Pumped Storage Environmental Effects: Assessment of Research Needs

D. H. Fickeisen

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PUMPED STORAGE ENVIRONMENTAL EFFECTS:
ASSESSMENT OF RESEARCH NEEDS

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SUMMARY

Pumped storage hydroelectric systems convert large quantities of electrical energy to a form that may be stored and efficiently reconverted to electricity. Water is pumped from a lower reservoir to an upper reservoir during periods of low power demand. The stored water is then used to generate additional power when demand peaks. Since the basic requirements of the system are simple, the design of individual plants and their locations vary widely. These variations make assessment of the generic environmental impact of the pumped storage systems difficult. In addition, most studies have not examined the impacts of an operating plant comprehensively.

Assessment of the environmental effects of development and operation of a pumped storage plant requires an extensive set of baseline information, which is deficient in several aspects at the present state of the art. Additional research is needed to

- identify species groups likely to survive and reproduce in pumped storage reservoirs, their relationships and habitat preferences, and the basis for their production
- characterize anticipated reservoir ecosystem community development and relate it to physical characteristics of pumped storage reservoirs
- define effects of plant design and operating parameters on transport of organisms through the pump/turbine facility, accounting for behavior of the organisms potentially impacted
- assess the mortality rate of organisms likely to pass through pump-turbines
- identify the relative advantages and disadvantages of screening intake structures to prevent passage of large organisms through the plant
- assess the effects of currents and water withdrawal on migration and movement of aquatic species
- investigate the effects of fluctuating water levels on the littoral zone and riparian communities, effects of stranding on entrapment of fishes, and effects on fish spawning
- review the applicability of water quality and ecosystem models to pumped storage systems and develop more refined models for predicting effects of changes in water quality on aquatic production.

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FOREWORD

The objective of this report is to identify research appropriate for obtaining ecological information useful for analyzing pumped storage development plans. Such information should enable aquatic scientists to predict the environmental effects of a proposed development and to analyze alternative sites. This information could also be used in determining appropriate constraints on plant design and operation. The constraints would be intended to minimize impacts on aquatic communities and other aquatic impacts, enhance ecological communities in the reservoir, and to provide for multiple use of pumped storage facilities.

Potential impacts were identified and a reasonably thorough literature and resource review conducted to determine the state of the art of available information for analyzing potential impacts. Most of the published literature relating to aquatic impacts of pumped storage stations reported results of site-specific studies on a limited portion of the aquatic community. In many cases, the authors made little attempt to draw general conclusions or to synthesize available information. While it is true that the anticipated structure of the reservoir community and the impacts on it will be highly site-specific, a more generic background knowledge base of the effects of pumped storage plants on aquatic ecosystems would be useful. It could be applied to forecast both community structure and effects of development, as well as suggesting methods that would reduce adverse impacts and enhance beneficial aspects. This report is directed toward technology managers, research managers and personnel in agencies contemplating development of pumped storage. The introductory section provides an overview of pumped storage schemes and developments. The body of the report identifies information necessary for assessing environmental effects of pumped storage development and reviews the state of the art and research needs in this area.

INTRODUCTION

A pumped storage system consists of two reservoirs located near each other but separated by a difference in elevation, which provides sufficient head for falling water to drive turbine generators. Water is pumped from the lower reservoir to the upper reservoir during periods of low electrical demand, converting electrical energy to stored potential energy. When electrical consumption increases, the water stored at the higher elevation is returned through plant turbines to the lower reservoir, thus generating additional power.

HISTORICAL DEVELOPMENT OF PUMPED STORAGE

Pumped storage is the only operating system that permits conversion of large quantities of electrical energy to a form that may be stored and efficiently reconverted to electricity (about 2 MWe are produced for each 3 MWe used). The first pumped storage system in the United States was developed in 1929 by the Connecticut Light Company. Since then, technological development of reversible pump-turbines has reduced the capital cost of pumped storage systems and permitted stations of large capacity to be constructed. At present, the Ludington, Michigan plant (Consumer's Power Company) is the largest pumped storage facility in the United States, with six reversible units having a total capacity of 1872 MWe at an outflow of 58,200 cfs (Kaufman 1977). In 1976, pumped storage systems produced 9,700 MWe annually in the United States. The Federal Power Commission (1976) predicts that these systems will produce 37,300 MWe annually within two decades. At that time, they will represent about one-third of the total installed capacity of the nation's present hydroelectric generation (Table 1).

BENEFITS OF PUMPED STORAGE

The capability to store energy economically for later use is important to utilities committed to supply electricity to consumers whose aggregate power demands vary widely. Because the daily afternoon peak load is about twice the morning minimum demand, a large installed capacity is required that is not used full time (Figure 1). Thermal power plants (nuclear or fossil-fueled) operate more efficiently and with less mechanical stress on plant components when they are run continuously than when they are frequently cycled from partial to full power output. Transferring energy during off-peak hours to a pumped storage plant permits thermal plants to operate more continuously, and therefore more efficiently. The stored energy can be used during the peak demand period to replace more expensive power.

A pumped storage facility tends to stabilize a complex power generation and distribution system. It also offers some protection against unplanned power outages. The load on the system of the pump motors helps stabilize slight frequency drifts, compensating for variations in load demand. In an emergency caused by an unplanned outage of a base-load unit, the pumps may be

TABLE 1. Pumped Storage Hydroelectric Plants or Additions Developed, Under Construction, or Projected, January 1, 1976 (from Federal Power Commission 1976)

Plant	Owner	River	State	Status(a)	FPC Project Number	Reversible Capacity - kW				Total	Total Potential Conventional Capacity - kW
						Developed	Under Construction	Planned(b)	Other Projected(c)		
Bear Swamp	New England Power Co	Deerfield	MA	LO	2669	600,000				600,000	--
Northfield Mt	Conn Light & Power Co	Connecticut	MA	LO	2485	1,000,000				1,000,000	--
Rocky River	Conn Light & Power Co	Rocky	CT	LA	2632	7,000				7,000	24,000
Blenheim-Gilboa	Power Auth State of NY	Schoharie Cr	NY	LO	2685	1,000,000				1,000,000	--
Lewiston-Niagara	Power Auth State of NY	Niagara	NY	LO	2216	240,000				240,000	1,953,900
Yards Creek	Jersey Cntl Pwr & Lt	Delaware	NJ	LO	2309	388,961				388,961	--
Muddy Run	Phil Elec Pwr et al	Susquehanna	PA	LO	2355	800,000				800,000	--
Kinzua	Penn Elec & Clev Elec	Allegheny	PA	LO	2280	396,000				396,000	26,100
Ludington	Consumers Power Co	Lake Mich	MI	LO	2680	1,978,800				1,978,800	--
Taum Sauk	Union Electric Co	E Fk Black	MO	LO	2277	408,000				408,000	--
Upper Smith Mt	Appalachian Power Co	Roanoke	VA	LO	2210	132,050	104,000			236,050	300,200
Hiwassee	Tennessee Valley Auth	Hiwassee	NC	FA	--	59,500				59,500	57,600
Jocassee	Duke Power Co	Keowee	SC	LO	2503	612,000				612,000	(d)
DeGray	Corps of Engineers	Caddo	AR	FA	--	28,000				28,000	80,000
Salina	Grand River Dam Auth	Grand	OK	LO	2524	260,000			260,000	520,000	--
Buchanan	Lower Co Riv Auth	Colorado	TX	--	--	11,250				11,250	22,500
Flat Iron 3	Bureau of Reclamation	Co Big Thom Div	CO	FA	--	8,500				8,500	--
O'Neill	Bureau of Reclamation	Delta Mendota	CO	FA	--	25,200				25,200	--
Cabin Creek	Public Service Co	So Clear Cr	CO	LO	2351	300,000				300,000	--
Mormon Flat	Salt R Proj Pwr Dist	Salt	AZ	--	--	48,645				48,645	9,200
Horse Mesa	Salt R Proj Pwr Dist	Salt-Gila	AZ	--	--	99,878				99,878	34,155
Grand Coulee	Bureau of Reclamation	Columbia	WA	FA	--	100,000		200,000		300,000	--
Thermalito	Calif Dept of Wtr Res	Feather Div	CA	LO	2100	82,500				82,500	65,200
Edward G Hyatt	Calif Dept of Wtr Res	Feather Div	CA	LO	2100	293,250				293,250	702,000
Castaic	LA City & St of Calif	Castaic Cr	CA	LA	2126	425,000	850,000			1,275,000	56,000
San Luis	Bureau of Reclamation	San Luis Cr	CA	FA	--	424,000				424,000	--
Senator Wash	Bureau of Reclamation	Senator Wash	CA	FA	--	7,200				7,200	--
Harry S Truman	Corps of Engineers	Osage	MO	FA	--		160,000			160,000	(d)
Clarence Cannon	Corps of Engineers	Salt	MO	FA	--		31,000			31,000	27,000
Fairfield	So Carolina Elec & Gas	Frees Cr Bd	SC	LO	1894		518,400			518,400	--
Wallace Dam	Georgia Power Co	Oconee	GA	LO	2413	216,000				216,000	108,000
Carters	Corps of Engineers	Coosawattee	GA	FA	--	250,000				250,000	250,000
Raccoon Mt	Tennessee Valley Auth	Tennessee	TN	FA	--		1,530,000			1,530,000	--
Mt Elbert	Bureau of Reclamation	Ark Canal	CO	FA	--		100,000	100,000		200,000	--
Montezuma	Arizona Power Auth	Gila Offstream	AZ	LO	2573		505,400			505,400	--
Breakabeen	Power Auth State of NY	Schoharie Cr	NY	LA	2729			1,000,000		1,000,000	--
Boyd County	Nebraska Public Pwr	Missouri	NE	PO	2746					1,000,000	--
Bath County	Virginia Elec & Pwr	Back Creek	VA	LA	2716			2,100,000		2,100,000	--
Davis	Montongahela Pwr Co	Blackwater	WV	LA	2709			1,000,000		1,000,000	--
Bad Creek	Duke Power Co	Bad Creek	SC	LA	2740				1,000,000	1,000,000	--
Rocky Mountain	Georgia Power Co	Heath Creek	GA	LA	2725				675,000	675,000	--
Helms	Pacific Gas & Elec	Kings	CA	LA	2735		1,050,000			1,050,000	(d)
Missisquoi	Swanton Village of	Missisquoi	VT	PA	2759				80,000	80,000	(d)
Cornwall	Consolidated Edison	Hudson River	NY	LO	2338				2,000,000	2,000,000	--
Mount Hope	Jersey Cntl Pwr & Lt	White Meadow	NJ	LA	2753				1,000,000	1,000,000	--
St Petersburg	Corps of Engineers	Clarion	PA	FR	--				300,000	300,000	120,000
Prairie Creek	Bureau of Reclamation	Platte Offstream	NE	FA	--				16,800	16,800	--
Turnip-Falling	Southside Elec Coop	Turnip Creek	VA	PA	2749				830,000	830,000	--
Randolph-Hunting	Southside Elec Coop	Roanoke	VA	PA	2749				1,260,000	1,260,000	(d)
Roanoke-Wallace	Southside Elec Coop	Roanoke	VA	PA	2749				780,000	780,000	--
Cub Creek	Southside Elec Coop	Cub Creek	VA	PA	2749				800,000	800,000	--
Mollys-Seneca Cr	Southside Elec Coop	Seneca Creek	VA	PA	2749				420,000	420,000	--
Upper Blue Ridge	Appalachian Power Co	New River	VA	LO	2317				1,600,000	1,600,000	(d)
Rowlesburg	Corps of Engineers	Chest	WV	FA	--				350,000	350,000	(d)
Green River Proj	Epic Inc	Green	NC	PA	2700				500,000	500,000	--
Madison County	Carolina Pwr & Lt	Sugarcamp Br	NC	PO	2734				2,000,000	2,000,000	--
Spewell Bluff	Corps of Engineers	Fling	GA	FA	--				50,000	50,000	100,000
Village Bend	Brazos Elec Pwr Coop	Brazos	TX	PO	2733				730,000	730,000	--
Browns Canyon	PUO No. 1 Douglas Co	Columbia	WA	LA	2753				1,000,000	1,000,000	--
Black Star	So Calif Edison	Sanctago Cr	CA	PA	2730				1,235,000	1,235,000	--
Totals						9,735,734	4,264,800	5,450,800	16,886,800	37,337,334	

- (a) LO-FPC--License outstanding; LA-FPC--License or amendment applied for; PO-FPC--Preliminary permit outstanding; PA-FPC--Preliminary permit applied for; FA--Federally authorized; FR--Federally recommended.
 (b) Developments included in reports of April 1, 1976, to the FPC by regional electric reliability councils; plant data from FPC inventory.
 (c) Potential developments not under construction or included in reports of the regional electric reliability councils but which have FPC license or permit status, or are authorized or recommended for Federal construction.
 (d) Reversible capacity shown could be used for conventional generation.

FIGURE 1. Operation of Weekly-Cycle Pumped Storage in a Typical Winter System Load Pattern for the Northwest (from U.S. Army Corps of Engineers, 1977)

shut down, immediately reducing system load. A reversible unit also acts as a spinning reserve without wasting fuel, because it can be started very quickly in the generation mode or even reversed quickly from pumping to generation, should additional power be required.

It is possible to use upper reservoirs for purposes other than their primary one. Suggestions have been made to use upper reservoirs for improving downstream water quality or to increase flows during drought by controlled releases (Nolte and Schwab 1974, Velz et al. 1968) and to use pumping capacity of upper reservoirs to help control flooding. The upper reservoir could also provide a source of municipal or irrigation water (e.g., Bank's Lake, Grand Coulee project). Recreational and navigational use is limited, however, because of the fluctuations in the reservoir, expected to reach 30 vertical meters at some large proposed plants. Small sections of the upper reservoir have been impounded in some cases to limit drawdown and to accommodate recreational use (e.g., see Robins and Mathur 1976). In many cases, however, concern for public safety will result in limited access to reservoirs subject to severe daily fluctuations in water level.

REQUIREMENTS AND SITING OF PUMPED STORAGE FACILITIES

Typically, a pumped storage facility requires three units of pumping energy for each two units of energy generated because of friction and leakage losses. This inefficiency is offset by the higher value of energy supplied during periods of peak power demand, particularly when energy that would otherwise be generated by expensive gas turbines or by older, less efficient thermal plants is replaced. The economics of a pumped storage system are controlled by the cost of off-peak pumping energy and the value of peak power generation, in addition to capital costs.

Although the basic physical requirements for a pumped storage facility are simple, there is a large degree of variation in reservoir and powerhouse configuration. Principal site requirements are an upper reservoir with sufficient capacity to store water for several hours of power generation, located near a source of water at a lower elevation. Proposed configurations include 1) impoundments for both an upper and lower storage reservoir, with a source of surface water supplying either or both reservoirs; 2) an upper reservoir located near a river; 3) a river with a dam to impound the upper reservoir with water to be pumped back from the dam tailrace; 4) a surface reservoir and an underground reservoir; and 5) both reservoirs underground. Powerhouses are often located underground for aesthetic or design reasons. Impoundment of a river permits a combined conventional and pumped storage facility. Riester et al. (1976) surveyed 30 operating and planned plants and described the various configurations of storage reservoirs: intake/discharge structures; reservoir volumes, drawdowns and head differentials; and power generation capacities.

There are many potential sites for development of pumped storage facilities in the United States. Surveys have been or are being conducted in some regions to assess the availability of sites or to select specific candidate sites for feasibility studies (New England River Basins Commission 1973, Federal Power Commission 1975, U.S. Army Corps of Engineers 1976). For example, an inventory of topography, reservoir volume and drawdown, water availability, and head at 530 potential sites, and estimated development costs for plants of 1,000 MWe or larger was conducted in the Pacific Northwest by the U.S. Army Corps of Engineers (1976). All sites providing less than 3,000 MWe capacity or those located in areas of restricted land use (such as wilderness areas or wild and scenic rivers) were eliminated from the inventory, leaving 45 sites for further consideration. General environmental or sociological data were used to narrow the list to 27 candidate sites that are being studied extensively (U.S. Army Corps of Engineers 1977). A few of these sites will be selected and congressional authorization sought to conduct detailed feasibility studies. The goal will be to select sites for development of 3,000 to 5,000 MWe of pumped storage capacity by the 1990's.

POTENTIAL ENVIRONMENTAL EFFECTS OF PUMPED STORAGE FACILITIES AND RESEARCH NECESSARY FOR THEIR ASSESSMENT

Operation of pumped storage stations affects surrounding ecosystems primarily by the alternating movement of large volumes of water during the pumping and generation cycles. Release of water to the reservoirs results in currents and may affect stratification. Large numbers of organisms are passed through the pump-turbine plant between the reservoirs, and extensive fluctuations in water level may occur on a daily cycle.

Before pumped storage sites can be chosen and facilities can be designed, the environmental effects of construction and operation of pumped storage systems must be assessed. Unfortunately, little information is currently available on which to base the assessment. Most studies have been narrowly scoped and, therefore, have failed to examine overall effects of the operating plant. Reported models of water quality or population distributions in pumped storage reservoirs appear to be general and imprecise. A rigorous analysis of the usefulness of these models in designing plants would be beneficial. More refined models might need to be developed to assist in deriving optimum design parameters or operating schemes to protect the ecosystem. These effects are changes in community structure; entrainment and impingement of aquatic organisms; mortality to organisms passing through the turbines; hindrance of fish migration by their transport to the upper reservoir; stranding of fish, desiccation of fish eggs and changes in littoral and riparian communities due to water fluctuations; impacts from temperature changes in the water; and gas supersaturation. Altered nutrient cycling, changes in thermal stratification, increased turbidity, and effects of water level fluctuations may also affect carbon flux by altering primary production. However, the direction and magnitude of the change will vary among sites. Since primary production is the basis of the food web supporting the higher trophic levels, the impact may indirectly affect production of aquatic organisms important to man.

CHANGES IN COMMUNITY STRUCTURE

Effects of any project that produces large-scale physical changes in the environment are greatly dependent on the ecological community structure of the impacted areas. Major restructuring of the physical environment, as is expected with nearly all conventional or pumped storage hydroelectric development, directly causes major changes in aquatic community structure. When an existing stream is impounded, the change in its physical characteristics leads to changes in the aquatic community structure analogous to an acceleration of ecological successional processes. In general, fewer but larger fish species are expected, and warmwater species are more prevalent than coldwater species. For example, carp, suckers and largemouth bass may replace trout and smallmouth bass. Sculpins may be replaced by the smaller sunfish and perch, and stoneflies and caddisflies by chironomids and mayflies.

When a new reservoir is created over what was previously dry land or a small creek, a new successional series is initiated and seeded with organisms

from the water source. Typically, such new reservoirs experience rapid community development and high productivity in initial years, followed by a trend toward community stabilization and reduced productivity as the reservoir ages.

Thus, a pumped storage project, because it involves construction of a reservoir, will change community structure. This expected new structure should be considered in siting, design and operation of pumped storage plants in order to manage the altered ecosystem appropriately and to reduce adverse impacts on the preconstruction ecosystem. While anticipated ecological community development in the altered ecosystem will be dependent on individual characteristics (e.g., topography, substrate and pre-existing ecosystem), some generalizations may be drawn, based on a review of pumped storage plant and reservoir characteristics.

To define the anticipated ecological community, we must identify the species groups likely to live in reservoirs, their relationships and habitat preferences, and the basis for their production. Thus, we need to assess primary production (both qualitatively and quantitatively), and the likely composition of the anticipated food base and its quality for fish production (benthic invertebrates, aquatic insects, zooplankton and forage fish species); and identify expected predator species. Waterfowl may also need to be considered in some sites.

In order to develop the generic information required for such forecasting of community development, we need a comprehensive review of reservoir ecosystem development related to pumped storage systems and their characteristics. Physical characteristics of pumped storage plants and their reservoirs were compiled by Riester et al. (1976), who categorized plants by intake/discharge design, reservoir geomorphology, and operating characteristics. However, such characteristics and water quality factors have not been related to community development for pumped storage systems.

Additional research characterizing the relationship between ecological community structure of pumped storage reservoirs and the reservoirs' physical characteristics would be useful in predicting development at new sites. Such a study would involve a review of existing reservoirs, drawing on a variety of sources describing both the physical and the ecological characteristics of existing pumped storage and other comparable reservoirs.

ENTRAINMENT, IMPINGEMENT AND MORTALITIES FROM PUMPING

The movement of large volumes of water between the lower and upper reservoirs of a pumped storage station transports entrained organisms. This has the effects of killing some organisms; bringing others, including some of new species, into the reservoirs from outside; and redistributing trophic energy. The overall impact of this is based on a number of poorly understood factors: intake and discharge design parameters, timing of the pumping and generation cycles, individual organism behavior and mean residence time in the reservoir. An understanding of these factors is important for impact assessment, site selection, design criteria and management and operation parameter definition. While some highly site-specific studies have been conducted and some over-

simplified generalizations have been advanced, available information has not been synthesized in a form that would permit generic application to impact analysis.

Passage of organisms through piping systems and pump-turbines subjects them to the sudden pressure transients and to possible mechanical injury from contact with piping or turbines. The rate of injury or mortality is difficult to assess because of the very large volumes of water involved and the magnitude of the required sampling effect. In a study by Liston and Tack (1977), rainbow trout measuring 15 to 52 cm were passed through turbines at the Ludington pumped storage facility with styrofoam floats attached to them. About 30% of the trout were recovered at the discharge, and of those, 57% were killed during the pumping cycle. In a second test, 51% of those recovered were killed in the generation cycle. Tagging studies estimated that 16,000 trout would be lost at Ludington annually.

Robins and Mathur (1976) investigated the passage of adult fish through the Muddy Run pumped storage plant. They compiled nearly identical species lists for Conowingo Pond (the lower reservoir) and Muddy Run Pond (the upper reservoir). Few mortalities could be traced specifically to passage effects, although some adult fishes were apparently damaged by contact with the pumps. They concluded that no damage to the recreational fishery of Conowingo Pond had occurred and recommended against screening the plant intake to prevent entrance of adult fish.

Pumping mortalities could be examined by releasing marked fish at the intake and recapturing them at the discharge. However, the difficulty of efficient recapture would limit success. One approach would be to use internal radiofrequency transmitters and monitor the movement of fish after they have passed through turbines, with the assumption that a dead fish would be indicated by a stationary tag. Alternatively, greater precision could be obtained (at a higher cost per tag) by using similar transmitters to monitor heart rate.

Snyder (1975) studied the passage of fish eggs and young-of-the-year at the Muddy Run pumped storage facility. Data describing the densities of young-of-the-year and fish eggs were estimated from plankton net data taken during pumping and discharge. During pumping, 37 to 44 young-of-the-year and 4 to 53 eggs per 1000 m³ were found in the pumped water, while only 5 to 17 young-of-the-year and less than 0.1 egg per 1000 m³ were present in the water used during generation (Figure 2). Thus, more fish were moved into the upper reservoir during pumping than were lost during generation. No assessment of mortality rates was made. Snyder proposed limiting pumping to daylight hours when young fish might be less susceptible to entrainment, in order to reduce the impact during periods of high vulnerability. However, off-peak power for pumping is generally available at night, and such a scheme might severely limit the usefulness of the facility.

A general model proposed by Alesi et al. (1975) predicts that the density of organisms in Muddy Run Pond will approach that of Conowingo Pond (the upper and lower reservoirs of the Muddy Run pumped storage facility, respectively) in less than seven pumping-generating cycles. This prediction assumes a uniform

distribution of organisms in the water column. Snyder's data fit the model poorly, probably because of nonhomogeneous distribution of organisms resulting from their individual behavior and mobility. The spatial distribution and behavior of organisms subject to potential passage through a pumped storage plant are critical.

Mysis shrimp in Twin Lakes, Colorado, are important food organisms for lake trout, a valued trophy and game fish. La Bounty (1977) indicated that these shrimp are more active in the water column at certain hours than at others and, hence, are differentially susceptible to entrainment during pumping. The operating plan for the pumped storage plant under construction (Mt. Elbert) includes provisions to limit pumping to hours of mysis shrimp inactivity.

The claim has been advanced that screening of intakes is impractical because of several factors: the large volumes of water involved (tens of thousands ft³/sec); the high velocities involved (several ft/sec); and the reversible nature of the flow. Large turbine passageways are thought to permit smaller aquatic organisms to pass through with little harm. When operating at peak efficiency, the turbines should not cavitate or produce sharp pressure gradients (Bell 1973). The major cause of entrainment damage to organisms is injury from direct contact with turbine blades and abrasive surfaces.

Losses due to impingement of fish and other aquatic organisms on traveling screens for water intakes would probably exceed losses due to entrainment. This should be verified by comparing rates for mortality from passage with mortality rates from impingement on large travelling screens, for which we have information from cooling water intakes. Information on the behavior of reservoir organisms would be useful in designing intake/discharge structures or in establishing operating criteria. Additional research in these areas is needed to define effects of passage through a pumped storage plant.

EFFECTS OF PUMPED STORAGE ON FISH MIGRATION

Pumped storage systems could potentially block orderly migration of fish species by disrupting normal current patterns, which are important to the migration of many aquatic organisms. The effect of reversing currents on the migration of diadromous fishes is of particular ecological concern. The systems can also hinder migration by reducing flow rates through impoundments, by imposing a physical barrier or by removing organisms from the stream to an upper reservoir.

Removal of water from a flowing river system to an upper storage reservoir for later release increases the average travel time for a block of water moving downstream. The migration of such organisms as young anadromous salmon, which depend on natural flow for transport to the sea, may be delayed, exposing them to dissolved gas supersaturation or pollutants present in the river for an extended period of time. Delays in migration of adult and juvenile anadromous salmonids due to conventional hydroelectric impoundments have been demonstrated

to reduce survival in the Columbia River system. Research to develop methodology for estimating numbers of fish subject to passage into the upper reservoir and for estimating residence time in the reservoir prior to return to the main river would help assess the potential effect of this delay on migration.

Daily water level changes of several meters are common in pumped storage reservoirs. These fluctuations adversely impact aquatic biota dependent on a stable shoreline. The severity of the effect depends partially on the topography of the exposed area of the reservoir. Alternate dewatering and flooding may result in stranding of organisms on the exposed beach or entrapment in ponds or puddles. Organisms may then die from dewatering, solar heating, lack of oxygen or predation in the small ponds.

EFFECTS OF WATER LEVEL FLUCTUATIONS ON AQUATIC AND RIPARIAN ORGANISMS

Losses of salmonid and coarse fish fry caused by entrapment and subsequent desiccation of ponds as well as predation in entrapment areas have been observed in the Columbia River below a conventional river-run dam where flows are regulated for storage and power demands (Fickeisen et al. 1978). Losses due to stranding below conventional hydroelectric dams have been reported as well (Thompson 1970). In at least one case, a utility is filling in shoreline ponds created by drawdown to prevent entrapment of valued fishes (Lambert 1977).

Wide fluctuations in water level result in unstable shorelines and the diel changes restrict development of normal littoral communities. The benthos in freshwater systems, normally abundant in littoral communities, includes many organisms important for the production of fish. Loss of production of periphyton, emergent vegetation, aquatic insects, and crayfish could have a direct effect on the production of fish. Little information on freshwater organisms is available which would be useful in estimating production of a littoral zone subject to extensive daily water level fluctuations, or for defining the quality of the fish food base.

Research is needed to define the potential effects of fluctuating water levels on the riparian community. Potential adverse impacts on riparian vegetation and small mammals (for example, beavers and muskrats) apparently are not addressed in published literature, nor has consideration been given to effects of large daily fluctuations in water level on nesting waterfowl. Bank erosion has resulted in restrictions on the rate of change in river flow below conventional hydroelectric facilities, and may also be of significance at some pumped storage plants.

Water level fluctuations may also dewater normal spawning sites, reducing areas for spawning, inhibiting nest construction or killing eggs and larvae. For many species, shoreline areas are important nursery grounds and water level fluctuations might adversely impact recruitment to the adult stock.

The nests or redds of many freshwater fish, particularly centrarchids and salmonids, are subject to exposure and desiccation during reservoir drawdowns.

Poor bass hatching success has been related to water level fluctuation.⁽¹⁾ However, studies have shown that bass and sunfish have spawned successfully and reproduced despite fluctuating water levels (Estes 1971, Bennet 1976). In these studies, experimental ponds were stocked with several fish species, and reproduction and growth were measured in control and treated ponds where the water level fluctuated in different magnitudes. Centrarchids constructed nests and spawned, but desiccation caused by the fluctuation killed some eggs and reduced fry survival rates. Pelagic spawners also spawned, but reproduction was more successful in the control than in the fluctuating ponds (Baren 1971, Baren and Howlett 1971). Kokanee alevins in Banks Lake, Washington, have been destroyed in the redds during spring drawdowns for construction (Stober 1977). Geiger, Meng and Ruhle (1975) found that mortality of northern pike fry increased, especially in the adhesive stage, when exposed to a 10-cm-daily water level fluctuation in test aquaria.

Examination of effects on salmon redds would first require extending basic knowledge of the development of salmon eggs within the redd, fry movement, and measurement of groundwater drainage rates as the water level decreases. This could be partially accomplished by using artificial laboratory redds, such as plexiglass columns filled with gravel and planted with fertilized eggs. Field studies would require a series of groundwater wells in the littoral zone of a reservoir or a river subject to fluctuation. The wells would have to be located in a variety of substrates at various elevations above the mean low water level.

WATER TEMPERATURE CHANGES

Pumping and subsequent release of water may affect the quality of available water cycled between reservoirs. (See Riester et al. 1976 for a review of physical characteristics.) Several studies at the Smith Mountain pumped storage plant examined water quality in the upper and/or lower reservoir. Cold water is drawn from the upper reservoir and flows along the bottom of the lower reservoir and out through the impoundment dam. Warm water from the surface of the lower reservoir is recycled back into the upper reservoir during pumping. Water from the Pigg River, a tributary to the lower reservoir with different water quality parameters from the mainstem of the river (Estes and Cumming 1969), supplies a portion of the water pumped back. Mixing of the two water types and displacement were observed near the dam (Reynolds 1967). The discharge of cold water during generation also decreases the temperature of the lower reservoir and apparently delays the spawning of largemouth bass (Estes 1971).

Simmons and Neff (1969) examined phytoplankton in the upper reservoir and concluded that observed increases in primary production near the dam resulted from increased eddy diffusion of nutrients across the metalimnion. Chen and Orlob (1972), by applying a mathematical model to the situation, predicted

(1) To be published in Northwest Science; "Factors influencing smallmouth bass production in the Hanford Area, Columbia River" by J. C. Montgomery, C. D. Becker and D. H. Fickeisen.

that reducing the rate of pumping and extending the duration of pumping would reduce the effects on thermal stratification of the upper reservoir. However, operating the pumps at less than peak efficiency might increase mortality to fish passing through them (cf. Bell 1973).

Currents produced by pumping and discharge could increase turbidity, reducing the penetration of light into the water. This would inhibit phytoplankton photosynthesis and interfere with predation by planktivores or piscivores. The Mt. Elbert pumped storage plant at Twin Lakes, Colorado, posed this problem because the lakes contain deep deposits of fine glacial flour (La Bounty 1977, La Bounty et al. 1976). Physical modeling studies were used to design the plant intake/discharge to minimize the likelihood of stirring these bottom sediments into suspension (Rhone 1976).

Solar radiation and heat from pumping frictional losses or changes in reservoir stratification may increase the water temperature in the reservoir before it is released back to the river. In streams in which maximum temperatures become critically warm, the heat may adversely affect aquatic biota. Special provisions have been made by Pacific Gas and Electric Company to offset this potential problem at one of their installations (Lambert 1977).

GAS SUPERSATURATION

Passage of large volumes of water through piping systems under pressure may result in supersaturation and changes in dissolved gas content. The problem of dissolved atmospheric gas supersaturation in piping and pump-turbines has been related to entrainment of air into piping systems and injection of gas at the turbines of some conventional hydroelectric plants to control cavitation. Dissolved gas supersaturation may cause lethal gas bubble disease on fishes. This phenomenon is fairly well understood. It should be considered in the design of pumped storage piping and turbine systems.

Altered nutrient cycling, changes in thermal stratification, increased turbidity, and the effects of water level fluctuations may affect carbon flux by altering primary production. However, the direction and magnitude of the change will vary among sites. Since primary production is the basis of the food web supporting the higher trophic levels, the impact may indirectly affect production of aquatic organisms important to man.

CONCLUSION

There are significant gaps in our knowledge of effects of aquatic ecosystem perturbations caused by pumped storage plant operation. Investigations designed to address the specific research needs identified in this report would improve the knowledge base. Generic conclusions drawn from the expanded information would permit environmental effects to be forecast with greater confidence. Improved design and operating criteria that would result would reduce adverse effects and perhaps enhance beneficial uses of pumped storage systems. Analyses of alternative development plants, designs, or operating criteria would be facilitated by the improved data. Comprehensive analysis of environmental effects of operating pumped storage plants and of their reservoir ecosystems would be useful to validation of predicted effects.

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