Review of Ecological Effects of Rapidly Varying Flows Downstream from Hydroelectric Facilities[1,2]

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ABSTRACT

Rapid changes in flow below hydroelectric facilities result from peaking operations, where water is typically stored in a reservoir at night and released through turbines to satisfy increased electrical demand during the day. Potential impacts of these short-term, recurring disturbances of aquatic systems below dams are important considerations in hydropower development. Reduced biotic productivity in tailwaters may be due directly to flow variations or indirectly to a variety of factors related to flow variations, such as changes in water depth or temperature, or scouring of sediments. Many riverine fish and invertebrate species have a limited range of conditions to which they are adapted. The relatively recent pattern of daily fluctuations in flow is not one to which most species are adapted; thus, such conditions can reduce the abundance, diversity, and productivity of these riverine organisms. Information needs for site-specific evaluations of potential impacts at hydroelectric peaking projects are outlined, along with management and mitigation options to reduce anticipated adverse effects.

In typical hydroelectric peaking operations, water is stored in reservoirs at night when electrical demand is relatively low and then is released through turbines during the day to satisfy increased electrical demand. Generally, there are one or two releases each weekday, and discharge at other times is essentially zero (leakage only) or at a regulated minimum (Fig. 1). These large and rapid (within minutes) changes in discharge result in corresponding changes in flows in tailwaters (streams below the dams). Associated with changes in flow are changes in other variables (e.g., depth, width, velocity, water temperature, and quality). Potential impacts of these short-term, recurring disturbances of aquatic systems below dams are important considerations in hydropower development (Hildebrand and Goss 1981). There are other causes of rapid changes in discharge from dams in addition to hydroelectric peaking, although they may not occur repeatedly in a given season, such as releases for irrigation (Sartoris et al. 1981), flushing of reservoir sediments (Gray and Ward 1982; Hesse and Newcomb 1982), spills during spring floods (Ruggles and Watt 1975), and shutdowns for repairs (Gore 1977).

In this paper, I will summarize (1) observed effects on fisheries and fish-food organisms in tailwaters below peaking facilities, (2) underlying mechanisms responsible for those effects, (3) factors to be considered in an evaluation of potential adverse effects at a given site, and (4) some possible design or operational changes that may reduce those effects.

OBSERVED EFFECTS

Published studies of biological effects of rapidly varying flow below hydroelectric facilities are summarized in Table 1. It is apparent that the authors differ in how they have chosen to quantify the extent of variation. Flow fluctuation may be described on the basis of changes in flow, riffle area, velocity, depth, or wetted substrate. Specificity as to the time periods over which the fluctuation occurs or the recurrence periodicity likewise varies among authors.

Fluctuations in flow resulting from peaking operations have been associated with reductions in river productivity (Radford and Hartland-Rowe 1971), specifically in terms of tailwater fisheries

(Powell 1958; Fraser 1972; Trotzky and Gregory 1974; Becker et al. 1981), aquatic plants and bottom-dwelling invertebrates on which the fish populations depend (Powell 1958; Fisher and LaVoy 1972; Trotzky and Gregory 1974; PNRBC 1974; Covich et al. 1978), and wildlife that depend on the biological productivity of the river for food or cover (PNRBC 1974).

A number of variables have been used by biologists to document the reduced productivity or carrying capacity of affected tailwaters. Trotzky and Gregory (1974), citing unpublished data, reported a decline in the rainbow trout (*Salmo gairdneri*) sport fishery in the upper Kennebec River (Maine) from rapid flow variations. Powell (1958) found that tailwater brown trout (*Salmo trutta*) had a low mean condition factor. Fraley and Graham (1982) reported that fluctuating flows interfered with reproduction of kokanee salmon (*Oncorhynchus nerka*) by reducing egg and alevin survival. Fraser (1972) also noted that fluctuating flows reduced the survival of salmonid eggs.

Benthic organisms have been reported to demonstrate reduced species diversity, density, biomass, mean individual weight, and "quality" (as trout food) as a result of rapidly varying flows (Powell 1958; Fisher and LaVoy 1972; Trotzky and Gregory 1974; Abbott and Morgan 1975; Covich et al. 1978; Williams and Winget 1979). On the other hand, Abbott and Morgan (1975) found that a fluctuating flow regime caused a relative increase in the importance of "tolerant" (not defined) species. Other researchers also have found certain species to be affected selectively by fluctuating flows. Trotzky and Gregory (1974) reported reduced populations of insects such as *Rhyacophila, Chimarra, Iron,* Perlidae, Elmidae, *Blepharicera,* and *Rhithrogena,* while *Paraleptophlebia, Alloperla,* and Chironomidae increased. Similar, Williams and Winget (1979) found that certain mayflies, stoneflies, and caddisflies (*Epeorus, Acroneuria, Glossosoma, Arctopsyche, Rhyacophila, Dolophilodes,* and Philopotamidae) were adversely affected while chironomids were favored. Powell (1958) reported decreased populations of mayflies, stoneflies, and caddisflies while Gislason (1980) also found that the relative abundance of mayflies decreased, but that dipterans (primarily chironomids) represented a greater percentage of the community. Gersich and Brusven (1981) observed that it took benthos longer (66 vs. 47 days)
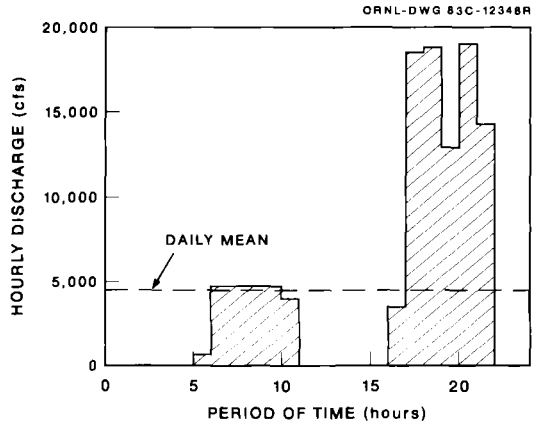

Figure 1. Typical daily discharge regime from a hydroelectric peaking facility (from Hildebrand and Goss 1981).

to colonize habitats in rapidly varying flows than in unregulated flows.

UNDERLYING MECHANISMS

Interaction of Hydraulic Variables

When flow varies, a number of other stream variables may be affected, including velocity, depth, width, and wetted perimeter (the distance along the stream bottom from one shoreline to the other). Cross-sectional geometry will be the primary determinant of the interaction among these variables (Brusven and Trihey 1978); thus, the empirical relationship between discharge and velocity is site-specific (PNRBC 1974). For example, Kraft (1972) reported that, when flow was reduced 90% in a well-defined stream channel, velocity decreased 71 to 85% while surface area and average depth decreased less than 42%. Williams and Winget (1979) also found that velocity was affected more by a given change in flow than was width or depth. The percent of stream bottom characterized as "deep fast," "pool," "riffle," "flow shallow," or "exposed bottom" also will vary with flow (Brusven and Trihey 1978).

A number of authors have observed that productive riffle areas are particularly affected (flooding or drying) by changes in flow (Briggs 1948; Neel 1963; Abbott and Morgan 1975). In an extreme case, a stream that at normal flow contains mostly fast-water habitats may at low flow consist mostly of pools; runs can be more affected (in terms of surface area, depth, and cover) than pools by a drop in flow (Kraft 1972).

Table 1. Some published studies of effects of rapidly varying flows below hydroelectric peaking facilities.

Study location	Characterization of flow variation[a]	Reference
North Fork of the Clearwater River, Idaho	Flow 30 to >300 m³/second; Δ depth 0.3–0.6 m/day over a 1–2 hour period; Δ wetted perimeter 68 m	Gersich and Brusven 1981; Brusven and Trihey 1978
Connecticut River, Massachusetts	Δ depth 1.0 m, 10 km below dam	Fisher and LaVoy 1972
Kennebec River, Maine	Flow <8.5–170 m³/second; ~¼ of bottom dewatered; velocity 0.1–0.5 m/second at bottom, with a 4-fold increase in <1 hour	Trotzky and Gregory 1974
Grand River, Oklahoma	Δ depth ≤2 m, "rapid"	Covich et al. 1978
Lower Kananaskis River, Alberta	Δ depth 32 cm in 0.5–4 hours	Radford and Hartland-Rowe 1971
Green River, Utah–Colorado	Δ depth 10–65 cm in 24 hours	Pearson and Franklin 1968
Snake River, Idaho–Oregon–Washington	Δ depth >0.3 m in 24 hours	PNRBC 1974
Tennessee River system	Δ flow 100× in "minutes"	TVA 1978
Columbia River, Washington	Δ depth "several" m in 24 hours, "rapid"	Becker et al. 1981
Blue River, Colorado	Δ flow 52 m³/s in <1 minute; Δ depth >1.2 m	Powell 1958
Tennessee River tributaries, Tennessee	"Extreme fluctuation in velocity and volume of flow"	Pfitzer 1954
Obey River, Tennessee	Δ depth 3 m, increasing in a "few minutes"; decreasing in "several hours"	Parsons 1955
St. John River, New Brunswick	"Rapid alterations in flow"	Ruggles and Watt 1975
Caney Fork River, Tennessee	Δ depth 9 m; ≤63% loss of riffle habitat	Abbott and Morgan 1975
Flathead River system, Montana	Diurnal flow 7.5–300 m³/second	Hauer and Stanford 1982
Flathead River system, Montana	Δ depth 2.1 m	Appert 1980
Flathead River system, Montana	Δ flow 5–258 m³/second; Δ depth ≤2.5 m daily	Fraley and Graham 1982
Sturgeon River, Michigan	Flow 0.4–17.5 m³/second, twice daily; 67% of streambed dewatered	Evans 1979
Savannah River, Georgia–South Carolina	<10–688 m³/second in ~3 hours; Δ depth 1.7 m	Matter et al. 1983a, 1983b
Skagit River, Washington	Monthly mean daily Δ depth ≤0.9 m	Gislason 1980

[a] Δ = change.

One direct and obvious consequence of increased variability is that the daily range between minimum and maximum flow, velocity, depth, width, et cetera may increase over the corresponding unregulated range. Thus, the minimum depth below a peaking facility may be lower than the normal unregulated minimum and the regulated maximum depth may be greater than the unregulated maximum (Fig. 2). The range of physical habitat conditions experienced by the biota may be greater in regulated than in unregulated streams over short periods of time. This could pose a particular threat to net-spinning caddisflies, for example, that require specific velocities for food capture (Radford and Hartland-Rowe 1971; Alstad 1982). Lack of a hydraulic equilibrium violates a major assumption of the Instream Flow Incremental Methodology (Bovee 1982) developed by the U.S. Fish and Wildlife Service to evaluate instream flow requirements of aquatic biota and could complicate the use of such methodologies in protecting tailwater fisheries (Loar and Sale 1981).

Alternating Torrent and Pond Conditions

Many species have evolved to tolerate, and indeed require, either torrential flows of well-oxygenated water or low flows of perhaps poorly oxygenated warm water but not both. Behavioral, physiological, and morphological adaptations to these conditions are all involved. Many stream insects, for example, require water currents for renewal of their oxygen supplies (Hynes 1970). In a similar manner, mayflies of the family Heptageniidae can withstand torrents but not very low flows (Ward and Short 1978), while riverine fishes may experience thermal and oxygen stress in pools formed by dewatering (Becker et al. 1981). Conversely, pool species such as the dragonfly *Ophiogomphus* and the caddisfly *Pycnopsyche* are adapted for low-flow conditions but may be unable to maintain their position in a strong current (Trotzky and Gregory 1974). Stability of flow at a certain time of year may be critical. Fish in the Columbia River evolved to tolerate a spring spate, followed by relatively stable late-summer and fall flows; the hydroelectric

flow regime in that river is an unnatural modification (Becker et al. 1981). Fish migration may be disrupted by very high or low flows (Neel 1963; Fraser 1972). Fisher and LaVoy (1972) have likened fluctuating flow regimes to an intertidal situation (cf. river-ocean estuaries) to which freshwater biota have not evolved.

Stream organisms can be stranded as waters recede. A number of authors (Powell 1958; Neel 1963; Pearson and Franklin 1968; Corning 1970; Fisher and LaVoy 1972; Kroger 1973; PNRBC 1974; Bauersfeld 1978a, 1978b; Becker et al. 1981; Extence 1981) have described stranding of invertebrates and fish. The accompanying mortality may be due to a number of factors including dewatering of isolated pools and desiccation, lack of food, low dissolved oxygen, high temperatures, and predation by birds and mammals (Powell 1958; Neel 1963; Corning 1970; PNRBC 1974; Becker et al. 1981). High mortality of salmonid eggs in dewatered redds may be due to thermal stress, insufficient oxygen, or desiccation (Fraley and Graham 1982). Stranding is more of a problem when there are gently sloping shores or bars (PNRBC 1974; Brusven and MacPhee 1976; Bauersfeld 1978a), but substrate composition, elevation above a river, bank storage, and flow from springs all determine the dewatering potential of isolated pools (Becker et al. 1981). Stranding may occur even when license requirements such as minimum flow and "ramping" (discussed later in this paper) rules are satisfied (Bauersfeld 1978a; Nelson et al. 1978). Stranding actually may limit the carrying capacity of tailwaters (Neel 1963). Sloughs often represent important spawning sites (Becker et al. 1981) and are particularly susceptible to dewatering.

Not all taxa are equally vulnerable to being stranded. For example, in a study of benthic invertebrates, Extence (1981) found that *Gammarus pulex, Potamopyrgus jenkinsi, Valvata piscinalis, Bithynia* spp., *Athripsodes aterrimus, Hydroptila tineoides,* and (citing previously published research) *Heptagenia sulphurea* were relatively sensitive to stranding, while *Lymnaea* and (citing previously published research) *Elmis aenea* were resistant. Similarly, Pearson and Franklin (1968) found *Baetis* sp. to be resistant and Simuliidae to be sensitive to stranding. Species such as the stonefly *Pteronarcella badia* which migrates into shallow, river-edge areas to emerge may be particularly vulnerable (Kroger 1973). Bauersfeld (1978a) estimated that 60% of
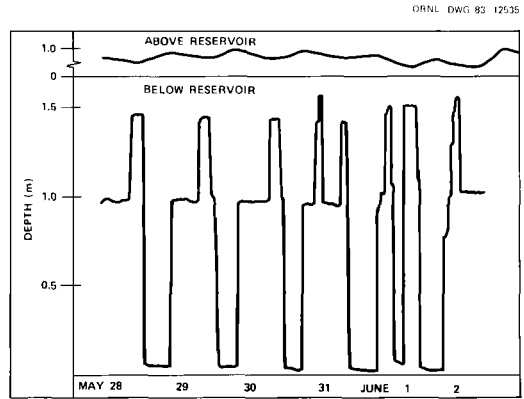

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Figure 2. Water depth above and below a peaking facility on the Blue River, Colorado (modified from Powell 1958).

the native chinook salmon (*Oncorhynchus tshawytscha*) fry in the Cowlitz River could be stranded and die from flow fluctuations during the rearing season. Becker et al. (1981) found that the possibility of stranding fish was increased when (1) flow decreased at night (because escape was more difficult), (2) flow decreased after a high discharge (because flooded shore areas provided pools), (3) there was a rapid decrease in flow after a peak (because there was less escape time), and (4) flow was very low (because of more depressions and potholes to trap fish).

Stimulation of Drift

Many invertebrates drift downstream, leaving the substrate by active and passive mechanisms. Changes in the flow or water level have been observed to increase drift rates (Minshall and Winger 1968; Pearson and Franklin 1968; Radford and Hartland-Rowe 1971; PNRBC 1974; Brusven and MacPhee 1976; Gore 1977; Ciborowski et al. 1977; Beckett and Miller 1982). Similarly, Brusven and MacPhee (1976) found that increasing or decreasing the flow in a diversion channel caused juvenile chinook salmon to emigrate. At a given site, the response of invertebrates to a change in flow may vary among different taxa; thus, Minshall and Winger (1968) found that drift of *Baetis, Ephemerella coloradensis,* Oligochaeta, *Dugesia, Nemoura cinctipes, Simulium, Cinygmula, Rhyacophila,* and Chironomidae increased, while drift of *Neothremma, Dixa, Pericoma,* and Stratiomyidae decreased. Increased drift, particularly if it oc-

curs during the daytime, could increase feeding activity by fish (Minshall and Winger 1968; Brusven and MacPhee 1976). However, if this increased drift were to continue for a long time, the benthos could be depleted (Minshall and Winger 1968; Brusven and MacPhee 1976; Gore 1977), resulting ultimately in lower fish productivity. Matter et al. (1983a) calculated that drift losses caused by peaking operations could represent almost 14% of the benthic standing crop in a month's time in a 12.5-km tailwater reach, but that inputs of zooplankton, *Chaoborus,* and fish larvae from the reservoir supplemented the tailwater food base. Changes in depth, width, and velocity have all been implicated in the stimulation of drift (Radford and Hartland-Rowe 1971; Gore 1977; Ciborowski et al. 1977), as has the erosion of newly deposited silt with its resident insects (Pearson and Franklin 1968).

Organic Materials

Changes in water level or flow may cause benthic algae to die or break loose (Powell 1958; Neel 1963; PNRBC 1974; Hauer and Stanford 1982). Gislason (1980) found the amount of periphyton chlorophyll to be inversely related to exposure to desiccation. A significant change in the type of organic matter available in the stream could have direct effects on insect populations (such as caddisfly or mayfly larvae) that feed on the algae (Powell 1958; Radford and Hartland-Rowe 1971; Hauer and Stanford 1982), and indirect effects on higher trophic levels.

Coarse particulate organic matter such as leaf packs, bark, and twigs provides important microhabitats and food sources for many stream organisms. Rapid flow variations reduce the abundance of such materials (Ward and Short 1978; Matter et al. 1983a) and of organisms such as the stonefly *Nemoura* which inhabits leaf packs (Radford and Hartland-Rowe 1971).

Fluctuating Water Level

A number of changes in stream habitat and productivity may be attributed to fluctuating water levels. For example, ice may be kept broken up and mineral coatings may build up on waterline rocks and sand (Neel 1963). Such mineral-coated stones provide a smaller number of benthic microhabitats and hold less detritus than do substrates covered with filamentous algae (Spence and Hynes 1971). Fluctuating water level inhibits the development of macrophytes (Fisher and LaVoy 1972). In shallow meandering channels, especially, variations in water level will be associated with variations in wetted perimeter (Hauer and Stanford 1982) so that reductions in these variables may concentrate stream organisms in a narrow channel (Radford and Hartland-Rowe 1971), resulting in increased mortality. Brusven and Trihey (1978) found that only substrates consistently submerged for at least 28 days would support a productive benthic community; while midges would recolonize areas above the low-water mark when flow and river stage increased, some rewetted areas still would not be recolonized several hours later.

Reservoir Phenomena

Some tailwater effects of rapidly varying flows may be explained on the basis of processes occurring in the impoundment that affect the characteristics of discharged water. For example, rapid changes in reservoir water level associated with peaking operations can increase mixing and productivity (Paulson et al. 1980) and reduce nutrient trap efficiency, thereby increasing nutrient inputs to tailwaters (Hildebrand 1980) and possibly increasing downstream productivity. Peaking operations also can increase outflow of silt, clay, organic matter, and (if at night) some aquatic insects (Hildebrand 1980). Thus, an understanding of events in the impoundment may be necessary for an evaluation of potential effects on tailwater biota. Hildebrand (1980) presented a thorough summary of the effects of water-level fluctuations on reservoirs.

Sediments

Retention of sediments by impoundments, coupled with fluctuating downstream velocities, can result in altered patterns of suspended and bed sediment transport which, in turn, can affect tailwater biota. As a result, frequent flow variations may delay the reaching of an equilibrium in the rearrangement of downstream bed materials and combat the solidification of littoral areas (Neel 1963). There may be cycles of deposition and erosion of sediment (Pearson and Franklin 1968; Ruggles and Watt 1975), along with collapse and erosion of banks (Hildebrand 1980) and erosion of sand bars (PNRBC 1974). Sediment-free discharge can be aggressively erosive (Hildebrand 1980). In addition to velocity, rate

of the rise in water levels has been cited as a determinant of the erosive capacity of streamflow (Hildebrand 1980).

Slugs of turbid water can be abrasive to biota (Radford and Hartland-Rowe 1971; Ruggles and Watt 1975), and benthos in downstream reaches can be smothered when suspended sediments settle out (TVA 1978). Stands of macrophytes can increase their "hydraulic drag" while growing until they are uprooted by increasing velocity, resulting in a large amount of suspended sediment as the disturbed bottom substrate and root-associated sediments wash away (TVA 1978). Even natural patterns of fish predation on insects may be affected by changes in substrate composition and suspended sediment loads (Brusven and Rose 1981).

Water Quality and Temperature

Rapid flow variations may be accompanied by rapid fluctuations in water quality and temperature, particularly when there is a hypolimnial discharge. As a result, slugs of discharged water may be different from downstream water with respect to not only temperature but also dissolved oxygen, hydrogen sulfide, ammonia, iron, and manganese. Abbott and Morgan (1975) reported "rapid thermal fluctuations" of up to 5 C below a hydroelectric dam in Tennessee, while Matter et al. (1983a) found that temperature and dissolved oxygen dropped rapidly by 7 C and 4 mg/liter, respectively, 4.5 km below a dam in Georgia-South Carolina after a peaking surge was released. Tailwater biota are affected by both the magnitude and rate of change of such water quality variables. The effect will be moderated by a return to equilibrium as the tailwater flow is warmed by sunlight and reaerated, and by tributary inflow (TVA 1978).

EXPLANATIONS FOR RESISTANCE TO OR MODERATION OF FLOW EFFECTS

Certain groups of organisms or their life stages are relatively resistant to effects of rapid flow variations. For example, some chironomids are opportunistic invaders of such situations and are able to tolerate changes in flow and water level; species with high fecundity and ability to disperse would be especially favored (Covich et al. 1978). Others, such as the stonefly *Alloperla*, the caddisfly *Cheumatopsyche*, or the mayfly *Paraleptophlebia*, may persist or even flourish be-

cause they burrow into the substrate during adverse periods (Trotzky and Gregory 1974; Brusven and MacPhee 1976; Brusven and Trihey 1978; Ward and Short 1978). Thus, Trotzky and Gregory (1974) found that a rapidly varying flow regime caused an increase in the abundance of *Paraleptophlebia*, *Alloperla*, and chironomids. Extence (1981) indicated that pulmonate (air-breathing) snails and uncased (relatively mobile) caddisfly larvae were relatively resistant to stranding mortality. Moth, caddisfly, and dipteran larvae were found to be more resistant to stranding than were mayflies (PNRBC 1974); the ability to burrow into algal mats or under cobble contributed to this resistance. Thus, the rapid flow fluctuations may allow a community of relatively resistant species to replace the natural species assemblage. Mature fish may be less susceptible to stranding mortality because their habitat preference may shift from shallow, shoreline waters to riffle-pool areas in the main channel (Bauersfeld 1978a).

Ward (1976) noted that adverse effects of daily flow fluctuations could be overcome by more seasonal-flow constancy, attributing this phenomenon to a more stable substrate. Even the fluctuating conditions themselves could promote an increased diversity if such conditions alternately favored different species, allowing increased niche overlap (Ward and Short 1978).

INFORMATION NEEDS FOR SITE-SPECIFIC EVALUATIONS

Existing information does not permit a quantitative prediction of the effects of rapidly varying flow at a given hydroelectric site but it is possible to list factors that cause tailwaters to experience greater or lesser impacts. These factors determine the minimum information needs for the site-specific evaluations that are summarized below.

Discharge Regimes

Historical data are needed on discharge in the tailwater reach, in terms of both long-term variations (monthly, annual) and short-term fluctuations (hourly and daily). These natural flows will then be compared with the anticipated flow regimes for corresponding time periods under hydroelectric regulation. As discussed earlier, while rapid flow variations are expected to disrupt stream biota and reduce productivity, a reduc-

tion in this variation on an annual time scale may compensate for this effect.

Channel Morphometry

Data on the cross-sectional configuration(s) of the tailwaters are necessary to derive a relationship between changing flow and changing velocity, depth, width, and wetted perimeter. This information also is required to estimate the variations in the extent of riffle and pool habitat at different flows, and the likelihood of stranding in isolated pools and sloughs.

Discharge Quality

Data are needed on the expected quality (temperature, dissolved oxygen, iron, manganese, hydrogen sulfide, ammonia, suspended solids, and nutrients) of the water to be released from the hydroelectric facility, and the variability of that quality both seasonally and as a function of discharge rate. This information will require a prediction of the limnological characteristics (biotic and abiotic) of the impoundment created for hydroelectric regulation.

Tributary and Spring Inflow

Tributary inflow to the tailwaters will moderate the variability and physico-chemical effects of flow changes (Appert 1980; Gislason 1980). Tributaries also serve as both a source of organisms for recolonization of stressed areas and a refuge for tailwater biota during adverse periods. Consequently, biological, flow, and water-quality data are needed on any tributaries to the tailwater reach. Similar data also are needed on spring flows near potentially isolated pools.

Channel Composition

Information on the physical composition (especially particle size) of both streambed substrates and bank materials is needed. This information will contribute to an understanding of (1) erosion and sedimentation potential and (2) the role of bank storage both in facilitating bank erosion and moderating the phenomenon of pool dewatering.

Present Biota

Information will be needed, also, on the species composition of the tailwater community. In particular, data on environmental requirements (e.g., velocity, temperature, dissolved oxygen), mobility (including drift), and behavioral adapta-

tions (e.g., burrowing into the substrate) of the tailwater organisms throughout the year will permit an evaluation of their susceptibility to rapidly varying flow.

MANAGEMENT OPTIONS

If analyses of site-specific factors indicate that rapidly varying flow may adversely affect tailwater biota or if impacts at a site have been observed, three major areas of management are available to minimize these impacts: operational changes, structural changes, and habitat modification.

Operational Changes

One approach to reduce the adverse effects of rapid flow variation is to specify an upper limit to the amount of variability of one or more of the physical or chemical characteristics of the tailwaters. Among the rules that have been proposed or adopted are limitations on the change in downstream water depth per unit time (PNRBC 1974; Nelson et al. 1978), percent change in wetted perimeter per unit time (Nelson et al. 1978), change in water temperature per unit time (TVA 1978), and change in discharge per unit time as a function of preexisting discharge or "ramping" (Table 2) (Bauersfeld 1978a). Maintaining a small, instantaneous minimum discharge at facilities that otherwise would have virtually zero discharge also has been proposed as a means of maintaining a constant temperature, increasing reaeration, and maintaining a wet substrate (TVA 1978). Although control of flow fluctuation has been implemented at a number of sites (Nelson et al. 1978), there may be unavoidable conflicts with hydroelectric generation, flood control, irrigation, and navigation (Nelson et al. 1977; Nelson et al. 1978; TVA 1978).

Bauersfeld (1978b) found that increasing the number of hours when no more than a minimum flow was maintained during the peak salmon spawning season reduced the number of redds established in areas that eventually would be dewatered. This action apparently reduced later mortality but it may have dewatered existing redds and reduced total spawning area, thus limiting production.

Structural Changes

Re-regulating dams (smaller dams downstream from the primary hydroelectric facility that release water at a fairly constant rate com-

pared with flow into their relatively small impoundments) can stabilize flows farther downstream, thus benefitting fish and wildlife populations (Nelson et al. 1978; Anon. 1983). For example, Gray Reef Dam on the North Platte River, Wyoming, increases minimum flow below Alcova Dam more than three-fold (Nelson et al. 1978). As an added benefit, re-regulating dams also can generate additional electricity (Nelson et al. 1978). Iron Gate Dam in California was built to protect salmon and steelhead (*Salmo gairdneri*) from flow fluctuations below two hydroelectric dams and also it can generate 19 megawatts (Nelson et al. 1978). Effects of rapidly varying flow attributable to pulses of deoxygenated releases from stratified reservoirs can be minimized by destratification, aeration of either the reservoir itself or the discharge, or by the use of a submerged weir, flexible curtain barrier, or multilevel intakes (TVA 1978). Structural changes may involve a major capital expenditure, however.

Habitat Modification

The extent of continuously wetted substrate can be increased by manipulating the cross-sectional geometry of the stream channel (TVA 1978). However, such modifications likely would be achieved only with a concomitant loss in habitat diversity if, for example, productive riffle-pool sequences were replaced with more uniform substrate contours. Shirvell and Dungey (1983), for example, demonstrated the importance of microhabitat diversity to brown trout in six New Zealand streams.

CONCLUSIONS

Increasing national attention is being directed towards the installation of new hydropower facilities or the retrofitting of existing dams for hydroelectric generation. Peaking operations can affect the ecological structure and function of tailwaters in terms of both subtle characteristics such as the species composition of bottom-dwelling invertebrates and the more obvious manifestations such as reduced fisheries yield. However, it is possible to identify some of the mechanisms producing these effects, thus permitting an early evaluation of the potential impacts of rapidly varying flow below some hydropower peaking facilities. Such impacts can be incorporated as factors in the selection of alternative sites, facility designs, and operation regimes. Additional stud-

Table 2. Example of "ramping" (from Bauersfeld 1978a).

Discharge before change (m³/second)	Maximum permissible change per 30 minutes (m³/second)
210–280	27
160–210	21
110–160	17
80–110	10
60–80	5

ies of rapid flow variation are needed that relate ecological effects (from aquatic plants and invertebrates through fish and wildlife) to quantitative characterization of the hydraulic variables. Data also are needed on the habitat requirements of many species (if not already available) and on the effects of rapid flow variation on such behavioral aspects of stream biota such as drift, colonization, and migration. Ultimately, it should be possible to protect and enhance downstream productivity while utilizing available hydroelectric potential.

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