Part 3. Long-term Food Web and Ecosystem Monitoring

Conceptual basis

As described in the preceding sections of this report, quantitative food webs developed for select reaches of the Colorado River provide strong evidence for both bottom-up and top-down control of the food web. This finding leads us to conclude there is not so much a need for monitoring of the “food base” as there is a need for monitoring key indicators of the food web and ecosystem as a whole. Put another way, we believe food web and ecosystem monitoring protocols should include traditional metrics of food availability for fishes (i.e., invertebrate drift measurements), but also ecosystem-process metrics that may not have a clear relation or link to food availability for fishes *per se* (i.e., DOC budgeting and production estimation). Such an integrated, ecosystem approach allowed us to easily reconcile counterintuitive food web responses to the 2008 artificial flood. Recall, a significant increase in rainbow trout populations occurred after the flood, in spite of a large decrease in total invertebrate production (~60% reduction, from 30 g AFDM m^{-2} yr^{-1} to just 13 g AFDM m^{-2} yr^{-1}) that was largely driven by a 70% reduction in the production of a dominant taxon (*G. lacustris*; from ~8 g AFDM m^{-2} yr^{-1} to 2.5 g AFDM m^{-2} yr^{-1}), which earlier investigators had concluded was a critical prey item for rainbow trout. This same counterintuitive ecosystem response would have confounded interpretation of traditional ‘foodbase monitoring’ indicators such as benthic invertebrate biomass. Although this food web/ecosystem approach represents somewhat of a departure from the current conceptual basis for Goal 1, we think this is a logical step in the overall process of “learning by doing” that is the hallmark of adaptive management.

Designing a food web and ecosystem monitoring program for the Colorado River is complicated by the remote nature of the ecosystem, and complex spatial and temporal variation in key drivers. For example, the effects of Glen Canyon Dam and its operations (e.g., alterations in water temperature regimes, hydropeaking, etc.) are strongest in the tailwater, but the effects of turbidity moderate these effects further downstream. The degree of hydropeaking (i.e., daily range and average discharge) varies seasonally in response to changes in human demand for power, with the largest daily range and average volume occurring in winter and summer and lower daily range and average volumes occurring in spring and fall. Short-duration floods from tributaries (1-10 days) that deliver suspended sediment turbidity are strongly seasonal (summer/fall monsoon season and winter snowmelt), and, importantly, the timing and duration of these floods is now independent and asynchronous with mainstem flow conditions. Water temperature regimes are also seasonal, but the timing of the annual minima and maxima that can serve as a cue for key invertebrate life-stage changes is relatively independent of local climate and therefore asynchronous with temperature regimes in tributaries that support source populations of native insect taxa (Olden and Naiman, 2009). In a system as complex as the Grand Canyon, there would appear to be countless ways to go about allocating limited resources and effort to food web and ecosystem monitoring. It is therefore essential that a food web and ecosystem monitoring program focus on the use of metrics that integrate across large spatial and temporal scales. The basis for this is further strengthened when one considers that Colorado River native fishes are highly mobile—fish populations are likely integrating food resources over similarly large spatial and temporal scales.

Understanding the relative influence of natural environmental variation vs. Glen Canyon Dam operations on fish populations is of great importance to managers and a primary motivation for Goal 1 monitoring (see Table 3). Therefore, the process of determining appropriate spatial and temporal resolution for core monitoring should be informed by spatial and temporal trends in humpback chub and rainbow trout because these species motivate the vast majority of adaptive management experimentation. Indeed, two new management actions planned as part of the adaptive management process directly target these species (non-native rainbow trout control to benefit humpback chub), or will likely affect them (additional testing of artificial floods as a sediment conservation tool). Proposed non-native control includes direct removal of rainbow trout for large reaches of river, and rapid decreases in discharge designed to strand and kill juvenile rainbow trout in Glen Canyon. Our research findings suggest that these experimental actions will likely alter food web structure and ecosystem processes. A robust ecosystem monitoring program that integrates research and monitoring across Goals 1, 2, 4, 7 (i.e., foodbase, native fish, non-native fish, and water quality) will be critical to the process of identifying mechanisms underlying fish population response to these two planned management actions.

Table 3. Goal 1 Core Monitoring Information Needs

1.1.1	Determine and track the composition and biomass of primary producers below Glen Canyon Dam in conjunction with measurements of flow, nutrients, water temperature, and light regime.
1.2.1	Determine and track the composition and biomass of benthic invertebrates below Glen Canyon Dam in conjunction with measurements of flow, nutrients, water temperature, and light regime.
1.3.1	Determine and track the composition and biomass of drift in the Colorado River in conjunction with measurements of flow, nutrients, water temperature, and light regime.

Here, we outline what we believe are the critical elements to Goal 1 monitoring needed to meet the Core Monitoring Information Needs identified by the GCDAMP. This description is somewhat general in nature, omits detailed description of sampling *per se*, and emphasizes description of the overall approach; exact sample sizes, sampling locations, timing of sampling, etc. will be determined after consultation with permitting agencies (i.e., Glen Canyon NRA, Grand Canyon NP, US Fish and Wildlife Service), and after coordination and consultation with other GCMRC Programs (i.e., Goals 2, 4, and 7). Precise description of Goal 1 monitoring should only occur after consultation and coordination with monitoring programs for Goals 2, 4, and 7 to ensure it is completely integrated with these related efforts.

Sampling Design and Approach

We propose monitoring the Colorado River food webs and ecosystem using many of the same approaches and techniques that were developed during the research phase of this project. We also propose evaluating some new metrics that integrate over large spatial and temporal scales, and are therefore promising tools to be explored during implementation of long-term monitoring in Grand Canyon.

We suggest that frequent, near monthly, sampling of transported organic matter, primary production, invertebrate drift, and emergence production should occur at Lees Ferry, Phantom

Ranch, Diamond Creek, the Little Colorado River itself, and in the Colorado River near the LCR confluence. The feasibility and utility of this intensive sampling approach was demonstrated at a subset of these sites during the research phase of the project. Although frequent sampling in the Little Colorado River and in the mainstem near the confluence presents a considerable challenge because of limited accessibility, long-term monitoring at these two locations is critical because of the strong effect this tributary has on Colorado River ecosystem processes, and because of its importance to humpback chub populations specifically. We propose frequent sampling in the Little Colorado River and near the confluence only during the first 1-2 years of monitoring implementation in order to identifying seasonal patterns in production and ecosystem processes. After 1-2 years of intensive effort at these sites, sampling effort may be reduced in an informed manner. For example, sampling could just target months that are most critical to young-of-year humpback chub. A monthly sampling regime in the Little Colorado River could reasonably be sustained for 1-2 years, even in the context of regular sampling at other several other sites, if LCR sampling trips were supported by helicopter. Long-term monitoring of the food web and ecosystem processes in the Little Colorado River will provide valuable information needed to evaluate the relative importance of this tributary versus the mainstem to humpback chub populations. Further, monitoring data from the Little Colorado River would help put similar data from the mainstem Colorado River into a larger context by allowing comparison to a system with a natural thermal and flow regime.

We additionally propose sampling benthic habitats throughout Glen and Grand Canyon once per year using river trips. Traditional benthic sampling represents an important, but relatively minor, component of the proposed monitoring strategy because these samples are integrating over small temporal and spatial scales, and collection of these samples in a large river with hydropeaking is extremely difficult. Frequent sampling at relatively few fixed sites will emphasize detection of temporal trends, particularly describing the effects of flow operations on the ecosystem, while less frequent river trip sampling across a large number of sites will emphasize detection of large-scale spatial trends. To ensure the scope of inference for river trip sampling is truly canyon-wide, we suggest sampling occur at the same location as intensive sampling, and also at additional random sites, similar to the approach for fish monitoring.

Organic matter budgeting and primary production

Organic matter budgeting for long reaches of river provides a relatively quick and low-cost metric of ecosystem processes that nicely complements more robust continuous primary production measurements. We propose organic matter budgeting for four long reaches (Glen Canyon Dam to Lees Ferry, Lees Ferry to Little Colorado River confluence, LCR confluence to Phantom Ranch, Phantom Ranch to Diamond Creek; see Table 4) using monthly measurements of all size fractions of transported organic matter and chlorophyll. Such a budgeting approach was conducted along two long reaches during the research phase of the project (Glen Canyon Dam to Lees Ferry, Lees Ferry to Grand Canyon). We propose segmenting the Grand Canyon reach with the addition of two sites to further resolve organic matter budgets for Marble Canyon versus the Colorado River below the LCR. Better resolving organic matter budgets and primary production in Marble Canyon will aid in understanding habitat quality for rainbow trout in Marble Canyon, and because autochthonous production from Marble Canyon is a potential subsidy to less productive reaches below the Little Colorado River. This approach to sampling will also allow us to determine whether Phantom Ranch, which is relatively accessible, is a reasonable proxy for the Colorado River near the LCR confluence, which is relatively inaccessible. Exact methods and approaches will be developed in coordination with GCMRCs Lake Powell monitoring program, who will conduct sampling within Glen Canyon Dam, and also with the downstream water quality monitoring program, which conducts sampling and maintains equipment at the other proposed sampling locations. Sampling organic matter is relatively quick and low-cost.

As our research efforts identified, there is a critical need to begin resolving the relative importance of tributaries versus the mainstem to native fish production and population dynamics. We therefore suggest that long-term monitoring of primary production, transported organic matter, and chlorophyll from the Little Colorado River also be initiated. Regular, at least monthly collections, of organic matter and chlorophyll will be necessary to describe material budgets in the Little Colorado River in comparison to the mainstem river. Further, frequent servicing of water quality monitors will be required given the harsh conditions (i.e., heavy travertine deposition) in the LCR. Sampling in the Little Colorado River would be done in concert with sampling of the mainstem near the confluence. After 1-2 years of intensive sampling effort at both sites, we suggest the temporal frequency of sampling be reduced to critical seasonal time periods that are identified in collaboration with scientists studying humpback chub populations there.

Table 4. Proposed long-term monitoring protocols for Goal 1 including sample type, frequency, and locations.

Sample Type	Sampling Frequency	Locations
Ecosystem Metabolism	Daily	Lees Ferry, RKM48, RKM 100, RKM 140, RKM 266, RKM 362, Little Colorado River, Bright Angel Creek
Dissolved Organic Matter	10X per year	Glen Canyon Dam, Lees Ferry, RKM 100, RKM 140, RKM 362, Little Colorado River
Fine Particulate Organic Matter (<250 μm; to be processed for AFDM and chlorophyll *a*)	10X per year	Glen Canyon Dam, Lees Ferry, RKM 100, RKM 140, RKM 362, Little Colorado River
Coarse Particulate Organic Matter (>250 μm; to be processed for AFDM and chlorophyll *a*)	10X per year	Glen Canyon Dam, Lees Ferry, RKM 100, RKM 140, RKM 362
Invertebrate Drift	10X per year	Lees Ferry, RKM 100, RKM 140, RKM 362, Little Colorado River, Bright Angel Creek
Emergent Insect Production	10X per year	Lees Ferry, RKM 100, RKM 140, RKM 362, Little Colorado River
Benthic Algae and Invertebrates	1X per year	Sites throughout Glen and Grand Canyon

We propose long-term chlorophyll monitoring and budgeting should employ multiple techniques. Fluorometry was used during the research phase of this project, while spectrophotometry has been used by GCMRCs Lake Powell monitoring program since its inception in 1990. Fluorometry is precise and low-cost; however, this technique may not always yield accurate results across the range of turbidity conditions typical of Grand Canyon. Spectrophotometry is more accurate, and less affected by sediment turbidity than fluorometry, but spectrophotometric determination of chlorophyll is far more expensive and difficult than fluorometers. Both techniques are considered acceptable methods for estimating chlorophyll by the US Geological Survey (USGS 2010). A long-term monitoring program for the Colorado River that employs both techniques will be the most robust.

We also propose long-term monitoring of primary production at all organic matter budgeting sites (Lees Ferry, Little Colorado River confluence, Phantom Ranch, Diamond Creek, Little Colorado River) and two additional sites where ongoing water quality monitoring activities occur (RKM 48 and RKM 266). An expanded network of primary production monitoring will allow us to evaluate whether strong effects of flow operations on primary production observed at Diamond Creek are occurring throughout Grand Canyon.

Invertebrate Drift and Emergence Production

We propose monitoring invertebrate response to changing flow and environmental conditions using invertebrate drift and emergence production measurements. Both types of samples can integrate over relatively large spatial and temporal scales, and therefore have the greatest potential to detect invertebrate response to major physical driers. Further, focal fish species—rainbow trout and humpback chub—are both drift feeders, so invertebrate drift measurements will provide a direct metric of food availability to important fish species.

The utility of invertebrate drift measurements was demonstrated during the research phase of this project at Lees Ferry; however, additional research and sampling is needed to identify the best technique for collecting invertebrate drift at proposed sites that are only hike-in accessible (see Table 4). To date, invertebrate drift sampling has been conducted using motorboats and in a depth-integrated fashion because this approach was recommended by the 2001 review panel (Anders et al. 2001). Regular boat-based invertebrate drift sampling is possible at Lees Ferry and Diamond Creek, but this sampling technique is not possible at Phantom Ranch and the Little Colorado River confluence with the hike-in and helicopter supported approach being proposed. We suggest that paired collections of invertebrate drift samples using both boat- and shore-based techniques at Lees Ferry and Diamond Creek be conducted during the first year of monitoring to identify differences among methods. Only shore-based techniques will be used at other sites, except during annual river trips when both techniques can be used at these sites. This approach should provide the data needed to allow comparison of daily and annual invertebrate drift loads among sites. Even if the relation between boat and shore-based techniques is poor and difficult to describe statistically, data from each site will be internally consistent and useful for tracking trends at those sites through time. Invertebrate drift sampling in the Little Colorado River will follow protocols established for wadeable streams; drift nets equipped with flow meters will be anchored to the river bottom.

Collecting invertebrate drift samples that are integrated over longer time periods than 5 minutes is another area worth exploring as core monitoring is implemented. During the research phase of the project, we settled upon 5 minute tows because this was the maximum amount of time technicians could be expected to continuously raise and lower a 75 lb sounding weight. Integrating drift samples over longer time periods (i.e., hours) is commonly done in drift studies in small streams (Smock 2006). Long-duration drift samples could be collected from the center of the channel at Lees Ferry by attaching nets to existing navigation buoys; however, long-duration drift sampling at other sites is only feasible if done near-shore. In essence, there appears to be a tradeoff among the two sampling approaches we recommend exploring—boat based techniques allow for better spatial integration while shore-based techniques allow for greater temporal integration of samples. Additional research is needed to further evaluate these apparent tradeoffs.

Although estimating emergence production has never been attempted in Grand Canyon, it appears to be a promising tool for long-term ecosystem monitoring. There is a strong relationship between benthic production and emergence production (Statzner and Resh, 1993; Gratton and VanderZanden, 2009), so estimating the flux of insects that are emerging from the Colorado River should provide an indicator of overall benthic insect production. Further, because the two insect taxa that dominate invertebrate production at downstream locations (i.e., Simuliidae and Chironomidae) also have high interaction strengths with fishes, monitoring emergence production may provide a metric of food availability that complements drift measurements.

Measurement of emergence production has the added strength of integrating across the terrestrial-aquatic interface. Long-term monitoring of emergence could greatly increase our understanding of the potential importance of aquatic subsidies to adjacent terrestrial ecosystem. Ecological theory suggests (River Continuum Concept; Vannote et al. 1980), and our own empirical work on the Colorado River confirms (Kennedy and Ralston, 2012), that terrestrial-to-aquatic subsidies are relatively minor in a system as large as the Colorado River, but emergence production could represent an important organic matter flux supporting terrestrial food webs in the Grand Canyon.

Samples of emergent insects are far easier and quicker to process than traditional benthic samples because there is little organic matter or debris on emergence samples, and winged adults are easier to identify than aquatic larvae. This is an important consideration in the selection of monitoring metrics because a program that emphasizes samples that are quick and easy to process is more likely to provide timely information to decision makers relative to a program that emphasizes samples that are difficult and time-intensive to process.

We propose evaluating the utility of emergence production as monitoring metric by continuously deploying sticky traps at the three accessible locations, Lees Ferry, Phantom Ranch, and Diamond Creek (Table 4). Acetate sheets (8 ½ x 11 in) will be covered with a thin coating of Tanglefoot ® and then deployed along multiple transects perpendicular to shore. Traps will be deployed using natural materials (i.e., sticks, rocks, vegetation) or small pieces of re-bar. Traps will be located away from established camps or day-use areas to minimize visitor impact. Sticky traps could also be deployed from existing USGS cableways at these three locations. Deploying traps from cableways has several advantages including an identical spatial distribution of traps among locations, and sampling across the entire river surface, as opposed to transects that run parallel to shore. Both approaches to trap deployment could be tried during initial testing of this metric.

Benthic algae and invertebrate biomass

Traditional benthic sampling of invertebrates is another important part of a food web and ecosystem monitoring strategy because it will provide information on the non-insect taxa that tend to dominate production budgets, but do not emerge or drift, and would therefore be missed using just drift and emergence measurements. However, directly sampling benthic habitats in the Colorado River is extremely difficult and time intensive, which limits the utility of benthic biomass as a monitoring metric. For example, hydropeaking constrains benthic sampling to a brief window of low water that varies in timing throughout the canyon (i.e., low water at the RKM 48 site typically occurred during the late morning while low water at our RKM 100 site occurred during the middle of the night), which greatly limits the area of habitat that can be sampled in a day. Further, just a small percentage of benthic habitats can actually be sampled (<20%) due to the constraints that depth and velocity create. Individual benthic samples are integrating over very small spatial scales, so they have limited value as an ecosystem monitoring index unless they are collected over large areas. Benthic samples can also take considerable time and effort to process because of abundant inorganic and organic debris.

We therefore propose traditional benthic sampling should only occur once per year and that when this occurs, benthic habitats throughout Grand Canyon should be sampled using river trips. We recommend benthic sampling be done in association with lower monthly discharge volumes to facilitate integrating sampling effort over the largest area logistically possible. We propose sampling all habitat types, not just the most productive ones (i.e., cobble), in order to develop habitat-weighted estimates of algae and invertebrate abundance, biomass, and composition that can be compared among years. These data will provide a comprehensive snapshot of the benthic environment in Grand Canyon that can be repeated annually and will allow for detection of major trends such as the arrival of new invertebrate taxa, or changes in the diversity or richness of the invertebrate assemblage. A detailed benthic sampling design that incorporates randomly selected sites will be developed in consultation with GCMRCs research statistician to ensure the scope of inference for these samples is canyon-wide.

Organic matter sampling will follow specific methods developed during the research phase of the project and that are described in detail in Rosi-Marshall et al. (2010). Individual rocks will be collected from cobble habitats, and all algae will be removed from rocks by scrubbing the rock with a wire brush in a small bucket of water. The volume of the resulting slurry will be estimated in a graduated cylinder. Small sub-samples of the slurry will be put onto glass fiber filters for determination of ash-free dry mass and chlorophyll concentration. The surface area of the rock will be estimated by taking a digital photograph of the rock on a piece of gridded paper and then using image analysis software to determine the area of the rock. Algae on cliff faces and irregular talus slopes will sampled using a modified syringe sampler. Depositional environments will be sampled using a Ponar dredge sampler. Estimates of ash-free dry mass and chlorophyll content on these habitats will follow the same sub-sampling procedures outlined above.

Invertebrate sampling will follow methods described in Cross et al. (2011). A Hess sampler will be used to sample cobble habitats in Glen Canyon, while individual rocks will be picked up from more downstream reaches because of armoring there. Rocks will be scrubbed in a large bucket to remove invertebrates. Samples will be preserved in the field using ethanol and then processed in the lab by size fraction.

We propose long-term storage of the processed invertebrate samples should be done using formalin. This will result in a large collection of samples that need to be cataloged and maintained, increasing overall monitoring program costs. However, we feel archiving benthic invertebrate samples is warranted given the potential importance of the samples in answering novel questions that will only occur to scientists or managers *post hoc*; a hallmark of long-term monitoring is the ability to go back to archived samples and verify conclusions, or ask fresh questions.

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