CARBON CYCLE DISRUPTION WHITE PAPER

INTRODUCTION

The Sacramento Municipal Utility District (SMUD) and Pacific Gas and Electric Company (collectively referred to as the "Licensees") are in the process of preparing applications to obtain new licenses for two existing hydroelectric projects on the South Fork American River (collectively referred to as the "Projects"). The Projects include the Upper American River Project, for which SMUD holds the existing license, and the Chili Bar Project, for which Pacific Gas and Electric Company is the existing licensee. SMUD and Pacific Gas and Electric Company each intend to file an application for a new license with the Federal Energy Regulatory Commission for its project by July 2005.

The Licensees have agreed that the combined operation of the UARP and Chili Bar Project might overlap to the extent that the Projects cause cumulative effects to environmental resources in Chili Bar Reservoir and in the 19.1-mile-long section of the South Fork American River known as the Reach Downstream of Chili Bar, which extends from Chili Bar Dam to the normal high water line of Folsom Reservoir, which is owned and operated by the U.S. Bureau of Reclamation as part of the Central Valley Project. Therefore, the Licensees are coordinating their discussions with federal and state agencies and other parties interested in the relicensing of the UARP and Chili Bar Project.

One such coordinated effort pertains to information regarding potential carbon cycle disruption. In early 2004, the Aquatic Technical Working Group (TWG), which was formed by the UARP Relicensing Plenary Group, requested that the Licensees prepare a "white paper," based solely on a literature review, to provide a general overview regarding how an impoundment might affect the natural carbon cycle in a river. Specifically, the TWG was interested in Chili Bar Reservoir. The TWG asked that Pacific Gas and Electric Company include in the white paper information regarding current collection and disposal of woody material in Chili Bar Reservoir.

This white paper, prepared by Devine Tarbell & Associates, provides the information regarding the carbon cycle requested by the Aquatic TWG. Specific guidance was provided by Stafford Lehr of the California Department of Fish and Game, a member of the Aquatic TWG, through direct communication with DTA staff on July 21 and August 9, 2004. Mr. Lehr requested that the white paper provide a general review of the terrestrial and aquatic carbon cycling, impacts of creating a reservoir on carbon storage and transport as it relates to the River Continuum Concept, Flood Pulse Theory and Serial Discontinuity. Additionally, Mr. Lehr requested that the white paper examine carbon cycling disruptions within the riverine, transition and lacustrine zones of a reservoir, as well as the influence of water level fluctuation on dissolved carbon transport.

Information from Pacific Gas and Electric Company regarding current collection and disposal of woody material in Chili Bar Reservoir is included in Appendix A of this white paper. Similar information from SMUD regarding Slab Creek Reservoir is included in Appendix B.

GENERAL REVIEW OF CARBON CYCLES

As one of the most abundant elements in the universe, carbon (C) provides the structural basis for life. Carbon exists in various forms, which include inorganic carbon, found in both sedimentary rocks and gaseous forms, and in a reduced state, as organic carbon, found in living organisms, soil humus, and fossil fuels. The global carbon cycle refers to the movement of carbon from one form to another and various associated pathways. Carbon can be cycled completely within a terrestrial setting or an aquatic setting, or within both. Often the carbon cycle is discussed and demonstrated as two distinct cycles occurring in terrestrial or aquatic settings, and as such, is discussed separately below.

The Terrestrial Carbon Cycle

The key natural processes involved in the movement of carbon through terrestrial ecosystems include photosynthesis, respiration, volcanic activity, and combustion of fossil fuels. In these natural processes, carbon transfer occurs predominantly in the atmosphere where carbon dioxide (CO_2) is released as a result of aerobic respiration, volcanic activity, or fossil fuel combustion. Carbon dioxide is then converted to organic carbon through photosynthesis and incorporated in vegetative matter, which then decomposes and is released into the atmosphere via aerobic respiration, or is consumed and incorporated into higher life forms creating a self-perpetuating cycle.

The greatest concern regarding man-made disruption of the terrestrial carbon cycle relates to the abundance of carbon dioxide and methane ($CH4_4$) released as byproducts of human activity, most notably, the burning of fossil fuels. This concern is based on the concept that there is a finite amount of carbon on Earth and the burning of fossil fuel by man alters the natural balance of carbon because “trapped” carbon is being released. It has been suggested that, at one time, more carbon was sequestered in carbon “sinks,” and with recent historical consumption of fossil fuels by man, unprecedented quantities of carbon are being released into the atmosphere, contributing to an overall greenhouse effect. However, the effect of greenhouse gas emission on the environment is a complex issue in itself, and will not be specifically developed further in this white paper.

The Aquatic Carbon Cycle

Carbon cycles through aquatic ecosystems primarily through photosynthesis, respiration, and to a lesser degree, weathering of sedimentary rock. However, almost all of the organic carbon on earth is created through photosynthesis, whether on land or in water (Ludwig 2001).
Inorganic forms of carbon found in marine sediments and sedimentary rocks include bicarbonate and carbonate. These two forms of inorganic carbon comprise the majority of the Earth’s carbon supply. Inorganic forms of carbon strongly affect the acidity of natural waters, the heat insulating capability of the atmosphere, and the rates of such key natural processes as photosynthesis, weathering, and biomineralization (NSF 2000).

One of the greatest natural inputs of organic carbon into the hydrosphere principally occurs via rivers emptying into the world's oceans. The major biogeochemical role of river systems in the global carbon cycle has commonly been considered to be the fluvial export of total organic carbon and dissolved inorganic carbon to the oceans (Chen 2002). Dissolved organic carbon in the oceans is one of the biggest reservoirs of carbon, and is comparable in size to all of the carbon in terrestrial plants, or to all of that in the form of carbon dioxide in the atmosphere (Ludwig 2001).

In any aquatic ecosystem, a number of sources may contribute to storing and subsequent transfer, of organic matter, or carbon. In this white paper, we focus only on carbon sources within lotic and lentic ecosystems. Sources may include imports into the system via upstream ecosystems, soil organic matter and terrestrial litter, and, to a lesser degree, in-system suspended or attached algae.

Within riverine ecosystems, organic matter is present in the form of coarse particulate organic matter (CPOM), fine particulate organic matter (FPOM), and dissolved organic matter (DOM). CPOM measures greater than 1 millimeter (mm) in size and consists of woody debris, leaves, needles, and foliage of terrestrial and aquatic vegetation. FPOM measures between 0.5 nanometers to 1 mm in size and consists of fragmented pieces of CPOM, imported terrestrial and wetland organic matter, and aggregated dissolved organic matter. Lastly, DOM measures less than 0.5 nanometers in size and consists of dissolved and colloidal organic matter.

THE EFFECT OF RESERVOIRS ON CARBON CYCLING

River Continuum Concept

The River Continuum Concept was synthesized to serve as a framework for describing the function of lotic ecosystems from source to mouth, and accommodate the variations among sites that results from differences in their terrestrial settings (Vannote et al. 1980). The physical basis of the River Continuum Concept is size and location along the gradient from tiny ephemeral brooks to large rivers (Allen 1995).

Though historically natural lakes and man-made lakes (reservoirs) have been viewed as separate from the river, under current ecological views, they are one in the same. A lake or reservoir is considered as one part of a complex system that includes headwaters, small creeks, floodplains, wetlands, and the entire catchment of the watershed associated with the river system.

Damming of a river to form a reservoir can change the characteristics of the river system, not only affecting hydrology but also influencing physical, chemical, and biological characteristics of the river system. The extent of the change is often dependent on the size of the reservoir (larger reservoirs that capture most of the upstream flow typically have a greater effect) and the location of the reservoir in the river. Changes can include an increase in residence time, changes in water temperature, stratification, and reduction in turbulence. Together, these changes can affect the carbon cycle by decreasing particulate matter and turbidity, and sometimes increasing autochthonous primary production (Friedl and Wüest 2002).

Deep reservoirs can experience oxygen depletion, particularly in the deeper areas of the impoundment. Within lacustrine portions of reservoirs, *in-situ* produced particles settle to the sediment and consume oxygen. Increased biological oxygen demand (BOD) and thermal stratification may reduce the exchange between the sediment surface and hypolimnion, eventually leading to anoxic (lack of dissolved oxygen) conditions (Wetzel 2001). The depletion of oxygen triggers reduction of nitrate, manganese, and iron hydroxides and oxides, as well as the production of sulfates. The accumulation of these reduced compounds keeps the sediment/water interface anoxic (Friedl and Wüest 2002). Under anoxic conditions, microbial methanogenesis and denitrification lead to the production and potential emission of greenhouse gases, carbon dioxide and methane. While both carbon dioxide and methane are considered greenhouse gases, the adverse climate impact of a unit weight of methane is 21 times greater than that of carbon dioxide (Neumann-Silkow Undated).

Alteration to the carbon budget can also be seen in unimpounded portions of highly segmented and regulated systems. When a dam enhances water clarity and reduces the variability of flow, there is often a greater abundance of periphyton or higher vascular plants below the dam than is found elsewhere in the river (Allan 1995). Net primary production of periphyton can range from 0.01 to almost 20 $gCm^{-2}d^{-1}$ (Allan 1995). Periphyton production within a system containing a series of dams may lead to substantial inputs to the particulate detritus pool. While allochthonous inputs are reduced within the riverine and transition zone, leading to a potential nutrient poor environment, the production of periphyton often serves as a downstream source of carbon and nutrients for the riverine zone of the next reservoir complex downstream.

Changes in nutrient cycling and food availability resulting from alteration of flows and fluctuating water levels, can be seen as shifts in biotic communities as well as ecological processes. In an unimpounded system, based on Vannote et al's (1980) River Continuum Concept, one would expect to see a natural shift in invertebrate composition from upstream to downstream. In headwater areas (stream orders 1-4), the benthic community would be dominated by organisms associated with the collector and shredder trophic guilds. In stream orders 5-8, the benthic community would normally exhibit a shift from shredders and collectors to collectors and grazers. While in stream orders greater than 8, the invertebrate community normally would be dominated by collectors and predators. A series of dams may disrupt this continuity. Based on the Serial Discontinuity Theory, Ward and Stanford (1983) proposed that rivers have an innate tendency to reset ecological conditions toward natural or unregulated conditions as distance downstream from the dam or point of regulation increases.

Below a dam, the benthic community often shows a reduction in species richness but an increase in overall abundance of invertebrates (Allan 1995). Therefore, the benthic community below a dam of a mid- order river would likely exhibit characteristics of a low order stream. As distance increases from a dam, the benthic community begins to exhibit shifts toward a composition that would likely be present with a stream of a given order. However, approaching the headwaters of the next reservoir system, the benthic community begins a shift from a lotic environment towards a lentic environment. By the very nature of changing a free-flowing system to an impounded system, it would be expected that the benthic community would change. It is well understood that many benthic invertebrates rely on the presence of CPOM and FPOM for both a direct and indirect source of energy. Therefore, it is plausible, depending on the configuration of a dam, to impact the benthic macroinvertebrate community directly below the dam.

Flood Pulse Theory

Many river systems routinely flood riparian areas. The Flood Pulse Theory (Junk et al. 1989) describes a process in which nutrients are regularly exchanged between the river and the flood plain. The ecological characteristics and productivity of both the river and the flood plain are linked and influenced by the frequency and duration of flood events.

Inundation changes the availability and capacity of the flooded area to contribute and sequester carbon through a reduction in the intensity and duration of flooding periods, which has been shown to reduce the input of all forms of organic matter to the river (Junk et al. 1989). However, immediately following the creation of an impoundment, organic biomass is often abundant in the flooded area in the form of flooded forests, wetlands, and fertile floodplains. The decomposition of recently flooded organic matter in shallower parts of reservoirs, particularly within the riverine zone and transition zone, lead to the production and release of methane and carbon dioxide, which can last up to 20 years in tropical systems, and even longer in northern climates (Friedl and Wüest 2002). The vegetative matter prior to inundation served as a local carbon sink, while after inundation the vegetative matter decomposes and is released into the reservoir, resulting in a net gain in available carbon in the river system. However, this same vegetation breaks down and releases carbon dioxide and methane. The increased BOD caused by this decay and other activities associated with surrounding land use may cause anoxic conditions in deep reservoirs, which may foster the release of additional methane. Flooded wetlands and peatlands might emit less methane after being flooded with oxygen-containing water because methane may get converted to carbon dioxide within the water column (Friedl and Wüest 2002). The latter is more likely to occur in deep waters where methane undergoes efficient microbial oxidation to carbon dioxide (Friedl and Wüest 2002).

Water Level Fluctuations

Recent work by Tietjen and Schlickeisen (2004) suggests that water level fluctuations in response to hydropower demands add additional complexity to carbon sequestration and transport both within a fluctuating reservoir and downstream by disrupting the natural accretion and decay of deposited organic matter. Drawdown phases further enhance the complexity by exposing previously inundated shoreline, in many cases allowing for regeneration of vegetative matter, adding to a perpetual cycle of adding organic carbon to the system, only to have it act as a source of free carbon. In addition to the complexities associated with fluctuating reservoir levels, peaking flows appear to have an impact on downstream transport of dissolved organic carbon (Tietjen and Schlickeisen 2004). Not only is dissolved organic carbon affected, CPOM and FOM are also susceptible to being flushed from the system.

SUMMARY

Our efforts did not identify any scientific studies regarding carbon cycle disruption that have been performed at specific new or existing reservoirs. We postulate that one reason for this is that carbon cycling is very complex and not completely understood, which renders any specific studies questionable. In addition, the changes that might occur are likely very specific to the river system, reservoir and the timing of such a study. A further difficulty arises when one attempts to integrate potential carbon cycle effects with ecological, biological and anthropogenic changes. Without historical data on pre-impoundment conditions and a comprehensive understanding of the carbon cycle prior to the construction of a dam and how carbon cycling changes with changing climatic and hydrologic conditions, it would be extremely difficult to determine a precise causal relationship between a specific dam and its effect on carbon cycling in the river.

However, the scientific literature does postulate a theoretical relationship between the formation of reservoirs and carbon cycle. The effect to the carbon cycle is likely greater for larger reservoirs that substantially affect hydrology, have long retention times, and become anoxic than smaller reservoirs that spill often and have high oxygen saturation. In theory, when a reservoir is formed, carbon trapped in flooded vegetation is released into the reservoir and downstream, which can continue to occur for many years. In contrast, particulate matter that enters the reservoir settles to the bottom, reducing carbon in the system. If the reservoir is anoxic, methane can be produced in the bottom of the reservoir. However, if the reservoir is relatively clear and some nutrients are available, carbon in the system is used by phytoplankton, resulting in increased carbon dioxide.

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APPENDIX A

CHILI BAR RESERVOIR & COLLECTION AND DISPOSAL OF WOODY DEBRIS

Based on recent bathymetric investigations, Chili Bar Dam has a gross storage capacity of about 2,128 acre-feet (ac-ft) of water and a usable capacity of 1,088 ac-ft. Under regulated conditions, Chili Bar Powerhouse typically begins to ramp up as water is released from SMUD's White Rock Powerhouse, located at the upstream end of Chili Bar Reservoir, and ramps down when inflows from White Rock Powerhouse decrease and Chili Bar Reservoir water level begins to decrease. The reservoir surface typically fluctuates daily by about 8 feet, usually between elevation 990 feet and 998 feet. Water is released downstream from Chili Bar Dam through a 14-foot-diameter intake to the power tunnel that supplies water to the Chili Bar Powerhouse located at the downstream base of the dam. Water may also be released from the dam through a 10-foot diameter tunnel equipped with a synchronous bypass valve, or it may spill over the 170-foot wide spillway. Pacific Gas and Electric Company normally does not draw Chili Bar Reservoir down below an elevation of 984 feet. The power tunnel/powerhouse has a maximum capacity of 1,979 cfs when Chili Bar Reservoir is at full pool (El. 997.5 feet, the spillway invert elevation).

Flows into Chili Bar Reservoir can vary considerably, even within a day, depending on the natural flow in the river and operation of the UARP White Rock Powerhouse. When White Rock Powerhouse is not operating, inflow to the reservoir can be as low as about 50 cfs. When the powerhouse is operating at full capacity, inflows to the reservoir can be up to about 3,800 cfs. Outflow from Chili Bar Reservoir also can change considerably within a day, often times ranging from 200 cfs to 1,800 cfs. This combination of small reservoir size and variable outflows generally results in a short reservoir retention time (as long as about 1 week if inflow is about 50 cfs, and as short as a half day if inflows are about 3,800 cfs).

Chili Bar Reservoir is polymictic: that is, it never has an ice cover, does not stratify, and mixes freely. Even in low summer flow conditions, water temperature varies by only a few degrees from the surface to the bottom of the reservoir (3° C in 2003, from about 17° C on the surface to 14° C near the bottom). As a result, Chili Bar Reservoir is well oxygenated. During the Licensees' sampling in 2002 and 2003, dissolved oxygen ranged from 10.03 to 10.95 mg/l (95.8 to 102.6% saturation). The Licensees' 2002 and 2003 studies also found that biostimulatory substances were in low concentrations in Chili Bar Reservoir, and Total Organic Carbon ranged from 1.2 to 1.6 mg/l. (Licensees' Water Quality and Water Temperature technical reports.) The Licensees did not observe any wetland areas along the margin of Chili Bar Reservoir (Licensees' Riparian Vegetation and Wetlands Technical Report).

Woody debris that enters Chili Bar Reservoir, typically during natural high flow events in the spring, usually passes over the Chili Bar Reservoir spillway in spite of the upstream log boom, which captures floating material at lower inflows. Material that does not pass over the spillway accumulates on the trash racks in front of the turbine inlet or bypass pipe, or in front of the floating log boom. Pacific Gas and Electric Company routinely monitors the trash racks and the log boom. If a substantial amount of material is observed, it is collected from the log boom and removed from the trash racks using a manually operated trash rake. The removed material is temporarily deposited on the dam near the trash racks until enough is piled to fill a pick-up truck. The debris is then transported to the north side of the reservoir northeast of the boat ramp.

Pacific Gas and Electric Company reported that, prior to the heavy flows in January 1997, Pacific Gas and Electric Company removed about 5 or 6 pick-up truck loads of debris (typically small to medium sized pieces) annually from the trash racks and log boom. Since January of 1997, Pacific Gas and Electric Company has removed about 2 pick-up truck loads of debris annually. Given this small amount of material, Pacific Gas and Electric has not disposed of the debris pile by the boat ramp for about 10 years. When it accumulates to a large enough volume, it will likely be burned as was done in the past. Pacific Gas and Electric also reported that Operations Staff does not observe much debris floating in the reservoir, except following very high flows if high flows have not occurred for several years.

APPENDIX B

SLAB CREEK RESERVOIR
COLLECTION AND DISPOSAL OF WOODY DEBRIS

SMUD reports that woody debris floating in Slab Creek Reservoir is corralled by a floating log boom located immediately upstream of the dam. The material is moved by boat to the Slab Creek Reservoir boat ramp. There, heavy equipment operators use an excavator and dump truck to remove the wood and take it to one of the approved Forest Service slash piles, where it is dumped for future burning. The amounts vary considerably based upon how severe the winter storms are and how much deadwood is captured in the spring run off.