mercury in the lake powell ecosystem

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lake powell research project

The Lake Powell Research Project (formally known as Collaborative Research on Assessment of Man's Activities in the Lake Powell Region) is a consortium of university groups funded by the Division of Environmental Systems and Resources in RANN (Research Applied to National Needs) in the National Science Foundation.

Researchers in the consortium bring a wide range of expertise in natural and social sciences to bear on the general problem of the effects and ramifications of water resource management in the Lake Powell region. The region currently is experiencing converging demands for water and energy resource development, preservation of nationally unique scenic features, expansion of recreation facilities, and economic growth and modernization in previously isolated rural areas.

The Project comprises interdisciplinary studies centered on the following topics: cultural eutrophication, shoreline ecology, heavy metals, streamflow trends, evaporation, bank storage, sedimentation, physical limnology, lake geochemistry, background air quality, environmental impact analysis, systems analysis, economics, epidemiology, anthropology, law, and political science.

One of the major missions of RANN projects is to communicate research results directly to user groups of the region, which include government agencies, Native American Tribes, legislative bodies, and interested civic groups. The Lake Powell Research Project Bulletins are intended to make the research results readily accessible to user groups. The Bulletins will supplement technical articles published by Project members in scholarly journals.

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ABSTRACT

Flameless atomic absorption analyses of samples from Lake Powell yield the following mercury levels (in mean parts per billion): 0.01 in lake water, 30 in bottom sediments, 10 in shoreline substrates, 34 in plant leaves, 145 in plant debris, 28 in algae, 10 in crayfish, and 232 in fish muscle. Concentrations are expressed on a wet-weight basis for animals; all other samples are on a dry-weight basis. In bottom sediments, mercury levels are found to be highest in sediments with high organic content and fine texture. The mercury content of plant leaves is higher than that of stems or roots. The mercury levels in lake-transported plant debris are higher than in shoreline plants. In rainbow and brown trout, bloody tissues have higher mercury levels than do muscle or other tissues. In six other species of fish analyzed, mean relative mercury levels (compared to muscle as 1.00) are the following: liver, 0.51; heart, 0.43; kidney, 0.36; spleen, 0.28; stomach, 0.20; brain, 0.16; gonads, 0.14; skin, 0.13; gills, 0.12; and bone, 0.07. Larger fish of a given species and fish of higher trophic levels have higher mercury concentrations, with the muscle of large walleye and largemouth bass exceeding 500 ppb.

Bioamplification and the association of mercury with organic matter are evident in this recently created, relatively unpolluted reservoir. Formulation of an estimated mercury budget suggests that the restriction of outflow in the impounded Colorado River leads to mercury accumulation, and that projected regional coal-fired power generation may produce sufficient amounts of mercury to augment significantly the mercury released by natural weathering. The extent of this augmentation and its effect on Lake Powell principally depends on the actual mercury content of the coal; the degree to which this mercury enters the lake drainage; and the movement and bioamplification of the mercury within the system.

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INTRODUCTION

The vulnerability of freshwater habitats to mercury contamination has been established by extensive Swedish investigations (Johnels and Westermark, 1969). Fimreite's study of Lake St. Clair calls attention to aquatic mercury problems in North America (Dunlap, 1971). Subsequent analyses of fish from many locations reveal mercury levels which exceed the 500-ppb limit set by the Food and Drug Administration as a safe standard for human consumption (Peakall and Lovett, 1972). Mercury levels which are above 500 ppb are considered evidence for pollution (Evans and Bails, 1972). However, such levels are reported from waters without a known pollution source (Sumner and Saha, 1971; D'Itri, 1972; Wood, 1972), which indicates the difficulty of determining whether aquatic mercury levels are due to human activities or to natural mercury. Fossil fuel combustion further complicates the determination of mercury sources in freshwater systems.

As a recent impoundment remote from major pollution sources, Lake Powell provides an opportunity to assess the mercury levels of a large reservoir in which extensive sedimentation and eutrophication have not yet occurred and in which most of the mercury in the system would be expected to be of geological origin. Also of interest are the extent of bioamplification in such a recently created, relatively unpolluted lake and the mercury levels in the lake fish (the point at which human consumers enter the food chain). The rapid recreational development of this scenic region and the future operation of large-scale, coal-fired power generation facilities in the area make current mercury levels of particular interest, as they may provide an opportunity to determine if such activities will detectably alter the background mercury levels.

Lake Powell, a Bureau of Reclamation storage and hydroelectric generation reservoir, initially was impounded in 1963 and reached a 1971 elevation of 1104.3 meters with a volume of 17,860.6 x 10^6 cubic meters (14 million acre-feet). The lake has a potential capacity of 33,304.5 x 10^6 cubic meters (27 million acre-feet), with a length of 300 kilometers. Annual runoff into the lake is approximately 14,800 x 10^6 cubic meters (12 million acre-feet). The deeply dissected sandstones and shales of the canyons of the Colorado River system in southeastern Utah and northern Arizona produce a shoreline characterized by precipitous cliffs, sparse vegetation, and little soil development.

The reservoir is a warm monomictic lake of low turbidity. Secchi disk visibility in the lower reservoir is 10.4 meters (Gloss, 1971) with more turbid conditions occurring at the head of Lake Powell near Hite. Based on productivity studies during 1971 to 1972, Hansmann et al. (1973) classify the lower reservoir as being naturally eutrophic, with a mean annual productivity rate of 465.9 mg C/m^2 per day and a mean daily productivity rate during the growing season of 645.7 mg C/m^2.

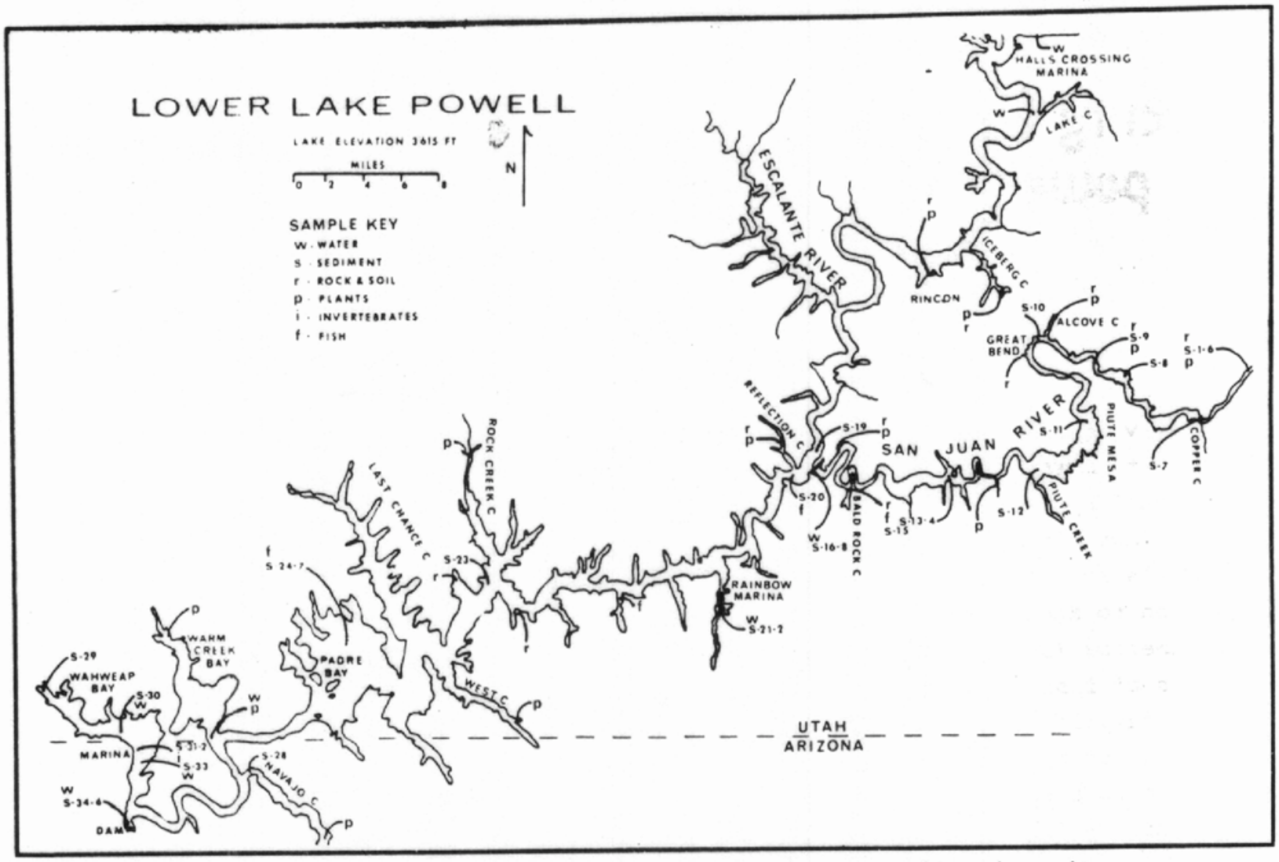

Figure 1: Map of lower Lake Powell showing sample collection sites. The lake extends an additional 80 kilometers north to Hite, Utah, where additional fish and water samples were taken.

MATERIALS AND METHODS

Samples were collected at the sites shown in Figure 1 from June 1971 to October 1972. Terrestrial materials were collected in plastic bags, air dried, and stored in the original bags. Water samples were preserved in glass or polyethylene containers with 3 ml/liter 50% nitric acid and were analyzed within 2 weeks after collection. Sediments were collected with an Eckman dredge, immediately bagged in plastic, field refrigerated, and frozen until analysis. Fish were measured and weighed, wrapped in foil, and frozen. Other lake materials were field refrigerated in plastic containers and kept frozen until analysis.

When sufficient material was available, sample sizes of 1 g for organic material and 5 g for mineral material were used. From two to five replicates of each sample were prepared. If practical, materials were ground or blended to prepare homogeneous samples. To facilitate tissue separation, fish were dissected while partially frozen. The mercury in water samples was concentrated 10 to 20 times, as described by Chau and Saitoh (1970).

Analyses were made through the flameless atomic absorption procedures of Hatch and Ott (1968) and Uthe et al. (1970), as modified for use with a Perkin-Elmer Model 306 atomic absorption spectrophotometer and a Perkin-Elmer mercury analysis system.

RESULTS AND DISCUSSION

Water

Wershaw (1970) concludes that unpolluted fresh waters, except when associated with special geological conditions, can be expected to have mercury levels of 0.1 ppb or less. U.S. Geological Survey data (Wershaw, 1970) indicate levels at or below the 0.1-ppb detection limit for 34 of 73 samplings, including a level of <0.1 ppb for a section of the Colorado River near Yuma, Arizona. Stock and Cucuel (1934), as well as other analyses cited by Wershaw, report levels as low as 0.01 ppb. Analyses of 12 water samples from 9 locations in Lake Powell (Figure 1), including surface and 4- or 5-meter depths, yielded a mean level of approximately 0.01 ppb ($\bar{x}$ = 0.0091 ppb; S.D. = 0.0010; recovery = 92.2%) with no significant difference between the stations or depths sampled. At this concentration, the upper 5 meters, which represent 12% of the 1971 maximum volume, would contain only 21.5 kg of mercury. The lake water itself thus contains only a small quantity of mercury, and any input of mercury is likely to move through the water phase of the system into sediments or organic material (Jenne, 1970; Carr and Wilkniss, 1973).

Rocks, Soils, and Sediments

The U.S. Geological Survey reports a wide range of mercury levels (<10 to >6000 ppb) in the sedimentary rock strata of the Lake Powell region (Cadigan, 1970). Navajo Sandstone, a major formation at Lake Powell, yields levels of <10 to 40 ppb and a mean of 21 ppb at sites near the lake (Cadigan, 1969). Cadigan reports higher mercury levels in the Navajo Sandstone elsewhere in the drainage, and median mercury levels of 100 to 260 ppb in other strata outcropping in the lake region. Currently, these extensive beds of mercury-bearing sedimentary rocks probably are the primary source of the mercury in the Lake Powell ecosystem.

Table 1: Mercury content of rocks and unconsolidated terrestrial substrates.

	$\bar{x}$ ppb mercury (range)	Samples/ Replicates	Median C.V. (S.D. x 100 / $\bar{x}$)
Sandstone	9.7 (3-14)	7/21	9.1
Mudstone and shale	6.7 (0-27)	10/30	13.4
Sand	4.1 (1-18)	17/51	15.3
Silt and clay	10.5 (2-21)	8/27	14.6
Substrates containing organic matter	16.6 (2-48)	15/75	16.5

Percent recovery for geological materials:

µg mercury added	Percent Recovered	Samples/ Replicates	Mean C.V.
0.040	96.0	2/5	7.1

Surface rock material collected for this mercury survey from the Navajo Sandstone and other major formations outcropping on the shoreline yields levels less than 30 ppb (Table 1). These levels do not reflect the higher portion of the range reported by the U.S. Geological Survey. The discrepancy may be due to limited sampling of only weathered surface material. It is also possible that the acid-digestion procedure used for both organic and inorganic materials is a less efficient extractor of geological mercury than the vaporization-precious-metal-trapping procedure designed for inorganic mercury and used by the U.S. Geological Survey (Ward, 1970).

The predominant surface substrates of the Lake Powell region are the barren sedimentary rock strata and the unconsolidated low-organic materials derived from them. Samplings of these low-organic materials yield mercury levels below 30 ppb. Sand is particularly low in mercury content; 76% of the 17 samples collected yield mercury levels below 5 ppb and only 1 sample has a level above 10 ppb. In areas where soil organic matter does occur (e.g., seeps, oak and cottonwood groves, and shallow mudflats), mercury levels are frequently higher than those of inorganic substrates. Fifty-three percent of those samples which contain appreciable organic matter yield mercury levels greater than 10 ppb (the litter and A-1 horizon from a cottonwood grove yield 48 ppb, the highest of any shoreline substrate analyzed). At Lake Powell, substrates containing appreciable organic matter are probably not sufficiently prevalent to be of major importance. As water impoundments are common in such arid and semiarid regions, a clear definition of the weathering and movement of heavy metals in dry, low-organic, terrestrial environments may be a significant factor in understanding the problems of heavy metals in reservoirs.

Although the mercury levels in bottom sediments from behind Glen Canyon Dam (Table 2) are among the highest of the sediments sampled, no clear gradient of mercury levels is observed with respect to distance upstream from the dam. This finding is consistent with that of Drake (1972a) who observes that there is variable sedimentation due to slumping and to the formation of sediment dams, with fine-grained sediments predominating in the lower reservoir. Fineness of texture, relatively high organic content, and a mid-channel location are characteristic of bottom sediments with higher mercury levels. With the exception of one sediment sample taken from the Wahweap Marina, all sediments which contain more than 20 ppb of mercury are either fine-grained or relatively high in organic matter. Tributary canyon and off-channel sediments, which are usually sandy and low in organic content, are usually low in mercury content. A sewage-laden sediment from near Rainbow Bridge Marina yields 26 ppb mercury, compared to 14 ppb for a sample upstream from the sewage outlet. Although additional sampling at sites of organic enrichment is needed to confirm the relationship, the findings thus far indicate that recreational developments may affect mercury levels by increasing the organic content of sediments.

Drake (1972b) estimates that sedimentation is occurring at the rate of 2.3×10^6 metric tons per month, and that about one-twenty-fifth of the 1971 maximum volume of Lake Powell has been filled with sediment during the first 8 years of the Lake's impoundment. Because the mercury

Table 2: Mercury content of bottom sediments from lower Lake Powell and the San Juan arm of the lake.

Site	$\bar{x}$ ppb mercury (95% C.I.=$\bar{x}\pm t0.05s_{\bar{x}}$)	Samples/ Replicates	Depth (m)	Texture - relative organic content
Main Channel				
(19) Above San Juan R.	32 (24-40)	1/3	105	clay-med. organic
(20) Below San Juan R.	49 (34-64)	1/3	103	clay-med. organic
(23) Below Rock Creek	13 (4-22)	1/4	5	sand-low organic
(24) Padre Bay	30 (19-41)	1/3	132	clay-med. organic
(34-36) Dam	49 (45-53)	3/11	120	clay-high organic
San Juan River				
(1-6) Head of Lake	40 (34-46)	6/18	1-9	clay-med. organic
(7) Copper Canyon	29 (28-29)	1/3	13	clay-low organic
(8-10, 12-14) Midway	31 (29-34)	6/18	22-78	clay-med. organic
(11) Piute Mesa	18 (15-21)	1/3	15	sand-med. organic
(15) Bald Rock Canyon	30 (26-33)	1/3	99	clay-med. organic
(16) Mouth	37 (34-40)	1/3	107	clay-med. organic
(17) Mouth	17 (13-22)	1/3	106	silt-med. organic
(18) Mouth	5 (3-7)	1/3	36	sand-low organic
Tributary Canyons				
(21) Rainbow Marina	26 (25-27)	1/3	87	sand-high organic (sewage)
(22) Rainbow Marina	14 (11-16)	1/3	81	sand-low organic
(22) Rainbow Marina	4 (2-6)	1/3	81	sandstone rock
(25) Padre Bay	6 (5-8)	1/3	58	sand-med organic
(26) Padre Bay	18 (16-19)	1/4	55	sand-low organic
(27) Padre Bay	22 (18-25)	1/3	59	clay-med organic
(28) Navajo Canyon	19 (16-22)	1/3	130	sand-low organic
(29) Wahweap Bay	13 (12-15)	1/3	9	sand-low organic
(30) Wahweap Beach	9 (1-17)	1/3	13	sand-low organic
(31) Wahweap Marina	13 (11-16)	1/3	16	sand-low organic
(32) Wahweap Marina	5 (3-7)	1/3	25	sand-low organic
(33) Wahweap Marina	33 (31-36)	1/4	60	sand-low organic
(33) Wahweap Marina	53 (31-74)	1/3	56	clay-low organic

concentrations of sediments in Lake Powell are about 3000 times that of the surface water, the major portion of the mercury in the lake system can be expected to accumulate in the sediment load, from which mercury may be released to the biota and water by both biological and abiotic processes (Jernelöv, 1969).

Plant Material

Mercury levels in the terrestrial vascular plants (Table 3) are found to be within a range common to the rock strata, as Shacklette (1970) suggests is usually true for land plants. Leaves and other green tissue have significantly higher

Table 3: Mercury content of plant material.

Plant material	Leaf and other green tissue	Stem	Root
	$\bar{x}$ ppb mercury (Samples/Replicates) (95% C.I.=$\bar{x}\pm t0.05s_{\bar{x}}$)		
Vascular plants			
Singleleaf ash (*Fraxinus anomala*)	65[a] (2/5) (11-118)	18 (2/7) (8-28)	
Gambel oak (*Quercus gambelii*)	59 (1/4) (55-64)	16 (2/7) (13-19)	
Fivestamen tamarix (*Tamarix pentandra*)	57 (1/4) (43-71)	12 (1/4) (6-18)	
Sacred datura (*Datura meteloides*)	46 (3/9) (44-48)	14 (2/7) (12-16)	11 (2/3) (3-19)
Jointfir (*Ephedra* sp.)	40 (4/10) (23-56)	42 (1/4) 38-47)	16 (2/5) (11-21)
Southern maidenhair fern (*Adiantum capillus-veneris*)	44 (1/4) (39-50)		
Arrowweed (*Pluchea sericea*)	41 (1/2)	3 (1/3) (0-7)	
Willow (*Salix* sp.)	39 (1/4) (36-43)	6 (1/2)	
Sand dropseed (*Sporobolus cryptandrus*)	35 (2/7) (29-41)		
Threadleaf snakeweed (*Gutierrezia microcephala*)	32 (2/8) (27-36)		19 (4/11) (17-21)
Fremont cottonwood (*Populus fremontii*)	30 (2/7) (27-33)	9 (2/10) (7-11)	
Fourwing saltbush (*Atriplex canescens*)	28 (7/23) (25-31)	6 (5/19) (5-7)	6 (5/19) (4-8)
Deserttrumpet eriogonum (*Eriogonum inflatum*)	27 (4/13) (22-32)		9 (4/14) (5-12)
Cocklebur (*Xanthium saccharatum*)	23 (1/3) (20-26)	4 (1/3) (0-9)	16 (1/2)
Shadscale (*Atriplex confertifolia*)	22 (2/7) (18-27)		
Indian ricegrass (*Oryzopsis hymenoides*)	19 (5/18) (14-24)		
Sedge (*Carex* sp.)	18 (1/4) (14-23)		
Utah juniper (*Juniperus osteosperma*)	18 (1/4) (15-21)	13 (1/4) (8-17)	
Yucca (*Yucca utahensis*)	15 (2/7) (5-25)		

Table 3 (Continued)

Plant material	Leaf and other green tissue	Stem	Root
	$\bar{x}$ ppb mercury (Samples/Replicates) (95% C.I.=$\pm t0.05 s_{\bar{x}}$)		
Nonvascular plants			
Algae-lichen soil crust	23 (1/4) (14-22)		
Moss from flowing seep	16 (1/3) (12-20)		
Shallow water periphyton	32 (3/10) (21-42)		
Algae on shoreline sand	15 (1/4) (8-21)		
Lake-submerged plants			
Threadleaf snakeweed (*Gutierrezia microcephala*)		90[b] (2/8) (76-104)	
Unidentified shrub		39 (1/2)	
Common cattail (*Typha latifolia*)	36 (1/4) (25-47)		
Jointfir (*Ephedra* sp.)	25 (1/2)		
Utah juniper (*Juniperus osteosperma*)	18 (1/3) (0-40)	21[b] (1/4) (19-23)	
Unidentified grass	15 (1/4) (10-20)		
Lake-transported plant debris			
Head of San Juan River		283[b] (1/3) (203-364)	
Rincon		173[b] (1/5) (160-186)	
Warm Creek Bay		143[b] (4/16) (124-162)	
Rock Creek Bay		141[b] (2/8) (131-151)	
Navajo Canyon		85[b] (1/5) (78-91)	
West Canyon		43[b] (4/16) (38-48)	

Percent recovery for plant material:

µg mercury added	Percent recovered	Samples/ Replicates	Mean C.V.
0.0250	99.8	2/9	14.2

[a] Line denotes no significant difference between underlined tissues ($P < 0.05$)

[b] Denotes significant difference between lake influenced material and terrestrial plant material ($P < 0.05$)

mercury levels than do nongreen stems and roots. Mercury levels in water-associated plants and nonvascular plants do not differ markedly from those of the typical desert vegetation. Submerged decomposing snakeweed (Gutierrezia microcephala) from Reflection Canyon has a mean mercury content of 90 ppb compared to 32 ppb for adjacent unflooded snakeweed growing on the same substrate. Mercury levels in lake-transported debris are significantly higher than those of terrestrial plant material, further suggesting that mercury is concentrated in some flooded plant material. While biological uptake, as reported by Wood et al. (1968) and Jensen and Jernelöv (1969), could be occurring in this material, Hannerz (1968), Heme (1970), Jenne (1970), and Friedman and Waiss (1972) suggest that abiotic sorption is an important uptake mechanism in organic materials.

Even with sparse vegetation, debris impoundment from an extensive drainage and the growth of tamarix (Tamarix pentandra) and other plants in the drawdown zone provide an additional route for mercury movement into the aquatic system. Through enrichment, plant debris with mercury levels 10^4 times that of the surface water may enter the lake food chain. Jernelöv (1969) emphasizes the importance of organic matter as an energy source for the biotransformation and biological uptake of mercury. Thus, plant material, as a nutrient source, may also contribute to mercury movement in the lake system.

Invertebrates

The only invertebrates analyzed are 17 crayfish collected from the shoreline near Wahweap Marina. These crayfish have a mean whole-body mercury content of 10.0 ppb, wet weight (range: 2 to 23 ppb). On a dry-weight basis, the mercury content of these crayfish would indicate some accumulation of mercury above the levels of the shallow-water sediments of Wahweap Bay ($\bar{x}$ = 10.0 ppb). Mercury levels in crayfish are 10^2 times that of the surface water. These concentrations represent a low-level source to predatory fish, but the increase in mercury levels in larger crayfish (Figure 2) provides a higher dietary mercury source to larger predatory fish.

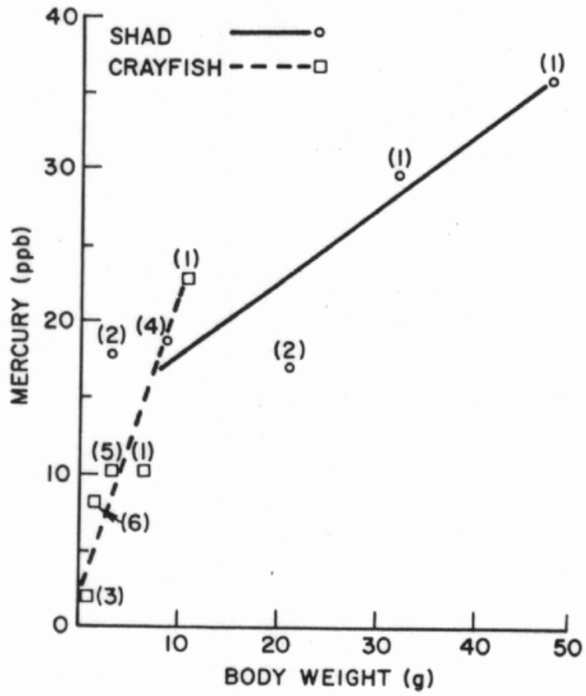

Figure 2: Relationship of the whole-body mercury concentration of threadfin shad and crayfish to body weight. (The number of specimens of each size class is in parentheses.)

Fish

The mercury content of fish tissue ranges from <5 to >700 ppb (Table 4).

Table 4: Sample size, weight, and mercury content of fish (in ppb).

	WALLEYE	LARGE-MOUTH BASS	TROUT	BLACK CRAPPIE	BLUEGILL	CARP	FLANNEL-MOUTH SUCKER	$\bar{X}$ ALL SAMPLES	MEDIAN COEFF. OF VARIATION
No.	8	7	3	7	8	5	3	41	
Wt. (g)	1597	1098	1125	441	193	574	653	812	
Wt. Range	(300-3350)	(350-2225)	(140-2015)	(300-600)	(151-230)	(513-638)	(650-660)	(140-3350)	
Muscle	427 (209-763)	314 (192-688)	84.5 (73-101)	204 (157-294)	91.0 (57-127)	252 (181-339)	98.8 (48-186)	232 (48-763)	12
Liver	149 (42-362)	163 (53-587)	186 (27-384)	62.2 (38-88)	86.6 (62-96)	152 (55-217)	36.2 (9-33)	122 (9-587)	14
Heart	135 (63-320)	102 (19-421)	228 (137-404)	22.4 (11-37)	129 (87-158)	66.7 (51-84)	14.6 (11-25)	97.8 (11-421)	12
Kidney	86.2 (40-136)	144 (44-498)	253 (93-326)	26.9 (10-43)	28.6 -	180 (95-251)	33.9 (19-56)	107 (10-498)	13
Spleen	77.7 (28-160)	168 (26-673)	257 (192-346)	25.6 (9-50)	-	-	29.0 (28-30)	101 (9-673)	10
Stomach	87.3 (30-158)	79.2 (26-280)	89.3 (78-107)	27.2 (18-47)	35.9 (28-47)	32.0 (21-43)	11.6 (3-25)	56.1 (3-280)	17
Brain	17.2 (4-31)	41.0 (4-74)	98.2 (67-152)	5.5 (0-10)	29.5 (23-36)	86.5 (60-120)	10.9 (6-14)	35.1 (0-152)	-
Gonads	42.2 (16-91)	34.0 (11-107)	68.7 -	11.1 (4-16)	23.6 -	60.4 -	9.9 (4-19)	29.6 (4-107)	12
Skin & Scales	22.5 (12-37)	17.4 (4-27)	13.1 (12-15)	5.5 (-1-9)	40.3 (29-68)	23.7 (16-36)	11.6 (3-21)	18.7 (-1-68)	17
Gills	51.1 (29-78)	42.7 (14-100)	94.4 (55-128)	11.6 (5-20)	15.7 (9-22)	28.1 (19-39)	10.0 (8-11)	36.6 (5-128)	13
Bone	15.7 (7-29)	18.8 (3-37)	16.4 (2-33)	5.5 (1-11)	10.4 (0-24)	25.2 (16-31)	8.1 (3-11)	14.0 (1-37)	28

The mean recovery of mercury from fish muscle tissue was 101.6% (S.D. = 9.81), and, as suggested by Johnels et al. (1967), patterns of concentration occur among tissues. Axial muscle has the highest mercury content of all tissues analyzed in five of seven taxa. Only in rainbow and brown trout (*Salmo gairdneri* and *Salmo trutta*), where bloody tissues have the highest levels, is the mercury content of other tissues markedly higher than those of muscle (Figure 3). Hasselrot (1968) reports similar relative levels for *Salmo*, as do Rucker and Amend (1969) for tank experiments with rainbow trout. The mercury contents of skin and bone are relatively low in all species, as are gill levels for species other than trout. Gonad, brain, and stomach levels are low to intermediate; higher levels occur in spleen, kidney, heart, and liver tissue. The ratio of mean mercury content of all nonmuscle tissue to muscle content (Figure 3) seems characteristic of a species, and it suggests that patterns of uptake, accumulation, and elimination differ among species, with those of trout being particularly distinctive.

For those species for which fish of widely differing weights were analyzed, larger fish have higher mercury levels (Figures 2 and 4). This relationship is evident for the muscle and liver tissues of

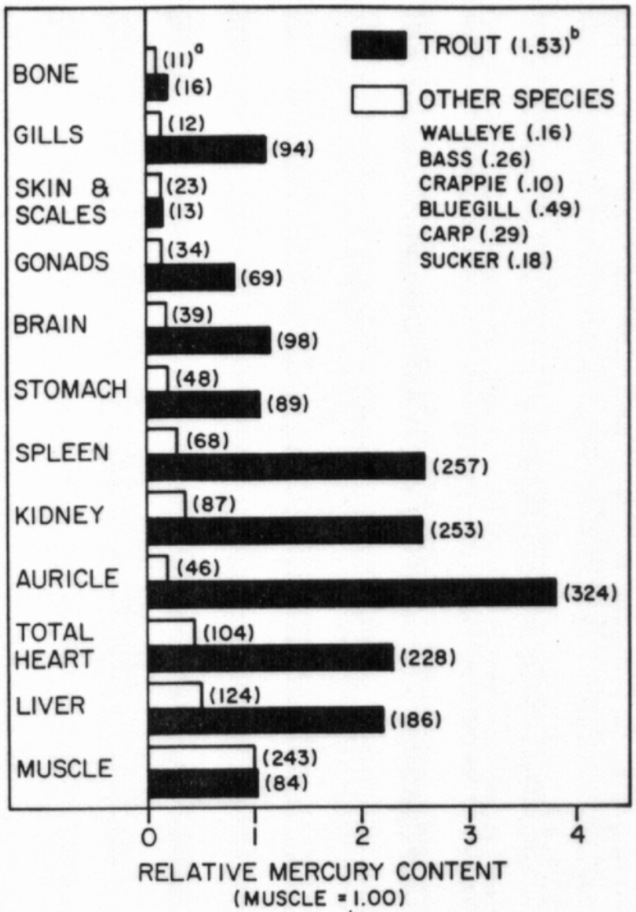

Figure 3: Relative mercury content of fish tissues: (a) mean ppb mercury; (b) mean relative mercury content of taxa nonmuscle tissue compared to muscle as 1.00.

walleye (Stizostedion vitrium), largemouth bass (Micropterus salmoides), and rainbow trout, and for the whole-fish analysis of threadfin shad (Dorosoma petenense). Mean muscle levels of fish taxa are also positively related to mean body weights (Figure 5). No sampled fish which weigh less than 2000 g have mercury levels above the currently accepted safe standard for human consumption of 500 ppb. Of six fish weighing more than 2000 g each, four (one largemouth bass and three walleye) have muscle levels exceeding 500 ppb. The mean muscle content of the three large walleye ($\bar{x}$ wt. = 2615 g) is 680 ppb, and that of the largest bass (2225 g) is 688 ppb. A slightly smaller bass (2050 g) has a muscle content of 394 ppb, while a rainbow trout of similar size (2015 g) has only 101 ppb mercury in axial muscle tissue. This reflects the marked difference in mercury content of trout bloody tissue versus trout muscle tissue. Significant findings of this preliminary survey are that levels exceeding 500 ppb may be common in the larger predatory fish of Lake Powell, and that these levels occur in a recently impounded reservoir with no evident local pollution.

There is a positive relationship of food habits to both stomach and axial

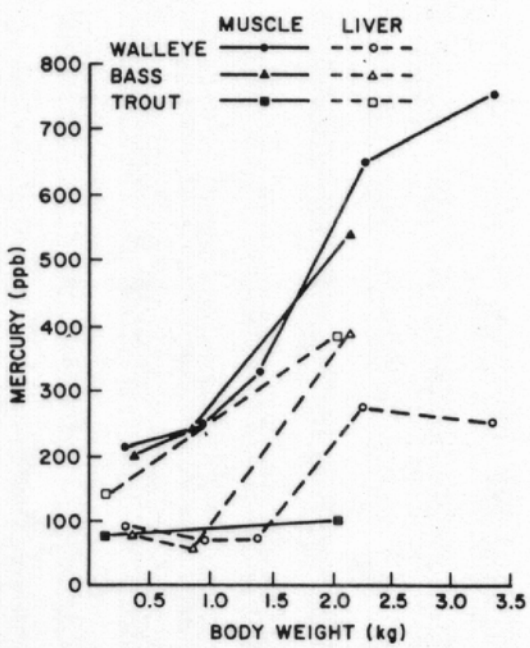

Figure 4: Relationship of the mercury concentration of axial muscle and liver tissue to body weight in walleye (n=8), largemouth bass (n=7), and rainbow trout (n=2).

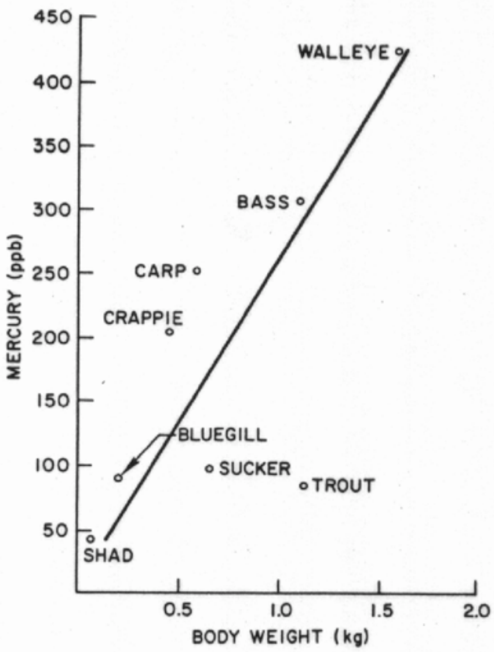

Figure 5: Relationship of the mean mercury concentrations of axial muscle tissue of eight taxa of fish to the mean body weight of each taxon.

muscle levels (Table 4 and Figure 6). Walleye, bass, and trout (the three species with the highest tissue mercury levels) are the highest trophic level fish. Flannelmouth sucker (Catostomus latipinnus), a low trophic level fish which feeds on plant material and small invertebrates, has the lowest species mercury levels for 5 of the 11 tissues analyzed. (The displacement of flannelmouth sucker to the right in Figure 5 is most logically explained by its trophic level.) Carp (Cyprinus carpio), a low trophic level omnivore, seems to contain higher mercury levels than its food chain position would indicate. However, plant debris, which has high mercury levels, is a major carp food. Also, the carp habit of bottom feeding may associate it with a higher mercury environment than that of fish with different foraging habits. The indication of a positive weight-mercury-content relationship in threadfin shad, the principal forage fish, and in other fish and crayfish as well, suggests that fish which take large prey have higher

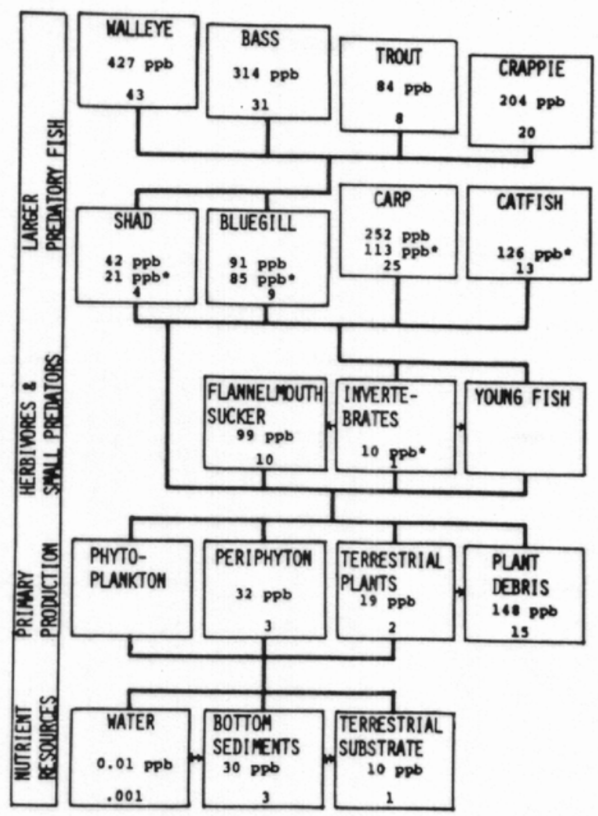

Figure 6: Relation of Lake Powell trophic levels to mean ppb mercury and magnification factor (underscored) relative to shoreline substrate. Values with an asterisk (*) are whole-body analyses; other fish values are of axial muscle. Plant and mineral values based on dry weight.

dietary mercury levels, and this factor is a major reason for the correlation of size with mercury levels. However, other factors such as age, body surface area, metabolism, habitat, and activity patterns are also important variables that affect the mercury levels in fish of various weights and species (Hannerz, 1968).

In gathering data from short-term tank experiments, Hannerz has found that mercury uptake occurs through both food uptake and surface absorption, with the latter predominating under most test conditions. In absorption experiments, Hannerz commonly has found an inverse relationship between size and mercury content and has found that gills and skin often contain higher levels than does muscle. Data from the current study of a natural system reflect the reverse of both these trends. However, the mercury concentrations in the skin and gills of the Lake Powell fish have a magnitude of 10^3 times that of the water, which might indicate direct absorption of mercury by these tissues. From his extensive tests, Hannerz concludes that mercury uptake and elimination are controlled by a complex of variables and that conclusions drawn from high-level short-term experiments are not likely to be applicable to most natural situations. Controlled experiments in Lake Powell or other relatively unpolluted waters perhaps would more clearly define the roles of diet, surface absorption, and metabolism, and would help clarify the extent to which observed trophic-level concentration is actually due to food intake.

Ecosystem Mercury Flow

Critical mercury concentrations are being approached in the higher trophic levels due to bioamplification (Figure 6). If mercury contents above 500 ppb are confirmed as being common to the muscle of large game fish, mercury levels could become a significant factor in the management of the Lake Powell fishery. Imposing consumption limits on large game fish or managing the fishery in order to yield a low-mercury catch might become advisable, if there is an increase in mercury in the system. As critical levels are being approached, the formulation of a quantitative mercury budget is desirable in order to evaluate the probability of increased mercury levels due to man's activities in the region.

Figure 7 is a model of the mercury budget and flow in the Lake Powell ecosystem. Using Drake's (1972b) estimate of the natural sediment load of the Colorado River, the net annual degradation of the Upper Colorado River Basin is 27.2 million metric tons. Based on U.S. Geological Survey data (Cadigan, 1970), a reasonable estimate of the mercury in the geological material degraded from the Basin is in the 50- to 200-ppb range. Using this range, the annual weathering of mercury in the Lake Powell drainage can be set at from 1360 to 5440 kg of mercury.

If the water of the natural Colorado River is assumed to contain 0.01 to 0.1 ppb mercury in its 15.3×10^9 cubic meters of annual flow (Jacoby and Anderson, 1972), the unimpounded flow from the upper basin would carry 153 to 1530 kg of mercury. At 30 ppb (the mean for this study's analyses of Lake Powell sediments), the sediment load of the natural river would be 816 kg of mercury. Thus, the total estimated annual mercury load for the free-flowing river is from 969 to 2346 kg. Any difference between the total amount of mercury transported by the river and that weathered would represent either net atmospheric transport or accumulation within the system.

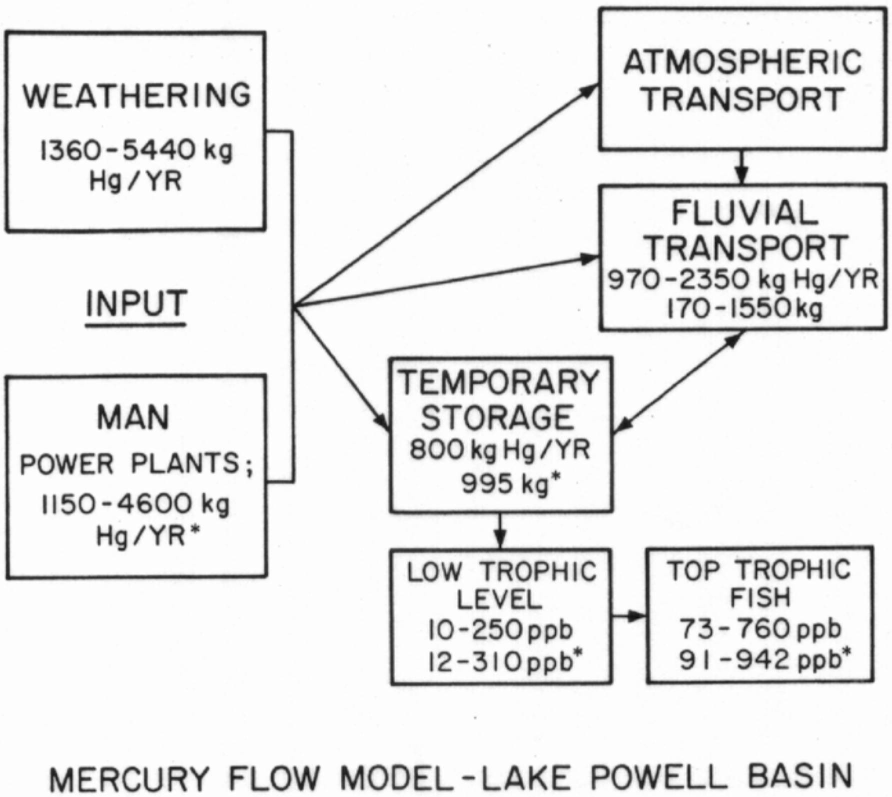

Figure 7: Model of budget and flow in the Lake Powell ecosystem.

In the present impounded system, water flow has been slightly reduced, and the sediment load of the river below Glen Canyon Dam has been reduced to less than 1% of the original load. Because weathering and other terrestrial components of the system remain fundamentally unchanged, impoundment logically will lead to the accumulation in the lake of most of the original sediment load of the river, suggesting that approximately 800 kg of mercury may now be accumulating annually. That this accumulation occurs in an aquatic system containing the organisms and energy sources necessary for the uptake and biotransformation of mercury is likely to be the fundamental reason that such impoundments may be vulnerable to environmental mercury problems. In addition to giving an estimate of the quantities of mercury involved, these computations suggest that a natural equilibrium situation has been converted into a storage system. Both the Lake Powell data and those from other aquatic systems (Peakall and Lovett, 1972) indicate that biological components become the points of maximum concentration of mercury in such storage systems.

From data compiled by the U.S. Department of the Interior (1972), it can be estimated whether or not mercury produced by coal-fired power-generation facilities will add significantly to the natural mercury budget of the Lake Powell drainage system.

Three major powerplants in the Upper Colorado River Basin (essentially the Lake Powell drainage) are considered in the analysis which follows. The Four Corners plant, near Shiprock, New Mexico, approximately 200 kilometers (125 miles) from Lake Powell, has been in limited production since 1964, and it reached a fuel consumption level of 6.5 million metric tons in 1971. The Navajo plant at Page, Arizona, currently under construction approximately 6.4 kilometers (4 miles) south of Lake Powell, will consume 5.4 million metric tons annually by 1976. A proposed Kaiparowits plant, approximately 18 kilometers (11 miles) north of Lake Powell, is expected to burn 10.8 million metric tons of coal annually when it reaches full capacity sometime after 1980. Thus, the total annual coal consumption by these major facilities is estimated to be approximately 23 million metric tons. At this consumption level, an annual mercury output of 23 kg for each part per billion of mercury in the coal would occur. Based on studies of the Four Corners plant, 96% of the mercury in the coal is released as vapor. Since a significant fraction of the remaining mercury enters the environment as fly ash or other wastes, essentially all of the mercury in the coal is released into the environment. If a 200-ppb mercury content is assumed for the coal (200 ppb is the estimated mean mercury content for U.S. coals), the annual mercury output of the three Upper Colorado River Basin powerplants would be 4600 kg. As this output is of the same magnitude as the estimated weathering (1360 to 5440 kg), it is likely that the mercury budget of the Basin will be significantly augmented. This augmentation may be particularly important in view of the fact that impoundment has reduced the ability of the Colorado River to carry even its original mercury load.

Preliminary tests of coal from the Navajo plant indicate that coal mercury levels may average only 30 ppb. At this level, the Navajo plant would produce only 162 kg of mercury per year. Using the estimate that 40% of this mercury enters the lake drainage (Walther, 1971), 65 kg of mercury would be added to the system annually, which is 8% of the estimated present annual accumulation of mercury in the lake system, and only 1 to 5% of the estimated natural annual weathering of mercury in the Upper Colorado River Basin. Thus, due to the magnitude of the lake system and to the movement of natural mercury within it, it is likely that the Navajo powerplant can operate adjacent to Lake Powell without significantly affecting lake mercury levels, if mercury levels of coal are in fact near the range which current analyses indicate.

No data on the mercury content of the coal for the Kaiparowits plant are available. However, if the combined effect of the Navajo and Kaiparowits plants is computed on the basis used for the Navajo plant, enough mercury could enter the system to raise sediment mercury levels by approximately 24%. While this would represent the addition of only 7 ppb mercury to the sediments, if biological concentration factors remain similar to those found in this study (Figure 6), detectable and environmentally significant elevation of mercury concentrations in the higher trophic levels would occur. Based on current bioamplification factors, a 24% increase in sediment levels would result in a 70-ppb increase in the mean muscle levels of bass and a 105-ppb increase in walleye muscle levels. In walleye, the 105-ppb increase would elevate the mean mercury content of a sampling similar to the one analyzed to above 500 ppb (532 ppb). The mean mercury content in muscle tissue of bass and walleye weighing more than 2000 g would be elevated 150 ppb from 627 to 777 ppb. Increases in mercury levels of these magnitudes would not result in levels known to be harmful to the lake biota, but such increases could affect the human utilization of the lake fishery. It should be emphasized that these calculations are based on mercury levels in coal of 30 ppb and on mercury movement within the system as indicated by this preliminary study. If mercury levels in the coal are higher than the estimated 30 ppb, or if the mercury from the higher level coals (estimated to be 300 ppb) from the more distant Four Corners powerplant does move effectively into the lake system, a more serious impact would result.

These estimates suggest that both the impoundment of the Colorado River and the projected development of power-generation facilities are events of sufficient magnitude to affect the mercury budget of the Upper Colorado River Basin. The definition of the mercury budget of this system, the actual quantities and movement of mercury released by human activity, and the movement of mercury into the biota of the reservoir both currently and as the system ages, should provide the basis for a constructive regional mercury research program. As numerous institutions are already involved in environmental research in the Upper Colorado River Basin, a cooperative regional mercury program could appropriately be directed toward the development of an accurate model of mercury movement that would increase the efficiency of the currently diverse efforts to predict or monitor mercury levels in this major drainage basin.

SUMMARY

Lake Powell is a major storage and hydroelectric reservoir on the Upper Colorado River in northern Arizona and southern Utah. Impoundment began in 1963, and by 1971 a water volume of 17,860.6 x 10^6 cubic meters (14 million acre-feet) had been reached. Samples of organic and inorganic components of the Lake Powell ecosystem were collected during 1971 and 1972, and were analyzed for mercury content by flameless atomic absorption.

Surface shoreline substrates, consisting mostly of sandstones and shales, and low-organic unconsolidated materials derived from the sedimentary strata, have a mean mercury content of 10 ppb. Where significant quantities of soil organic matter are present, mercury levels as high as 48 ppb are found.

Leaves of terrestrial plants have a mean mercury content of 34 ppb dry weight, which is significantly higher than levels in plant stems and roots. Nonvascular plants and water-associated plants have levels in the same range as those of the typical terrestrial vascular plants. Lake-transported plant debris has a mean mercury level of 145 ppb, which is significantly higher than that of terrestrial plants. It is suggested that the mercury content of this plant material may result from either biological uptake by associated microorganisms or from passive absorption due to the affinity of mercury for organic materials.

Twelve water samples taken from the upper 5 meters of the lake yield a mean mercury level of 0.01 ppb, indicating that the lake water contains relatively small quantities of mercury.

Mercury levels in bottom sediments average 30 ppb, with no clear gradient of mercury concentrations relative to distance from Glen Canyon Dam. Fine-grained sediments and sediments of relatively high organic content have higher mercury levels than do coarser, low-organic sediments.

Crayfish, the only invertebrates analyzed, have a mean whole-body mercury content of 10 ppb wet weight and exhibit a positive relationship between mercury content and body weight.

Threadfin shad, the major forage fish of the lake, and three major large predatory fish (walleye, largemouth bass, and rainbow trout) also show a positive mercury-content wet-weight relationship. In fish, the mercury levels of axial muscle are generally higher than those of other tissues. Muscle levels range from 84 ppb in trout to 427 ppb in walleye, with a mean of 232 ppb for all species analyzed. In largemouth bass and walleye, fish weighing more than 2000 g have mean muscle levels exceeding 500 ppb ($\bar{x}$ = 626 ppb), the accepted upper limit considered safe for human consumption. In rainbow and brown trout, bloody tissues have the highest mercury levels, and trout have a pattern of tissue mercury levels distinctly different from those of the other species sampled. In the six other species of fish analyzed, relative mercury levels (compared to muscle as 1.00) are the following: liver, 0.51; heart, 0.43; kidney, 0.36; spleen, 0.28; stomach, 0.20; brain, 0.16; gonads, 0.14; skin, 0.13; gills, 0.12; and bone, 0.07.

Bioamplification is found to occur, and it results in mercury levels in the larger predatory fish that approach or exceed current safe-consumption standards. In order to evaluate the effects of future human activity on Lake Powell, an estimated mercury budget for the Upper Colorado River Basin is developed. This budget suggests that from 1360 to 5440 kg of mercury may be released annually by natural weathering in the Basin, and that impoundment of the river may lead to the accumulation of approximately 800 kg of mercury in the lake system each year. Coal-fired power-generation developments may produce 4600 kg of mercury annually and, thus, may augment significantly the mercury released by natural weathering in the Basin.

The operation of the Navajo powerplant, currently under construction adjacent to Lake Powell, is not likely to elevate significantly the lake mercury levels (if the mercury levels of the coal burned are near the current estimate of 30 ppb), due to the magnitude of the system and to the movement of natural mercury within it. However, the combined effects of the two major powerplant developments planned near the lake could significantly raise mercury levels in lake sediments and, through bioamplification, could increase mercury levels in large game fish by as much as 150 ppb.

The actual impact of power-generation facilities will depend on coal mercury levels and on the degree to which mercury output moves into the lake system and through the aquatic food chain. It is concluded that a clearer definition of these major factors of mercury flow can serve as a constructive framework for future regional mercury studies of the Upper Colorado River Basin.

ACKNOWLEDGMENT

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GLOSSARY [Ed. Note]

abiotic	not caused by the action of living species
bioamplification	buildup in concentration of a substance in the process of going from one trophic level to a higher one
biotransformation	conversion of a substance from one form to another (e.g., inorganic mercury to methyl mercury) as the result of the activity of living organisms
Eckman dredge	a device for collecting lake-bottom sediments
eutrophication	the process of becoming richer in dissolved nutrients
g	the symbol for weight in grams
mg C/m^2	milligrams of carbon per square meter
ml/liter	concentrations expressed in milliliters per liter
monomictic	describes a lake with only one yearly overturn, which is the process by which the oxygen-deficient bottom waters are raised to the surface and reoxygenated
ppb	concentrations expressed in parts per billion
Secchi disk	an instrument used to measure lake water transparency or clarity
taxon, taxa	units used to classify plants and animals
trophic	a feeding level in a food chain
turbidity	the state, condition, or quality of opaqueness of a fluid due to suspended matter
vascular	fluid-conducting tissues

Statistical Definitions

$\bar{x}$	arithmetic mean or average
S.D.	standard deviation
C.V.	coefficient of variance
C.I.	confidence interval
$\bar{x}$ + t0.05s	confidence interval at the 95% probability level

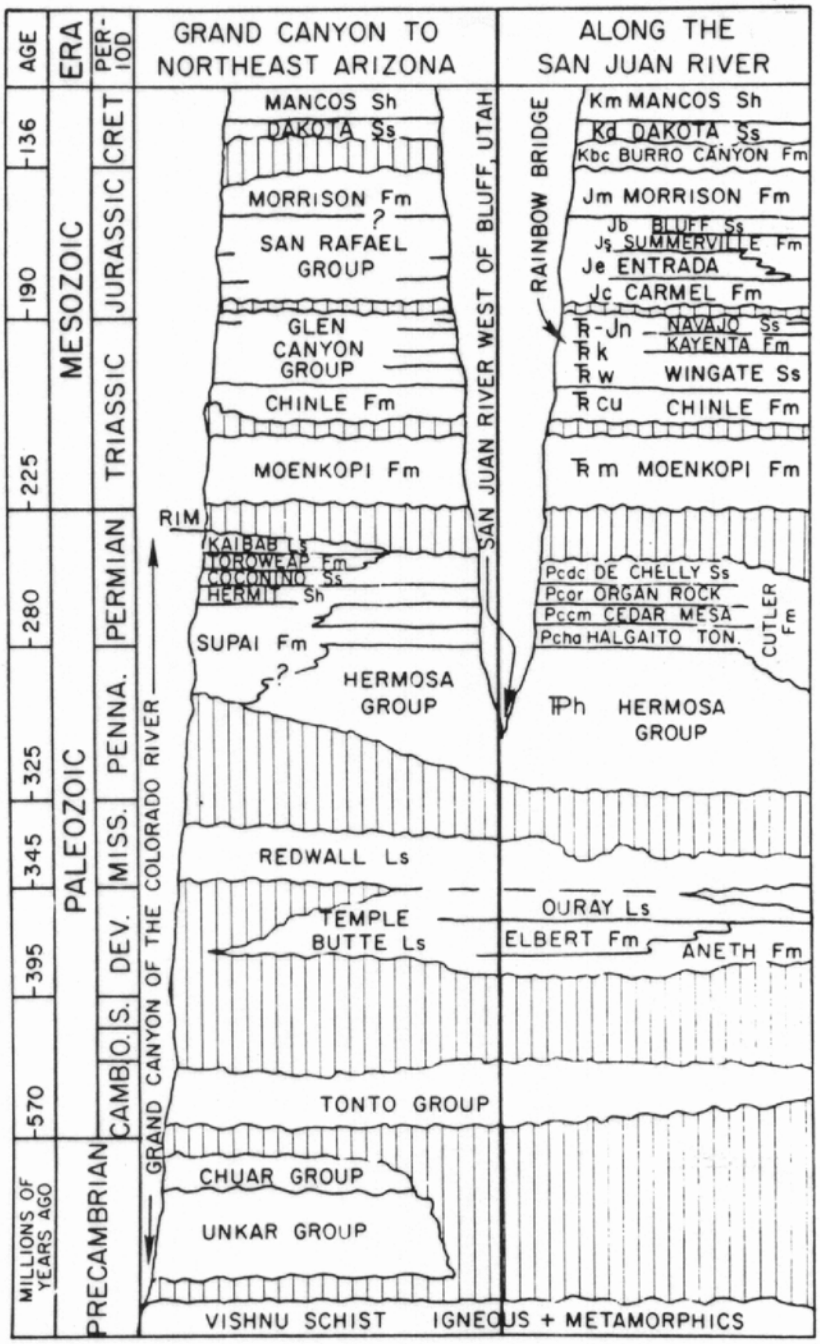
GEOLOGICAL FORMATIONS NEAR LAKE POWELL [Ed. Note]

Relative abundance of formations near Lake Powell[1]

Outcrops of Formation	Percentage of Total Area*
Navajo Sandstone, Glen Canyon Group	40.0
Chinle Fm	14.5
Cutler Fm	13.8
Kayenta Fm	12.7
Wingate Sandstone, Glen Canyon Group	6.0
Moenkopi Fm	5.6
Carmel Fm	4.5
Entrada Fm	2.9

*Percentage of area at earth surface consisting of each formation; area considered is lake substrate and zone within 2 miles of shoreline at maximum capacity.

Geologic columns for the Grand Canyon and Glen Canyon regions, Arizona and Utah[2]



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In addition to his research on Lake Powell, Kidd has studied the algae and ecology of ranch ponds in northern Arizona and the biology of Elephant Butte Reservoir in New Mexico. He is currently Principal Investigator of the Cultural Eutrophication Subproject and Co-Principal Investigator of the Heavy Metals Subproject of the Lake Powell Research Project.