OVERVIEW OF RESERVOIR RELEASE IMPROVEMENTS AT 20 TVA DAMS

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ABSTRACT: In 1987, the Tennessee Valley Authority (TVA) authorized a comprehensive review of reservoir operating priorities that had been followed since 1933. The purpose was to ensure optimum operation of the reservoir system, recognizing that needs, demands, and values change over time. The review resulted in a five-year, $50 million program to improve the quantity and quality of releases from 20 dams in the Tennessee Valley. TVA worked with state and federal resource agencies to define minimum flow and dissolved oxygen targets for each tailwater. Facilities and operating procedures were designed and installed to meet the target conditions. This paper describes the facilities, operating procedures, and performance of the reservoir release improvements. Alternative approaches, monitoring requirements, operational problems, and costs are discussed. Results from four years of operation are presented.

INTRODUCTION

In 1996, the Tennessee Valley Authority (TVA) completed a five-year, $50 million program to improve the quantity and quality of releases from 20 dams in the Tennessee Valley. Prior to the program, over 500 km of tailwaters were being adversely impacted by reservoir releases. Hydropower operations resulted in periods of zero flow below some dams. Thermal reservoir stratification resulted in the release of water low in dissolved oxygen (DO), affecting downstream water quality, aquatic habitat, recreation, and waste assimilation. To improve the releases, TVA worked with resource agencies and nongovernmental organizations to define minimum flow and dissolved oxygen targets. Facilities were installed and operating procedures developed to meet the target conditions.

This paper provides an overview of the five-year program. Conditions creating the need for improvements and the planning process are described. The facilities installed and their operation are discussed. The resulting improvements in downstream flows, water quality, and aquatic biota are summarized. Conclusions are presented from the release improvement program and use of the minimum flow and aeration technologies.

BACKGROUND

Fig. 1 shows the 20 dams included in the release improvement program. These and other TVA dams are operated according to priorities defined in the TVA Act of 1933. Section 9a of the act requires that the reservoir system be operated primarily for navigation and flood control, and to the extent consistent with these purposes, for power production. From 1933 until initiation of

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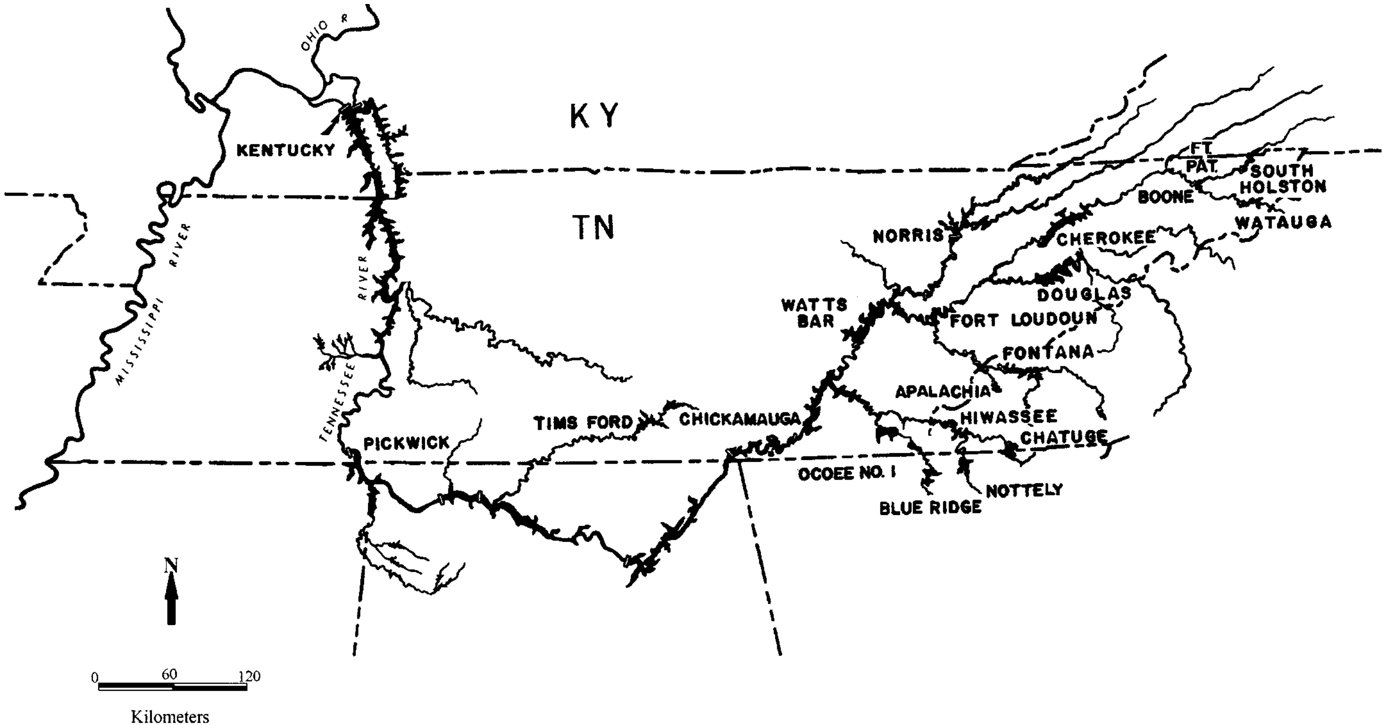

FIG. 1. Reservoir Release Improvement Projects in Tennessee Valley

the release improvement program in 1991, TVA interpreted section 9a to permit reservoir operations for other objectives, such as water quality and recreation, only if consistent with the three primary objectives of navigation, flood control, and power (TVA 1990).

Maximizing system benefits for the primary purposes has a variety of consequences for lake levels, release patterns, and the quality of reservoir tailwaters. Among the consequences are periods of no discharge and other periods of low DO in water released (Table 1).

Hydropower is most valuable during peak demand hours. For this reason, night and weekend releases are typically minimized, resulting in extended periods of no discharge. Prior to 1991, 12 of the 20 reservoirs shown in Table 1 had a mean minimum daily flow of less than 5 m^3/s Two- to three-day periods of zero discharge were common at some projects. Tailwater aquatic habitat was limited, and fishery resources were poorly developed.

Most of the projects have low-level or mid-level turbine intakes that withdraw water from near the bottom of the reservoir. During the summer and fall months, thermal stratification isolates the lower portion of the reservoir from atmospheric aeration. DO concentrations at 16 projects are significantly depressed during this period by natural biochemical processes. The subsequent release of this hypolimnetic water can create tailwaters with a DO concentration that is below the state water quality standard. Historically, the average period of depressed DO ranged from 17 days at Fort Loudoun Dam to 199 days at Tims Ford Dam (Table 1). The minimum DO concentration ranged from near zero at Cherokee and Tims Ford Dams to 5.0 mg/L at Apalachia Dam. As the released water traveled downstream, natural reaeration restored the DO. The distance required for reaeration varies from dam to dam and is dependent on the flow rate. Under normal flow conditions, over 500 km of tailwaters experienced low DO concentrations (Table 1).

In 1987, TVA authorized a comprehensive review of reservoir operating priorities that had been followed since 1933. The purpose was to ensure optimum operation of the reservoir system, recognizing that needs, demands, and values change over time. Navigation, flood control, and power production are still important objectives, but water quality, recreation, and economic development also provide substantial regional benefits. The review was in response to a growing number of requests from people in the Tennessee Valley for major adjustments in TVA's reservoir management policy. Two basic changes were evaluated: (1) improving water quality and aquatic habitat by increasing minimum flow rates and aerating releases to raise dissolved oxygen levels; and (2) extending the recreation season on TVA lakes by delaying drawdown for other reservoir operating purposes, primarily hydropower generation.

Trade-offs between operating objectives and alternatives require broad public and private participation. The National Environmental Policy Act requires a formal Environmental Impact Statement and public review. The initial scoping process included 11 information meetings attended by over 800 people; two intensive planning meetings involving 60 technical, governmental, and private representatives; and written comments from over 100 individuals and groups. Twelve public meetings were held to solicit review comments on the Draft Environmental Impact Statement. Nearly 1,200 registrants attended the meetings, providing 627 written and 196 verbal responses. The public participation process assisted TVA in defining the issues, objectives, alternatives, and values to be balanced. The process was also instrumental in evaluating

TABLE 1. Characteristics of Reservoir Release Flows and DO Concentrations

Dam (1)	Mean flow (m^3/s) (2)	Mean minimum daily flow (m^3/s) (3)	Stream length impacted by low flow (km) (4)	Mean minimum DO concentration (mg/L) (5)	Mean number of days DO concentration below target[a] (6)	Stream length impacted by low DO (km) (7)
Apalachia	62	4	24	5.0	64	3
Blue Ridge	17	0	21	3.4	83	24
Boone[b]	72	6	0	3.9	46	16
Chatuge	13	0	29	1.3	91	11
Cherokee	130	2	76	0.2	122	80
Douglas	197	4	40	0.9	113	129
Fontana[b]	114	1	2	2.7	54	8
Fort Loudoun[b]	466	41	0	3.7	17	68
Fort Patrick Henry	75	20	53	3.8	59	8
Hiwassee[b]	60	1	0	4.1	82	5
Norris	119	2	21	1.0	120	21
Nottely	12	0	23	1.0	81	5
South Holston	28	0	23	0.8	122	10
Tims Ford	27	1	69	0.4	199	64
Watauga	20	0	13	3.8	66	3
Watts Bar[b]	798	124	0	4.5	27	48
Chickamauga[b]	984	192	0	5.3	0	0
Kentucky[b]	1,797	376	0	6.1	0	0
Ocoee No. 1	40	5	19	6.9	0	0
Pickwick[b]	1,614	312	0	6.5	0	0
[Total]	—	—	413	—	1,346	503

Note: Based on daily flow and weekly DO data from 1960 through 1996. Data affected by release improvements have been omitted.
[a]DO target is 6.0 mg/L for nine dams with coldwater downstream fishery, and 4.0 mg/L for 11 dams with warmwater downstream fishery.
[b]These tailwaters are not impacted by low flows due to backwater from downstream reservoirs.

the effects of potential operational changes and in establishing specific numerical objectives (e.g., minimum flows and DO targets).

Results of the review are presented in the Final Environmental Impact Statement, issued in December 1990. Modified operating policies are recommended for 20 of the 40 major TVA dams. Minimum DO targets are recommended for 16 dams. Minimum flows are recommended for 12 of the 16 dams and for four other dams. Minimum flows are based on downstream water needs (e.g., aquatic habitat, water supply, and waste assimilation), hydropower generation, and reservoir pool elevations. DO targets are generally set at 6.0 mg/L for coldwater fisheries and 4.0 mg/L for warmwater fisheries (warmwater targets are actually 5.0 mg/L, with 4.0 mg/L coming from release improvements and 1.0 mg/L coming from pollution control measures to be implemented in the upstream watershed). In early 1991, the TVA Board of Directors accepted the report recommendations and initiated the Reservoir Releases Improvements Program. The program was to be completed in five years at a cost of $50 million.

IMPROVEMENT MEASURES

Planning for reservoir release improvements did not begin with authorization of the program in 1991. Twenty years of TVA studies, tests, and pilot projects preceded the implementation decision. The earlier work focused specifically on TVA dams and on the performance of alternative improvement measures (e.g., turbine venting, hub baffles, air and oxygen injection, and diffusers to increase DO concentrations; and small turbine units, weirs, and unit pulsing to increase minimum flows). The background work provided technical and design information. Two findings guided the selection of alternatives. First, no single alternative or set of solutions is appropriate for all projects. Each dam is physically different and requires a unique set of facilities and operations. Second, some redundancy or mix of alternatives is needed to provide operational flexibility. These principles are apparent in the diversity and combinations of facilities installed at the 20 projects (Tables 2 and 3).

Minimum Flows

Minimum flows provide a wetted channel for benthic organisms, improved water velocities for fish spawning, reduced thermal shock to aquatic biota, and improved flushing of stagnant pools. Table 2 gives the flow commitments for the 16 minimum flow projects. The technique for maintaining flow and the operational frequency and duration are also shown. Four basic methods are used: (1) appropriate daily scheduling; (2) turbine pulsing; (3) small hydro units; and (4) reregulation weirs (Montgomery et al. 1997).

Daily scheduling is used to meet minimum flows at four projects (Chickamauga, Fontana, Kentucky, and Pickwick). Sufficient water, reservoir storage, and operational flexibility exist at these projects to maintain flows by appropriately scheduling normal releases. The cost of this approach is minimal, generally involving the incremental value of power at different hours or days.

Turbine pulsing is used at seven dams (Apalachia, Boone, Cherokee, Douglas, Fort Patrick Henry, Ocoee No. 1, and Watauga). Periods of no discharge, such as nights or weekends, are supplemented with periodic operation of one unit. The supplemental operation is at a regular interval and for a duration sufficient to recharge the tailwater and maintain the desired flow rate. The duration, frequency, and feasibility depend on the minimum

TABLE 2. Minimum Flow Commitments and Techniques

Project (1)	Minimum flow (m^3/s) (2)	Techniques (3)	Frequency and duration (4)
Apalachia	5.7	Turbine pulsing	Every 4 h for 30 min
Blue Ridge	3.3	Small hydro unit	Start small unit within 45 min of large unit shutdown
Boone	11.3	Turbine pulsing	Average daily requirement
Chatuge	1.7	Reregulation weir	Pulse every 12 h for 30 min
Cherokee	9.2	Turbine pulsing	Every 6 h for 30 min
Chickamauga	368.2	Appropriate daily scheduling	Biweekly average: June–August
	198.2		Biweekly average: May and September
	85.0		Daily average: October–April
Douglas	16.6	Turbine pulsing	Every 4 h for 30 min
Fontana	28.3	Appropriate daily scheduling	Daily average: May–September
Fort Patrick Henry	22.7	Turbine pulsing	3 h average discharge
Kentucky	509.8	Appropriate daily scheduling	Biweekly average: June–August
	424.8		Biweekly average: May and September
	339.8		Daily average: October–April
Norris	5.7	Reregulation weir	Pulse every 12 h for 30 min
Nottely	1.6	Small hydro unit	Start small unit within 30 min of large unit shutdown
Ocoee No. 1	4.0	Turbine pulsing	Every 4 h for 1 h
Pickwick	424.8	Appropriate daily scheduling	Biweekly average: June–August
	254.9		Biweekly average: May and September
	226.6		Daily average: October–April
South Holston	2.5	Reregulation weir	Pulse every 12 h for 30 min
Tims Ford	2.3	Small hydro unit	Start small unit within 90 min of large unit shutdown
Wilbur	3.0	Turbine pulsing	Small unit every 4 h for 1 h or large unit every 4 h for 15 min

Note: Apalachia plus Ocoee No. 1 must meet combined minimum flow of 17.0 m^3/s. Fontana minimum flow is met at downstream Chilhowee Dam. Watauga minimum flow is met at downstream Wilbur Dam. Portable pumping system is used to maintain minimum flows at Chatuge, Nottely, and Blue Ridge Dams during unit outages when lake levels are below spillway crests.

TABLE 3. DO Deficit and Aeration Facilities

Project (1)	DO Conditions: Target (mg/L) (2)	Mean deficit (mg/L) (3)	Mean oxygen deficit[a] (tons/year) (4)	Aeration Facilities: Type (5)	Size (6)
Apalachia	6	0.8	56	Turbine venting	1.42 Nm^3/s
Blue Ridge	6	1.6	43	Oxygen injection	0.176 Nm^3/s[b]; 2,200 m diffuser line
Boone	4	1.2	56	Turbine venting	6.8 Nm^3/s
Chatuge	4	1.9	39	Aerating weir	—
Cherokee	4	2.5	747	Turbine venting	—
				Surface water pumps	9–30 kW pumps
				Oxygen injection	1.102 Nm^3/s[b]; 14,630 m diffuser line
Douglas	4	2.0	694	Turbine venting	—
				Surface water pumps	9–30 kW pumps
				Oxygen injection	0.808 Nm^3/s[b]; 16 diffuser frames and 4,880 m diffuser line
Fontana	6	0.8	89	Turbine venting	2.83 Nm^3/s
Fort Loudoun	4	0.8	95	Oxygen injection	0.265 Nm^3/s[b]; 3,960 m diffuser line
Fort Patrick Henry	4	1.1	76	Upstream improvements	—
Hiwassee	6	1.2	101	Turbine venting	0.57 Nm^3/s
				Oxygen injection	0.110 Nm^3/s; 3,658 m diffuser line
Norris	6	2.9	684	Turbine venting	—
Nottely	4	2.0	36	Turbine air injection	—
South Holston	6	2.4	138	Turbine venting	—
				Aerating weir	—
Tims Ford	6	3.5	195	Turbine air injection	1.60 and 2.10 Nm^3/s blowers
				Oxygen injection	0.264 Nm^3/s[b]; 4,023 m diffuser line
Watauga	6	1.2	23	Turbine venting	2.26 Nm^3/s
Watts Bar	4	0.8	226	Oxygen injection	0.367 Nm^3/s[b]; 7,320 m diffuser line
[Total]	—	—	3,298	—	—

[a]Mean oxygen deficit is based on mean deficit below target, number of days DO is below target, and mean discharge during this period.
[b]Oxygen flow rate is given in normal gaseous cubic meters per second (Nm^3/s).

flow, turbine capacity, and hydraulic characteristics of the tailwater. For example, steep confined channels that drain quickly require more frequent pulsing. A small turbine may require several hours to provide the needed water, while a large unit might fill the channel in several minutes. The TVA projects have a pulsing interval from 4 to 12 h and a duration of 15 to 60 min. Turbine pulsing is economical with little or no capital cost. The primary cost is the reduced power value of off-peak generation.

A small turbine unit is used at three dams (Blue Ridge, Nottely, and Tims Ford). The small unit operates any time the main unit is not running and provides a continuous discharge equal to the minimum flow. Each unit generates about 0.5 MW but is less efficient than the primary turbine. Costs are significantly higher than turbine pulsing due to capital and operational expenses.

The location and installation of the small unit varies due to site characteristics. At Blue Ridge Dam, the small unit is adjacent to the power house on the downstream toe of the dam. Water is delivered to the unit through a 122 cm diameter penstock extending 46 m to the surge tank of the main unit. At Nottely Dam, the small unit is located on the right downstream bank about 50 m from the power house. A 91.4 cm diameter penstock line is connected to the scrollcase. The Tims Ford unit is located on the power house taildeck and receives water through a 91.4 cm line from the sluice way.

A downstream weir is used at three dams to maintain minimum flows (Chatuge, Norris, and South Holston). The weir retains water after unit operation and slowly releases the water during the period of no generation. Discharge from the weir is controlled by float valves that open as the weir pool drops, maintaining a constant release. Advantages of a weir include reliability, automatic operation, low maintenance, and a potential for aerating releases. Disadvantages include the loss of turbine head if the tailwater pool is increased, and a potential navigation or safety hazard from the channel obstruction. The TVA weirs are located far enough downstream to provide an adequate weir pool volume and to limit the backwater rise and corresponding loss of turbine head. Physical model tests were used to ensure safe flow and recirculation patterns.

The Chatuge weir is located 1.3 km downstream of the dam. It is a broad crested, timber crib, infuser weir filled with loose rock. The weir spans a 30.7 m channel and is 3.6 m long by 2.6 m high. Openings between timbers on the infuser deck create a series of water curtains as the water falls to the plunge pool. Deck openings increase in the downstream direction to maintain a constant flow. The weir maintains flow for 12 h.

The Norris weir, located 4.5 km downstream of Norris Dam, is a stepped timber crib weir filled with loose rock. The upstream face is lined with tongue-and-groove timbers to make it impermeable. The structure spans 129 m, is 1.5 m high, and has 15 discharge pipes of 61 cm diameter each.

The South Holston weir is 1.9 km downstream of the dam and spans a channel width of 107 m. The zigzag labyrinth design, with a 640 m crest length and a height of 2.3 m, reduces the crest elevation and backwater on upstream turbines. Ten 61 cm diameter pipes with flow control devices maintain the discharge when the pool elevation falls below the weir overflow. The weir can sustain minimum flow for 18 h.

DO Concentrations

DO occurs naturally in rivers and lakes and is essential to aquatic life and the assimilation of treated wastewater. For this reason, it is a key parameter in water quality management.

Most state standards require a minimum concentration of 4.0 to 6.0 mg/L depending on the water use classification. Many reservoirs in warmer climates experience thermal stratification during the summer or fall. Thermal stratification isolates the lower portion of the reservoir from atmospheric reaeration. During this period, the available oxygen is consumed by biological or chemical activity associated with sediment deposits, algal growth, and inflowing organic material (Gunnison 1985). In reservoirs with sufficient depth and retention time, the DO concentration can fall below desired levels and is often depleted. Subsequent release of the low-DO water through low-level hydroturbine intakes can adversely affect downstream biota and stream uses.

Table 3 summarizes the low-DO condition at TVA dams and the facilities installed to increase the concentration in turbine releases. Five basic techniques are used: (1) turbine venting; (2) turbine air injection; (3) surface water pumps; (4) oxygen injection; and (5) aerating weir (Fig. 2). These techniques offer a range of aeration alternatives with varying costs and operational requirements. Each TVA project was evaluated separately to determine which alternative or set of alternatives is most appropriate. The primary factors included aeration capacity, physical characteristics, and cost.

Turbine venting takes advantage of subatmospheric pressure that exists at the vacuum breaker outlet of some turbines (Bohac and Ruane 1990; Carter 1995). Air bubbles drawn into the draft experience contact times and pressures that enhance air (oxygen) transfer. This approach is used for 22 turbine units at nine TVA dams (Apalachia, Boone, Cherokee, Douglas, Fontana, Hiwassee, Norris, South Holston, and Watauga). All units have Francis-type runners and range from 25 to 80 MW. Aeration is increased using hub baffles and a vacuum breaker bypass. Hub baffles create a separation zone in the flow that further reduces the outlet pressure. The bypass conduit reduces pressure losses due to friction. New auto-venting turbines, specifically designed to aspirate air without hub baffles, are used at Norris Dam (March et al. 1992; Hopping et al. 1997). Dissolved oxygen uptake at the nine projects ranges from 0.7 mg/L at Boone Dam to over 3 mg/L at Norris Dam. The loss in power efficiency is less than 1.3% at all projects. Turbine venting is often the least costly aeration alternative.

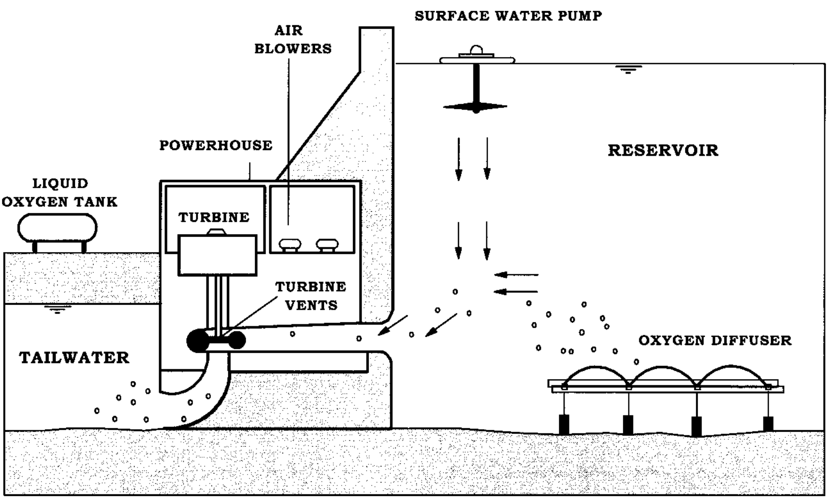

FIG. 2. Illustrations of Potential Aeration Methods

Turbine air injection is used at Nottely and Tims Ford Dams where draft tube pressures are not low enough to aspirate sufficient air. At Nottely, two 186 kW blowers for the large unit and two 18.6 kW compressors for the small unit are used. Modification to the small unit outlet structure in 1996 eliminated the need for compressors under most operating conditions. At Tims Ford, two large-unit blowers (261 and 149 kW) and three small-unit compressors are used. The air injection systems increase DO approximately 5 mg/L at Nottely and 2 mg/L at Tims Ford. The capital and operating costs of blowers and compressors make this alternative more costly than turbine venting.

Nine surface water pumps are used at Cherokee and at Douglas Dams when the DO falls below the turbine venting capacity (Mobley et al. 1995). Each pump includes a 30 kW electric motor, a gear reduction drive, and a 4.6 m diameter stainless steel impeller submerged 5 m below the surface. The pumps float just above the turbine intakes and force aerated surface water into the withdrawal zone. The pumps are designed to move 15 m^3/s of water and make up about 30% of the total discharge. Velocities are designed to avoid disturbing bottom sediments. The pumps increase DO from 1.5 to 2.0 mg/L. Costs are typically much more than turbine venting but less than oxygen injection.

Oxygen injection is used at seven dams where other, less costly alternatives cannot meet the DO target (Blue Ridge, Cherokee, Douglas, Fort Loudoun, Hiwassee, Tims Ford, and Watts Bar). The basic system consists of an oxygen supply facility and diffuser system for transferring the oxygen to the turbine intake water (Mobley and Brock 1996). All projects except Hiwassee use commercially purchased liquid oxygen, storage tank, evaporators, and appurtenances. A pressure swing adsorption system is used to produce oxygen at Hiwassee Dam due to the difficulty in transporting oxygen to the remote site.

All projects use a porous hose diffuser for oxygen transfer. Every project except Tims Ford uses line diffusers installed in the reservoir just upstream of the dam within the turbine withdrawal zone. The diffuser line consists of an oxygen supply line, a flotation line, a porous hose diffuser line, and anchors (Fig. 2). Diffuser lines range from 2,200 m in length at Blue Ridge to 14,630 m at Cherokee. Douglas uses a combination of line diffuser (4,880 m) and an earlier frame-type diffuser (16 frames, 30.5 by 36.6 m each). At Tims Ford, the diffusers are located in the penstock intake tunnel (264 lines of 15.2 m each).

Oxygen injection is the only aeration method used at Blue Ridge, Fort Loudoun, and Watts Bar. At Cherokee, Douglas, Hiwassee, and Tims Ford, other alternatives are feasible and help to minimize oxygen requirements. The DO increase achieved by oxygen injection ranges from just over 1 mg/L at Fort Loudoun and Watts Bar to over 3 mg/L at Blue Ridge. Capital costs typically exceed $1 million.

An aerating weir is the only facility used for aeration at Chatuge Dam and the primary facility at South Holston Dam. The Chatuge infuser weir increases DO by 2 to 4 mg/L. The South Holston weir increases DO by 2 to 3 mg/L (Hauser and Morris 1995). These passive aeration facilities function automatically with few operational requirements. Routine maintenance of the flow control valves and periodic debris removal are necessary.

OPERATIONS

Operation of the minimum flow facilities is incorporated into existing responsibilities. The organizational, procedural, and personnel requirements of turbine pulsing, daily scheduling, small unit operation, and weir releases are the same as existing reservoir and hydropower operations. Minimum flow commitments require only minor modification of existing procedures. In contrast, aeration of reservoir releases involves new facilities, responsibilities, and procedures. The basic requirements include (1) equipment operation and maintenance; (2) monitoring of reservoir releases and equipment performance; and (3) operational decisions and coordination. Existing organizations and personnel perform these functions with additional training, communications, and operating procedures.

Equipment Operation and Maintenance

Development of aeration capabilities created major new facilities at many projects. These facilities are the responsibility of hydro plant personnel. Responsibilities include routine maintenance, operation of the equipment when aeration is needed, and repair and replacement as necessary. Since the equipment was designed and installed by other TVA personnel, detailed operation and maintenance manuals are provided for each plant. Initial and routine training programs are conducted with annual startup reviews prior to the aeration season. Individual aeration orders are issued during the season for the operation of each system (i.e., initiating, terminating, or modifying aeration to maintain the desired DO level in the tailwater). Technical support is provided by design engineers for nonroutine operation and maintenance problems.

Monitoring

Three types of performance and operational monitoring are conducted. The first involves visual and instrument observations by on-site plant personnel. Minor adjustments and repairs are made as needed with more serious needs reported. The second type of monitoring involves remote observation, recording, and transfer of equipment performance parameters for operation and maintenance purposes. The third type involves monitoring of downstream (reservoir release) conditions for operational decisions.

Remote equipment monitoring includes hydro operations data previously collected at each plant (e.g., water flow rates and megawatts for each turbine unit). It also includes aeration system data not previously collected (e.g., air flow rate through turbine vents, oxygen flow rate, oxygen tank level, surface water pumps running, and alarm signals). The latter data are collected only at plants with active aeration equipment (Blue Ridge, Cherokee, Douglas, Fort Loudoun, Hiwassee, Norris, Nottely, Tims Ford, and Watts Bar). The data are used to identify malfunctioning equipment and to determine adjustments in aeration by comparing river conditions with operating status.

River conditions are monitored to determine aeration effects and to modify operations. The primary parameters are DO, temperature, and total dissolved gas. The criteria for sampling frequency are complexity of aeration facilities, severity of Do depletion, and cost of aeration. For example, biweekly grab samples are collected at Apalachia Dam, where the DO rarely falls below 5 mg/L, is passively maintained above 6 mg/L through turbine venting, and has no means of increasing or decreasing aeration. In contrast, Douglas Dam has an automatic, continuously recording monitor because the DO can approach zero without aeration, and there are three aeration systems involving significant operational complexity and costs. Using these criteria, grab samples are collected at seven projects (Apalachia, Boone, Chatuge, Fontana, Fort Patrick Henry, South Holston, and Watauga), and continuous DO and temperature monitors are installed at the remaining nine projects. Total dissolved gas is continuously monitored at Tims Ford and Norris Dams, where improper aeration could result in elevated levels.

Reservoir release monitoring is conducted by field personnel with specific training in environmental monitoring. Automatic monitors are calibrated at least weekly and up to three times per week during periods of heavy probe fouling.

Data transfer, management, and storage are key elements of the monitoring program. All relevant data are communicated to a central point for processing and analysis by water management personnel. A variety of data transfer methods are employed to provide timely information. Grab sample and calibration field sheets are faxed on the day of collection. The TVA wide area network provides real-time continuous data from six projects. Data from the three remaining continuously monitored projects are provided through telephone modem connections. Recorded (backup) data from the continuous monitors are sent weekly via e-mail. All data are reviewed daily, summarized in a user-friendly format (e.g., plots and summary statistics), and provided to operation personnel on a systemwide server. Performance results and operational status reports are also provided. After removal of bad data, appropriate DO, temperature, total dissolved gas, and water flow data are stored on the U.S. Environmental Protection Agency data storage and retrieval system (STORET).

OPERATIONAL DECISIONS AND COORDINATION

Minor adjustments in aeration equipment, based on real-time observation of current conditions, are the responsibility of hydro plant personnel. The oxygen injection rate, for example, may be increased or decreased to maintain the desired tailwater DO. Decisions regarding deployment or major change of an aeration system require a broader view of river conditions and system operations. Current conditions and operational changes are evaluated in the context of normal DO levels, existing aeration, reservoir operations, monitoring data and equipment reliability, and decision criteria. Decisions are coordinated among a water quality specialist, an aeration specialist, and a reservoir operations specialist. The specialists represent or have access to the expertise and information needed for the three basic operational activities: (1) aeration orders to start, stop, or modify aeration; (2) repair or replacement of malfunctioning equipment; and (3) material procurement, primarily liquid oxygen.

An aeration order is used to significantly modify the operation of the aeration equipment. The order is a formal instruction from the reservoir water manager to the hydro plant senior operator. It is issued upon request of the water quality specialist who has determined that additional aeration is needed and obtained concurrence from the aeration specialist as to the proper method. Written verification of implementation is required.

The aeration, monitoring, and communication systems are subject to a variety of failures. Common disruptions include mechanical valve failures, electrical outages due to storms, leaking and broken supply lines, monitor failures, and loss of instrument calibration. Problem identification, analysis, and repair are ongoing activities. Operational data are reviewed daily by the water quality and aeration specialist. The cause and preferred resolution of each problem are determined and corrective action initiated. Records are maintained for forced outages and repair times.

Availability of parts and liquid oxygen is critical to performance. Start-up inspections and tests are conducted at each project prior to the low-DO season. The inspections are scheduled early enough to secure parts and make repairs. During the operating seasons, spare parts are obtained for critical components with long delivery times. Six projects require regular deliveries of liquid oxygen. The demand is significant, seasonal, and varies greatly from day to day as power demands and reservoir releases fluctuate. For this reason, a seven-day oxygen use forecast is provided to suppliers each week. The forecast is based on projected reservoir discharges and aeration needs. Significant variations in the forecast are communicated daily. In addition, suppliers have telemetry access to real-time tank volumes and oxygen flow rates.

PERFORMANCE

Short-term performance is based on meeting minimum flow commitments and DO targets. Long-term benefits are reflected in increased tailwater recreation and improved biological habitat.

Minimum flows are essentially met at all times, since they serve as constraints on operation of the reservoir system. Hourly flow records for each dam are available for monitoring minimum flows. The only difficulty occurs at Blue Ridge, Chatuge, and Nottely, where water cannot be released when the turbine is out of service. A portable pumping system is provided to pump reservoir water over the spillway during the outage. The system is reserved for this use and can be operational within 24 h.

DO performance is measured by comparing actual river concentrations with the target concentration. Fig. 3 shows the 1997 (with aeration) and the historical (without aeration) DO concentration of releases from Cherokee Reservoir. Aeration actions and the target DO concentration of 4 mg/L are also shown. Historically, the DO level fell below the target between mid-May and mid-June. In 1997, turbine venting was initiated in May, the surface water pumps started in July, and oxygen injection initiated in August. With few exceptions, the aeration systems maintained DO above the target until lake turnover (thermal mixing) restored natural aeration in October. The period of monitor probe fouling is also indicated.

In 1997, the DO of reservoir releases from Cherokee Dam was below the target for three days (based on the daily average of 15 min observations and excluding low readings due to probe fouling). Table 4 compares 1994–1997 results for the 16 aeration projects with the historical record. The total number of days for all projects has been reduced from an historical average of 1,346 days per year to less than 300 days per year. Approximately 70% of the remaining days below the target are from Hiwassee, Norris, and Tims Ford, where additional work is needed to improve aeration capacity.

Table 5 shows a second measure of aeration performance. The DO deficit-days include not only the time that the DO is below the target (in days), but also the magnitude of the deficit (in milligrams per liter). Historically, there were 2,712 total mg/L-days below the target at these projects. In 1997, the deficit was 170 mg/L-days. The 94% improvement restored 496 km of the 503 km of impacted tailwaters.

Fish and macroinvertebrate communities have generally responded positively to the improved flow and DO conditions (Scott et al. 1996). Data from 1971 through 1995 were compared for historical, preproject, and postproject periods. Standard indices of benthic community well-being were examined for total taxa, proportion of tolerant taxa, total mayfly-stonefly-caddisfly taxa, and proportion of the community represented by the most dominant taxon. Fish community assessments were made using fish indices developed for

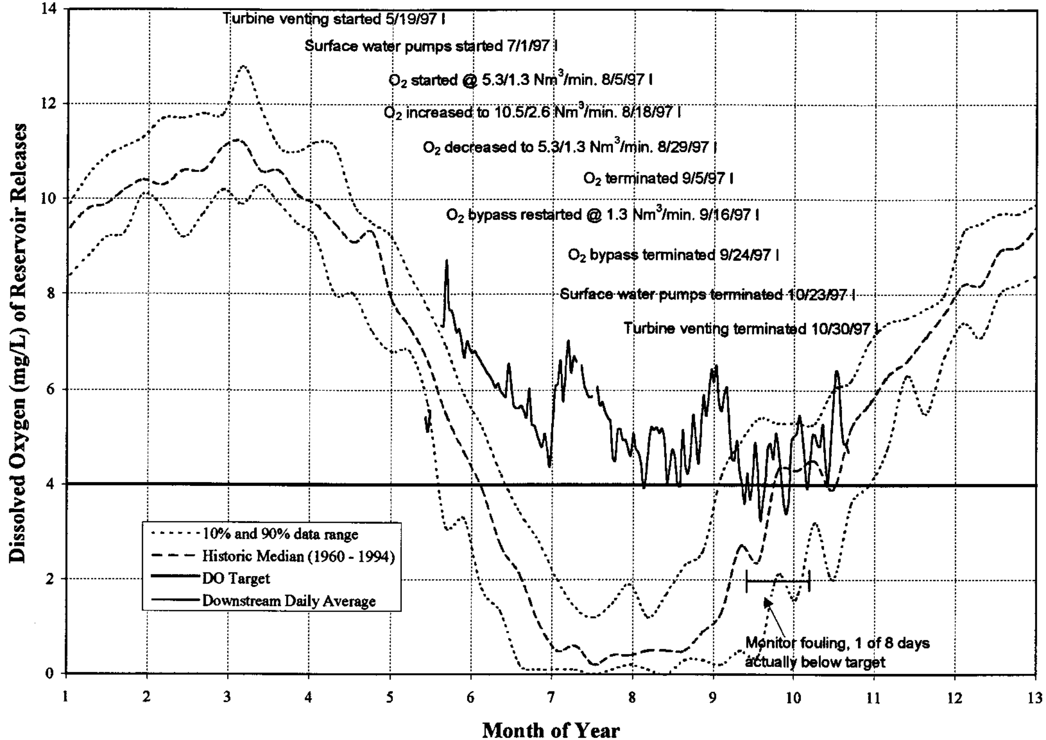

FIG. 3. DO Concentration of Releases from Cherokee Dam in 1997

TABLE 4. Annual Number of Days DO Concentration Is below Target

Project/system (1)	Number of Days DO Is Below Target: Historic record (2)	1994 (3)	1995 (4)	1996 (5)	1997 (6)
Apalachia	64	40	2	0	0
Blue Ridge	83	42	34	17	24
Boone	46	1	2	0	0
Chatuge	91	0	0	0	0
Cherokee	122	92	8	11	3
Douglas	113	25	40	22	16
Fontana	54	3	0	0	0
Fort Loudoun	17	0	21	0	0
Fort Patrick Henry	59	0	2	0	0
Hiwassee	82	92	93	53	83
Norris	120	95	77	66	72
Nottely	81	6	0	7	1
South Holston	122	0	0	0	0
Tims Ford	199	32	34	33	47
Watauga	66	24	57	20	21
Watts Bar	27	2	54	2	0
[Total]	1,346	454	424	231	267

TABLE 5. Reductions in DO Deficit

Project (1)	DO Deficit: Mean of historic data (mg/L-days) (2)	Current year (mg/L-days) (3)	Improvement (%) (4)	Stream Length: Impacted (km) (5)	Improved (km) (6)
Apalachia	54	0	100	3	3
Blue Ridge	133	7	95	24	24
Boone	43	0	100	16	16
Chatuge	170	0	100	11	11
Cherokee	306	1	100	80	80
Douglas	225	3	99	129	129
Fontana	44	0	100	8	8
Fort Loudoun	13	0	100	68	68
Fort Patrick Henry	25	0	100	8	8
Hiwassee	99	48	52	5	0
Norris	344	68	80	21	21
Nottely	165	1	99	5	5
South Holston	290	0	100	10	8
Tims Ford	697	36	95	64	64
Watauga	83	6	93	3	3
Watts Bar	21	0	100	48	48
[Total]	2,712	170	94	503	496

Note: DO deficit is measure of duration and severity of deficit. It is combination of time (days) and magnitude (mg/L) that DO is below target concentration.

warm and cold tailwaters. While available data and results vary from project to project, the analysis generally indicates improvements in both benthic macroinvertebrate and fish communities.

Benthic communities' improvements include a greater number of taxa and a proportional reduction in tolerant and dominant taxa (i.e., increases in both biota and biotic diversity). The most significant improvement is in the Blue Ridge tailwater. Tailwater stations at some dams exhibit a drop in indices, due to incomplete recovery, insufficient habitat, or unknown effects. Most measures demonstrate a longitudinal response, with the poorest conditions near the dam and improvement moving downstream. Even with more diverse and abundant tailwater communities, conditions do not approximate those found in undisturbed, free-flowing rivers of the Tennessee Valley. However, a positive response to improved flow and DO is clear.

Fish community trends reflect similar improvements. The most improved tailwater fish community is below Douglas Dam, where the earliest flow and DO enhancements occurred. Cherokee Dam, with similar flow improvements, did not show a positive response until after the DO was improved. The fish community in the Nottely tailwater actually decreased following the flow and DO improvement in 1993, due primarily to habitat degradation from bank erosion and sedimentation. The Chatuge tailwater shows a decline in fish communities in the two years following weir construction and improvements in the third year.

Seven tailwaters are specifically managed as coldwater trout fisheries. Four show significant improvement (Chatuge, Norris, South Holston, and Watauga), and three show no significant change (Apalachia, Blue Ridge, and Tims Ford). At the projects showing improvement, the abundance and diversity of macroinvertebrates have increased the available food base for sport fish. Increases in the number and size of sport fish have resulted in increased fisherman visits and economic activity.

CONCLUSIONS

The following conclusions are based on TVA experience in developing and implementing the Reservoir Releases Improvements Program:

1. With proper public and stakeholder participation, historic reservoir operating policies can be reviewed and updated, where appropriate and consistent with statutory requirements. Such a process must explicitly evaluate all relevant factors, including benefits, costs, environmental impacts, and effects on upstream and downstream water users.
2. Sufficient technology and operating experience are available for economically improving minimum flows and the DO concentration of reservoir releases. Applications should be considered on a case-by-case basis, however, accounting for the physical uniqueness of each project and variations in costs and potential benefits.
3. Operation and maintenance of minimum flow and aeration systems are significant, requiring integration of diverse expertise, personnel, and responsibilities. As operating procedures evolve, the acquisition, processing, and communication of relevant data among participants are crucial. Use of electronic data transfer and network servers can greatly facilitate information sharing.

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