Appendix D
Technical Analysis of the Potential Water Quality Impacts of the LEAPS Project on Lake Elsinore

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TECHNICAL ANALYSIS OF THE POTENTIAL WATER QUALITY IMPACTS OF THE LEAPS PROJECT ON LAKE ELSINORE

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Introduction

Pumped-storage hydroelectric plants are widely recognized for their ability to rapidly produce electricity in response to peak demands, control supply frequency of the grid, store renewable energy and provide reserve generation capacity (Wicker, 2004; Sims, 1991). Pumped-storage plants are used extensively in Japan, where there are 16 such facilities, although plants are also located in Australia, China, Taiwan, Poland, Germany, Russia, Ireland, the UK and the US. Within California, the Castaic and Helms pumped-storage plants each provide in excess of 1000 MW capacity (FERC, 1998). Much smaller systems are operated by some irrigation districts as well (ITRC, 2001).

The Lake Elsinore Advanced Pump Storage (LEAPS) project currently under review would produce 500 MW at 83.3% wire-to-wire efficiency for electricity storage with no air quality impacts and shorter start-up times relative to combustion peaker plants (EVMWD, 2004). The environmental impacts on Lake Elsinore remain unclear, however. The SARWQCB has identified a number of possible water quality impacts associated with operation of the LEAPS facility that require consideration. This document summarizes some of the possible impacts, reviews available information from other pumped-storage hydroelectric plants, and considers potential physical, chemical and biological effects on Lake Elsinore resulting from LEAPS operation.

1. Physical Effects

The potential physical effects of pumping water from Lake Elsinore to the upper reservoir and the subsequent return of that water during the generation phase include: (a) regular exposure and subsequent inundation of shoreline sediments, (b) resuspension of bottom sediments resulting in an increase in lake turbidity, and (c) changes in thermal stratification and lake circulation and mixing.

(a) Regular oscillations in lake surface elevation will result in the exposure of shoreline sediments during pumping and subsequent inundation during generation.

As part of the FERC application process, The Nevada Hydro Company (THNC) indicated that the daily drawdown of Lake Elsinore would range from 2413 to 2942 acre-ft during the week and 5340 acre-ft on Saturday (THNC, 2005). These volumes would represent about 5 – 10% of the total volume of Lake Elsinore at a nominal volume of approximately 50,000 acre-ft. At the planned minimum operational lake level of 1240 ft or 38,519 acre-ft, these volumes represent a larger relative volume (6.3 – 13.9 %), while at a normal maximum operational lake level of 1247 ft (61,201 acre-ft) (THNC, 2005), these daily drawdowns represent a correspondingly smaller portion of the total lake volume (3.9 – 8.7 %). It should be mentioned that we have developed slightly more detailed area-volume-elevation relations based upon bathymetric measurements we made at lower lake levels than those originally developed by Black & Veatch and provided in the FERC application (referred to as FERC volume and area in Fig. 1), although the volumes above do not change substantially over the target surface elevations of 1240 – 1247 ft. Our bathymetric data indicated slightly lower minimum lake elevations than reported in the FERC response document (1218 vs. 1223 ft); surface area-elevation relationships also differed between the 2 datasets at lake levels <1250 ft (Fig. 1). Notwithstanding, withdrawal of water during pumping will result in exposure of sediments, while the subsequent generation cycle will result in inundation. Using the area-elevation data in the FERC response, one estimates that 49 acres will be alternately exposed and wetted during the weekday cycle that changes the lake level by about 1 ft, while the weekend (maximal) surface elevation change of 1.7 ft will expose about 83 acres (Table 1).

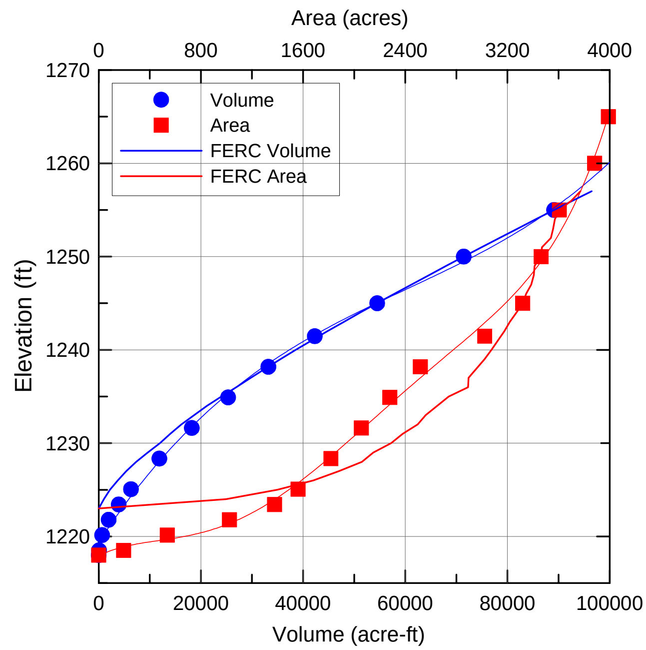

Fig. 1. Hypsographic data for Lake Elsinore comparing Black and Veatch data used in original FERC documents and that obtained more recently by Anderson (2004).

These values are in excellent agreement with those reported in the Response to FERC Deficiency Letter of 49 and 86 acres (THNC, 2005). A higher amount of sediments will be exposed at nominal (1240-1247 ft) lake levels assuming the area-elevation relationship that we developed holds (Table 1).

Table 1. Predicted areas of exposed sediments using alternate hypsographic data.

	Area of Exposed Sediments (acres)	
Elevation Change	**THNC (2005)**	**Anderson (2004)**
1.0 ft (weekday)	49	79
1.7 ft (weekend)	83	134

The bathymetry of the lake is such that comparatively little sediment area will be exposed along most of the shoreline (*e.g.*, weekday shoreline migration will be about 8 ft along the northern shores, although the southern portions of the lake will see greater shoreline migration, est. 40 ft). These values are broadly consistent with the 21 ft shoreline migration values indicated in Ch. 7 of Exhibit E of the FLA (e.g., Fig. 7-3). While that document addressed shoreline movement at parks on the lake, it is useful to also consider the extent of shoreline migration in response to LEAPS operation on other areas around the lake. The shallow embayments in the southern part of the lake will see the greatest daily oscillation in exposed sediments, where hundreds of feet of sediment may be exposed (Fig. 2). (Note that the number of depth measurements made in this portion of the lake was very limited, so the areal representation of exposed sediments is rather crudely approximated assuming a surface elevation of about 1242 ft).

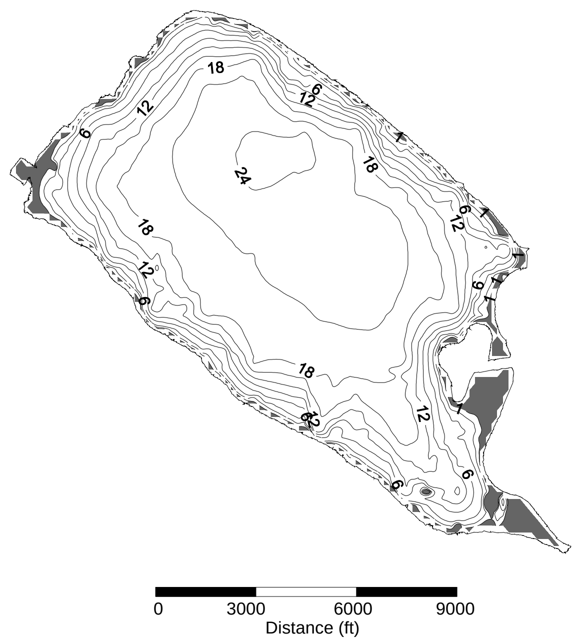

Fig. 2. Lake bathymetry (surface elevation at approximately 1242 ft) and areal extent of sediment exposure/inundation resulting from 1 ft lake level changes (shaded areas).

The alternate exposure and inundation of shoreline sediments is not expected to generate significant amounts of turbidity, however, since natural wave action from wind will keep fine material from accumulating near the active shoreline over much of the lake. This can be demonstrated from relationships that use wind speed, wind direction, fetch and depth to sediment to infer loci and extent of resuspension (*e.g.*, Carper & Bachmann, 1984). For example, it has been shown that resuspension and erosion of fine-textured bottom sediment occurs when deep-water waves enter water shallower than one-half the wave length (Bloesch, 1995). The wavelength, *L*, of a deepwater wave is related to its period, *T*, by the relation:

$$L = \frac{gT^2}{2\pi} \qquad (1)$$

where *g* is the gravitational constant (Martin & McCutcheon, 1999). A wave's period can be estimated using the empirical equation developed by the US Army Coastal Engineering Research Center (Carper & Bachmann, 1984) that states:

$$T = \frac{2.4\pi U \tanh\left[0.077\left(\frac{gF}{U^2}\right)^{0.25}\right]}{g} \qquad (2)$$

where *U* is the wind speed and *F* is the fetch.

The hourly wind record from 2001 was used to calculate wavelengths (L) as a function of wind speed at an average fetch of 2.63 km using eqs 1 and 2; knowing the fraction of time in which the wind exceeded some value allows for the estimation of the probability of sediment resuspension as a function of depth (Fig. 3a). Thus we see that nearly 70% of the time, sufficient wind is present at the lake to mix and resuspend sediment to at least a depth of 1 ft (Fig. 3a).

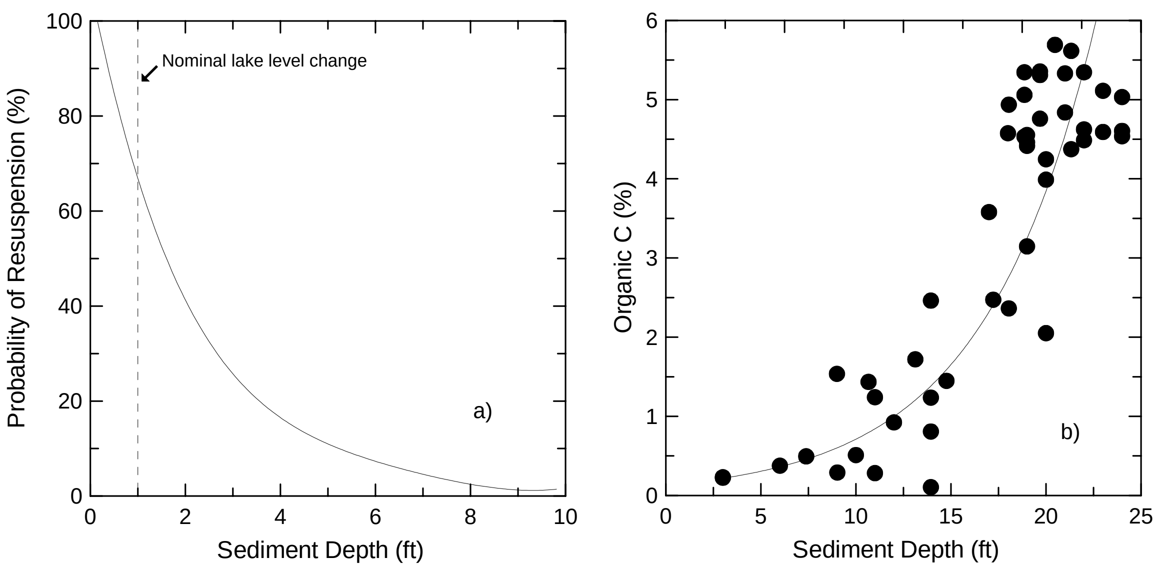

Fig. 3. Plots showing: a) probability of mixing/resuspension as a function of sediment depth, and b) organic C content of sediments vs. sediment depth.

This wind energy will keep fines from settling there, leaving only coarse-textured inorganic sediments that are highly stable against resuspension. Measurements of sediment properties in Lake Elsinore support this, where % organic C increased exponentially with depth, with very little organic C present in the shallow sediments (Fig. 3b). An exception to this will be the protected embayments at the southern end of the lake where, because the strong winds out of the southwest or less frequently east (data not shown) result in a very limited fetch and lower wave energy there.

(b) Resuspension of bottom sediments near inlet/outlet and increased turbidity as a result of pumping and generation.

The potential exists for substantial resuspension of bottom sediments near the inlet/outlet of LEAPS due to the large flows and high velocities there. Flows of 2000 – 3000 cfs are expected, with a stated maximum discharge velocity of 1.5/1.8 ft per second (THNC, 2005). In their deficiency letter response, THNC (2005) indicates that these LEAPS discharge velocities are comparable to those found near the recycled water inlet, and that no evidence for resuspension there was found. While they correctly conclude that there was no evidence for chronic resuspension, the channel did cut and migrate during high flow conditions, so some erosion and transport of soil/sediment materials did occur. As indicated above however, the sediments near the shoreline were very coarse textured (sandy-rocky) there. These materials require very high shear velocities to mobilize them. This is in contrast to the fine, high organic matter sediments found deeper in the lake (Fig. 3b). These sediments are potentially much more mobile, and thus are expected to be resuspended and redistributed away from the inlet/outlet during the generation cycle, although they may be brought back and redeposited near the inlet-outlet during pumping.

Sediment resuspension has been observed in other pumped-storage reservoirs. For example, operation of the Mt. Elbert pumped-storage hydroelectric plant lowered water column transparency and light penetration due to resuspension of fine bottom sediments as well as increased nutrients (USBR, 1993).

Thus, while it seems clear that LEAPS will generate substantial turbidity during construction and start-up, the *persistence* of turbidity induced by sediment resuspension from regular LEAPS operation is not clear. In a regular unidirectional flow, one would expect sediment resuspension would occur upon start-up, although the sediments would quickly redistribute and equilibrate with the new flow/energy environment. This has been observed with the axial flow pumps, where the bottom sediments have been recontoured in response to the locally high energy inputs there (Fig. 4, bold solid lower line), although chronic increased turbidity levels near the pumps have not been observed. Here acoustic backscatter profiles measured using an RDI 600-kHz Workhorse Sentinel acoustic Doppler current profiler (ADCP) in bottom-tracking mode show a redistribution of sediment away from the pumps, with sediment erosion out to about 8 m from the pumps and net sediment deposition occurring at distances of 8 – 16 m from the edge of the pumps (Fig. 4, bold solid lower line).

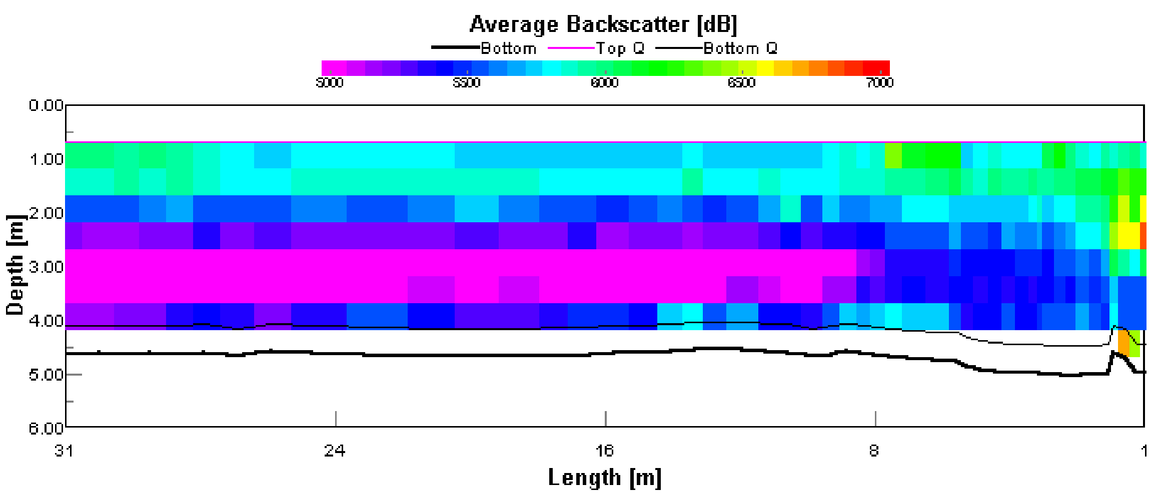

Fig. 4. ADCP transect away from axial flow pumps showing uniform acoustic backscatter profiles (measure of turbidity) beyond about 8 m.

A vertical gradient in scatterers (i.e., turbidity) was present, with 5000-6000 dB backscatter in the upper 2 m, and lower backscatter at greater depths. No clear gradient with distance away from the axial flow pumps was present beyond about 10 m (Fig. 4). Higher backscatter adjacent to the pumps is attributed to some entrainment of air bubbles. Hydrolab measurements of turbidity also do not indicate the presence of a turbidity plume away from the pumps (data not shown). Thus, although currents are extending out some modest distance from the pumps, turbidity levels are not correspondingly elevated.

The reversal of flows during LEAPS operation could, in principle resuspend bottom sediments and pull them into the inlet-outlet during initial pumping, and then resuspend and push them away from the inlet-outlet during generation. The sediments near the middle (deepest) part of the lake are fine-textured and enriched in organic C (Fig. 3b) (so-called type III sediments, with an average of 4.1 % sand, 44.8% silt, 51.2% clay, and 4.8% organic C) (Anderson, 2001). As a result, they could be resuspended with velocities as low as 0.7 ft/s (Gordon et al., 1992). Velocities of 1.5 – 1.8 ft/s produced by LEAPS operation could thus resuspend these sediments, although it seems that redistribution and deposition of the fine sediments out of the zone of influence of the inlet-outlet would eventually lower the amount of sediment available for resuspension so that, longer-term, the sediments would also come to equilibrium with respect to the kinetic energy inputs during operation of LEAPS. Some sediment is expected to accumulate near the inlet/outlet structure and other high-energy zones during non-operation however, so limited sediment resuspension would also be expected upon start-up each spring. Such resuspension events should be quite minor compared to that during construction and initial start-up of the plant.

(c) Operation of LEAPS may alter thermal stratification and lake mixing dynamics in Lake Elsinore.

Operation of pumped-storage hydroelectric plants has been found to significantly alter seasonal stratification and mixing processes in lakes. Kinetic energy inputs from Mt. Elbert powerplant operation shortened the duration of thermal stratification and the strength of that stratification in both the Lower and Upper Twin Lakes (USBR, 1993). Operation of the Lake Oconee pumped-storage facility in 1980 was also found to substantively alter the physical properties of the reservoir, effectively destratifying the lake (Potter et al., 1982). A mathematical model further demonstrated that operation of a pumped-storage plant delayed the onset of thermal stratification of a Swiss lake in the spring by approximately 2 months, increased thermal heat content during the summer, and lowered it during the winter (Imboden, 1980).

The natural stratification and mixing regime in Lake Elsinore is a complex function of lake level and meteorological conditions. The lake is polymictic, i.e., mixes frequently, with the frequency of mixing increasing with decreasing lake level. For example, at low lake levels as found during the summer of 2002-2004 (Z_{max} <5 m), relatively strong daytime stratification set up, although the afternoon winds combined with convective cooling at night routinely eliminated any vertical gradients in temperature by early morning (Fig. 5a). This was not necessarily the case at greater lake levels; for example, on July 14, 2005, when the lake was about 10 m deep, isothermal conditions were not found at any time (Fig. 5b).

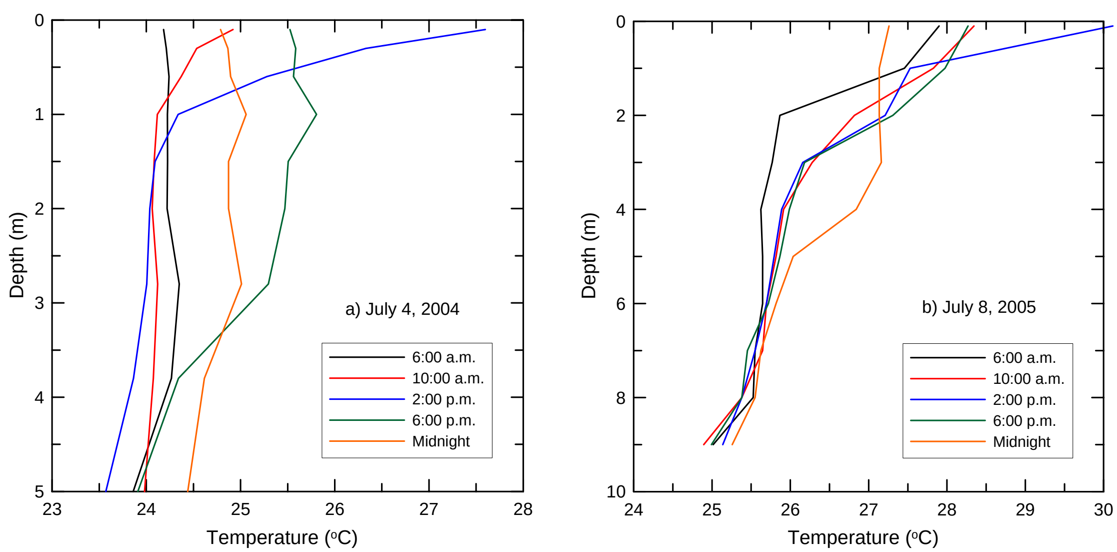

Fig. 5. Diel variation in temperature profiles at two different lake levels and maximum depths: a) 5 m and b) 10 m.

The operation of the axial flow pumps was not found to alter these findings significantly, implying very large inefficiencies in the transfer of their mechanical energy to the water column (Anderson, 2005). Velocity measurements made near the pumps using the ADCP confirm excessive local turbulence immediately adjacent to the pumps with very limited advective currents developed. Recent retrofitting of draft tubes and flow deflectors to Docking Station 1 substantially improved mixing efficiencies there (Anderson, unpubl. data), although the cumulative effect on lakewide stratification will have to await empirical assessment later this summer.

Operation of LEAPS will input additional mechanical energy to the lake, thus supplementing the natural mechanical energy inputs due to wind and convective mixing, as well as the energy inputs from the axial flow pumps and, when installed, the diffused aeration system. This will alter the lake's energy balance and should further weaken or even eliminate thermal stratification. Detailed hydrodynamic modeling will be necessary to fully quantify the impacts of pumped-storage operation on stratification and mixing in Lake Elsinore, although such modeling is beyond the scope of this assessment.

Nevertheless, analytical calculations can provide some insight. As indicated above, wind-forcing is a major source of energy input to lakes. The turbulent kinetic energy input from wind per unit area and time (η_w) can be calculated from:

$$\eta_w = \rho_w \left(\frac{C_D \rho_a}{\rho_w}\right)^{\frac{3}{2}} U_w^3 \qquad (3)$$

where ρ_w is the density of water (kg/m^3), C_D is the drag coefficient, ρ_a is the density of air, and U_w is the wind speed (m/s). From our weather station deployed at the lake, we estimate the average U_w^3 at Lake Elsinore at about 41.3 (m/s)^3. Assuming a drag coefficient of 1.3x10^{-3} (Martin and McCutcheon,1999) and water and air densities of 997 and 1.2 kg/m^3, respectively, one calculates the average turbulent kinetic energy input to Lake Elsinore due to wind is 8.06x10^{-5} W/m^2.

The turbulent kinetic energy input during power generation (η_T) can be calculated from (Imboden, 1980):

$$n_T = \frac{Q_T U_T \rho_{in}}{2A_0} \qquad (4)$$

where Q_T is the flow rate at the turbines (m^3/s), U_T is the turbine outflow velocity (m/s), ρ_{in} is the density of inflowing water (kg/m^3) and A_0 is the lake surface area (m^2). Assuming a flow rate through the turbines of 2000 cfs (56.7 m^3/s), an outflow velocity of 1.5 ft/s (0.46 m/s) and a lake surface area of 3000 acres (1.21×10^7 m^2), one estimates an energy input of 4.94×10^{-4} W/m^2. However, since generation is slated for about 80 h/week (whereas wind blows at some velocity all the time), η_T during to the generation cycle is reduced to a weekly-averaged value of 2.35×10^{-4} W/m^2. Nonetheless, one notes that the turbulent kinetic energy input to Lake Elsinore from turbination (2.35×10^{-4} W/m^2) is predicted to be 2.9x *greater* than that due to natural wind-mixing (8.05×10^{-5} W/m^2). Not included in this calculation is the turbulent kinetic energy input to the lake due to natural convective mixing nor from the effects of pumping, but it nevertheless indicates that that operation of LEAPS will *substantially* increase the kinetic energy available for mixing the water column. The frequency and duration of thermal stratification is thus expected to be substantially reduced relative to natural conditions at the lake. The effects of this on water quality are discussed below.

2. Chemical Effects

Operation of LEAPS may also alter the chemical conditions in Lake Elsinore, including: (a) increased or decreased nutrient release from sediments, (b) increased DO levels, especially near the sediments, and (c) resuspension of particle-associated contaminants.

(a) Increased turbulent kinetic energy from pump-generation cycles may alter the rate of nutrient release from sediments.

Laboratory and field studies have shown that the rate of nutrient release from sediments can be enhanced with increased turbulence and flow near the sediment-water interface (Holdren and Armstrong, 1980; Reddy et al., 1996). Sediment resuspension (discussed in 1.b above) will certainly increase the concentrations of particulate-associated N and P in the water during the initial start-up of LEAPS; dissolved forms of N and P may also be increased, especially if anoxic conditions persist near the sediments since nutrient diffusive flux will be hastened due to advective processes. The flux of dissolved P may be reduced, however, if the enhanced mixing also conveys significant amounts of DO to the sediment-water interface such that an oxic layer with $Fe(OH)_3$ forms; the presence of $Fe(OH)_3$ limits PO_4-P release because of the very high affinity of the ferric hydroxide solid phase for phosphate (Lijklema, 1980).

Review of the literature indicates that the longer-term effects of pumped-storage plant operation may be to either increase or lower nutrient levels in the lake. The Mt. Elbert powerplant increased nutrient levels in Twin Lakes, CO (USBR, 1993), while plant operation lowered nutrient levels in Lake Oconee, GA (Potter et al., 1982). Chronic sediment resuspension was apparently responsible for the increased nutrient levels in Twin Lakes, while the destratification increased DO levels near the sediments of Lake Oconee, thereby lowering SRP flux and dissolved phosphate levels in the water column (USBR, 1993; Potter et al., 1982).

Which of these 2 possible effects on nutrient levels will occur in Lake Elsinore? The lake does have a high sediment oxygen demand as well as high water oxygen demand that must be met before oxic conditions will develop at the sediment-water interface (Anderson, 2005). Moreover, as is often found in arid regions, the sediments are rich in calcium carbonate and relatively deficient in Fe (Anderson, 2001). Thus the P cycle in Lake Elsinore is thought to be controlled to some extent at least by Ca rather than Fe. The high level of productivity in the lake and high oxygen demand has resulted in a high rate of sulfate reduction; the hydrogen sulfide formed from this microbial process has resulted in very low levels of Fe^{2+} in the porewater of the sediments and precipitation of pyritic phases (Anderson, 2001). Thus, sufficient DO must be supplied to eliminate sulfate reduction and free up Fe for precipitation as the sorptive $Fe(OH)_3$ phase. This will be a challenge, although natural mixing processes combined with the increased efficiency of the axial flow pumps, installation of the diffused aeration system and LEAPS should all help to achieve oxic conditions in the subsurface.

Oxic conditions have been shown to reduce SRP flux by about 30% in previous core-flux measurements (Anderson, 2002).

(b) The operation of LEAPS may favorably affect the DO level in Lake Elsinore.

As indicated in 1(c) and 2(a) above, the operation of LEAPS will weaken thermal stratification, enhance mixing and may also increase DO levels in Lake Elsinore. Improved vertical mixing will help mix high DO surface water produced as a result of photosynthesis deeper into the water column during the day, and also allow greater exchange of O_2 between the atmosphere and the entire water column that is especially important at night. Increased sediment resuspension, however, could increase overall oxygen demand within the water column and actually lower DO levels. This effect is likely to occur during initial testing and operation, and should decrease over time as the long-term O_2-demand in the system is met.

In the response document, THNC (2005) indicates that operation of the turbines can increase DO levels by 0.5 – 1 mg/L, so there may be some additional incremental increase in DO concentrations during power generation as well.

(c) Resuspension of sediment-associated contaminants may also occur during pumpback and generation cycles.

Many contaminants in lakes are associated with the sediments. PCBs, DDT, PAHs and other hydrophobic organic contaminants all preferentially sorb to sediments that are enriched in natural organic matter (Schwarzenbach et al., 2003). Trace elements such as Cu, Hg and As are often also found in sediments (Ankley et al., 1996). The sediments in Lake Elsinore contain on average 3.19% organic C, with the deepwater sediments found near the center of the lake averaging 4.84% (Anderson, 2001), and so have the capacity to retain large amounts of hydrophobic organic contaminants and many metals. The resuspension of bottom sediments can thus reintroduce particle-associated forms of these contaminants into the water column, where they may become bioavailable or simply be redeposited elsewhere in the lake.

The sediments of Lake Elsinore do contain trace elements that sometimes exceed “lowest effect levels” (LELs) as reported by Persaud et al. (1992) and Long and Morgan (1990). The LEL is defined as the lowest concentration or amount of a substance found to have an adverse effect on growth, development, functional capacity or life span of a target organism. For example, LELs range from 0.15 ug/g for Hg to 2.0% for Fe. Severe effect levels (SELs) are typically 2-10x higher than the corresponding LEL. Considering the 26 samples for which metals analyses were reported in the LEAPS documentation (Vol. 7, Water Quality Related Reports), none of the sediment samples exceeded the LEL for Hg (0.15 μg/g) or Cd (0.6 μg/g), while 6 (23%) of the samples exceeded the LEL for As (6.0 μg/g), 15 (58%) exceeded the LEL for Cr (26.0 μg/g) and 18 (69%) of the samples exceeded the LEL for Cu (16.0 μg/g). Excluding Fe, none of the samples exceeded SELs for any of the metals. Concentrations of trace organic contaminants (e.g., pesticides, PCBs) were not included in this documentation, although concentrations in water samples from the lake were all below detection limits for pesticides and PCBs. Notwithstanding, arsenic, DDE and PCBs were all detected in fish tissue samples that often exceeded MTRL and/or OEHHA screening values. This was especially true for total PCBs in fish tissue samples that almost always exceeded these threshold values.

While an incomplete understanding of the forms and distribution of organic and metal contaminants in the sediments of the lake currently exists, it is reasonable to assume that much of the contaminants are associated with fine organic material that has been preferentially focused to the deep portions of the lake. Thus any resuspension that does occur due to shoreline migration (expected to be minimal, as indicated in 1.a above) is not expected to result in significant release of contaminants. Operation of LEAPS may have a greater impact, however, on the deeper sediments near the inflow/outflow, especially during construction and initial operation. Just as with nutrients and sediments, however, the longer-term effect of plant operation on resuspension of sediment-associated contaminants is unclear. Moreover, maintenance of oxic conditions near the sediments may also favor retention of some trace metals (*e.g.*, Cu, Cr, Pb, Zn) that, like phosphate, have a high affinity for $Fe(OH)_3$ solid phase. Alternatively, oxic conditions may enhance release of some metalloids (*e.g.*, Se) whose oxidized form is more mobile than its reduced form.

3. Biological Effects

The pumped-storage hydroelectric plant planned for Lake Elsinore may also affect the biotic community in the lake. Impacts may include: (a) changes in the types and abundance of algae in the lake as a result of changes in nutrient levels and due to entrainment, (b) possible entrainment of zooplankton and fish, resulting in direct mortality and/or reduced reproductive capacity, and (c) increased difficulty in establishing and maintaining aquatic macrophytes in the littoral zone of the lake.

(a) Operation of LEAPS may alter the types and abundance of phytoplankton in the lake due to changes in water column nutrient levels and through entrainment.

Sediment resuspension and increased shear near the sediment-water interface may serve to increase the rate of nutrient release to the water column, although if oxic conditions prevail, may actually lower phosphate levels. Assuming that algal populations are constrained by the availability of phosphate, LEAPS may thus alternately increase or decrease algal production, chlorophyll concentrations and transparencies in the lake. Currently the lake is not limited by nutrients; rather it appears that top-down control through grazing by *Daphnia* and other cladocerans has generally been limiting phytoplankton levels in the past year (2005). Nutrient limitations and apparent light limitation have been in place over the past several years, however. Given the highly dynamic nature of external (and internal) loading of nutrients to the lake, it seems reasonable to conclude that any effects of LEAPS on nutrient levels will be within the wide natural range of conditions there. As a result, it may be empirically difficult to demonstrate a clear effect one way or the other when compared with the range in nutrient concentrations and water quality witnessed over the past several years.

Direct entrainment of phytoplankton through pumping may result in increased mortality of phytoplankton, especially buoyant blue-green algae that possess gas vacuoles that aid in buoyancy regulation. As suggested by Horne (2005), the generation cycle will subject entrained phytoplankton to severe pressure changes that will likely rupture the gas vacuoles, resulting in mortality; thus pumped-generation will help control these nuisance algae in Lake Elsinore. To have a significant effect on the cyanobacteria levels, however, the loss of phytoplankton will have to exceed the rate at which natural reproduction would replace any lost organisms. To assess the extent of this beneficial impact, I will assume that the growth of blue-green algae in the lake can be described using a carrying capacity model, where the change in the phytoplankton population over time (dP/dt) is given by:

$$\frac{dP}{dt} = \frac{\mu(K-P)}{K}P \qquad (5)$$

In this equation, μ is the phytoplankton growth rate constant (d^{-1}), K is the carrying capacity, and P is the phytoplankton population. The growth rate constant varies with availability of nutrients and light, as well as temperature; at a summer temperature near 25 °C, the work of Eppley (1972) and others point to a value of μ near 2.5 d^{-1} (Thomann and Mueller, 1987). The carrying capacity of the lake also varies as a function of nutrients, light and other factors; here I set K to 100 and thus refer to populations as a percentage of the carrying capacity.

Loss of phytoplankton due to entrainment and generation is simply a function of the daily pumping rate Q relative to the lake volume V; thus reductions in phytoplankton population over time due to LEAPS operation can be written as:

$$\frac{dP}{dt} = -m\frac{Q}{V}fP \qquad (6)$$

where m is the fraction of organisms killed during a pump-generation cycle, and f is a factor that accounts for daily operation 5 days out of 7 during a week (i.e., f is 5/7 or 0.714).

At steady-state, dP/dt=0, and the steady-state population is thus given by:

$$P = \left(1 - \frac{mQf}{\mu V}\right)K \qquad (7)$$

Assuming 100 % mortality of entrained organisms (i.e., *m* is 1.0), one predicts a steady-state phytoplankton population that is reduced only slightly from the carrying capacity for the lake. A Q/V of 0.039 (i.e., pumping only 3.9% of the lake volume each day, as found when the lake is at its nominal maximum operating level) lowered the predicted phytoplankton population *P* by only 1.1% (a steady-state population of 98.9 % of *K*). Exchanging the lake volume more frequently (Q/V of 0.139, as found when the lake is at its lowest operational elevation and volume), lowered the steady-state phytoplankton population 4% to 96.0% of the lake's carrying capacity for phytoplankton. Thus, the rapid reproduction rate of the phytoplankton will make it difficult to substantially lower their population in the lake under the proposed pumping schedule. For comparison, a Q/V ratio exceeding 1.7 would be needed to reduce the predicted phytoplankton populations by 50%.

(b) The pumpback and generation cycles will result in entrainment of zooplankton and fish, with possible injury, loss of reproductive capacity, and death.

Although entrainment of cyanobacteria and other phytoplankton was not predicted to substantially alter their populations in the lake due to their rapid growth rates, entrainment of slower growing zooplankton and fish could have a significant effect on the lake ecosystem. As noted above, a large volume of water will be exchanged each day (3.9 – 13.9% of the lake volume, depending upon conditions and assumptions). Entrainment of organisms within these volumes during pumping, and their subsequent return to the lake during generation, will result in significant mortality.

(i) Fish - Heisey and Mathur (1980) found 40% mortality of larval catfish that had been entrained during pumping from the Muddy Run Pumped Storage Project, while mortality was somewhat lower for larval carp (17% mortality). Adult fish entrained during operation of the plant experienced 75% mortality, although the authors acknowledged that this value may have been biased to the high side given the nature of their methodology (Heisey and Mathur, 1980). They also noted that about 6.5x more larval fish were entrained during pumping than generation, with compositions of entrained larval fish similar to that found in the lower reservoir. Similar to the findings of Heisey and Mathur (1980), Prince and Mengel (1980) also found (6x) more larval fish entrained during pumping than generation at the Jocassee Pumped Storage Station; they attributed this to the configuration of the basin around the penstocks, the diel depth distribution of the larvae, and the time of day of plant operation. Mortality resulting from entrainment, pumping and generation was taken as 63% in model calculations, with operation of the plant resulting in 7 – 24% loss of fish larvae for the whole lake (Prince and Mengel, 1980). Serchuk (1976) found passage mortalities of marked juvenile and adult fish of 56 – 68% at the Ludington Pumped Storage Power Project in Michigan. In their review, Miracle and Gardner (1980) reported 68 - 85% of mortality resulted from abrasion and collision/contact with intake pipes, turbine blades and other fixed or moving objects within the system. Mortality also resulted from pressure changes, especially due to low pressure conditions and cavitation, and shear forces due to strong velocity changes. Acceleration effects were recognized as a possible factor as well, although this effect was not considered a significant source of mortality. The percent mortality was proportional to size (i.e., mortality decreased with decreasing size, in the order adult>juvenile>larval forms).

The physical characteristics of the plant and lower and upper reservoirs and the operational schedule play strong roles in the overall impacts on the fishery (Miracle and Gardner, 1980). Increased mortality is found during spawning season; habitat preference also plays a large role in what species are entrained and the total number of individuals impacted, both during spawning season and during the rest of the year. Related to this, the depth and location where water is drawn, and other physical characteristics of the facilities, directly influence the impacts on the fishery (and other aspects of the ecosystem). Moreover, spawning habitat can be reduced during plant operation. Turbidity can also affect fish populations by direct mortality, modification of reproduction rates, changing of growth rates, altering habitat and changing behavior (Miracle and Gardner, 1980). Other water quality changes (e.g., water temperature and DO levels) can also affect the fishery (e.g., Oliver and Hudson, 1980).

(ii) Zooplankton - Direct measurements of entrainment and mortality of zooplankton during pumping and generation do not appear to have been made. In an assessment of possible zooplankton effects from pumped-storage plant operation on Lake Ivosjon in southern Sweden, Horst (1980) assumed mortality rates of 10, 50 and 100% for individuals entrained during plant operation in a finite-segment model that also included advective-dispersive exchange and natural production. His model predicted overall reductions in zooplankton populations in the lake that were generally modest (e.g., 2 - 12% reduction in *Bosmina* population in the lake depending upon assumed mortality rates of 10 – 100%) and within the natural observed variability in zooplankton levels there (Horst, 1980). The volumes exchanged during pumping and generation were not provided, although the volumes of the upper reservoir and Lake Ivosjon ($2.5x10^7$ and $6.0x10^8$ m^3, respectively), indicates that daily exchange rate must necessarily be fairly low (<4.2%). This compares with the relative exchange rate of 3.9 – 13.9% projected for L. Elsinore, so impacts might be expected to be comparable or up to 3x or more greater for L. Elsinore.

To minimize entrainment of fish and other organisms, use of the Gunderboom Marine Life Exclusion System (MLES™) filtering curtain has been proposed for the lake. The MLES includes a compressed air system to periodically clear the filter barrier of entrapped material and maintain flow through the curtain. Ichthyoplankton monitoring at a conventional fossil-fueled steam electric plant on the Hudson River found approximately 80% efficiency in its reduction of larval fish entrainment (Raffenberg et al., in THNC, 2005).

The model of Prince and Mengel (1980) can be used to estimate the impacts of LEAPS operation on ichthyoplankton levels in Lake Elsinore. The benefit from use of the MLES can also be estimated. The model assumes that the % loss of ichthyoplankton from the lake (L) is a function of larval concentrations in the pumped volume (C_p), the volume-averaged larvae population in the whole lake (if different than the pumped volume) (C_v), the mean flow through the plant (Q_p), the net mortality rate within the pumped volume (m), the volume of the lake (V), and the number of days before hatched fish are of sufficient size and developmental stage to no longer be considered planktonic (T). That is:

$$L = \frac{\frac{mC_p}{C_v} Q_p T}{V} x100 \qquad (8)$$

In their model calculations, Prince and Mengel (1980) assumed 63% net mortality from entrainment and that the time to mature to free-swimming forms was 29 days. Using a slightly more conservative assumption for net mortality (50%) and assuming the concentration of larval fish in the pumped volume is equivalent to the lake-wide average concentration, one calculates a 40.4% loss of larval fish from pumped-storage operation when operated at the highest nominal lake volume and 100% loss when operated at low pool (Table 2). Although not explicitly stated in their study, we assume *m* defines net mortality that results from both pumping and subsequent return to the lake during generation; for the calculations as used here we assigned *m* a value of 50%, based upon 30% mortality (70% survival) on each side of the pumping and generation cycle. This mortality rate is consistent with the averaged rate from the findings of Heisey and Mathur (1980) for carp (17%) and catfish (40%). Although a simplified model, the findings imply potentially strong effects on larval survival and recruitment from operation of LEAPS during spawning season. While loss of larval sport fish should be mitigated against, this may actually prove to be an efficient way to control unwanted rough fish in the lake. That is, most sport fish spawn between 17 and 21°C, while carp typically spawn under warmer conditions, peaking at 22-26 °C. Thus, the scheduling of LEAPS operation should consider spawning seasons, with limited operation during spawning season for the sport fish (April, based upon historical temperature records for the lake), and regular use during the carp spawning season (May-June) (assuming no additional mitigation, *e.g.*, through use of the MLES).

The use of the MLES, if adopted, would lower the pumped concentration (C_p) relative to that in the lake (C_v); if the Gunderboom system can reduce entrainment of larval fish by 80%, then C_p in eq 8 is simply $0.2C_v$. Under these operating conditions, one predicts % ichthyoplankton loss in Lake Elsinore of 8 – 29% (Table 2). This presumes that widespread larval fish mortality does not occur through entrapment in the filter curtain, nor during periodic pulsed air - pressure cleaning, or from increased predation near the curtain.

Table 2. Predicted % reductions in ichthyoplankton due to LEAPS operation.

	% Reduction in Ichthyoplankton due to LEAPS	
	Minimum lake level	**Maximum lake level**
LEAPS	100%	40.4%
LEAPS+Gunderboom	29.0%	8.1 %

Although not part of this assessment, more detailed calculations could be made to predict longer-term changes in fish populations due to LEAPS operation with and without the Gunderboom system, including optimization of the system to minimize sport-fishery impact and to maximize mortality of larval carp. Such an optimization may thus allow for a favorable shift in the fish ecology of Lake Elsinore.

The effects of LEAPS operation on the zooplankton of the lake can also be calculated; following the approach outlined above for phytoplankton, the change in the zooplankton population (P_Z) over time (t) can be predicted assuming:

$$\frac{dP_Z}{dt} = (\mu_Z(\frac{K_Z - P_Z}{K_Z}) - m_Z \frac{Q}{V} f)P_Z \qquad (9)$$

where μ_Z is the zooplankton birth rate constant, K_Z is the zooplankton carrying capacity of the lake, m_Z is the net mortality rate for zooplankton entrained during LEAPS operation, Q is the daily flow rate, V is the volume of the lake and f is an operational factor (to correct for planned summer operation of 5 days per week).

The steady-state solution to eq 9 is of the same form as eq 7, however zooplankton reproduce more slowly than phytoplankton (μ often near 0.4 d^{-1}), so entrainment results in greater reductions in predicted steady-state populations relative to phytoplankton (Table 3). Assuming complete mortality of entrained organisms, the operation of LEAPS is predicted to lower the steady-state zooplankton population by 7.0 – 24.8 %, depending upon lake level (Table 3). For comparison, entrainment lowered phytoplankton populations only 1.1 – 4.0 %. The Gunderboom MLES system will lower the number of zooplankton entrained during pumpback-generation; for illustration, I will assume the Gunderboom system will lower the pumped concentration by 50%. Under these conditions, LEAPS operation is expected to have less of an effect on zooplankton levels, lowering zooplankton populations by only 3.5 – 12.4 % (Table 3). As with the ichthyoplankton, it is implicitly assumed that the filter curtain will not result in mortality to zooplankton from contact, cleaning or increased predation.

Table 3. Predicted reductions in steady-state zooplankton populations as a result of LEAPS operation.

	% Reduction in Zooplankton Population	
	Minimum lake level	**Maximum lake level**
LEAPS Operation	24.8 %	7.0 %
LEAPS+Gunderboom	12.4 %	3.5 %

While a number of assumptions were made in the model predictions for phytoplankton (eq 7), larval fish (eq 8) and zooplankton (eq 9), some general trends are clear. First of all, the impact of LEAPS will be more pronounced when the lake is at a comparatively low volume, that is, when the relative pumping rate is high. Secondly, the impacts from pumped-storage operation will be larger for the higher trophic level organisms whose reproduction rate is slow compared to the relative pumping rate; thus, bacteria and phytoplankton, with rapid doubling times, will be minimally affected by plant operation, while zooplankton will be impacted to an intermediate degree and, other things being equal, fish will be impacted to the largest degree. Thirdly, careful design of the inlet/outlet, combined with judicious operational scheduling and implementation of other strategies to reduce entrainment can help minimize any negative ecological impacts from LEAPS operation.

(c) Effects of LEAPS on the establishment and maintenance of aquatic macrophytes in the lake.

One of the goals of the restoration plan for Lake Elsinore is to stabilize the lake level and foster the growth of aquatic macrophytes. Macrophytes provide shelter for zooplankton and ichthyoplankton, serve as habitat for sport fish, and compete with phytoplankton for light and nutrients (Moss, 1998). There will be a significant financial incentive to maintain the lake level within the previously identified operational range of 1240-1247 ft above MSL, and so the >20 ft oscillations in surface elevation seen over the past decade (1233.5 to over 1255 ft) are expected to be diminished. The potential for revenue from power generation should help ensure that the low lake levels witnessed in 2002-2004 do not recur, so on that basis, LEAPS should be considered to have a positive effect on the lake. Of course, lake level variations need to be controlled more carefully than simply to fall within 1240-1247 ft range to enhance macrophyte development within the littoral zone. Since lake level fluctuations of 1.0 – 1.7 ft are anticipated during LEAPS operation, the shallowest waters near the shoreline will be regularly exposed and then rewetted. This level of daily shoreline migration is not expected to limit overall colonization and growth of aquatic macrophytes in the lake, however, since these near-shore waters over much of the lake will be subjected to regular wind mixing, turbulence and sediment resuspension. These natural processes would limit macrophyte growth in this high energy region anyway. Regions of the lake that receive lower wind energy inputs, such as the southern embayments, should be able to foster some emergent macrophytes, even with daily drawdown and rewetting, since they can inhabit both submerged sediments as well as saturated soils. Rather, the major limiting factors to establishment of aquatic macrophytes in Lake Elsinore will more likely be the overall turbidity of the water column, and the larger annual variations in lake surface elevation that can exceed 3-4 ft.

As previously discussed, LEAPS operation may increase turbidity in the lake directly through sediment resuspension and indirectly through additional inputs of nutrients. The contributions of LEAPS to the overall turbidity in the lake are not entirely clear although, as noted, it is expected that, longer-term, the sediments would come into equilibrium with the kinetic energy inputs from operation of LEAPS. Reductions in the annual variation of lake level through flow augmentation to the lake should improve the prospects for establishing an aquatic macrophyte community in the lake.

Additional Studies

While this analysis identified both positive as well as negative impacts from operation of LEAPS, several key studies are still needed to better quantify water quality impacts, reduce uncertainty in predicted effects, and improve the design and operation of LEAPS.

First of all, heat calculations should be made for the upper storage reservoir and for Lake Elsinore. As indicated by Prof. Horne (2005), one would like the water that is returned to the lake during generation to be cooler and more dense that the lake water, resulting in an underflow condition that will help keep the relatively well-aerated water moving above the sediment-water interface (assuming that the shear force is not so large that it results in extensive sediment resuspension). Pumping will heat the water, however, so temperature of the water as it is pumped into upper reservoir should initially be warmer than that at the lower withdrawal depths of the lake; greater convective cooling at the higher elevation may subsequently lower the water temperature. Turbination during the generation phase will also heat the water, however, so it is unclear whether the water discharged to the lake will be warmer, cooler or at the same temperature as that in the lake. The temperature of the released water will dictate where the resulting jet inserts into the water column (Martin and McCutcheon, 1999). If the temperature of the water released to the lake were warmer than the surface waters, an overflow condition would result, although since water would be released during the day when strong surface heating occurs, this seems unlikely. The heating from the pumping and generation phases may be sufficient to create an interflow condition, however, with the water released during generation being intermediate in temperature and thus inserting into a neutrally buoyant position within the water column (Martin and McCutcheon (1999). Thus, the balance of heat inputs from pumping and generation, and heat loss due to nighttime convective cooling, needs to be determined.

While the heat calculations can be made using relatively simple analytical expressions, there exists a very strong need for development and application of a 3-D hydrodynamic model for the lake. A 3-D hydrodynamic model will be able to predict velocity fields near the intake/outlet, quantify shear stress at the sediment-water interface and thus resuspension effects, assess impacts of operation on thermal stratification and DO levels (including overflow, interflow and underflow conditions), and predict turbulent kinetic energy inputs, mixing and circulation. Moreover, it is my view that hydrodynamic simulations should be used as part of the design process for the intake/outlet structure.

Finally, there is also a need for an ecological model to better understand the trophic cascades that may result from LEAPS operation. For example, in the above analyses, phytoplankton, zooplankton and fish were all treated as isolated sets of organisms whose populations were assumed to be controlled by their respective reproduction rates, the lake's carrying capacities for these organisms, and rates of entrainment and mortality from pumping. In reality, of course, the dynamics of these organisms are all coupled to each other in a complex way through the food web in the lake. Development and application of an ecological model would allow one to quantify, for example, how enhanced nutrient levels, reduced transparency and loss of zooplankton through entrainment affects phytoplankton levels in Lake Elsinore.

Summary

Installation and operation of the proposed pumped-storage hydroelectric plant at Lake Elsinore is expected to have a number of impacts on its limnology and water quality. Substantial turbulent kinetic energy will be input into the water column through the operation of LEAPS, with calculations indicating energy inputs during generation that exceed natural wind-forcing by a factor of approximately 2.9. This additional energy input is expected to substantially weaken or eliminate the periodic thermal stratification present in the lake, thereby assisting the axial flow pumps in achieving a well-mixed condition in Lake Elsinore. The increased mixing will also help distribute DO throughout the water column and should improve the redox status near the sediments. Depending upon productivity levels in the lake, sufficient DO may be present to satisfy the oxygen demand of the surficial sediments and promote formation of a sorptive $Fe(OH)_3$ layer that will slow the rate of PO_4-P release. The additional mechanical energy inputs during pumping and generation do, however, also have the potential to resuspend bottom sediments and increase turbidity, total and dissolved nutrient concentrations, and contaminant levels in the water column. Sediment resuspension may also increase oxygen demand and *lower* DO levels, especially during construction, testing and early operation. That is, short-term negative effects are expected during initial testing and operation of the facility, although the persistence of these effects are difficult to judge without detailed hydrodynamic modeling. It appears likely that the longer-term effects will overall be modest, with the bottom sediments coming into relative equilibrium with the new (higher) energy environment there. Thus chronic, severe sediment resuspension and the attendant water quality problems seem somewhat unlikely.

Lake level variation of 1 – 1.7 ft over a pump/generation cycle is estimated to expose 49 – 134 acres depending upon the hypsographic data set used; sediment exposure will be most extensive in the shallow embayments in the southern part of the lake. Shoreline migration is expected to be modest (8 – 20 ft) over much of the lake, although daily shoreline migration will be larger in the southern embayments. In addition to the physical and chemical impacts from

LEAPS operation, there will also be biological/ecological impacts. Pumping between 3.9 and 13.9% of the lake volume each day (at the nominal maximum and minimum lake operating levels, respectively) will result in entrainment of significant numbers of organisms. Of particular concern is the entrainment and mortality of zooplankton and fish.

Model calculations suggest that ichthyoplankton (larval fish) levels could be reduced by LEAPS operation from 40 – 100% depending upon the lake level, assuming that the plant ran through spawning season and did not include any mitigation measures to reduce entrainment. With installation of a filter curtain that reduced entrainment by 80%, the calculated loss of larval fish through LEAPS operation decreases to 8 – 29% (assuming that widespread larval fish mortality does not occur through entrapment in the filter, nor during periodic pulsed air-pressure cleaning, or from increased predation near the curtain). The use of a filter curtain would also keep juvenile and adult fish from becoming entrained; the mortality rate is 2-4x higher for juvenile and adult fish than larval forms. The entrainment of larval fish could be used to advantage, however, if LEAPS operation (without the filter curtain) was coordinated with the carp spawn. This could offer a more efficient way to control the carp population in the lake than current netting efforts.

Entrainment of zooplankton is also a concern, since zooplankton, especially *Daphnia*, can exert strong grazing pressure on phytoplankton that can keep algal levels in check; high levels of mortality within the entrained zooplankton population would lower grazing pressure and result in elevated algal levels in the lake. Calculations made assuming 100% mortality of entrained organisms indicate that LEAPS operation could lower zooplankton populations by as much as 7.0 – 24.8% depending upon the volume of the lake. With either a lowered mortality rate of one-half for the entrained organisms during pumping/generation, or assuming the filter curtain reduces the pumped concentration by one-half, steady-state zooplankton populations were calculated to decline less (predicted reductions of 3.5 – 12.4 %). The use of the filter curtain could thus lower the amount of entrainment and also reduce loss of zooplankton (subject to the previous assumptions about limited mortality at the filter curtain due to entanglement, mortality during pulsed air cleaning of the filter, and no increased predation there). Pumped-storage was not predicted to alter phytoplankton populations however (1.1 – 4.0 % reduction). The LEAPS project could enhance the development of an aquatic macrophyte community in the lake by providing greater long-term stability to the lake level. The comparatively modest daily variations in lake level that result from pumping and generation are not thought to represent a serious limitation to the development of a healthy littoral zone assuming that nutrient concentrations and algal and non-algal turbidity levels are low.

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