Ecological Applications, 11(3), 2001, pp. 644–656

EXPERIMENTAL FLOOD EFFECTS ON THE LIMNOLOGY OF LAKE POWELL RESERVOIR, SOUTHWESTERN USA

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Abstract. In the spring of 1996, a nine-day test flood from Glen Canyon Dam involved the deepest and largest hypolimnetic withdrawals from the penstocks and the river outlet works (ROW) since 1986, interacting with ongoing hydrodynamic and stratification patterns to enhance freshening of the hypolimnion of Lake Powell reservoir and its tailwaters. Prior to the test flood, a six-year drought had produced a pronounced meromictic hypolimnion that was weakening from high inflow events in 1993 and 1995. Hypoxia, however, had continued to increase in the deepest portions of the reservoir. Over the course of the test flood, 0.893 km^3 were released from the ports located at and below the hypolimnetic chemocline. The increased discharge and mixing resulting from the test flood diminished the volume of this hypoxic and meromictic hypolimnion as far as 100 km uplake. This effect was reinforced by seasonal upwelling of hypolimnetic water at the dam and seasonal hydrologic patterns uplake. The timing and magnitude of the discharge maximized the release of the highest salinity and lowest dissolved oxygen (DO) water that typically occurs near the release structures of the dam annually. Subsequent high inflows and discharges in 1997 continued to freshen the hypolimnion.

During the flood, large aerated discharges in the tailwaters briefly increased DO to above saturation but dampened diel fluctuations in pH and DO. Downstream ion concentration levels were elevated during the test flood but resumed an enhanced freshening trend following the lower hydrograph. The results indicate that dam operations, timed with predictable limnological events, can be used to manipulate tailwater and reservoir water quality.

Key words: Colorado River; dam operations; experimental flood; Glen Canyon Dam; hydrodynamics; hypolimnion; hypoxia; Lake Powell; limnology; meromixis; multiple level withdrawal; reservoir; stratification.

INTRODUCTION

The use of dam operations as a variable to manipulate and experiment with reservoir and riverine systems is in its infancy. It is one element that differentiates reservoirs from natural lakes. In addition, reservoirs differ limnologically from natural lakes in their young age, their elongate and dendritic morphology, and because of the diversity of dam design, discharge patterns, and their typically sub-thermocline releases (Ryder 1978, Kennedy et al. 1982). These characteristics often limit the application of limnological theory derived from natural lakes to reservoirs (Kennedy et al. 1985, Thornton et al. 1990); and the great diversity of pattern and processes in reservoirs, as well as an incomplete state of knowledge, has restricted comprehensive predictive modeling of reservoir limnology. This has resulted in an individualistic management strategy for most reservoirs. The use of a large flood release from a dam allows a test of the effects on the limnology and productivity of both the upstream reservoir and the downstream river ecosystems (Ward and Stanford 1983). Thus, large reservoir discharge experiments may be used to improve the general understanding of reservoir limnology as well as refine strategies to improve reservoir management. In this paper we report on the impacts of a large experimental dam release on the limnology of Lake Powell, one of the largest reservoirs in the United States, and the Glen Canyon Dam (GCD) tailwaters downstream.

Manuscript received 22 April 1998; accepted 10 March 2000; final version received 25 July 2000. For reprints of this Invited Feature, see footnote 1, p. 633.

From its conception in the Colorado River Storage Project Act (1956) through 1991, GCD design and operations were motivated by hydroelectric power generation and storage allocations. With the advent of an Environmental Assessment, the Grand Canyon Protection Act (1992), and the Glen Canyon Dam Environmental Impact Statement and Record of Decision (U.S. Bureau of Reclamation 1995 and 1996, respectively), environmental concerns for the downstream ecosystems were introduced to management policy. While climate and the inflow of the Colorado and San Juan rivers primarily influence the stratification and hydrodynamics of Lake Powell, dam design and operations strongly influence the routing and discharge rates of various limnological strata within the reservoir and, consequently, reservoir water quality (Hart and Sherman 1996, Hueftle and Vernieu 2001). Although Colorado River ecosystem management has not been guided by concerns for Lake Powell's limnology, dam discharges have influenced the limnology of this large reservoir (Potter and Drake 1989), as well as the regulated river ecosystem downstream (Stevens et al. 1997; Valdez et al. 2001 in this feature).

Several features of dam design influence limnological development of Lake Powell. The location of the penstocks, the primary withdrawal port in GCD, has affected stratification patterns. The penstocks are located at a mid-depth bordering on the hypolimnion/epilimnion boundary, and draw from the hypolimnion almost half of the year. By isolating the hypolimnion from direct discharge, meromixis (stagnation and high chemical concentration) frequently occurs. Periods of meromixis are characterized by relatively high hypolimnetic specific conductance (a measure of salinity) and an upper boundary defined by a chemocline (chemical gradient) resistant to mixing.

Hypolimnetic stagnation and high dissolved oxygen (DO) demand can also result in hypoxia or anoxia. Anoxia and the associated reducing environment can produce hazardous compounds, such as hydrogen sulfide, which may pose hazards in-lake and downstream to both living organisms and to metal surfaces, such as the power-plant turbines. Drought conditions have resulted in several episodes of pronounced meromixis in Lake Powell since 1963, including the years preceding the test flood. Likewise, stagnation and DO demand has produced hypolimnetic hypoxia as low as 1.4 mg DO/L near the dam. Extremely low DO concentrations have not yet reached discharge elevations; a minimum of 4.5 mg DO/L has been recorded at the penstock elevation.

The river outlet works (ROW) are located deeper in the hypolimnion, almost always in the zone of meromictic stagnation. They are seldom used since they bypass power generation, but their location and operation would affect meromixis as they draw entirely from the hypolimnion except during the lowest lake stage. Data suggest that higher flow-through and ROW withdrawals may diminish the extent of hypolimnetic meromixis.

The existence and operation of Glen Canyon Dam (GCD) has significantly altered post-dam water quality in Glen and Grand Canyon (Stevens et al. 1997, Hueftle and Vernieu 2001). The presence and operation of the dam has greatly dampened seasonal variations in river flow; also, temperature, turbidity, and ionic concentration variability has been reduced to uniformly cold, clear, low nutrient waters. Post-dam discharge patterns have fluctuated greatly on a daily and weekly basis in response to power demands and are currently constrained by set ramping rates. Water quality and discharge below the dam is now dictated by reservoir water quality and the dam operations (Stanford and Ward 1986, 1991, Angradi et al. 1992). Interactions between the magnitude, duration, frequency, timing, and location of discharges from the dam influence uplake water quality, which, in turn, determines downstream water quality (Hueftle and Vernieu 2001). The effect of the unusually large and deep withdrawals of the test flood occurs in the context of seasonal limnological processes, obscuring cause-and-effect relationships. However, historical data allow comparisons of similar antecedent conditions without corresponding large discharges.

The 1996 test flood provided an opportunity to quantify these effects and elucidate the linkage between reservoir and downstream water quality. In this paper we address the following objectives: (1) describe the historical development of Lake Powell limnology; (2) determine whether the test flood's larger penstock discharges and releases from alternate structures affect Lake Powell limnology; (3) determine the extent of discharge required to produce measurable effects and how far uplake such effects are detectable; and (4) determine the impacts on downriver water quality. The large historical database (1964 through 1997), and the large size of this reservoir allow better comprehensive analysis of test-flood effects. Analysis of the limnological changes associated with a single, large discharge event may contribute to improved management of this and other large reservoirs that develop meromixis or hypoxia, in addition to improving the linkage to downstream water quality.

Methods

Study area

Glen Canyon Dam was completed in 1963, part of a series of dams resulting from the 1922 Colorado River Compact and the 1956 Colorado River Storage Act, providing for allocation and storage of water across the arid Colorado River basin. GCD is a 216.4 m high arch construction dam (Fig. 1). It provides three routes of release for the reservoir's water. Eight penstocks located 70 m below full pool elevation are the primary release structures. These can release a maximum of 940 m^3/s to the eight turbines for power generation, but are constrained to 892 m^3/s. The penstock draft tubes release below the surface of the tailwater pool, limiting aeration effects. Two alternate release structures may be used for greater discharge capacity, but both bypass power generation and their use is avoided. The ROW are located 99 m below full pool (29 m below penstock outlets) and can discharge 424–566 m^3/s. Their greater depth facilitates hypolimnetic discharge, and they have been used on seven occasions since 1963. The spillways draw from the epilimnion near the lake's surface at a depth of 16 m below full pool, although the lake

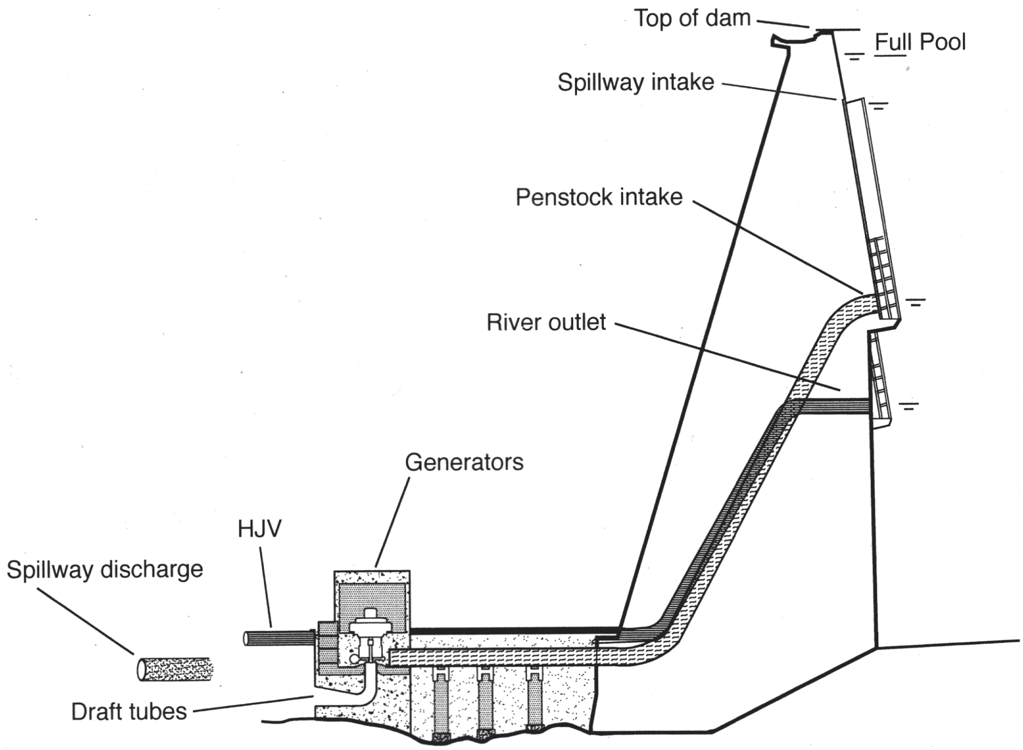

FIG. 1. Structure of Glen Canyon Dam with location and discharge capacity of outlet structures. Top of dam elevation = 1132.3 m; full pool elevation = 1127.8 m; dam base elevation = 958.6 m; spillways inlet elevation = 1111.9 m, outlet elevation = 962.3 m, maximum disharge (Q_{max}) = 5891 m^3/s; penstocks inlet elevation = 1057.65 m, outlet elevation = 947.6 m, Q_{max} = 892–940 m^3/s; river outlet works (ROW) inlet elevation = 1028.4 m, hollow jet valve (HJV) outlet elevation = 967.7 m, Q_{max}= 425–566 m^3/s.

has been below the spillways' operational levels for over half the lake's history. The spillways have a capacity of 5890 m^3/s to accommodate a 100-yr flood event, and have only been used in 1980, 1983, and 1984 (U.S. Bureau of Reclamation 1970, 1995).

Lake Powell is one of the largest U.S. reservoirs; located in southern Utah and northern Arizona, southwestern USA (Fig. 2). It first reached full pool in 1980, and has a maximum depth of 160 m, a surface area of 653 km^2, a length of 300 km, a volume of 32.1 km^3, and ~3200 km of shoreline at the full pool elevation of 1128 m above mean sea level (amsl) (U.S. Bureau of Reclamation 1970, 1995). The region has an arid continental climate: annual precipitation is 200 mm/yr and pan evaporation is 1800 mm/yr (Potter and Drake 1989).

Lake Powell is an oligotrophic lake (Potter and Drake 1989) with low nutrient levels; mean total phosphorus is 0.01–0.02 mg/L, and total Kjeldahl nitrogen is 0.16–0.2 mg/L. Results from the long-term (>30 yr) Lake Powell integrated water quality monitoring program (IWQP) identify Lake Powell as a warm meromictic reservoir; it has never completely mixed since its formation. It has a chemocline that persists near the depth of the penstock withdrawals. This meromictic hypolimnion, or monimolimnion, contains relatively stagnant water with elevated salinity (750 μS/cm to 1200 μS/cm), cold temperatures (6–9°C) and depressed DO (1.5–7 mg/L).

A previous period of meromixis at Lake Powell was disrupted by high inflows and multiple-level discharges in the 1980s during five years of exceptionally high inflows. The spillways (near the surface) and the ROW were operated on several occasions for extended periods in 1980 and from 1983 to 1986. Combined with three years of high flow-through and multiple-level withdrawals, the lake achieved a unique level of homogeneity in June 1985, with a conductance gradient 2.8 times less than the average for the lake's history. Data collection in the 1980s, however, was sporadic, with only two to five lake-wide collections per year. Trends were discerned, but relationships between dam operations and uplake processes were less clear. It was expected that analyses of the test-flood results would clarify some of the effects observed in the 1980s.

Data collection and sampling design

Historical and ongoing data from the IWQP were used, augmented with higher spatial and temporal resolution data near the dam surrounding the test flood (Fig. 2). The IWQP includes 25 long-term monitoring stations, eight that have been sampled since 1964. The

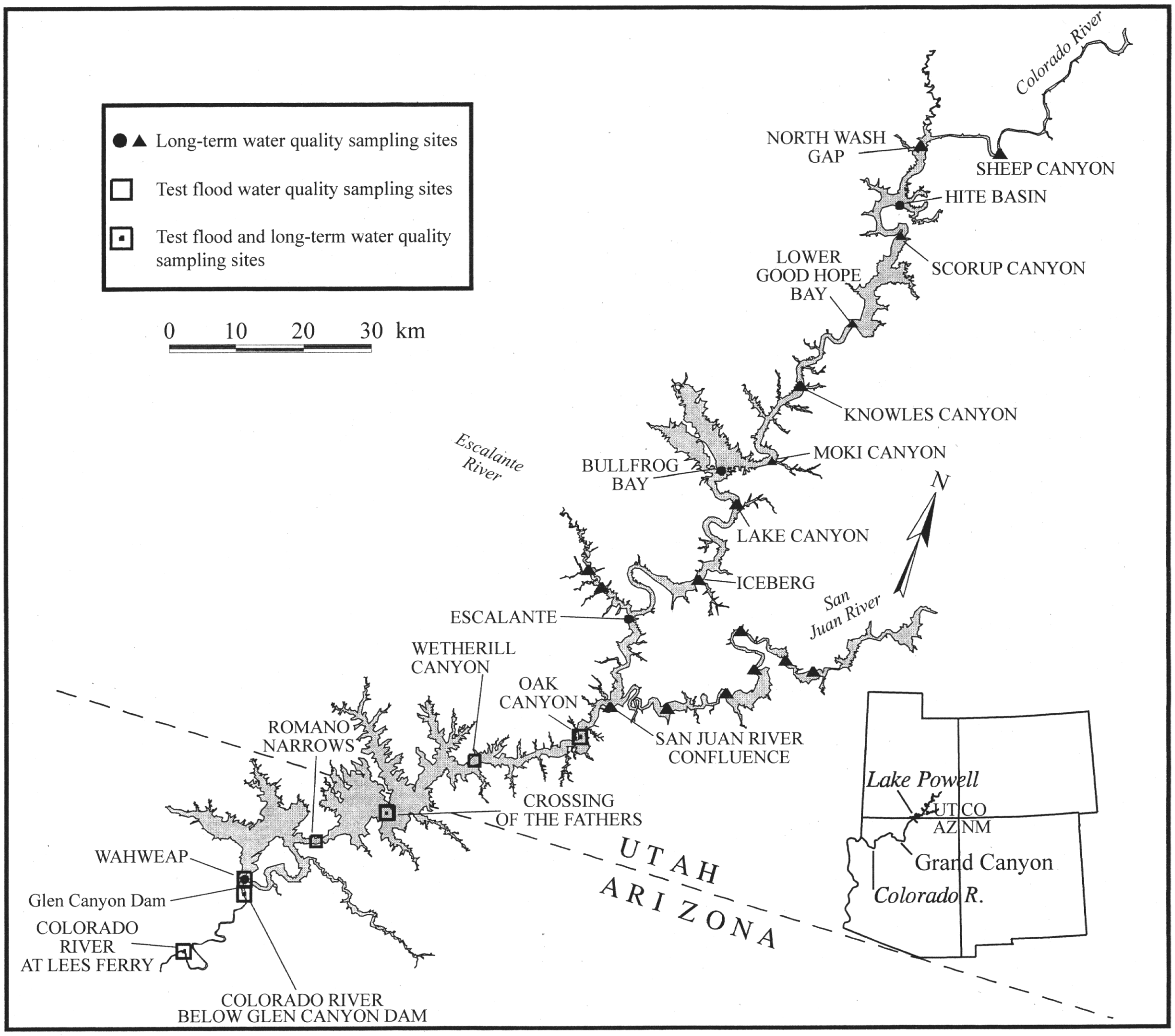

FIG. 2. Map of Lake Powell with sampling station locations, Utah and Arizona, USA.

test flood was bracketed by two full-lake quarterly IWQP sampling trips in the weeks of 1 March and 6 June 1996. These included 25 stations in the Colorado, Escalante, and San Juan river arms of Lake Powell. Using a Hydrolab Surveyor H2O multi-parameter submarine sonde (Hydrolab Corporation, Austin, Texas, USA), profiles of temperature in degrees Celsius (T), specific conductance (SC), dissolved oxygen (DO), pH, and turbidity were collected at depth intervals of 0.5 to 5 m at each station. Water chemistry samples were collected at 13 of these stations and analyzed for nutrient and major ion concentrations (APHA 1992) in the major stratigraphic layers. Secchi disk readings and biological samples of chlorophyll, phytoplankton, and zooplankton were collected at the surface. The IWQP also includes monthly sampling for all the above parameters at the Wahweap forebay station, and at the GCD and Lees Ferry tailwater stations.

The IWQP data was augmented with six additional physical profiles in the forebay immediately before, during, and after the test flood, on 22, 24, and 27 March, and 2, 3, and 5 April 1996. Synoptic channel profiling was conducted at four stations from the forebay uplake to river km 90 (Oak Canyon) on 22 and 27 March, and on 2 and 5 April; high winds, however, truncated some of these efforts. Chemical and biological samples were collected at the forebay station (2.4 km uplake from the dam) on 22 March and 5 April. An additional lake-wide collection of physical profile data was taken at 17 stations on the Colorado River arm of the reservoir to its inflow the week of 20 April 1996.

Higher resolution temporal data for the flood included three permanently deployed Hydrolab Recorders within and below the dam and at Lees Ferry, 25 km below the dam. These measured T, SC, DO, and pH at half-hour intervals. However, the high flows of the test flood rendered some of this information unusable. The Hydrolab profiles provided the finest res-

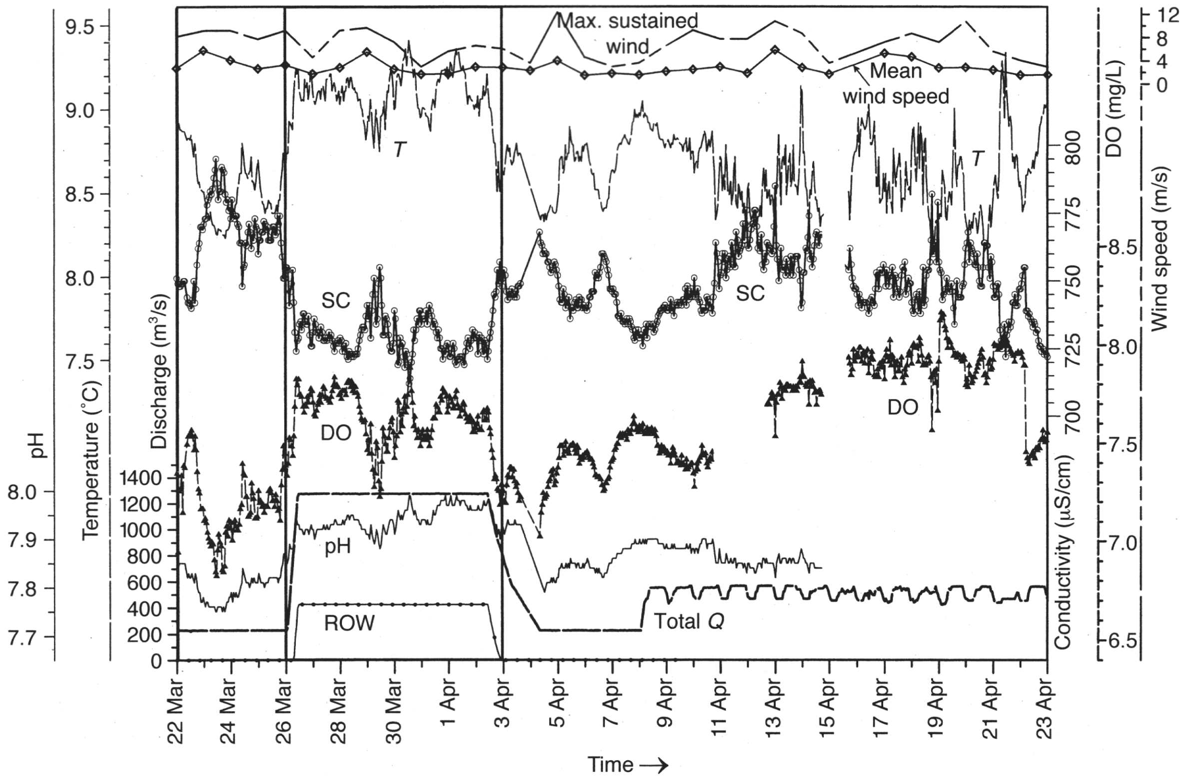

FIG. 3. Discharge (m³/s), temperature (°C), conductivity (μS/cm), dissolved oxygen (mg/L), and wind speed (m/s) from 22 March to 23 April 1996 at the penstock draft tubes in Glen Canyon Dam, Arizona. Synchronized oscillations reflect seiche and discharge effects. Blank areas indicate instrument failure. Abbreviations are: *T*, temperature; SC, specific conductivity; DO, dissolved oxygen; ROW, river outlet works; and *Q*, discharge.

olution and the most consistent data sets, particularly at the greater depths affected by the penstock and ROW withdrawals.

All Hydrolab instruments were calibrated using standard solutions and established protocol (Hydrolab 1994) before and after each sampling period. Blanks, duplicates, and spiked samples were collected for every 10 chemical samples.

Analyses

Data were compiled, reviewed, and analyzed using SAS and Lotus software. Grapher (Golden Software 1994), and Surfer (Golden Software 1996) software were used to generate two- and three-dimensional (isopleth) graphics, respectively. Isopleths illustrating lake-wide hydrodynamic processes plot various parameters against depth (in elevation) and river channel distance uplake from Glen Canyon Dam. Long-term trend analysis was facilitated by temporal isopleths plotting various parameters against depth and time. An animation sequence of the lake-wide conductivity isopleths since 1965 is available online.[3] This demonstrates hydrodynamics, underflows, and discharges of the reservoir including profiles of the test flood.

[3] URL = ⟨http://www.gcmrc.gov/iwqp/lpanisc.htm⟩

RESULTS

Discharge hydrograph and lake elevation

Prior to the test flood, the dam had discharged at above average levels since June 1995 as a result of large inflows that spring. Flows were increased from 280–340 m³/s to 480–537 m³/s in June and maintained there until October 1995, and thereafter averaged 340–425 m³/s until the test flood in 1996.

On 26 March 1996, penstock and ROW releases were increased to 850 m³/s and 425 m³/s, respectively (Fig. 3). A total volume of 0.893 km³ was discharged during the test flood; 0.626 km³ from the penstocks and 0.267 km³ from the ROW. Following the experiment, discharges from the dam were increased to high fluctuating levels of 450–566 m³/s for the duration of the spring to accommodate the large 1996 snowpack. Although the test flood is identified by the seven days of high releases, the experiment included eight days of low steady flows bracketing the flood, (Patten et al. 2001 in this feature) which also produced effects to lake and tailwaters.

The test flood directly affected lake elevation. Over the course of the experiment, between 22 March and 8 April, reservoir elevation had a net drop of 0.98 m. Although the reservoir dropped 1.12 m during the test

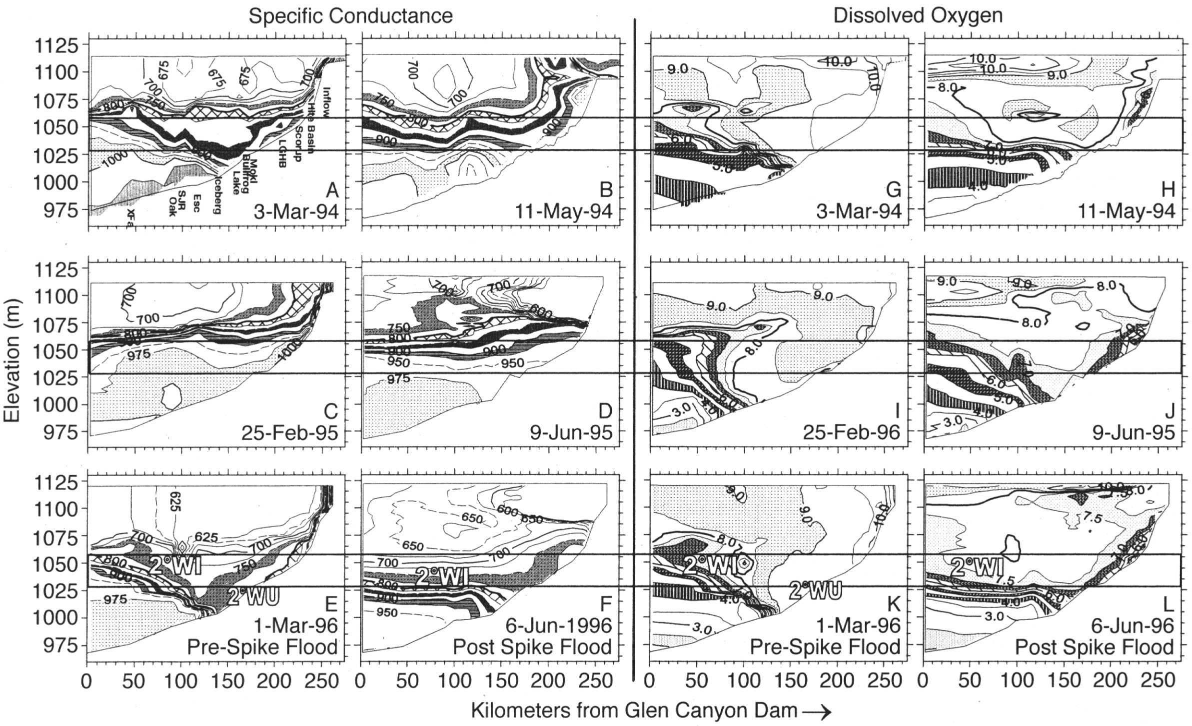

FIG. 4. Synoptic channel profiles of Lake Powell, Arizona and Utah, for conductivity (μS/cm; plots A–F) and dissolved oxygen (mg/L; plots G–L) in winter and spring from 1994 to 1996, comparing seasonal shifts in chemoclines for the test flood and two previous years. Contour interval = 25 μS/cm for SC (specific conductivity), 0.5 mg/L for DO (dissolved oxygen). Penstock, ROW (river outlet works), and sampling stations elevations are indicated on plot A. Underflows 2° WI (secondary winter interflow) and 2° WU (secondary winter underflow) are indicated on plots E, F, K, and L.

flood, the four days of 227 m^3/s discharges preceding and following the 1,274 m^3/s flood increased reservoir stage by 0.15 m. The lake elevation changes were slightly more than anticipated because of the later onset of the high spring inflows. Soon after the experiment concluded, the reservoir elevation increased substantially. The sudden drop in lake elevation required that water stored in the more eutrophic side-bays enter the mainstem (Thornton et al. 1990). The data suggests mainstem nutrient levels may have increased throughout the reservoir in June 1996, accompanied by increased chlorophyll *a* and *c* and pheophytin *a*. However, the existing IWQP includes few side-bay collections, particularly in the lower reach. Therefore, trends from side-bays are not conclusive and cannot be verified, but suggest further investigation and imply management considerations.

Stratification and hydrodynamics: antecedent conditions

The previous decade's climate and inflow patterns affected the limnological conditions prior to the test flood, and understanding these is critical to interpreting the results of the test flood on reservoir stratification and hydrodynamics. From 1987 to 1994, Lake Powell's drainage basin experienced extended drought; six of those years were among Lake Powell's lowest inflows in the reservoir's 33-yr history. This resulted in a pronounced monimolimnion with a pycnocline (density gradient) resistant to mixing. This stratification was weakened by two high inflows (fifth and sixth highest in the lake's history) in 1993 and 1995. These inflows introduced a large pool of lower SC water for winter mixing in the epilimnion.

Numerous authors, including Merritt and Johnson (1978), Johnson and Merritt (1979), Gloss et al. (1980), Gloss et al. (1981), Edinger et al. (1984), and Stanford and Ward (1986, 1991) have described Lake Powell's density currents. Normal winter hypolimnetic processes are dominated by partitioned underflows that form in the inflows and migrate advectively toward the dam (Hueftle and Vernieu 2001). The first winter underflow (1° WU) forms in the fall as a relatively warm, saline mass of dense water flows along the former riverbed toward the dam, dispersing through and thickening the monimolimnion. The secondary winter underflow (2° WU) forms in the inflow at the peak of winter, a cold, convectively mixed mass of relatively cold, oxygenated, and lower salinity water that follows the 1° WU downlake. Although its density is rarely sufficient to completely displace the hypolimnion, the 2° WU may refresh the stagnant hypolimnion if it is of sufficient

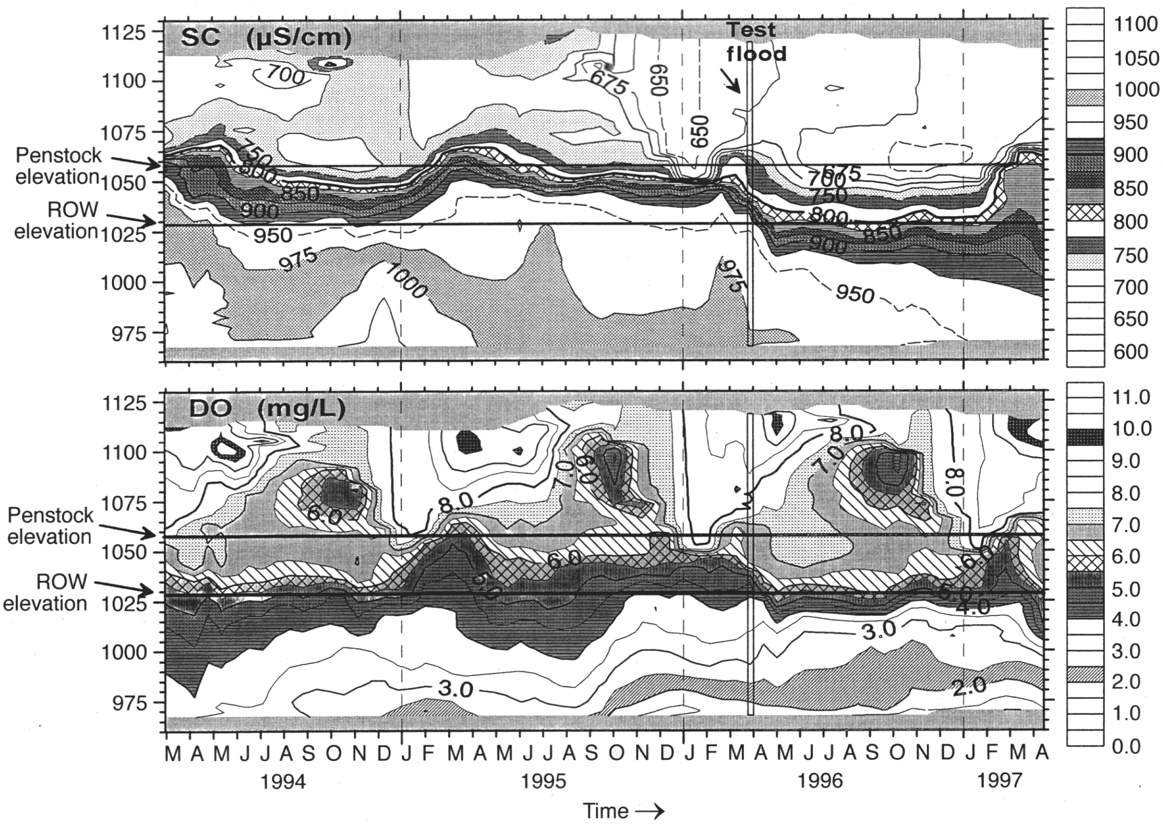

FIG. 5. Temporal isopleths of conductivity (μS/cm) and dissolved oxygen (mg/L) at the Wahweap forebay station demonstrating upwelling and chemocline migration, 1994–1997. Abbreviations are as in Fig. 3.

magnitude and density, and dam discharges are favorable. Most commonly, this 2° WU reaches the chemocline midway down the thalweg in the reservoir and becomes an interflow (2° WI), overriding or passing through the hypolimnion, depending on its relative density. It is then drawn into the penstock withdrawal zone. This 2° WI occurs regularly, and its freshening potential increases with the depth the density current achieves before diversion over the hypolimnion. Preceding the test flood, the 2° WU was in transition to a 2° WI 135 km uplake. These conditions were similar to those in 1994 (155 km) and 1995 (110 km) (Fig. 4).

A second component of the freshening 2° WU is the advective force it applies to the hypolimnion. While rarely able to penetrate the chemocline, the advective forces of the 2° WI are often sufficient to depress the hypolimnion, creating a periodic "upwelling" of the hypolimnion. As a result, the chemocline ascends the face of the dam for a period of weeks to months. This effect can be seen in the three-year forebay isopleths (Fig. 5), with the upwelling effect typically beginning in February, peaking in March, and diminishing by May. Prior to the test flood, upwelling had already peaked by mid-February and was subsiding. The upwelling effect is diminished: (1) by discharge through the dam and (2) subsidence of the upwelling as the advective forces of the 2° WI dissipate. The animation sequence as well as the synoptic channel profiles (Fig. 4) demonstrate annual winter upwelling cycles evident near the dam.

The upwelling pattern maximizes hypolimnetic discharge through the penstocks and ROW. However, the interflow pattern can confuse the interpretation of test flood impacts with seasonal hydrodynamics already underway. By late 1995, the 2° WU had shifted to a 2° WI, and its descent along the thalweg of the lake slowed as it impinged on the pycnocline and diverted horizontally downlake toward the penstocks. From the onset of the test flood, inflow hydrodynamics actively affected reservoir limnology at the penstock elevation. Therefore, distinguishing test flood effects from existing seasonal change required an examination of rates of change on water quality and the impacts from the ROW.

Effects on stratification and hydrodynamics

Test flood effects on Lake Powell were observed through shifts in chemoclines with consequent changes in strata volume, and through shifts in water quality. The synoptic channel profiles (Figs. 4 and 6) and temporal Wahweap forebay isopleths (Fig. 5) demonstrate the descending migration of the chemocline and DO

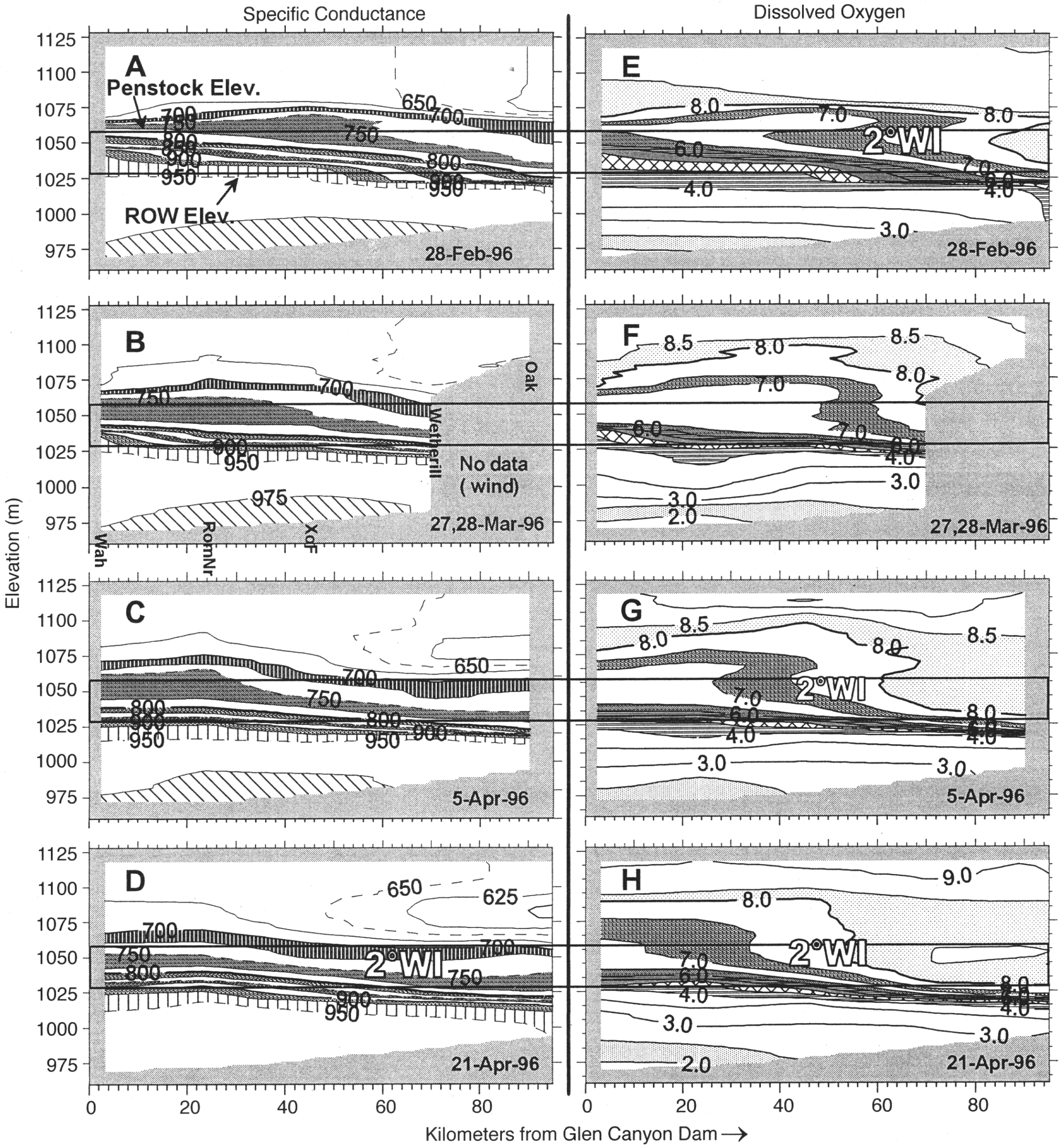

FIG. 6. Detailed synoptic channel profiles to river km 90 of Lake Powell, Arizona and Utah, showing the advancing front of the 2° WI (secondary winter interflow) through shifts in conductivity (μS/cm; plots A–D) and dissolved oxygen (mg/L; plots E–H) gradients from 28 February to 21 April 1996. Penstock and ROW (river outlet works) elevations are indicated on plot A. Sampling stations are indicated on plot B.

gradients during the test flood. Comparisons with the previous year's upwelling and subsidence patterns show the test flood effects were most pronounced at the ROW depth, where the freshening effects of the 2° WI discharge were most dramatic. Prior to the test flood, three distinctive strata were distinguished from SC and DO concentrations at the Wahweap forebay station (Figs. 4 and 6): (1) an upper convectively and wind-mixed epilimnion underlain by a distinct chemocline 7.5 m above the penstock outlets; (2) a 24-m thick 2° WI middle layer underlain by a second chemocline 13 m above the ROW; and (3) a lower 66-m thick monimolimnion. Changing the elevation and magnitude of discharge restructured these layers. As a general rule, increases in discharge result in a third power increase in kinetic energy available for mixing,

TABLE 1. Water chemistry results at the Glen Canyon Dam forebay station (Wahweap forebay station) on 22 March and 5 April 1996, before and after the test flood (respectively).

Parameter†	Surface		Penstock		ROW‡	
	22 March	5 April	22 March	5 April	22 March	5 April
Temperature (°C)	13.83	12.15	8.56	8.39	7.87	7.78
Field pH	8.18	8.12	7.78	7.76	7.6	7.58
Field SC	670	667	778	762	925	896
Turbidity (NTU)	0	0	1.2	0.9	1.2	1.1
DO (mg/L)	8.6	8.91	6.21	6.72	4.37	4.78
TDS (mg/L)	441	434	503	487	636	553
Ca (mg/L)	59.6	54.7	65.9	62.3	78.3	70.4
Mg (mg/L)	19.6	18.1	21.4	20.1	25.5	22.7
Na (mg/L)	53.8	49.7	63.8	59.1	79.9	69.2
K (mg/L)	3.37	3.21	3.22	3.63	3.94	4.08
HCO_3 (mg/L)	151	150	161	162	176	171
SO_4 (mg/L)	170	160	187	180	240	213
CI (mg/L)	35.4	33.8	49.1	46.8	63.5	56.6
TP (mg P/L)	<0.005	<0.005	0.005	<0.005	0.006	<0.005
OP (mg P/L)	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
NH_3 (mg N/L)	0.010	<0.010	<0.010	<0.010	<0.010	<0.010
NO_{2+3} (mg N/L)	0.16	0.18	0.33	0.34	0.42	0.39
TKN (mg N/L)	0.06	0.08	0.08	0.08	0.10	0.09
Ion average	102	107	116	120	140	139
Sum of ions (mg/L)	943	913	1061	1028	1298	1165

† Parameter abbreviations: SC, specific conductance; NTU, nephelometric turbidity units; DO, dissolved oxygen; TDS, total dissolved solids; TP, total phosphorus; OP, ortho-phosphate, TKN, total Kjeldahl nitrogen.
‡ ROW = River outlet works.

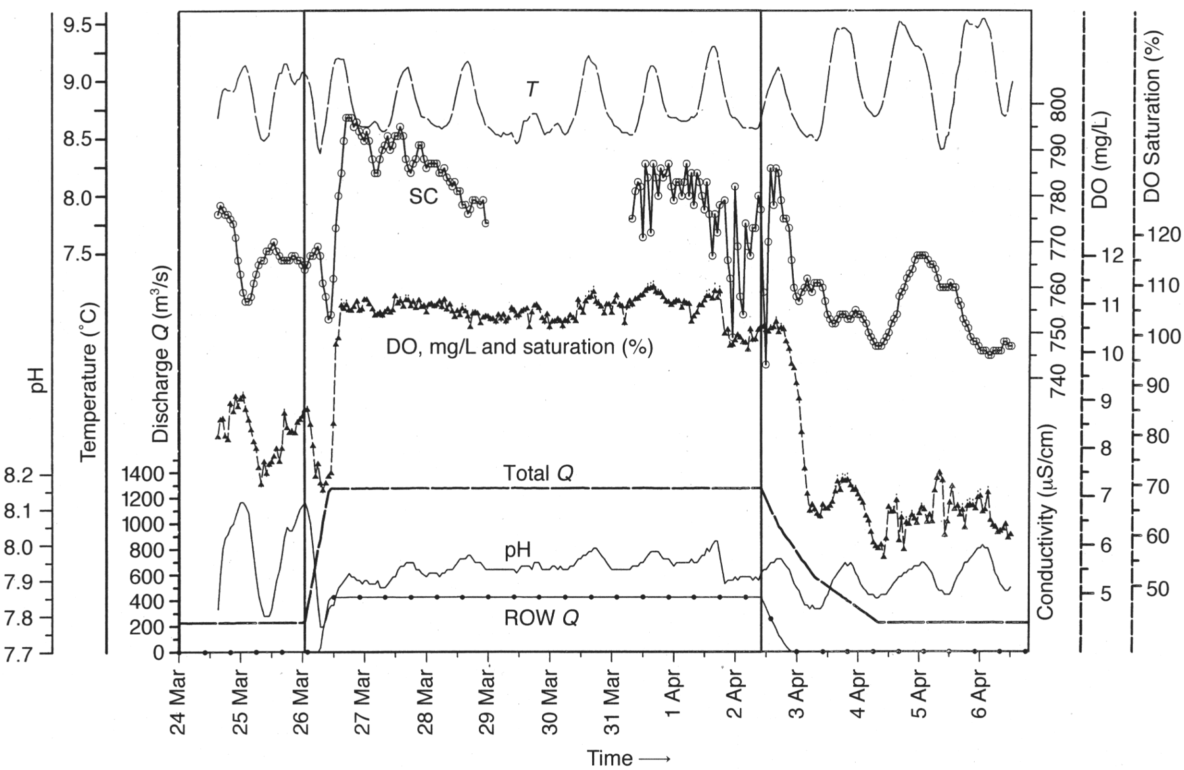

FIG. 7. Discharge (m³/s), temperature (°C), conductivity (μS/cm), dissolved oxygen (mg/L), and pH for 24 March–5 April 1996 at Lees Ferry, Arizona. Abbreviations are as in Fig. 3.

TABLE 1. Extended.

Bottom	
22 March	5 April
7.19	7.23
7.41	7.42
976	976
1.4	1.3
1.63	2.02
629	625
80.5	79.5
25.8	25.4
80.4	79.7
4.18	3.85
182	181
248	245
65.9	66.6
0.007	<0.005
<0.005	<0.005
<0.010	<0.010
0.44	0.45
0.14	0.09
144	153
1318	1309

as KE $\propto Q^3$ (Thornton et al. 1990); this extends the vertical draw of the outlets (Monismith et al. 1988). Hence, the increase from the normal penstock discharges of 390 m^3/s to bi-level discharges of 850 m^3/s and 420 m^3/s from penstocks and ROW increased mixing energy by an order of magnitude, while total discharge only increased threefold.

The addition of sub-hypolimnetic discharge intensified vertical mixing. With the onset of the bi-level high releases, the upper chemocline weakened as the penstocks drew more heavily from the epilimnion and the 2° WI. Profile data at the dam demonstrated refreshment at the penstocks as they drew from the epilimnion (Fig. 3). But below the dam at Lees Ferry, comingled penstock and ROW releases show an overall increase in ionic concentrations, reflecting the dominance of ROW hypolimnetic output (Fig. 7). The chemocline below the 2° WI and between the outlet ports weakened and descended more than 12 m to the level of the ROW at the conclusion of the flood. The 2° WI stratum was thickened 16 m as it drew from the wider wedge uplake, entraining the epilimnion and hypolimnion and weakening the associated chemoclines as it moved downlake. Isopleths indicate the withdrawal zone extended from 50 to 100 or more km uplake, even accounting for vertical uncertainty produced by localized seiche oscillations (Figs. 4 and 6). Chemical data collected near the dam before and after the test flood show consistent decreases in ionic concentrations by an average 4.4%, demonstrating the refreshment of the forebay, particularly in the upper hypolimnion (Table 1). The most pronounced shifts surrounding the test flood occurred near the ROW. This was not unexpected due to the meromictic conditions, the influx of fresher conditions provided by the 2° WI, and higher discharge. Surface and bottom samples demonstrated the least change. Calculations of the load of salt ions and DO vs. relative discharge from the ROW and penstocks illustrate the disparity in discharge vs. meromixis (Table 2). Although the ROW only accounted for a third of the flood discharge, they contained 23% higher conductance and 33% less DO than is found at the penstocks. Consequently, the introduction of discharges from the ROW had a disproportionate long-term freshening effect upon the hypolimnion compared with penstock withdrawals.

Continued dilution of the hypolimnion was apparent (Fig. 5) following the test flood through 1997. This resulted from another high inflow year and continued high releases from February to June 1997, again, commenced during the upwelling event.

Rates of change (in percentage change per day) for *T*, SC, and DO were calculated for a given point between each of the interpolated isopleths of the main channel from 28 February to 21 April. These calculations excluded the top 30 m of the lake and included the upper 100 km of the length (those zones affected by short-term seasonal influences). The results indicate the greatest changes occurred between 2–5 April immediately following the test flood (summarized in Fig. 8). The next highest rates of change were observed from 22 March to 2 April, during the test flood. These

TABLE 2. Discharge and ion load statistics for the penstocks (PS) and river outlet works (ROW).

Parameters	ROW	PS	Total for PS + ROW	Null hypothesis: no test flood†
Lake elevation (m)	1028.4	1057.65		
Dissolved oxygen (DO; metric tons)	1187	4137	5324	2062
DO discharged (%)	22.3	77.7	100.0	−61 or 2.6× less
Total dissolved solids (TDS; metric tons)	176 353	336 714	513 067	167 850
TDS discharged from each port (%)	34.4	65.6	100.0	−67 or 3.1× less
Volume discharged in test flow (km^3)	0.267	0.626	0.893	0.312
Volume discharge from each port (%)	29.9	70.1	100.0	100.0
Test release from total lake volume below port (%)	10.22	10.96	14.56	
Volume below port depth (km^3)	2.44	6.12	6.12	

† Null hypothesis values projected forecast releases of Q_{avg} = 392 m^3/s (Pattern et al. 2001) for the same period (9.21 d) as the large test flood releases.

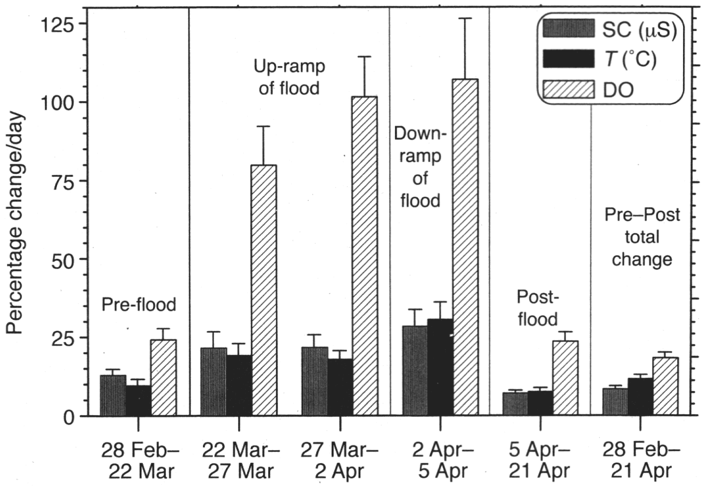

FIG. 8. Percentage change per day in Lake Powell for conductivity (SC), temperature (T), and dissolved oxygen (DO) before, during, and after the test flow from Wahweap to Good Hope Bay, Lake Powell, Arizona and Utah. Data are absolute values of percentage change per day; error bars indicate 95% confidence intervals.

results further substantiate the increased effects of the test flood over normal operations.

Withdrawal zone and tailwaters effects

During the experiment, wind and discharge conditions contributed to water quality oscillations from the Wahweap forebay station to Lees Ferry (Figs. 3 and 7). Internal seiche oscillations are frequently observed in high temporal resolution data sets during the winter at GCD. These oscillations are most evident when the reservoir's chemocline impinges on the penstock elevation, such as during the ascending and descending limbs of hypolimnetic upwelling. Isolated wind events such as those on 20 April 1996 (National Climatic Data Center 1996), initiate wind-induced internal seiche oscillations (Wetzel 1975, Cole 1994, Horne and Goldman 1994,) of T, SC, DO, and pH at the dam. As mentioned previously, changes in release rates also create rapid water quality shifts at the penstock level due to the strength and dimensions of the withdrawal plume (Hart and Sherman 1996, Hueftle and Vernieu 2001). Although at least four strong wind events (Fig. 3) occurred during the test flood and created complex interfering seiche patterns, the magnitude and timing of oscillations resulting from the test flood are clearly distinguished from wind induced seiches (Fig. 3).

The use of the hollow jet valves (the release structure for the ROW) also creates a unique signature. The valves ejected four plumes of aerated water 10 m above the tailwater pool. Combined with the draft tube discharges from the penstocks, the higher discharge was more turbulent than normal discharges. Turbidity and total suspended solids increased from 0.2 to 0.6 NTU (nephelometric turbidity units) and 2 to 19 mg/L, respectively, during the test flood (U.S. Geological Survey 1996). The effects of spray and turbulence from the hollow jet valves immediately oxygenated the tailwaters, resulting in mean DO saturation increases from 79% to 105% (Fig. 7). Typically, T, DO, and pH reflect fluctuating diurnal patterns that develop in the highly productive 25-km tailwater stretch of normally clear, lower flows (Angradi et al. 1992, Ayers and McKinney 1996). Respiration of *Cladophora glomerata* (the dominant algae) and other life-forms contribute to diel pH and DO fluctuations, while T responds to insolation. During the test flood, diurnal pH patterns were attenuated (Fig. 7), demonstrating the reduction of respiration due to increased drift (Shannon et al. 2001 in this feature) and lower light availability resulting from higher discharges, greater turbidity, and deeper water (M. Yard and D. L. Wegner, *personal communication*). Diurnal pH and DO fluctuations recovered quickly (within hours) once lower discharges recommenced, although net respiration was reduced from pre-flood levels due to the sheared biomass. Diurnal pH fluctuation levels had returned to pre-flood levels by late April 1996. During the test flows, diurnal DO patterns, though still present, were overshadowed by jet valve aeration. Conductivity reflected short-term seiche effects and higher salinity of the ROW dominated withdrawal plumes in the forebay.

DISCUSSION AND MANAGEMENT IMPLICATIONS

Given the context of antecedent conditions, these data demonstrated significant impacts on reservoir and downstream water quality. The most influential factors were the magnitude and composition of the 2° WI; followed by the location, magnitude, timing, and duration of dam discharges, not necessarily in that order. Had the test flood not occurred during the hypolimnetic upwelling, nor the ROW been used, the penstocks alone could not have substantially flushed the hypolimnion. The ability of the penstocks to mix and entrain the hypolimnion is considerably less under normal discharge levels. Without large, carefully timed, and/or bi-level discharges, the opportunity to release meromictic water may be foregone. In the reservoir, significant shifts in salinity and DO gradients were observed near the penstock and ROW elevations as far as 100 km uplake. Fresher, more oxygenated water was drawn into the middle depths of the forebay from the epilimnion and 2° WI uplake. These more dilute conditions persisted through 1997. Although of short duration, the test flood affected Lake Powell limnology in a fashion that provides insight into the dramatic shifts in water quality alluded to in the 1980s historical data set (Hueftle and Vernieu 2001).

In the tailwaters, jet valve aeration, attenuation of primary productivity, and the trace of seiches and meromictic discharge were strong signatures of the test flood, though short-lived. Shannon et al. (2001), Stevens et al. (2001), and Valdez et al. (2001), address longer term aquatic impacts on downstream resources.

These effects are important to in-lake water quality and determination of downriver water quality. Currently, large discharges are likely to occur only during periods of high lake levels and high inflows, thus, future high releases will probably occur during periods of declining meromixis. Should in-lake hypoxia or meromixis approach levels of concern, however, the test flood demonstrated a mechanism for their downstream release. Hypoxia, not always associated with meromixis, could be managed with well-timed ROW releases. Dam operations could influence the banking or release of ion concentrations, DO, *T,* and other components that were not examined here, such as biological components. Carefully timed dam releases could be used to avert problems with minimal impact to power production and water storage. For example, precise releases at peak upwelling in February or March would require less discharge volume to reduce meromixis than at other times of the year. But uplake and downstream effects must be considered prior to future actions.

This study of large and multilevel discharges from GCD has global implications for future reservoir, discharge, and downriver management opportunities, including future experimental floods, flow regimes, and other management options that are pending at Glen Canyon Dam.

Installation of a selective withdrawal system is an option outlined by the Final Environmental Impact Statement (Stanford and Ward 1996). Its purpose, via epilimnetic withdrawal, is to warm the Colorado River to encourage mainstem spawning of endangered native fish. Such action could produce unforeseen thermal, chemical, and biological changes above and below GCD. Use of hypolimnetic discharge may offset some of these impacts, and continued investigations could lead to more informed decisions.

The demonstration of the test flood effects as well as those observed during the 1980s spillway discharges alludes to impacts we could expect from the operation of a selective withdrawal system. Operational changes will have limnological impacts, and informed decisions will require a sound limnological foundation for management of water quality resources. Current knowledge of the strength, destination, and quality of winter underflows and inflows, strength of meromixis, antecedent conditions, and long-range considerations will be required for informed management in the future.

Acknowledgments

We would like to acknowledge D. L. Wegner and the Glen Canyon Environmental Studies office for their hard work in conducting the test flood, which could not have taken place without them. We thank William Vernieu for assistance in field collection and design, data management, and boat operations. For assistance in field collections, we thank R. Radtke (Upper Colorado Region, U.S. Bureau of Reclamation) and K. Berghoff and M. O. Cline (Glen Canyon National Recreation Area). We thank L. D. Garrett, E. C. Hueftle, J. P. Shannon, and M. Yeatts for editorial comments and encouragement. We also thank the anonymous reviewers for comments on the draft. This research was funded by Glen Canyon Environmental Studies, Grand Canyon Monitoring and Research Center, and the U.S. Bureau of Reclamation.

Literature Cited

Angradi, T. R., R. W. Clarkson, D. A. Kinsolving, D. M. Kubly, and S. A. Morgenson. 1992. Glen Canyon Dam and the Colorado River; responses of the aquatic biota to dam operations. Prepared for the Bureau of Reclamation, Upper Colorado Region, Glen Canyon Environmental Studies, Flagstaff, Arizona. Cooperative Agreement No. 9-FC-40-07940, Arizona Game and Fish Department, Phoenix, Arizona, USA.

APHA (American Public Health Association). 1992. Standard methods for the examination of water and wastewater. Eighteenth edition. APHA, Washington, D.C., USA.

Ayers, A. D., and T. McKinney. 1996. Water chemistry and zooplankton in the Lake Powell forebay, Glen Canyon Dam discharge and tailwater. Prepared for the Bureau of Reclamation, Upper Colorado Region, Glen Canyon Environmental Studies, Flagstaff, Arizona. Cooperative Agreement No. 9-FC-40-07940, Arizona Game and Fish Department, Phoenix, Arizona, USA.

Cole, G. A. 1994. Textbook of limnology. Waveland Press, Prospect Heights, Illinois, USA.

Edinger, J. E., E. M. Buchak, and D. H. Merritt. 1984. Longitudinal–vertical hydrodynamics and transport with chemical equilibria for Lake Powell and Lake Mead. Pages 213–222 *in* R. H. French, editor. Salinity in watercourses and reservoirs. Salt Lake City, Utah, Butterworth, Boston, Massachusetts, USA.

Gloss, S. P., L. M. Mayer, and D. E. Kidd. 1980. Advective control of nutrient dynamics in the epilimnion of a large reservoir. Limnology and Oceanography **25**:219–228.

Gloss, S. P., R. C. Reynolds, Jr., L. M. Mayer, and D. E. Kidd. 1981. Reservoir influences of salinity and nutrient fluxes in the arid Colorado River Basin. Pages 1618–1629 *in* H. G. Stephan, editor. Proceedings of the Symposium of Surface Water Impoundments. American Society of Civil Engineers, New York, New York, USA.

Golden Software. 1994. Grapher, version 1.26. Golden, Colorado, USA.

Golden Software. 1996. Surfer, version 6.04. Golden, Colorado, USA.

Hart, R. J., and K. M. Sherman. 1996. Physical and chemical characteristics of Lake Powell at the forebay and outflows of Glen Canyon Dam, northeastern Arizona, 1990–1991.

U.S. Geological Survey Water-Resources Investigations Report **96-4016**.

Horne, A. J., and C. R. Goldman. 1994. Limnology. Second edition. McGraw Hill, New York, New York, USA.

Hueftle, S. J., and W. S. Vernieu. 2001. Assessment of impacts of Glen Canyon Dam operations on water quality resources in Lake Powell and the Colorado River in Grand Canyon. Grand Canyon Monitoring and Research Center, U.S. Department of Interior, Washington, D.C., USA.

Hydrolab Corporation. 1994. Hydrolab Surveyor 3 multiparameter water quality monitoring instruments, operating manual. Austin, Texas, USA.

Johnson, N. M., and D. H. Merritt. 1979. Convective and advective circulation of Lake Powell, Utah–Arizona, during 1972–1975. Water Resources Research **15**:873–884.

Kennedy, R. H., K. W. Thornton, and D. E. Ford. 1985. Characterization of the reservoir ecosystem. Pages. 27–38 *in* D. Gunnison, editor. Microbial processes in reservoirs. Dr. W. Junk, Boston, Massachusetts, USA.

Kennedy, R. H., K. W. Thornton, and R. C. Gunkel. 1982. The establishment of water quality gradients in reservoirs. Canadian Water Resources Journal **7**:71–87.

Merritt, D. H., and N. M. Johnson. 1978. Advective circulation in Lake Powell, Utah–Arizona. Lake Powell Research Project Bulletin 61. Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.

Monismith, S., J. Imberger, and G. Billi. 1988. Shear waves and unsteady selective withdrawal. Journal of Hydraulic Engineering **114**:1134–1152.

National Climatic Data Center. 1996. Global Summary of the Day Website. Meteorological data retrieval. Online: ⟨http://www.ncdc.noad.gov/onlineprod/gsod/climvis⟩.

Patten, D. T., D. A. Harpman, M. I. Viota, and T. J. Randle. 2001. A managed flood on the Colorado River: background, objectives, design, and implementation. Ecological Applications **11**:635–643.

Potter, L. D., and C. L. Drake. 1989. Lake Powell: virgin flow to dynamo. University of New Mexico Press, Albuquerque, New Mexico, USA.

Ryder, R. A. 1978. Ecological heterogeneity between north-temperate reservoirs and glacial lake systems due to differing succession rates and cultural uses. Vereinigung fur Theoretische und Angewandte Limnologie, Veerhandlungen **20**:1568–1574.

Shannon, J. P., D. Blinn, T. McKinney, P. L. Benenati, K. P. Wilson, and C. O'Brien. 2001. Aquatic food base response to the 1996 test flood below Glen Canyon Dam, Colorado River, Arizona. Ecological Applications **11**:672–685.

Stanford, J. A., and J. V. Ward. 1986. Reservoirs of the Colorado River system. Pages 375–383 *in* B. R. Davies and K. F. Walker, editors. The ecology of river systems. Dr. W. Junk, Dordrecht, The Netherlands.

Stanford, J. A., and J. V. Ward. 1991. Limnology of Lake Powell and the chemistry of the Colorado River. Pages 75–101 *in* Colorado River ecology and dam management.

Stanford, J. A., J. V. Ward, W. J. Liss, C. A. Frissell, R. N. Williams, J. A. Lichatowich, and C. C. Coutant. 1996. A general protocol for restoration of regulated rivers. Regulated Rivers Research and Management **12**:391–413.

Stevens, L. E., T. J. Ayers, J. B. Bennett, K. Christensen, M. J. C. Kearsley, V. J. Meretsky, A. M. Phillips III, R. A. Parnell, J. Spence, M. K. Sogge, A. B. Springer, and D. L. Wegner. 2001. Planned flooding and Colorado River riparian trade-offs downstream from Glen Canyon Dam, Arizona. Ecological Applications **11**:701–710.

Stevens, L. E., J. P. Shannon, and D. W. Blinn. 1997. Colorado River benthic ecology in Grand Canyon, Arizona, USA: dam, tributary and geomorphological influences. Regulated Rivers Research and Management **13**:129–149.

Thornton, K. W., B. L. Kimmel, and F. E. Payne, editors. 1990. Reservoir limnology: ecological perspectives. John Wiley and Sons, New York, New York, USA.

U.S. Bureau of Reclamation. 1970. Glen Canyon Dam and Powerplant, technical record of design and construction. A Water Resources Technical Publication. United States Bureau of Reclamation, Washington, D.C., USA.

U.S. Bureau of Reclamation. 1995. Operation of Glen Canyon Dam final environmental impact statement. U.S. Bureau of Reclamation, Salt Lake City, Utah, USA.

U.S. Bureau of Reclamation. 1996. Record of decision for operation of Glen Canyon Dam final environmental impact statement. U.S. Department of Interior, Washington, D.C., USA.

U.S. Geological Survey. 1996. Water resource data for Arizona, water year 1996. Water Data Report, AZ-96–1. U.S. Geological Survey, Department of Interior, Washington, D.C., USA.

Valdez, R. A., T. L. Hoffnagle, C. C. McIvor, T. McKinney, and W. C. Leibfried. 2001. Effects of a test flood on fishes of the Colorado River in Grand Canyon, Arizona. Ecological Applications **11**:686–700.

Ward, J. V., and J. A. Stanford. 1983. The intermediate disturbance hypothesis: an explanation for biotic diversity patterns in lotic ecosystems. Pages 347–356 *in* T. D. Fontaine and S. M. Bartell, editors. Dynamics of lotic ecosystems. Ann Arbor Science, Ann Arbor, Michigan, USA.

Wetzel, R. G. 1975. Limnology. W. B. Saunders, Philadelphia, Pennsylvania, USA.