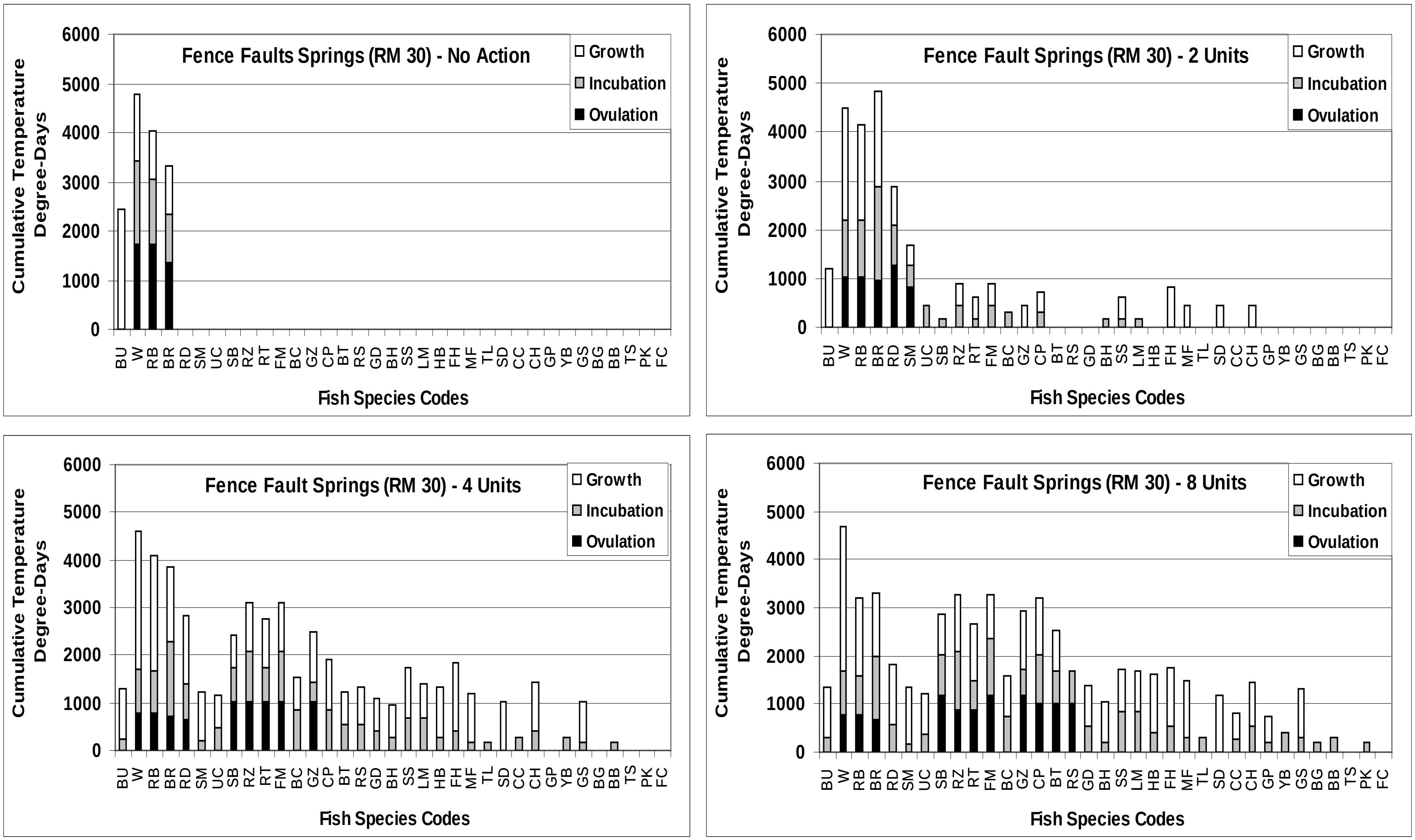

Figure C-32. Suitable temperature degree-days (STDDs) for ovulation, incubation, and growth by 35 fish species at Fence Fault Springs (RM 30) with No Action and a 2, 4, and 8-unit TCD. Species codes are provided in Table 2.

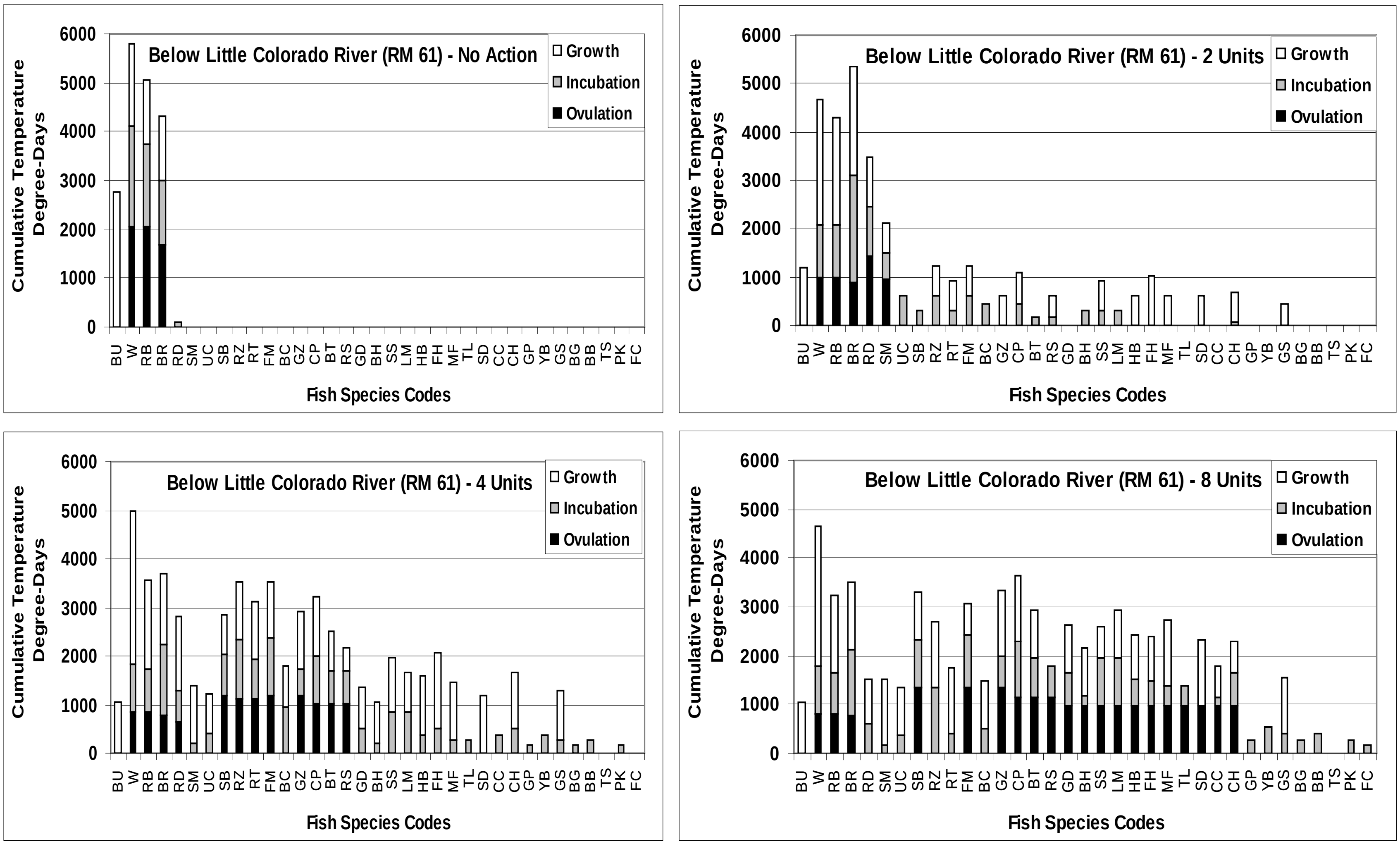

Figure C-33. Suitable temperature degree-days (STDDs) for ovulation, incubation, and growth by 35 fish species below the Little Colorado River (RM 61) with No Action and a 2, 4, and 8-unit TCD. Species codes are provided in Table 2.

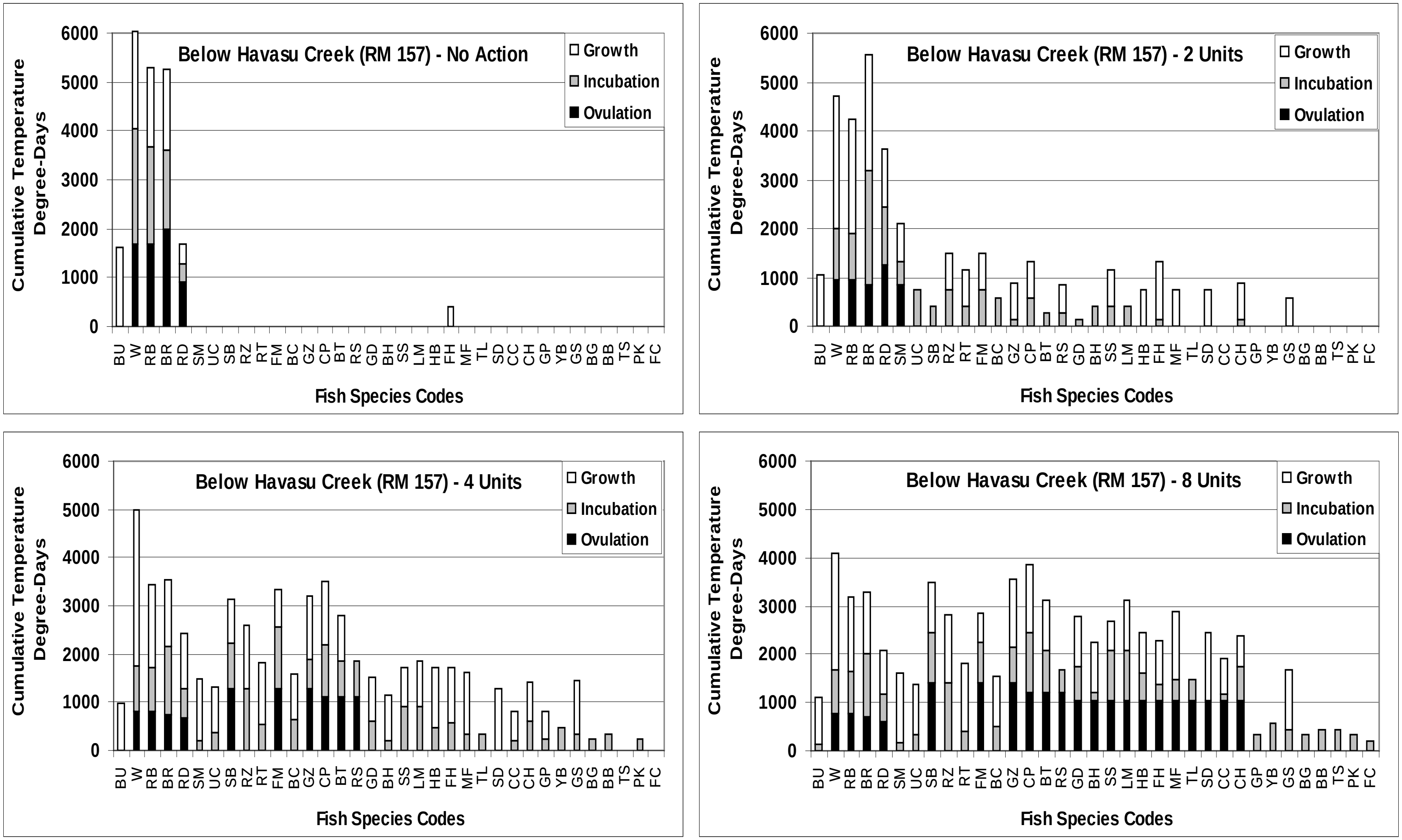

Figure C-34. Suitable temperature degree-days (STDDs) for ovulation, incubation, and growth by 35 fish species below Havasu Creek (RM 157) with No Action and a 2, 4, and 8-unit TCD. Species codes are provided in Table 2.

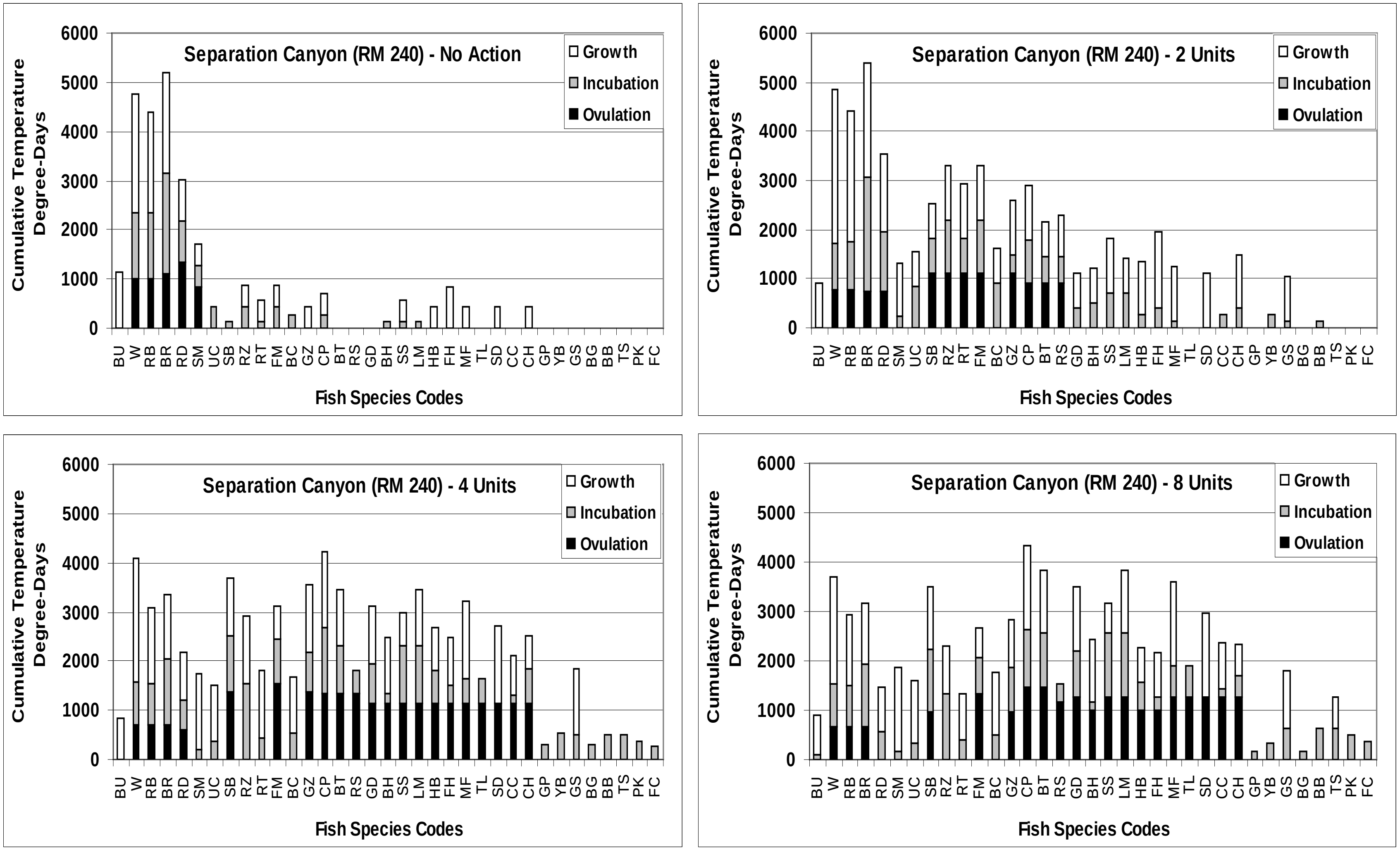

Figure C-35. Suitable temperature degree-days (STDDs) for ovulation, incubation, and growth by 35 fish species at Separation Canyon (RM 240) with No Action and a 2, 4, and 8-unit TCD. Species codes are provided in Table 2.