Appendix F

Ecological Impacts from LEAPS Operation Predictions Using a Simple Linear Food Chain Model

ECOLOGICAL IMPACTS FROM LEAPS OPERATION: PREDICTIONS USING A SIMPLE LINEAR FOOD CHAIN MODEL

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Introduction

Pumped-storage hydroelectric plants withdraw and return substantial volumes of water from the source reservoir in a short period of time; operation can thus potentially entrain a large number of organisms that lack sufficient motility to avoid being drawn into the turbines. Larval fish (ichthyoplankton) are particularly susceptible to entrainment and mortality (Miracle and Gardner, 1980). For example, Prince and Mengel 1980) reported 7 – 24% loss of fish larvae as a result of pumped-storage operation at the Keowee Reservoir. Similar losses of larval fish were predicted for the Jocassee Pumped Storage Station based upon a simple analytical model (Prince and Mengel, 1980). Application of this model to Lake Elsinore suggested that 40 – 100 % of larval fish could be lost as a result of regular (5 days a week) LEAPS operation depending upon lake level and assuming uniform dispersal of ichthyoplankton throughout the lake (Anderson, 2006). Use of a filter curtain that was assumed to reduce entrainment by 80% yielded much lower % reductions in larval fish (8.1 – 29%) (Anderson, 2006). Mortality rates generally increase with increasing size, from 17 – 40 % mortality for larval fish passing through a pumped-storage plant (Heisey and Mathur, 1980) to 56-68 % for juvenile and adult fish (Serchuk, 1976). Entrainment of juvenile and adult fish is lower, however, since most would be strong enough to avoid being drawn into the system during pumping.

Zooplankton (including both larval and adult forms) would also be subject to entrainment. Less is known about changes in zooplankton populations as a result of pumped-storage plant operation. Predicted impacts to zooplankton populations from plant operation on Lake Ivosjon in southern Sweden were modest (2-12 %) and within the natural observed variability there (Horst, 1980).

Preliminary model calculations for Lake Elsinore based upon a steady-state solution to a carrying-capacity model that included entrainment and mortality indicated less dramatic an effect on zooplankton populations than predicted for larval fish. LEAPS operation was predicted to lower zooplankton levels by 7 – 24.8 % depending upon lake level and pumping rate (Anderson, 2006); use of a filter curtain that reduced entrainment by 50% was predicted to yield reductions in zooplankton population due to LEAPS operation of 3.5 – 12.4 %.

Entrainment and potential loss of phytoplankton was also assessed using a carrying-capacity model with entrainment and mortality; the rapid natural reproduction rate of most phytoplankton (e.g., Eppley, 1972) was found to keep pace with loss from entrainment. As a result, LEAPS operation was assumed to lower phytoplankton levels by only 1.1 – 4 % from the reference (no operation) case (Anderson, 2006).

Preliminary calculations made for Lake Elsinore thus indicate that LEAPS operation would have a negligible impact on phytoplankton, a modest impact on zooplankton and the greatest impact on fish. These calculations treated each group of organisms (phytoplankton, zooplankton and larval fish) as isolated organisms whose populations were a function of the lake's carrying capacity for each group of organisms, their reproductive rate and the relative rate of pumping to overall lake volume that defined the probability of entrainment. While instructive, this approach does not allow for the interactions between these different groups of organisms. In reality, of course, the populations of phytoplankton, zooplankton and fish are all connected to each other through the food web of the lake. Thus, one may expect there to be a trophic cascade (Carpenter et al., 1985) that would result from loss of, *e.g.*, larval fish or zooplankton, due to LEAPS operation.

The objective of this study was to consider more carefully the changes in the ecosystem of Lake Elsinore that may result from LEAPS operation.

1. Predicted Ecological Impacts from LEAPS Operation

The potential consequences of LEAPS operation on the food web of the Lake Elsinore were evaluated through development and application of a simple ecological model. While highly sophisticated lake ecosystem models have been developed that allow, e.g., prediction of blue-green algal densities at a specific time, location and depth in a lake, the development and successful application of such a comprehensive lake ecosystem is an extremely challenging task that requires a tremendous amount of information about the study site. The question to be addressed in this study is more simple. Specifically, through a simplified linear food web model for Lake Elsinore, will LEAPS operation substantively alter the ecology of the lake relative to no pumped-storage plant operation?

To address this question, a simple linear food web model was developed based upon the proposed food web for the lake (EIP, 2004) (Fig. 1). The model is necessarily a simplification of the food web in the lake, and includes the lumping together of a number of different species and age classes into common trophic levels and ecological niches. Nonetheless, it is expected to provide an adequate representation of the food web for the purposes herein.

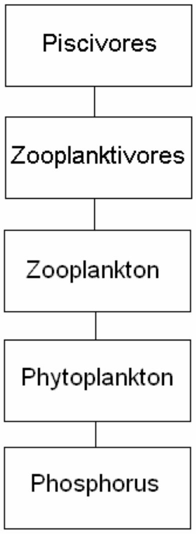

Fig. 1. Simplified food web for Lake Elsinore (explicitly linked to available phosphorus)

Phosphorus was taken as the biologically-available fraction that was assumed to be supplied to the water column via internal recycling and lost through the process of assimilation by phytoplankton. The population of phytoplankton (modeled explicitly as chlorophyll a concentration) was a function of phytoplankton growth that was limited by available P and modeled using Monod kinetics, and phytoplankton loss through grazing by zooplankton, settling and entrainment (for LEAPS simulations) (Fig. 1). The zooplankton population (especially large-bodied cladocerans) in the model was controlled by availability of phytoplankton, predation by zooplanktivores (e.g., larval and juvenile fish and adult shad), respiratory losses and death, and entrainment, while zooplanktivore levels in the lake were a function of availability of zooplankton, predation by piscivores (e.g., crappie, striped bass), other mortality and entrainment. Piscivore populations were constrained by the availability of prey (zooplanktivores), natural mortality and entrainment, although entrainment (during LEAPS simulations) was considered low since piscivores were assumed to be juveniles or adults and thus generally able to avoid entrainment under most circumstances.

The differential equation to describe biologically-available P [BAP} in the lake was written as:

$$\frac{d[BAP]}{dt} = \frac{J_{IL}}{Z} - \frac{\mu_{max}[BAP]}{K_M + [BAP]}\frac{[Phyto]}{Y} \qquad (1)$$

where *[BAP]* is the concentration of biologically-available P (mg m^{-3}), *t* is time (d), J_{IL} is the internal recycling rate (mg m^{-2} d^{-1}), *Z* is the mean depth of the lake (m), μ_{max} is the maximum growth rate constant (d^{-1}), K_M is the Monod constant (mg m^{-3}), *[Phyto]* is the concentration of phytoplankton (chlorophyll) (mg m^{-3}), and *Y* is the yield (amount of chlorophyll produced per unit mass of BAP) (mg chlorophyll mg^{-1} BAP).

The change in phytoplankton population over time was written as:

$$\frac{d[Phyto]}{dt} = \frac{\mu_{max}[BAP]}{K_M + [BAP]}[Phyto] - g_z[Zoo][Phyto] - \frac{\nu}{Z}[Phyto] \qquad (2)$$
$$- m_{LEAPS}^{Phyto} f_p \frac{Q}{V}[Phyto]$$

where g_z is the average grazing rate (or filtration rate) of each zooplankton (m^3 indiividual^{-1} d^{-1}), *[Zoo]* is the zooplankton population (# individuals m^{-3}), ν is the algal settling velocity (m d-1), $m^{Phyto}{}_{LEAPS}$ is the phytoplankton mortality during entrainment, f_p is the fraction of phytoplankton within the pumped volume entrained, Q is the average daily pumping flow rate (m^3 d^{-1}), and V is the volume of the lake (m^3).

The change in zooplankton population over time was taken as:

$$\frac{d[Zoo]}{dt} = g_z \varepsilon_z [Zoo][Phyto] - g_{f1}[Zoo][Fish1] - m_z[Zoo] \quad (3)$$
$$- m^{Zoo}_{LEAPS} f_z \frac{Q}{V}[Zoo]$$

where ε_z is the zooplankton production term (# zooplankton mg^{-1} chlorophyll), g_{f1} is the zooplanktivore grazing rate (m^3 individual^{-1} d^{-1}), *[Fish1]* is the population of the zooplanktivore (# individuals m^{-3}), $m^{Zoo}{}_{LEAPS}$ is the zooplankton mortality during entrainment, and f_z is the fraction of zooplankton within the pumped volume that are entrained.

The change in zooplanktivore population with time was given by an expression similar to that of eq 3:

$$\frac{d[Fish1]}{dt} = g_{f1}\varepsilon_{f1}[Fish1][Zoo] - g_{f2}[Fish1][Fish2] - m_{f1}[Fish1] \quad (4)$$
$$- m^{Fish1}_{LEAPS} f_{f1} \frac{Q}{V}[Fish1]$$

where ε_{f1} is the zooplanktivore production term (zooplanktivores zooplankton^{-1}), g_{f1} is the predation rate of piscivores (m^3 inidividual^{-1} d^{-1}), m_{f1} is the natural mortality rate of the zooplanktivores (due e.g., to disease) (d^{-1}), $m^{Fish1}{}_{LEAPS}$ is the zooplanktivore mortality during entrainment, and f_{f1} is the fraction of zooplanktivore within the pumped volume that are entrained.

The final expression describes the change in piscivore population *(Fish2)* over time:

$$\frac{d[Fish2]}{dt} = g_{f2}\varepsilon_{f2}[Fish2][Fish1] - m_{f2}[Fish2] - m^{Fish2}_{LEAPS} f_{f2} \frac{Q}{V}[Fish2] \quad (5)$$

where ε_{f2} is the piscivore production term (# piscivores zooplantktivore^{-1}), m_{f2} is the mortality rate of the piscivores (d^{-1}), $m^{Fish2}{}_{LEAPS}$ is the piscivore mortality during entrainment, and f_{f2} is the fraction of piscivores within the pumped volume that are entrained.

These 5 ordinary differential equations form the food web model, and are all coupled to each other (*e.g.*, the phytoplankton population appears in both eqs 1 and 2, the zooplankton term appears in eqs 2 and 3, and so on), and thus require a numerical solution. The equations were solved using a simple forward-difference integration scheme with a 0.05 d timestep. Simulations were run for 4 months to ensure approach to a steady-state solution to eliminate variable time dependencies and facilitate comparison between different conditions.

The constants used in the calculations were derived from a variety of sources, including Thomann and Mueller (1987), Chapra, 1997), Lorenzen (1996), Sammons et al. (1998), and are summarized in Table 1.

Table 1. Model parameters and values used in simulations.

Parameter	**Value**	**Parameter**	**Value**
J_{IL}	8 mg m^{-2} d^{-1}	ε_z	2500 ind ind^{-1} d^{-1}
Z	4.0 - 5.6 m	g_{f1}	1 m^3 ind^{-1} d^{-1}
μ_{max}	2.0 d^{-1}	f_z	1.0
K_m	5 mg m^{-3}	m_z	0.03 d^{-1}
Y	2.5 mg mg^{-1}	ε_{f1}	$2.5x10^{-6}$ ind ind^{-1}
g_z	$5x10^{-6}$ m^3 ind^{-1} d^{-1}	m_{f1}	0.019 d^{-1}
ν	0.1 m d^{-1}	g_{f2}	10 m^3 ind^{-1} d^{-1}
m_{LEAPS}	0.5	f_{f1}	0.5
f_p	1.0	ε_{f2}	0.01 ind ind^{-1}
Q	$2.83x10^6$ m^3	m_{f2}	0.005 d^{-1}
V	$4.85x10^7$ $-7.4x10^7$ m^3	f_{f2}	0.01

The values provided in Table 1 for the volumes and average depths represent the range expected for the lake based upon the bathymetric data of Anderson (2006). The fraction of organisms within the pumped volume that were entrained were assumed to be 100% (i.e., f_p=1) for phytoplankton and zooplankton, while one-half of the planktivorous fish were assumed to be larval or juvenile forms that would be susceptible to entrainment, while only a very small fraction of the piscivores were assumed to be entrained (1%). For those organisms entrained, mortality was assumed to increase with increasing size (Miracle and Gardner, 1980), from 20% for phytoplankton, to 50% for entrained zooplankton and zooplanktivores, and 70% of the larger piscivores.

Model calculations were performed assuming increasing complexity of the food web to demonstrate the effects that higher trophic levels can exert on chlorophyll and nutrient concentrations in Lake Elsinore. As a result, a total of 4 different food webs were assessed. The simplest food web assumed internal loading supplied biologically-available phosphorus (BAP) to fuel phytoplankton growth. The effect of zooplankton on predicted chlorophyll and BAP was then assessed, followed by the inclusion of zooplanktivorous fish, and then finally the effect of piscivores. This latter scenario thus represents the full food web depicted in Fig. 1. The reference case, when LEAPS was not in place, was compared with LEAPS operation at an average daily pumping rate (including 2 days of non-operation each week) of 2294 af d^{-1} at nominal lake levels of 1247 and 1240 ft above MSL (relative average pumping rates, Q/V, of 0.039 and 0.060 d^{-1}).

In the simplest food web that includes just BAP and phytoplankton, phytoplankton growth kept predicted BAP concentrations very low (<0.5 $\mu g\ L^{-1}$) (Fig. 2a), while chlorophyll levels were predicted to reach a steady-state concentration of 200 $\mu g\ L^{-1}$ (Fig. 2b). Operation of LEAPS was found to lower chlorophyll concentrations by 30-40% through entrainment and mortality, although concentrations remained high (Fig. 2b).

Addition of zooplankton to the food web yielded a much higher BAP concentration and a dramatically lower predicted chlorophyll concentration (Fig. 2). Grazing by zooplankton exerted a very strong effect on phytoplankton levels and thus also altered available nutrient levels in the lake. LEAPS operation increased slightly predicted chlorophyll levels and reduced BAP concentrations as a result of lower predation by zooplankters.

Incorporation of zooplanktivorous fish (including larval forms of almost all species, as well as adult shad and other planktivores) into the food web of Lake Elsinore lowered predicted BAP concentrations and increased quite substantially chlorophyll concentrations relative to the phytoplankton+zooplankton food web (chlorophyll levels of 36 – 64 μg L^{-1}) (Fig. 2b). These concentrations do remain below the phytoplankton-only food web, however. LEAPS operation was predicted to lower somewhat predicted chlorophyll levels.

The penultimate food web for the lake would include a large population of piscivorous sport fish; it can be seen that a healthy population of piscivores would also maintain quite low predicted chlorophyll levels in the lake (7 - 10 μg L^{-1}).

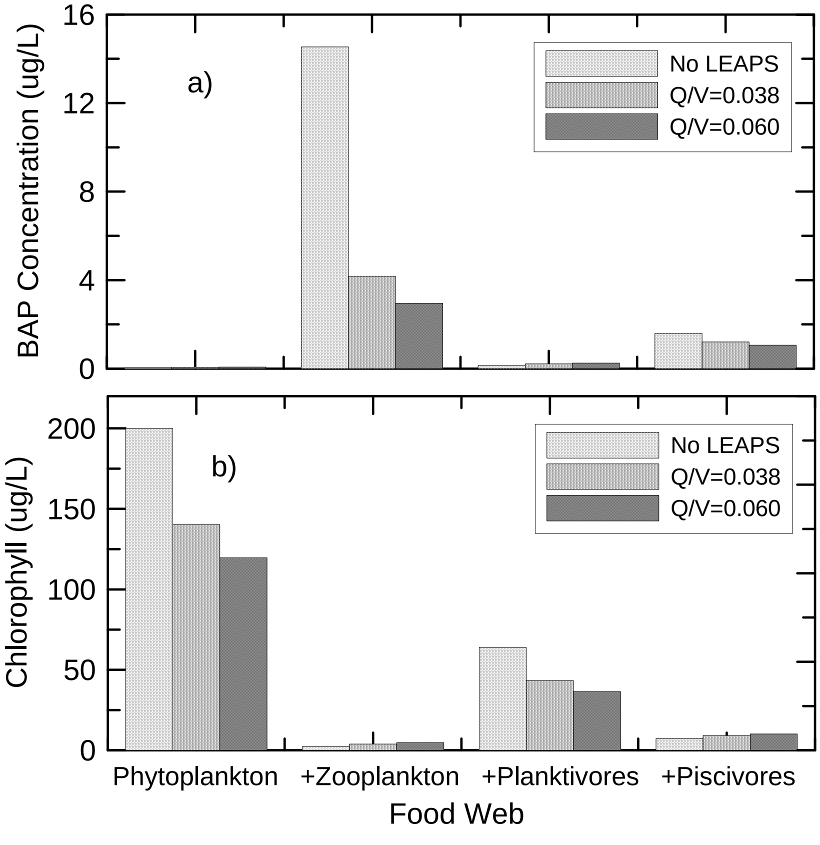

Fig. 2. Predicted a) BAP and b) chlorophyll concentrations in Lake Elsinore for food webs of increasing complexity (from left to right). The natural condition (no LEAPS) and LEAPS operation at two relative pumping rates (Q/V) are shown.

The higher trophic levels help explain the trends observed in Fig. 2. For example, with the phytoplankton-only system, chlorophyll levels are controlled by the balance of algal production and loss due to settling. Since algal settling rates are low (~0.1 m d^{-1}), high predicted chlorophyll levels result from the rapid rate of internal recycling in the lake (taken in these calculations as 8 mg m^{-2} d^{-1}) (Anderson, 2001). These high levels of phytoplankton production could in principle support a substantial large-bodied zooplankton population in the lake. The model in fact predicts a zooplankton population of nearly 300 individuals L^{-1} (Fig. 3a). Zooplankton effectively grazed down chlorophyll to very low levels (Fig. 2b) as phytoplankton production was converted to zooplankton biomass (Fig. 3a). LEAPS operation lowered zooplankton populations by up to 51% at the higher relative pumping rate. This reduced zooplankton population was less effective at algal control, however (Fig. 2b). The higher algal population utilized more BAP, thus lowering its predicted concentrations from >14 to <4 μg L^{-1} (Fig. 2a).

The high zooplankton production potential in Lake Elsinore that results from internally recycled P fueling algal growth could, in turn, support a large population of larval, juvenile and adult planktivorous fish (Fig. 3b). With some admittedly simple assumptions, the model predicted planktivore abundances potentially approaching 1 per m^3; the effect of the planktivores was to substantially lower the zooplankton population in the lake (Fig. 3a, +planktivores) relative to the food web without predation on zooplankters (Fig. 3a, +zooplankton). Reductions in zooplankton populations of 90-97% were predicted. LEAPS operation did also negatively impact planktivore levels (Fig. 3b); reductions in zooplanktivores increased zooplankton levels in the lake (Fig. 3a) that in turn led to a “trophic cascade”, wherein the higher zooplankton population yielded lower predicted chlorophyll concentrations (Fig. 2b). That is, chlorophyll levels are inversely related to zooplankton populations and thus tied to the relative abundance of planktivores in the lake (↑ planktivores: ↓ zooplankton: ↑ chlorophyll).

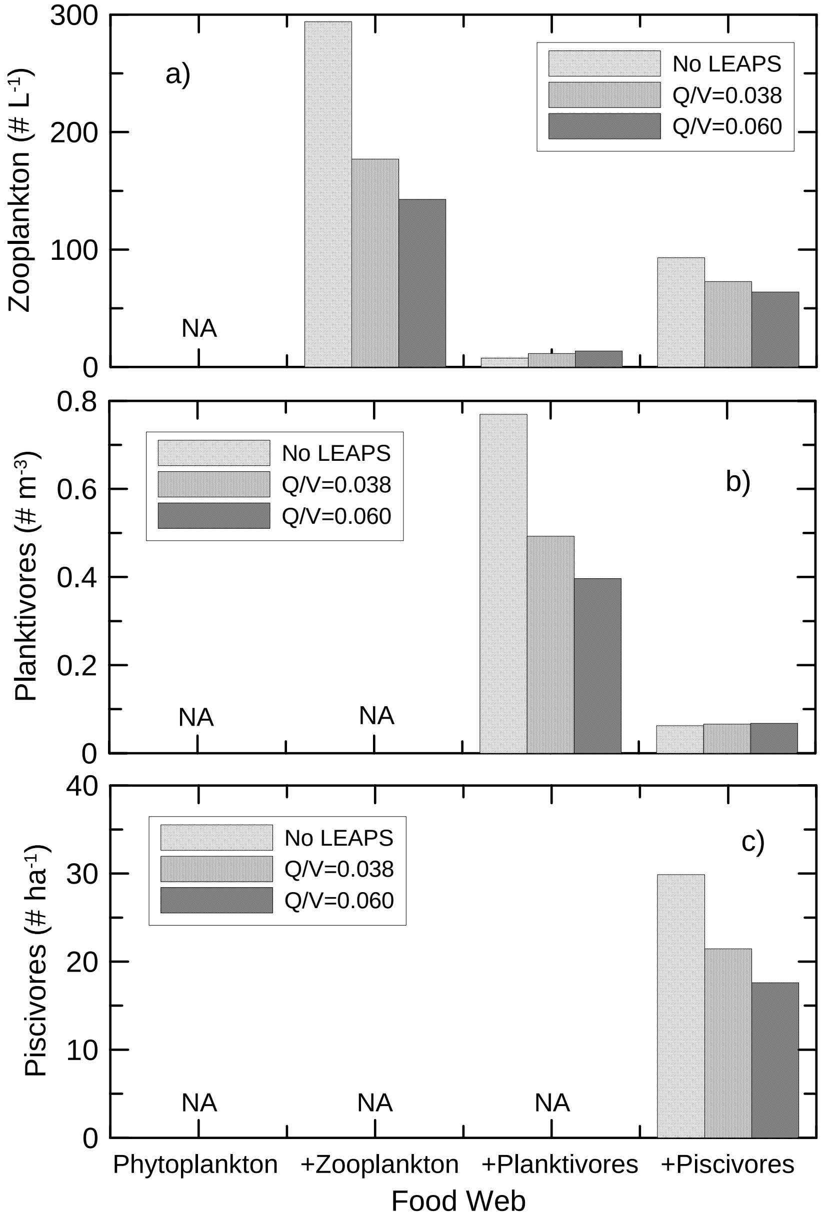

Fig. 3. Predicted a) zooplankton, b) planktivore and c) piscivore populations in Lake Elsinore for food webs of increasing complexity (from left to right). The natural condition (no LEAPS) and LEAPS operation at two relative pumping rates (Q/V) are shown. (Simple food webs lack the higher trophic levels, and so are represented as NA.)

One of the primary goals of the fisheries management plan is to maintain a viable sport fishery with piscivores capable of controlling planktivore (e.g., shad) levels in Lake Elsinore (EIP, 2004). Since algal levels are tied to planktivore abundance, piscivores would favorably shift the ecosystem to a zooplankton-rich food web with limited chlorophyll concentrations (↑ piscivores: ↓ planktivores: ↑ zooplankton: ↓ chlorophyll). The model suggests that piscivores could effectively control planktivore levels in the lake, and that would in turn help maintain a strong zooplankton community (Fig. 3) and help achieve low chlorophyll levels in the lake (Fig. 2b). LEAPS operation was predicted to affect the piscivore population and that effect cascaded through the food web, although the overall effect on chlorophyll levels was modest (Fig. 2b). It appears that the cumulative effect of entrainment and mortality to phytoplankton, zooplankton, planktivorous fish and piscivores tended to damp out slightly the trophic cascade through the food web.

Since transparency is probably the most useful index of the aesthetics and overall water quality in a recreational lake, predicted chlorophyll concentrations (Fig. 2b) were used to predict a mean Secchi depth (Z_{sd}) based upon the empirical equation developed by Veiga-Nascimento (2004). The equation was developed using 2001-2004 transparency and chlorophyll measurements (*Chl*) taken at Lake Elsinore, and is of the form:

$$Z_{sd}\ (m) = 47.48\ /[Chl\ (\mu g\ L\text{-}1) + 24.81] \qquad (6)$$

The time period from which this equation was developed represented generally very poor water quality (e.g., Secchi depths in all instances <1 m), so the equation is considered more accurate for higher chlorophyll levels. Notwithstanding, the simple ecosystem model (eqs 1-5), combined with eq 6, yielded transparencies <0.35 m for the algal-dominated (phytoplankton only) state, irrespective of LEAPS operation (Fig. 4). The presence of zooplankton yielded much improved Secchi depths (predicted transparencies of 1.6 – 1.75 m), while the presence of planktivorous fish, through the trophic cascade described above, resulted in a marked loss of water clarity (Fig. 4). Piscivores (including fish-eating birds, although they were not explicitly modeled in this analysis) were predicted to maintain transparencies that were 4-7x greater than the algal-dominated state and 2-3x that found for the planktivore-dominated food web.

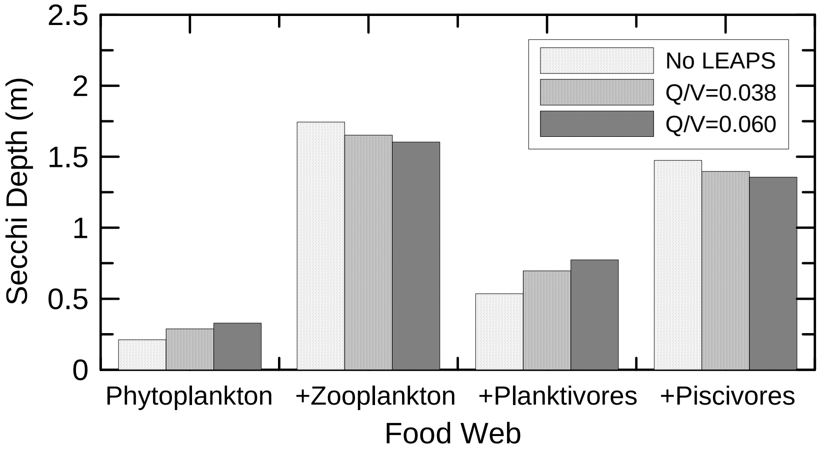

Fig. 4. Predicted Secchi depth in Lake Elsinore for food webs of increasing complexity (from left to right). The natural condition (no LEAPS) and LEAPS operation at two relative pumping rates (Q/V) are shown.

The effect of LEAPS on predicted transparency is more subtle than that of the food web composition and alternately improves or worsens Secchi depth depending specifically how the food web is terminated. Food webs that directly or indirectly favor zooplankton production (and algal consumption) were negatively impacted by LEAPS operation, although predicted reductions in Secchi depth were <10%. The effect of LEAPS operation on those food webs that favored algal production (*e.g.*, phytoplankton-only or the food web terminated with planktivores) were predicted to actually benefit from the entrainment and mortality of these organisms, although transparencies were predicted to increase only about 0.1 – 0.2 m.

A reasonable question, then, is which food web best represents Lake Elsinore? An incomplete picture of the lake’s food web persists at present; in particular, little information is available concerning the abundance of threadfin shad (*Dorosoma petenense*). Previous die-offs indicate that shad populations have, at times, been extremely large, and threadfin shad are thought to be the most abundant fish in Lake Elsinore (EIP, 2004). A die-off in 1998, in which an estimated 8 – 12 million shad died, indicates that the population at that time was at least 0.1 – 0.2 shad m^{-3}.

Notwithstanding the lack of information about the threadfin shad population, mark-and-recapture and other efforts over the past few years have provided valuable information about the fishery of the lake. What is clear from these efforts is that the food web in Lake Elsinore has varied quite substantially in the recent past, with a cladoceran-deficient zooplankton community (Veiga-Nasciemento, 2004) and carp-dominated fishery present in 2003-2004 (EIP, 2004). This was replaced by a more diverse food web following the winter storms in 2005. The food web in 2005 and 2006 included abundant *Daphnia* and other beneficial zooplankton (unpubl. data), as well as crappie, catfish and other (generally piscivorous) sport fish (Kilroy, pers. comm.).

This natural variation in the ecology of Lake Elsinore thus makes it difficult to focus on a single food web and the effects of LEAPS on that ecosystem structure. One could argue that in 2003-2004, the food web may have been best described as the simple algal ecosystem with no meaningful higher trophic levels (benthivorous carp, while abundant, would not generally be considered strong planktivores nor piscivores but would help fuel internal loading of nutrients). Anecdotal evidence suggests that the shad population may have been low during this time period based upon the absence of large-bodied zooplankton and the limited numbers of fish-eating birds relative to those present in 2001 or 2005-2006. The high levels of salinity at that time were demonstrated in laboratory studies to limit reproduction and induce direct mortality of *Daphnia* and *Ceriodaphnia* (Veiga-Nascimento, 2004). Moreover, the phytoplankton community that was dominated by *Oscillatoria* at that time (Oza, 2003) would have also clogged daphnid feeding-filtering apparatus and thus served as a very poor food resource (Infante and Abella, 1985). The levels of salinity present in the lake would have also been high enough to inhibit successful reproduction of many species of freshwater fish. (Note that the ecosystem model developed above does not explicitly account for such factors, and thus is valid only for conditions that can support natural zooplankton and fishery reproduction, with a suitable phytoplankton community to serve as a food resource for zooplankton in the lake.)

The more recent conditions in Lake Elsinore, that include much higher lake levels and substantially reduced salinities (Lawson and Anderson, 2005), are thought to have provided conditions more favorable for reproduction of zooplankton and fish. This seems to be borne out where, as mentioned above, much higher *Daphnia* populations, combined with large numbers of young catfish, crappies and other sport-fish are now found in the lake. A vast number of fish-eating birds were observed through the past 2 years, with piscivorous bird densities approaching an estimated 200 ha^{-1} in the open water some winter mornings. This implies a large abundance of small fish, likely shad (which favor open water), that would also be subject to intense predation. It seems reasonable to conclude that the food web for 2005-2006 most closely resembles the full food web with phytoplankton, zooplankton, zooplanktivores and piscivores (both sport fish and birds).

Qualitatively, then, the model does not seem out of line in terms of its predictions. 2003-2004 was in fact characterized by very poor water quality, with chlorophyll routinely exceeding 100 $\mu g\ L^{-1}$ and averaged somewhere near 200 $\mu g\ L^{-1}$ and Secchi depths that averaged 20-30 cm (Veiga-Nascimento, 2004). These values are in rather surprisingly good agreement with model predictions for the phytoplankton based food web (Fig.2 and 4, respectively), although this is no doubt partly serendipity. The more recent water quality condition at the lake appears to be reasonably represented with the full food web; predicted transparencies near 1.5 m (Fig. 4) are broadly consistent with measured values in 2005 and 2006 (1 – 2 m), although recent values indicate poorer water quality is returning (Secchi depths ~0.5 m). Chlorophyll values were generally 2-4x higher in 2005-2006 than that predicted by the model however (Lawson and Anderson, 2006).

Importantly, the effect of LEAPS operation on predicted water quality is small compared with the predicted (and observed) sensitivity of water quality to the structure of the food web. Thus, against a backdrop of a strongly varying ecosystem and dramatic variations in water quality, it is difficult to conclude that LEAPS operation will have a profound influence on the ecology and resulting water quality in the lake. Moreover, as noted previously, depending upon the particular food web in place, LEAPS operation may, albeit modestly, alternately improve or degrade water quality.

Assuming however, that improved control of lake level, salinity and other factors can maintain a functional phytoplankton-zooplankton-planktivore-piscivore food web, LEAPS operation would modestly negatively impact piscivore and zooplankton populations in the lake that would yield slightly higher chlorophyll concentrations and lower transparencies (Figs. 2-4). The use of a filter curtain would reduce entrainment of all planktonic organisms as well as some nekton. Simulations were thus conducted assuming exclusion and reductions of entrainment of larval fish by 80% and zooplankton by 50% following Anderson (2006). Entrainment of phytoplankton was assumed to be reduced more modestly (20%).

The installation of a filter curtain benefited overall water quality relative to LEAPS operated without the benefit of entrainment control. At an average relative pumping rate of 0.038 d^{-1} (corresponding to the daily pumping rate averaged over a weekly cycle that included off-time on Sunday at the nominal upper operating elevation of 1247 ft above MSL), use of a filter curtain lowered predicted chlorophyll concentrations by 11% and planktivore abundance by 6% (Table 2).

Table 2. Predicted steady-state lake properties with LEAPS operation with and without a filter curtain to limit entrainment.

Property	**Q/V=0.038**	**Q/V = 0.038 + Curtain**	**Q/V = 0.060**	**Q/V = 0. 060 +Curtain**
Chlorophyll (μg L^{-1})	9.2	8.2 (-11%)	10.2	8.6 (-15%)
Zooplankton (# L^{-1})	72.7	82.8 (+14%)	63.9	77.6 (+21%)
Planktivores (# m^{-3})	0.066	0.062 (-6%)	0.068	0.062 (-9%)
Piscivores (# ha^{-1})	21.4	25.6 (+20%)	17.6	23.4 (+33%)
Secchi depth (m)	1.40	1.44 (+3%)	1.36	1.42 (+4%)

At the same time, the filter curtain increased zooplankton populations by 14% and piscivore levels by 20%. The effect was more pronounced at the higher relative pumping rate (corresponding with LEAPS operation at 1240 ft above MSL) (Table 2). Use of the filter curtain appears to offer the greatest benefit to the piscivores (and thus also the sport fishery). Food webs terminated with either phytoplankton or planktivores would experience a moderate decrease in water quality through the use of a filter curtain, however.

2. EFDC Simulations of Entrainment Potential Near Intakes

EFDC simulations were previously conducted to quantify the effects of LEAPS operation of thermal stratification, mixing and potential for sediment resuspension in Lake Elsinore (Anderson, 2007). In this analysis, the drifter subroutine in the EFDC model was activated to better understand the effects of LEAPS operation at the Santa Rosa and Ortega Oaks sites on the entrainment of planktonic organisms. Simulations were conducted in which neutrally buoyant particles were released at site E2 (near the center of the lake) in the 2nd computational layer from the top (about 2 m depth) and their positions recorded every 2 hours over a 15 day simulation period. The particles were thus moved due to advective motion set up by wind-forcing, from convective flows due to heating and cooling and, when LEAPS was in operation, due to flows induced by pumping and generation at the Santa Rosa or Ortega Oaks sites.

There is a certain randomness to the observed trajectories, because the particular time, depth and location of release will move particles in vastly different ways, so the observed trajectories represent only 1 realization in an infinite range of paths and thus do not have any unique relevance. However, since all particles were released at the same time and location, the deflection in the particle trajectory can be attributed to LEAPS operation.

One example of such trajectories is provided in Fig. 5. Without LEAPS operation, the particle drifted in a clockwise direction near the center of the lake. The particle traveled a total of 8.96 km over the 15 days, thus yielding an average velocity of approximately 0.7 cm s^{-1}. Release of a particle at the beginning of the pumping cycle during LEAPS operation at the Santa Rosa site did yield a different trajectory, with movement in a more counter clockwise direction, although the particle remained near the center of the lake. The particle was transported a greater distance (12.67 km) at an average velocity of 1.0 cm s^{-1}, but was not entrained during pumping.

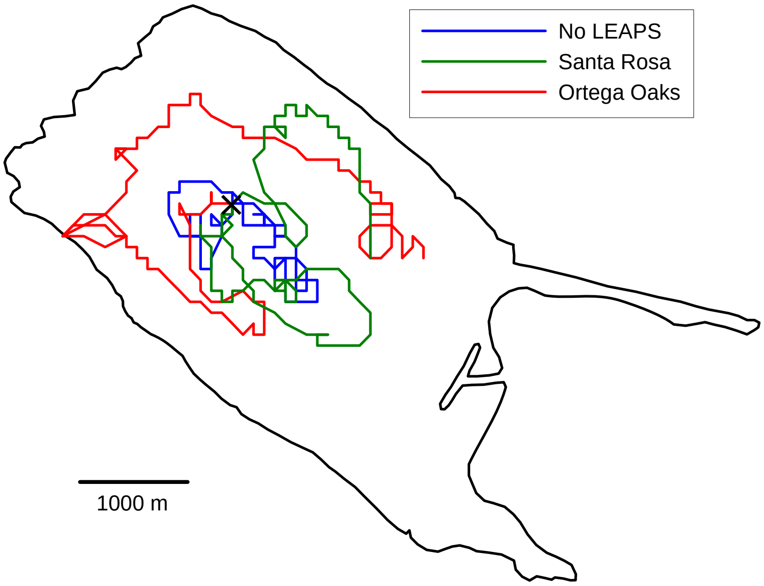

Fig. 5.Predicted 15-day drifter trajectories following release at site E2 (shown with an X), comparing the natural trajectory with those resulting from LEAPS operation at the Santa Rosa and Ortega Oaks sites.

Release of a particle during LEAPS operation at the Ortega Oaks site yielded greater total transport (14.76 km) and at a higher mean velocity (1.1 cm s^{-1}) (Fig. 5). More importantly, the particle was drawn into the intake on 2 separate events. Thus, advective currents transported the particle into the capture zone during a pumping cycle, the particle was then discharged during generation, and drawn back in during a 2nd pumping cycle before successfully migrating beyond the capture zone of the intake during pumping. Fig. 5 suggests that the capture zone extends about 600 – 800 m from the intake.

This was evaluated more rigorously for the Santa Rosa site by release of particles at grid locations extending at least 1200 m from the intake during the pumping cycle at the end of the week. This represents the largest drawdown and thus offers the greatest opportunity for entrainment. The median operational lake level of 1243.5 ft about MSL was used for the simulations with the meteorological condition the same as that used for previous velocity predictions near the intakes (Anderson, 2007). Trajectories were evaluated to determine whether entrainment from that initial location was observed. The radius of entrainment was then mapped (Fig. 6).

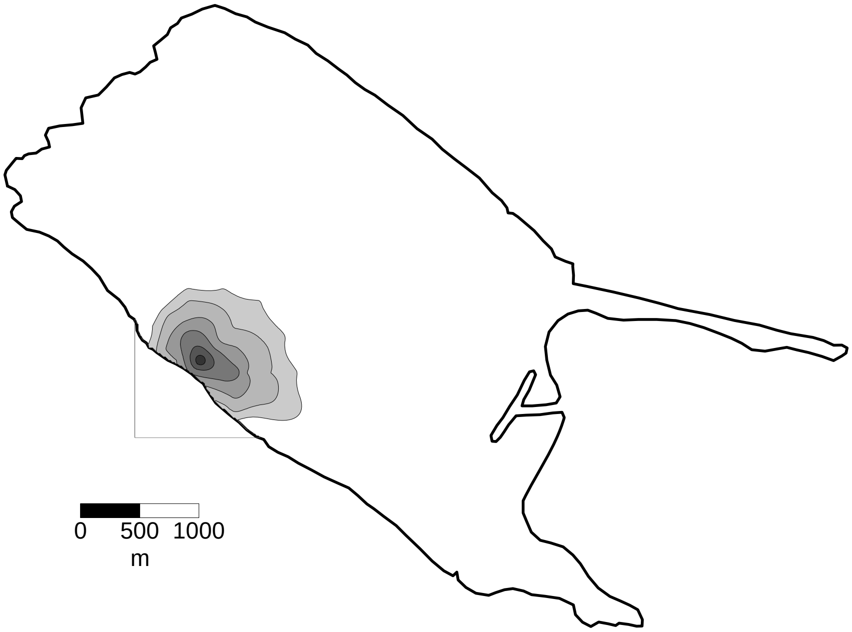

Fig. 6. Predicted capture zone during maximum pumping at the Santa Rosa site.

The entrainment or capture zone during maximal pumping was found to extend out 870 m in a perpendicular direction to the intake and up to 1500 m laterally (Fig. 6). The entrainment area comprised about 208 acres or 6.6% of the lake area. A smaller area would be expected during weekday pumping since the volume of water pumped is lower. Although not explicitly evaluated, broadly similar findings would be expected for the Ortega Oaks site based upon previous predictions of velocity profiles and bottom shear for the 2 sites (Anderson, 2007).

Summary

A simple linear food web model was developed for Lake Elsinore to evaluate potential trophic cascades as a result of entrainment of planktonic organisms during LEAPS operation. The model assumed phosphorus was the limiting nutrient in the lake and supplied to the water column through internal recycling. Biologically-available phosphorus was available for uptake by phytoplankton assuming Monod kinetics, with phytoplankton subject to losses due to zooplankton grazing and due to settling. Zooplankton population growth was in turn dependent upon phytoplankton availability, predation by (zoo)planktivores that included larval, juvenile and adult forms, and an additional mortality term due to non-grazing losses. Planktivore growth was taken as a linear function of predation rate and zooplankton abundance, while predation by piscivores and additional mortality terms were used to define loss. Piscivore populations were a function of planktivore (prey) availability and natural mortality rate. The effects of LEAPS operation were included in additional simulations through incorporation of entrainment and mortality.

Since available information about the food web in Lake Elsinore indicates that substantial variation has existed over the past several years, separate simulations were conducted for food webs terminated with phytoplankton, zooplankton, planktivores and piscivores. The effects of LEAPS operation on population dynamics and water quality for each of the different food webs was assessed at relative pumping rates of 0.038 and 0.060 d^{-1}.

The simple ecological model demonstrated that the structure of the food web will have a dramatic effect on water quality in Lake Elsinore, an effect that outweighs that due to LEAPS operation. High chlorophyll concentrations and low transparencies were predicted for a phytoplankton-dominated food web (that may include a large population of benthivorous fish such as carp). A theoretical food web terminated with zooplankton was predicted to have excellent water quality, although such a food web is found in nature only under very unusual circumstances. A food web terminated with zooplanktivores was predicted to have poor water quality due to excessive predation on large-bodied zooplankton that would allow algal levels to build up to substantial levels. The presence of piscivores, however, was predicted to yield very low chlorophyll concentrations and high transparencies.

LEAPS operation (without filter curtains or other provisions for limiting entrainment) was found to lower slightly predicted water quality in food webs terminated with zooplankton or piscivores, although the effect overall was modest. Conversely, LEAPS operation was predicted to improve somewhat the water quality for food webs terminated with phytoplankton and zooplantivorous fish due to entrainment and enhanced mortality of these organisms.

Use of a filter curtain was predicted to improve water quality and ecosystem health for a full food web that included sport fish and other piscivores, with chlorophyll levels declining by up to 15% and sport fish abundance increasing by up to 33% relative to LEAPS operation without efforts to control entrainment.

Three-dimensional EFDC simulations indicate that pumping can alter the trajectory of planktonic species in the lake, with planktonic organisms within 750-870 m radius of the intake, or about 6.6% of the lake area, susceptible to entrainment during pumping.

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