CHAPTER 3

INSTREAM FLOWS IN THE CONTEXT OF RIVERINE ECOLOGY

DEVELOPING THE RATIONALE FOR INSTREAM FLOW MANAGEMENT PRESCRIPTIONS

Riverine values can only be maintained by preserving the processes and functions of the river ecosystem. The structure and function of riverine systems are based on five riverine components: hydrology, biology, geomorphology, water quality, and connectivity. Explicit documentation of these elements is necessary when developing recommendations for or reviewing instream flow alternatives. Documentation should include the rationale for evaluating or excluding each element. Management for one element, such as the biology or status of a single species, is usually not effective because each element of a riverine ecosystem continuously interacts with the others (Winter et al. 1998). Even statutory language (e.g., CALIFORNIA FISH AND GAME CODE § 5937) calling for sufficient flow to maintain fish in good condition, addresses all riverine components.

The objective of an instream flow prescription should be to mimic the natural flow regime as closely as possible. Flow regimes must also address instream and out-of-stream needs and integrate biotic and abiotic processes. For these reasons, inter- and intra-annual instream flow prescriptions are needed to preserve the ecological health of a river. It is only by using those time frames that it is possible to adequately represent the five riverine components (Hill et al. 1991; Bovee et al. 1998). The ideal instream flow prescription will employ this spatio-temporal framework and include the institutional flexibility to allow adoption of new techniques as the science and understanding of rivers progresses.

Hydrology

There are four dimensions of hydrology: longitudinal (headwater to mouth), lateral (channel to floodplain), vertical (channel bed with groundwater), and chronological (Amoros 1987; Ward 1989). The River Continuum Concept (RCC;

Vannote et al. 1980) described the entire fluvial system as a continuously integrating series of physical gradients and associated biotic adjustments as the river flows from headwater to mouth. The flood pulse concept applied the RCC to the lateral dimension as a "batch process," operating distinctly from upstream inputs and accounting for the existence, productivity, and interactions of major biota in river-floodplain systems (Junk et al. 1989). Streams interact with groundwater in two basic ways: streams gain water from inflow of groundwater through the streambed; they lose water to groundwater by outflow through the streambed, or they do both--gaining in some reaches and losing in others (Winters et al. 1998). These processes are directly related to the five riverine components.

Because they interrupt the longitudinal, vertical, and chronological processes, human activities--such as land use, wetland drainage, channelization, and water withdrawal--alter flow regimes. Land use practices such as removal of permanent cover, grazing, row crop agriculture, and urbanization can accentuate high and low flows and reduce habitat diversity and length of the lateral edge between the terrestrial and aquatic environments (Schlosser 1991). Wetland drainage can increase peak flows and decrease base flows by reducing bank storage (Moore and Larson 1979). Channelizing and diking can increase peak flows (Campbell et al. 1872; Gordon et al. 1992) and accentuate low flows (Karr and Schlosser 1978). Miller and Frink (1984) estimated that 5% of the total variability in peak flows of the Red River at Grand Forks, North Dakota, was associated with changes in land use (including drainage). Direct withdrawals for industry, irrigation, municipal water supplies, and other uses reduce streamflow. In cases where water is withdrawn, stored, and later released, flow regimes can be dramatically shifted in time. For example, heavy withdrawals for wild rice production from the Clearwater River in northwestern Minnesota have resulted in low spring flows when rice paddies are filled and high summer flows when rice paddies are drained (USGS 1991, 1992).

Historic streamflow data are required to develop hydrologic time series and, if needed, water budgets. Streamflow records for gaged streams are available from the U.S. Geological Survey (USGS) and Environment Canada. If streamflow data have not been gathered or if a sufficient period of record is not available, several methods can be used to estimate hydrology (Bovee et al. 1998; Wurbs and Sisson 1999). Hydrologic simulation models (e.g., HEC-HMS, WMS) use information on watershed characteristics, precipitation, and runoff patterns to synthesize or extend a streamflow record. Furthermore, if streamflow data are available from gages within a region, runoff patterns for the watershed of interest can be synthesized by establishing statistical relations with similar watersheds. The underlying foundation for accurate synthesis of streamflow records from another river is the similarity of watershed characteristics (e.g., soil, area, topography) and precipitation patterns.

Hydrologic records are critical for understanding and investigating stream components other than flow. A hydrologic record is needed to assess habitat changes, hydraulic functions, water quality factors, channel maintenance, and riparian and valley forming processes. For example, an instream flow prescription will most likely include flows with some recurrence interval to maintain alluvial channels. Some geomorphologists have suggested that flows with a 1.5-year recurrence interval are needed--roughly corresponding to bankfull discharge—and others have recommended that bankfull flow should be evaluated for each stream or river (Hill et al. 1991; Rosgen 1996). Either approach requires a hydrologic record.

Riparian Zone. Riparian ecosystems are the complex assemblage of organisms and their environment that exist adjacent to or near flowing water and are directly influenced by it. These systems are connected to other ecosystems and are maintained by groundwater and flood pulses (Ewing 1978). Stream bank form depends on a balance between the erosive forces of flowing water and resistance of the bed, bank, and streamside vegetation (Platts 1979). Vegetation buffers the stream bank from flowing water and flowing water, in turn, keeps the vegetation from encroaching into the channel (Rosgen 1996). Riparian zones can modify, incorporate, dilute, or concentrate substances before they enter the stream (Chauvet and Décamps 1989; Johnson and Ryba 1992). In small to mid-size streams, forested riparian zones can moderate temperatures, reduce sediment inputs, provide important sources of organic matter, and stabilize stream banks (Osborne and Kovacic 1993). The riparian corridor provides critical physical and biological linkages between terrestrial and aquatic environments

(Gregory et al. 1991) including fish habitat and wildlife migration corridors (Johnson and Ryba 1992).

In recent years, riparian zones have come to be viewed as distinct habitats in the planning and management of state, federal, and provincial lands (Haugen 1985). Such recognition should continue and increase. However, there are no universally accepted methods for determining flow quantity and duration needed to maintain riparian habitats and their surrounding floodplains (Hill et al. 1991; Scott et al. 1996). The methods that are emerging include review of stage-discharge relations for a given stream reach. Another method is the U.S. Army Corps of Engineers' (USACE) HEC-2 model, which can be used to identify discharges at a given set of elevations and related upper and lower elevations of riparian habitat. Not all valley types support riparian vegetation. For example, steep-sided, V-shaped valleys that lack floodplains, or even terraces, may not require riparian maintenance flows. In these situations, other stream management purposes such as nutrient cycling, recharging water tables, and gravel recruitment may require out-of-channel flows.

The most productive work to delineate riparian maintenance flows is typically local or specific in scope and fairly intensive. Auble et al. (1994) presented a method for relating riparian vegetation to magnitude and duration of inundation, and predicting changes in vegetation as expressed in area occupied by each cover type. They suggested that substantial changes in riparian vegetation can occur without changing the mean annual flow because riparian vegetation is especially sensitive to changes in minimum and maximum flows. Stromberg and Patten (1990) found a strong relation between flow and riparian tree growth in Rush Creek, California, and they recommended flows for protecting the most flow-sensitive species as a way to maintain complex riparian systems.

Valley Form and Floodplain Maintenance. Changes within a river corridor occur when fluvial processes are altered to reduce natural flooding. When this happens (1) associated wetlands are no longer maintained; (2) local water tables are not recharged; (3) stream bar and channel areas no longer become inundated and scoured; (4) sediment collects on bars and channel edges and forms lower, narrower stream banks;

(5) side channels and backwater areas become disconnected from the main channel or abandoned by the mainstream as they fill in; (6) tributary channel confluences with main stems aggrade locally and push out into the main channel; and (7) the ratio of pools to riffles is significantly altered (Morisawa 1968; Platts 1979; Leopold and Emmett 1983; Hill et al. 1991). Hill et al. (1991) identified valley floodplain forming flows as those peak discharges that approximate Q_{25}, but cautioned practitioners about establishing this flow. Flow recommendations at this magnitude must consider the impact resulting from human encroachment onto the valley floodplain. Roads, homes, businesses, and schools may now occupy valleys. In addition, there is the uncertainty associated with accurately determining a Q_{25} flow. Consequently, recommendations for providing flows of this magnitude may be most feasible in areas where water development and human settlement are minimal.

Geomorphology

Hydraulic habitat for riverine organisms is provided by the shape of the channel and the water that flows through and sometimes over it. Instream flow studies that focus on habitat-discharge relations must also address the dynamic nature of alluvial and colluvial channels. It is important to recognize that the physical habitat essential to the aquatic community is formed by periodic disturbance, which--in the short-term--may be detrimental to individual fish. On the other hand, high flows reset the system by forming new channels, scouring vegetation, abandoning side channels, and creating habitat beneficial for some species over the long-term. Such a resetting of the system is an essential process. For example, a transbasin diversion project will add water to the receiving stream. The result may be a new more consistent discharge pattern that is beneficial to a specific species. But the new flow pattern will change the disturbance regime of the receiving system, perhaps resulting in higher channel-forming flows or altered sediment transport processes. If channel form is disrupted by the increased magnitude or duration of flows, previously estimated habitat-discharge relations will be rendered meaningless. Any comprehensive instream flow analysis must account for these kinds of changes by prescribing flows necessary to maintain the dynamic nature of an alluvial channel.

Channel Form. Channel form is a direct result of interactions among eight variables: discharge, sediment supply, sediment size, channel width, depth, velocity, slope, and roughness of channel materials (Leopold et al. 1964; Heede 1992; Leopold 1994). For many alluvial streams, the channel exists in a state of dynamic equilibrium in which the sediment load is balanced with the stream's transport capacity over time (Bovee et al. 1998). When sediment load exceeds transport capacity, aggradation or other alteration of channel form will occur. When transport capacity exceeds sediment load, as is often the case below a storage dam, the channel may adjust through enlarging the channel or degrading the bed. Clearly, alteration of flow regimes (Schumm 1969), sediment loads (Komura and Simmons 1967), and riparian vegetation will cause changes in the morphology of stream channels.

Bankfull flows are important for maintaining and forming stream channel and habitat in alluvial streams (Leopold et al. 1964). Bankfull stage is generally defined as the height of the floodplain surface or the flow that "just fills the stream to its banks" (Gordon et al. 1992) or the stage at which water starts to flow over the floodplain (Dunne and Leopold 1978). The floodplain is the relatively flat depositional area adjacent to the river that is formed by the river under current climatic and hydrologic conditions (USFS 1995). Bankfull flow is subject to minimum flow resistance (Petts and Foster 1985) and produces the most sediment transport over time (Inglis 1949; Richards 1982). Bankfull events have a recurrence interval of approximately 1.5-3.0 years (Leopold et al. 1964; Mosley 1981), but in streams with sharp peak flows and accentuated low flows the channel capacity may be more influenced by less frequent, higher events (Gregory and Walling 1973). Habitat is also a function of bankfull flows because scour in pools and deposition of bedload in riffles is most predominant at bankfull flow (Leopold et al. 1964). Determination of the bankfull flow condition through field observation is difficult and subjective (Johnson and Heil 1996). Floodplains may not exist along all stream channels; they are most noticeable along low-gradient streams. In steep-gradient channels, floodplains may be intermittent, on alternate sides of meander bends, or completely absent. It is also important not to confuse the level of the low terrace--located approximately 2-4 feet above the present stream--with that of the floodplain and to be able to recognize disturbed and incised channels (USFS 1995). The use of regional relations between bankfull discharge and channel characteristics, such as those found in Dunne and Leopold (1978), can be helpful for determining where to look for the floodplain and bankfull stage in specific geographic regions of the country. In severely altered systems the bankfull discharge concept may be too simplistic. In these cases, site-specific studies of bedload relations and transport capacity may be needed.

Water managers should look at the whole picture and not rule out providing important flows simply because they do not occur within a frequency defined by a "rule-of-thumb" standard of availability or are not mentioned in a policy. That whole picture includes efforts to maintain or return the stream to a condition of dynamic equilibrium. Because channel-forming, channel-maintaining, and flushing flows may not be included in some rule-of-thumb instream flow methods, it is easy to overlook the very significant effect of these higher flows on stream ecology (Wesche et al. 1987; Reiser et al. 1989; Kondolf 1998; Whiting 1998).

Geomorphological considerations include more than providing bankfull flows. It is also important to include channel migration, sediment transport, scour and deposition, bank erosion, and vegetation encroachment. Changes in bed profile, substrate distribution, instream cover, overhead cover, velocity patterns, island/bar formation and removal, among others, should be considered during study design. Streambeds that are in disequilibrium may confound stage-discharge relations over time because instream features may change, leading to misrepresentation of physical habitat and calibration problems for hydraulic modeling. Bovee et al. (1998) provided guidance on how to deal with channel disequilibrium. Expertise in fluvial geomorphology is essential for states and provinces to be effective when addressing instream flow issues in alluvial streams.

Winter conditions and ice are other important channel forming variables. There is a growing body of knowledge that recognizes that winter habitat is just as critical as habitat during other times of the year (Tesaker 2000). The formation and presence of ice strongly influences many variables and "modification of geometry of flow may change the winter habitat to the better or worse" (Tesaker 2000). Many scientists now understand that ice formation and break-up can significantly affect a variety of hydrological, biological, and geomorphological processes (Beltaos 1995). The manner of formation and type of ice present can affect (1) migration of fish under ice, (2) variation of velocity during ice formation and break-up, (3) physiological condition of local fish populations and types of fish, (4) available physical winter habitat, and (5) bedload scour and sediment transport. Consequently, instream flow studies and recommendations based solely on summer observations provide only a partial understanding of important ecological processes (Maki-Petays et al. 1999; Whalen et al. 1999).

Sediment Transport. Part of any comprehensive stream management plan should address sediment delivery to floodplains and riparian buffer zones. At least 30 variables are tied to the sedimentation processes. However, the degree of interdependence between these variables is not fully understood (Heede 1992). It is known that the condition of the watershed and stream can have a significant effect on the sediment component of water quality (Hynes 1975). Because discharge is the key variable connecting the stream to its riparian corridor and floodplain, it follows that specific attention must be paid to sediment in terms of maintaining the transport process, riparian corridor, and channel integrity. Livestock grazing standards (including fencing), conservation tillage practices, and sediment retention standards for urban runoff may be appropriate considerations. Whenever a stream is in sediment disequilibrium, and channel rehabilitation is the goal, specialists trained in river mechanics, sediment yield from all sources, and sediment transport can be an essential part of the interdisciplinary instream flow team.

Biology

To adequately address natural resource issues, many biological questions need to be addressed, such as: What is the composition of biological communities? What species, aquatic and terrestrial, are likely to be impacted? Should particular species be targeted for protection (e.g., game species, forage species, threatened/endangered species)? Are resources available to target ecosystem level protection or will efforts focus on vertebrates (e.g., fish, turtles, snakes), macroinvertebrates, or aquatic macrophytes? Are there out-of-channel, hydrologic connection considerations that need to be addressed (e.g., oxbows, bottomland hardwoods, wetlands)? The published literature provides valuable information. These resources include fish and game agency inventories of fishes found within their jurisdictions, state and federal fish and game agency surveys, and other water-oriented agency publications. Other sources of data include natural history collections at local universities, environmental assessments, land use surveys, and the like. After these resources have been examined, it may be necessary to undertake field studies to supply missing data. The result should be a thorough assessment of flora and fauna sufficient enough to build an understanding of community composition, connectivity, and function.

Life History Cues. Information on the life history of a species should be obtained to address questions concerning spawning and feeding habits, habitat use, migration patterns, and other needs. This information will allow study participants to identify obligate and facultative riverine species, generalists and specialists, and assess species-specific spatial and temporal issues such as critical habitats, critical life stages, and habitat bottlenecks. Bovee et al. (1998) provided some perspective on the nature of habitat bottlenecks, critical habitats, and their relation to population limitations.

The life history of all aquatic organisms has adapted to naturally occurring seasonal flow regimes. For instance, fish that spawn in riffles--most trout, most darters, and many suckers--do so during the spring when high flows provide the most riffle habitat (Becker 1983; Aadland 1993). The fry of many late-breeding fishes--minnows and sunfish--are intolerant of high water velocity (Simonson and Swenson 1990). Eggs of these species generally hatch in late-spring to mid-summer when flows and velocities are usually lower. For those species, high-summer flows have been associated with reduced year classes (Schlosser 1985). Human-caused changes that affect hydrology can reset the controlling variables for fish communities, eventually resulting in vastly different species assemblages if flow regimes are permanently changed. The resulting decline in biodiversity can alter the performance, or function, of ecosystems (Naeem et al. 1994).

One cause of decline in biodiversity is rapidly varying flow regimes, such as hydroelectric peaking. Such a regime may favor generalized fish species that quickly recolonize. On the one hand, human induced flow patterns that are rapid and varied may be unfavorable to young, small individuals and result in unstable communities characterized by low species richness. On the other hand, systems with high natural temporal variability may have evolved unique native biota. Examples of natural high flow variability can be found in the southwestern United States. While rapidly varying flows favor one type of fish community, stable flow regimes often favor piscivorous fish species, including old, large individuals and high species richness (Horowitz 1978; Schlosser 1982a, 1982b, 1990).

Hydraulic Habitat. Providing hydraulic habitat is a necessary part of any instream flow prescription, but it is not sufficient by itself. Habitat defined through hydraulic characteristics (such as water depth and velocity) and channel characteristics (such as substrate, cover, stream width) is sometimes referred to as hydraulic habitat. Aquatic organisms select habitat based, in part, on the physical characteristics of their surroundings. For some monitoring studies, hydraulic habitat is chosen as a surrogate for biological response because it is fundamental to an organism's existence and is directly related to flow. This approach is powerful because it ties the organism(s) of interest to the variable (discharge) that water managers can control. To evaluate existing hydraulic conditions as they relate to aquatic organisms, the relation of streamflow to habitat must be quantified over time. Existing or proposed projects may affect streamflow and habitat in different ways depending on location, design, and operation.

The variables usually associated with hydraulic habitat include depth, velocity, substrate, and cover. These flow-dependent microhabitat characteristics for fish have been observed by many researchers (Hynes 1970; Giger 1973; Hooper 1973; Bovee 1974; Wesche 1976; Gorman and Karr 1978; Paragamian 1978; Platts 1979; Schlosser 1982a; Ross 1986), and invertebrates (Cushman 1985; Gislason 1985; Jowett and Richardson 1990). Each species and life stage has specific microhabitat preferences that may vary with temperature or other factors (Peters 1982; Peters et al. 1989;

Aadland et al. 1991). The quantity of suitable microhabitat can be correlated with population size in some settings (Orth and Maughan 1982; Orth 1987; Nehring 1988; Schlosser and Angermeier 1990). The microhabitat associated with a given streamflow can be assessed with models such as the Physical Habitat Simulation System (PHABSIM) developed by the U.S. Fish and Wildlife Service (Bovee 1982). This group of models incorporates site-specific hydraulic data with habitat suitability criteria to determine an index of habitat (Weighted Useable Area [WUA]) available for a given species and life stage over a range of streamflows (Bovee 1982). The concept of total habitat is derived from PHABSIM analysis and consists of integrating microhabitat with distance of affected stream. Estimating the timing and duration of total habitat can be expressed as a habitat time series (Bovee et al. 1998), which allows estimation of the recurrence interval of habitat events.

The hydraulic habitat needs of species will be different in warm- and coolwater streams. There is a significant correlation between habitat diversity and fish species diversity (Schlosser 1982a). Warm- and coolwater streams differ from coldwater streams because of the diversity of habitat and fish and invertebrate assemblages (Schlosser 1982a; Leonard and Orth 1988, Aadland et al. 1991; Lobb and Orth 1991; Aadland 1993). That kind of species diversity and the resulting ecological integrity are increasingly recognized as important attributes of stream ecosystems (Karr 1991).

Because the prescribed flow regime directly affects ecological integrity, it is important to remember several basic relations for warm- and coolwater streams. First, base flow conditions generally favor shallow pool habitat, which is important for spawning smallmouth bass (*Micropterus dolomieui*), minnows, and young-of-year fishes, but provides little riffle and run habitat (Schlosser 1985; Leonard and Orth 1988; Aadland 1993). Second, high flow conditions generally favor riffle and raceway habitat that is important for food production (Schlosser 1982a; Vadas 1992), mussels (Neves and Widlak 1987), and other invertebrates (Schlosser 1989). High flows also provide spawning for species such as walleye (*Stizostedion vitreum*), suckers, darters, dace, and stonerollers (Leonard and Orth 1988; Aadland et al. 1991; Aadland 1993). Third, moderate flows generally provide diverse habitat with moderate to high amounts of riffle, pool, and raceway habitat (Leonard and Orth 1988; Aadland 1993).

Natural droughts are an important contributor to interannual hydraulic habitat variability. Droughts are needed to sustain biotic and abiotic resources and processes and can have both negative and positive effects on individual species. Low flows can result in downstream fish migration (Ross et al. 1985) as well as direct destruction of fishes by high water temperatures, low dissolved oxygen (DO) levels, and physiological stress (Becker et al. 1981; Schlosser 1991). Other site-specific factors associated with droughts include disruption of fish migration (Neel 1963; Fraser 1972), increased predation by birds and mammals (Lowe-McConnell 1987; L.P. Aadland, personal observation) and reduced invertebrate production. Drought can select against introduced or nonadapted fish in arid area streams where native fishes are drought-tolerant (Hawkins et al. 1997). Drought can also favor encroachment of woody vegetation, which can produce organic inputs, complex habitats, and sediment deposition. Although natural droughts can benefit the aquatic community, induced droughts or artificially low flows do not provide ecological benefits; instead, they may lead to extreme habitat alteration and negative biological consequences.

Flooding is just as important as drought for maintaining ecological processes. Although flooding can limit reproductive success of some fish species by displacing eggs and fry (Harvey 1987), covering eggs with sediment (Everest et al. 1987), and reducing food availability (Stock and Schlosser 1991), it also provides short- and long-term benefits. Flooding can increase fish reproduction in floodplains by (1) providing spawning habitat for species, such as northern pike that spawn on submerged terrestrial vegetation (Becker 1983); (2) enhancing food availability; (3) increasing the area of habitat available to juvenile fish; and (4) increasing the amount of time juvenile fish can use the floodplain before returning to the main channel. Because of these benefits, flooding can be a major determinant of overall river productivity (Junk et al. 1989; Schlosser 1991).

However, frequent or unusually rapid changes in flow, like the flow regimes often found downstream of “hardened watersheds,” or below some kinds of dams, can have a negative effect on the productivity of habitat. For instance, eggs spawned in habitat that is suitable at one flow can be destroyed due to changes in flow, which make that habitat unsuitable. Many invertebrates also lack the mobility to adapt to rapidly changing habitat conditions and perish when flows change radically. Fish, mussels, and other invertebrates can be adversely affected by stranding and desiccation due to rapid flow decreases (Powell 1958; Neel 1963; Pearson and Franklin 1968; Corning 1970; Fisher and LaVoy 1972; Kroger 1973; Bayha and Koski 1974; Bauersfeld 1978a, 1978b; Becker et al. 1981; Extence 1981). Flow fluctuations below hydropower facilities can cause reductions in fish population density and invertebrate diversity (Reed 1989), fishery productivity (Powell 1958; Fraser 1972; Trotzky and Gregory 1974; Becker et al. 1981), aquatic plant and benthic invertebrate productivity (Powell 1958; Fisher and Lavoy 1972; Bayha and Koski 1974; Trotzky and Gregory 1974; Covich et al. 1978; Gislason 1985) and wildlife (Bayha and Koski 1974).

Analysis of hydraulic habitat should employ methods suitable for examining drought, flooding, and rapid flow fluctuation. Available approaches include representative reaches (Bovee et al. 1998), mesohabitat mapping (Morhardt et al. 1983; Bovee et al. 1998), and spatially explicit indices (see Leclerc et al. 1995; Hardy 1998). The tools to characterize, quantify, and map physical habitat were summarized by Frissell et al. (1986) and Hawkins et al. (1993). The difficulties in building a biologically relevant characterizaton of habitat stem from several factors, including the complexity of interactions between biotic and abiotic factors, the high degree of environmental heterogeneity at various scales, and the tendency of people to describe dynamic processes in terms of static numbers. Compounding these difficulties is the influence of temporal flow variation on the hydraulic habitat. Hildebrand et al. (1999) discussed this problem in regard to habitat models, habitat availability, and fisheries management.

Water Quality

The amount of flow is one of several factors that affects maintenance of water quality, including the physical, chemical, and biological attributes of water. Chemical characteristics of a river, such as DO and levels of alkalinity, nitrogen, and pH reflect local geography, land use, climate, and sources of organic matter. These factors ultimately determine the river’s biological productivity. Managers seldom look at additive measures to enhance chemical characteristics of river water because the effects are generally short-lived and often unpredictable. However, regulation of point source (e.g., chemical, temperature) and nonpoint source (e.g., sediment) pollutants is an important, on-going effort. Of these, sediment and temperature are the primary physical constituents of water quality assessments.

In 1977, the Federal Water Pollution Control Act of 1972 was amended and renamed the Clean Water Act (CWA)(33 U.S.C. § 1251 et seq.). This new statute set the basic structure for regulating discharges of pollutants in waters of the United States. The 1977 amendments focused on toxic pollutants. In 1987, the CWA was reauthorized and again focused on toxic substances, authorized citizen lawsuits, and funded sewage treatment plants under the Construction Grants Program. Whereas oversight was retained by the U.S. Environmental Protection Agency (EPA), the CWA allowed the EPA to delegate many permitting, administrative, and enforcement responsibilities to state governments.

The law gave the EPA the authority to set effluent standards on an industry basis (i.e., technology-based standards) and continued the requirement that water quality standards be set for all contaminants in surface waters. As a result of the CWA, low flow statistics provided some of the design criterion for wastewater treatment plants. The now infamous $7Q_{10}$ low (the lowest flow present for 7 consecutive days in a 10-year period) was developed for setting a water volume to establish point discharge pollution thresholds and it remains the statistic typically used today. Although the $7Q_{10}$ flow represents a “worst case” situation for waters receiving wastewater discharges, it has been inappropriately promoted by several states (i.e., New Jersey, Pennsylvania, and Georgia) as a minimum instream flow for fisheries (Reiser et al. 1989). The $7Q_{10}$--and other statistics for similar infrequently low discharges, such as $3Q_{20}$ and $7Q_2$--are relevant only for designating the lowest streamflow into which a pollutant discharge can be allowed. This group of methods and the flow levels derived from them should not be approved as the instream flow for any other stream management purpose. In recent years, concerns about lower DO and changes in temperature resulting from alteration of a natural hydrologic regime, decreased discharges and slower average velocities, and the higher waste loads from such minimum flow approaches have set the stage for implementing analytical water quality assessment tools.

In the United States, the Index of Biologic Integrity (IBI) is used by the EPA to assess fish and invertebrate community structure because it serves as an indicator of the history and current health of a stream system (Karr and Chu 1997). Reduction of DO significantly impacts fish populations through its effects on physiological, biochemical, and behavioral processes (Davis 1975). Organisms in riverine communities respond to environmental and biological interactions, resulting in the species assemblage of fish and invertebrates. For example, changes in water quality can affect game fish growth by 10% per month and have a more profound impact on the numbers of game fish present--not through direct die-offs of fish, but by enhancing the competitive advantage of more tolerant species. As human populations rapidly increase in metropolitan areas, the need to address water quality issues through wastewater treatment plant upgrades or regulation modifications (water quality and quantity) will become even more important than it is today.

In Canada, the federal government has limited regulatory authority over water quality through its constitutional power over fisheries pursuant to section 92 (10) (c) of the Constitution Act, 1867 ([U. K.] 30 and 31 Vict., c. 3). Under this authority, Parliament passed the Fisheries Act (R.S.C. 1980, C. F-14.). The Act prohibits water pollution in waters frequented by fish, as well as the destruction of fish habitat, except as allowed by permit or regulation. This Act applies throughout Canada.

The authority of the Canadian federal government to regulate water quality is derived from its constitutional authority over federal lands and property. The federal government also may regulate some aspects of water quality throughout Canada under other constitutional powers. For example, under its power over criminal matters, the federal government may regulate toxic releases into the environment, including water. It does this through the Canadian Environmental Protection Act (S. C. 1988, c. 22).

However, provinces are the main regulators of water quality. Provinces may regulate water quality within their boundaries, except on federal lands; the federal government may agree to allow provincial regulation on federal lands. Water quality regulation is typically accomplished through environmental laws such as the Alberta Environmental Protection and Enhancement Act (S. A. 1992, C. E. 13 - 3).

***Temperature*.** Water temperature is one of the most important environmental factors in flowing water, affecting all forms of aquatic life. Temperature influences fish migration, spawning, timing and success of incubation, maturation and growth, inter- and intra-specific competition, proliferation of disease and parasites, other lethal factors and synergisms (Fry 1947; Armour 1991). Stream temperatures are directly affected by any alteration of flow, shade, and channel morphology.

Augmentation, impoundment, or release of flow can change light, temperature, and flow timing, as well as distribution of nutrient and organic inputs, sediment, and biota in downstream reaches (Ward and Stanford 1979; Cummins 1980; Crisp 1987; Newbold 1987; Gilvear 1987). Stratification of reservoirs makes level of flow release at all seasons a significant tool for controlling temperature, nutrient content, and biota downstream (Hudson and Lorenson, unpublished paper; Ploskey 1986).

Alteration of temperature and temperature regimes can have simple and complex effects on river systems. Impoundment behind dams, even small ones, increases surface area and thereby raises thermal input and increases water temperature. Lower temperatures decrease the viscosity of water and may cause faster settling of some solid particles. Temperature increase causes a decrease in oxygen solubility; at the same time the oxidation rate increases, further depleting the oxygen content. The combination of higher temperature and lower DO can have significant ecological effects. Artificially higher water temperature typically leads to less desirable types of algae in water. With the same nutrient levels, green alga tend to become dominant at higher temperatures and diatoms decline, while at the highest temperatures, blue-green algae thrive and often develop into heavy blooms (Dunne and Leopold 1978). In extreme cases, fish can be killed by wide temperature fluctuations, lethally high temperatures below power plants, or in dewatered reaches. At high temperatures, fish metabolism accelerates and efficiency in their use of oxygen decreases. Coldwater species, like trout, may suffer direct mortality whereas other fish species may not be killed outright but suffer increased mortality because some other aspect of their existence becomes unfavorable.

Super-cooled water (<0° C), of which frazil ice is an indicator, can also cause physiological stress in fish. At temperatures less than 7° C, fish gradually lose the ability for ion exchange and the efficiency of normal metabolic processes decreases (Evans 1997). At water temperatures near 0° C, most fish have very limited ability to assimilate oxygen or rid cells of carbon dioxide and other waste products. If fish are forced into an active mode under these thermal conditions (such as to avoid the negative physical effects of frazil ice or if changing hydraulic conditions force them to find areas of more suitable depth or velocity), mortality can occur. The extent of impact is dependent on the magnitude, frequency, and duration of frazil events and the availability (proximity) of alternate escape habitats (Jakober et al. 1998).

The temperature of most North American rivers generally increases toward the mouth, such that in larger river systems the main channel is at or very near mean monthly air temperature (Hynes 1975), although a few exceptions exist. Temperature varies diurnally in streams, depending on water depth, proximity to source, shading, and surface area. Temperature regimes also can be significantly altered by dams because they disrupt longitudinal linkages in the stream (Ward and Stanford 1983).

Fine Sediment. The amount of fine sediments produced by human activities is significant; sediment is the major pollutant of U.S. waters (Waters 1995). The U.S. Fish and Wildlife Service (USFWS) concluded that excessive siltation was the most important factor adversely affecting stream habitat (Judy et al. 1984).

Erosion is a natural watershed process, but the rate of erosion is influenced by human activities. Water flow, channel morphology, and watershed characteristics--including type of underlying bedrock, soil profile, and vegetation--all affect erosion rate (Leopold et al. 1964). Human activities that increase erosion and sediment production include agriculture, forestry, mining, and urban development (USEPA 1990). Agriculture is by far the most important cause of sediment pollution—providing over three times the amount of pollution contributed by the next leading source (USEPA 1990). Sediment arising from the actions of humans can be controlled by prevention, interdiction (e.g., capturing sediment somewhere between source and stream), and restoration (Waters 1995). Prevention is the more preferable option because the cost of intervention--to both the environment and society--increases the farther away from the source.

Connectivity

Connectivity of a river system refers to the flow, exchange, and pathways that move organisms, energy, and matter through these systems. These pathways are not always linear. The interrelated components of watershed, hydrology, biology, geomorphology, and water quality, together with climate, determine the flow and distribution of energy and material in river ecosystems. Complexity and interdependence is the hallmark of connectivity. The interaction of primary factors (i.e., water, energy and matter) creates an extensive physical environment that varies over time. The resulting habitat may be modified by the activities of animals that selectively eat vegetation; burrow, trample and wallow in soils; and build dams (Naiman and Rogers 1997).

As with hydrology, river system connectivity is manifested along four dimensions: longitudinal, lateral, vertical, and time (Ward 1989). Lateral connectivity is critical to the functioning of large floodplain river ecosystems. Nutrients and organic matter transported from the floodplain to the river encourage the development of aquatic plants, plankton, and benthic invertebrates, and, in turn, provide a rich food source for fish (Junk et al. 1989). Seasonal flooding also brings nutrients and organic matter from terrestrial areas to the river, enriching the river and benefiting the aquatic communities. Bankside vegetation provides habitat and acts as a regulator of water temperature, light, seepage, erosion, and nutrient transfer. Isolation of the main river from its alluvial plain, eliminating access to backwaters, floodplain, lakes, and wetlands, has had a major effect on both the ecological diversity of the highly productive alluvial corridor and riverine fish populations (Petts 1989). The river corridor is especially important for birds and mammals in high latitude watersheds (Nilsson and Dynesius 1994) and in arid lands (Brown et al. 1977). The seasonal flooding of an unregulated river maintains a variety of successional vegetation stages, thus creating excellent conditions for an abundant and diverse wildlife community (Nilsson and Dynesius 1994). Flooding also creates and maintains diverse species of vegetation (Nilsson et al. 1989), which, in turn, favors animal diversity.

When developing instream flow prescriptions, practitioners must account for the presence of physical, chemical, and even biological barriers to connectivity. Examples include an assessment of dams, including their position in the watershed; dam operation (hydrology); effects on water quality (e.g., DO, mercury methylization); sediment and thermal regimes; natural history of fishes in the area; and effect on aquatic communities (i.e., lacustrine or exotic species, predator concentrations). Even without dams, flow reduction through water withdrawal can affect connectivity by rendering riffles too shallow for passage of migratory fish. Fragmentation of an ecosystem in any of its dimensions disrupts the individual components and natural processes of the river system as a whole. Examples of disruption include physical (e.g., dams), biological (e.g., exotic species introductions or extinction of native biota), hydrological (e.g., dewatering of aquifers), and water quality (e.g., endocrine disruption, thermal, chemical, or sediment pollution).

Nutrient Cycling and Energy Pathways. River corridors are linear systems, at least in part, in which a gradient of physical, chemical, and biological change occurs from source to mouth. The RCC described biotic adjustments and organic matter processing along a river's length in response to the downstream gradient of physical conditions. Food relations usually play a large role in determining the structure and function of stream communities. Disruption of the physical and hydrologic connectivity will change the biological structure (Vannote et al. 1980).

Continuity of upstream and downstream reaches is a critical aspect of the river system. Nutrient spiraling (i.e., the downstream transport of organic matter and its coincident cycling--uptake, use, and release--by the instream biota) is the mechanism of energy transfer in headwater streams (Elwood et al. 1983). A stream and its watershed are critically linked (Hynes 1975; Likens et al. 1977); stream invertebrates are key components in the energy cycling dynamics of stream systems, directly breaking down terrestrial plant inputs or linking the processing of primary producers to higher trophic levels. Invertebrate consumers are important in regulating energy flow and nutrient cycling in stream ecosystems (see Brock 1967; Wallace et al. 1977; Elwood et al. 1983). The rate of spiraling and cycling nutrients and organic matter is influenced by the interaction of flow and channel form. Thus, physical retention of terrestrial inputs and macroinvertebrate processing are important mechanisms, along with microbial action, for closing or tightening the recycling process in streams and preventing the rapid through-put of materials (Minshall et al. 1985). In essence, the diversity and productivity of lower trophic levels (i.e., microbial and invertebrate populations and productivity) determine the diversity and productivity of higher trophic levels along the stream gradient.

Fish species are particularly sensitive to discontinuity in bio-energetic processes associated with changes in the thermal regime below dams. Downstream influences of temperature change varies depending upon the season, depths, and rates of withdrawal or reservoir release. Downstream waters are generally cooler in the summer and warmer in the winter (Baxter 1977). Such changes in temperature regime can affect fish at the genotypic level, favoring fish that are more tolerant of an unpredictable discharge schedule. Richmond and Zimmerman (1978) isolated a "coolwater" isozyme in populations of red shiners (*Cyprinella lutrensis*) in tailwater areas significantly influenced by hypoliminial discharges (i.e., within 60 km of the dam).

The concept of serial discontinuity explains the effect of dams, which displace aquatic communities along the river continuum (Ward and Stanford 1983). Modifying thermal and flow regimes by impoundment were considered to be "major disruptions of continuum processes." Changes in flow regime, water temperature, oxygen, turbidity, and the quality and quantity of food particles in the river downstream of impoundments shift the upstream-downstream patterns of biotic structure and function predicted by the RCC. The serial discontinuity concept predicts the way dams shift the expected continuum. The reach immediately downstream of the dam may be reset as measured by 16 variables, including the ratio of coarse particulate to fine particulate organic matter, relation of substrate size to biodiversity, and environmental heterogeneity. A dam may result in some conditions being more like those of the headwaters (an upstream shift), while other conditions become more like those of downstream segments (a downstream shift) (Ward and Stanford 1983). Other characteristics may not fit either paradigm (Annear and Neuhold 1983). Moreover, dams and reservoirs create lentic environments where production is based on plankton rather than the benthic algae and allochthonous material on which lotic production is usually based. When reservoir water is released to a stream, it carries with it the plankton that would otherwise be scarce in streams. The instream flow practitioner must consider these potential changes and document the rationale used to arrive at a decision.

Riverine connectivity is inextricably linked to hydrology and operates on several scales. For example, each watershed has a drainage network that is related to its shape, geology, geographic position, and climate. Drainage density and pattern are used to describe the drainage network and have been related to flood flows. According to laboratory studies on watershed models, drainage pattern (e.g., dendritic, trellis, radial, palmate) is more important than drainage density in influencing peak flows and lag times (Black 1972). Intensifying the drainage network, through tiling, channelization, and wetland draining, modifies the natural hydrograph and results in several potential costs, including channel instability, increased bank erosion, bed degradation or aggradation, simplification or modification of riparian or instream biota (Dunne and Leopold 1978). Urbanization and creation of impervious surfaces (watershed hardening) have similar effects.

Although riverine food webs are highly sensitive to the natural history attributes of the biota, discharge is the “master variable” that limits and resets river populations through entire drainage networks (Power et al. 1995). Trophic pathways on floodplains of southeastern rivers consist of dry and wet systems (Wharton et al. 1982). Flows can affect migration of fish from lake or ocean into streams; these migratory fishes redistribute nutrients and energy in the course of their migrations. Ponding (i.e., the creation of natural or artificial pools) can change the aquatic ecosystem from an allochthonous-based food chain to an autochthonous-based food chain; the relation between flow and pond volume can influence where on the allochthonous-autochthonous continuum the system will be. Flows can affect the transport of terrestrial nutrients into a channel or stream nutrients into the floodplain. Fishes of floodplain rivers, particularly in the southeastern United States and drainages to the Gulf of Mexico, depend heavily on annual excursions into the floodplain to feed; these excursions require floodplain inundation (Wharton et al. 1982).

The highest productivity of southeastern streams occurs under seasonal flooding (Conner and Day 1976; Odum 1978; Wharton et al. 1982). Winter is the season when annual flooding produces the greatest benefit for floodplain forest productivity (Gosselink et al. 1981). Fish and crayfish use of southeastern floodplains is discussed briefly by Wharton et al. (1982). Ross and Baker (1983) described the importance of seasonal flooding of southeastern floodplains for the spawning, survival, and growth of some fish species. In examining a stream in eastern Canada, Halyk and Balon (1983) concluded that the growth rate of some species of young fish that were spawned in the stream is controlled by the duration of the stream's connection to the floodplain. Oxbow lakes can be very productive fish habitats, supporting high densities of species that are highly sought after by humans (Lambou 1959; Beecher et al. 1973). On the Danube River floodplain, fish yield per-unit-area increased substantially from short inundation to long (half-year) inundation (Stankovic and Jankovic 1971). Fish were also shown to move onto the floodplain in a North Carolina stream (Walker 1980).

Although not as well studied as longitudinal connectivity, examinations of vertical connectivity have led to remarkable observations documenting the extensive biomass of riverine invertebrates living within the hyporheic zone. Stanford and Ward (1988) found stoneflies in 10-m deep wells in the floodplain of the Flathead River, Montana, as far as 2 km from the river channel and concluded that the biomass in the hyporheic zone may exceed the benthic biomass of the river.

Fragmentation and its Effects on Fish Movement. Fragmentation of river systems by dams is pervasive and affects 77% of the total water discharge in the northern third of the world (Dynesius and Nilsson 1994). Introduction of barriers, especially to migrant spawning fish, has had a widespread impact that is not solely confined to the large dams of the mid-1900s. The most visible effects are those occurring to salmon production as a result of the damming of the river systems in the Pacific Northwest (Goldman and Horne 1983). Atlantic salmon (*Salmo salar*) disappeared from the Dordogne River, France, soon after the first dams were built on the lower reaches between 1842 and 1904 (Decamps et al. 1979). Delayed up- and downstream migrations related to fish movement through reservoirs can adversely affect the survival and reproduction of migratory species. This observation seems valid irrespective of dam height (Raymond 1979). Adams and Street (1969) found that blueback herring (*Alosa aestivalis*) spawn in floodplains of Georgia rivers that are only accessible when annual high water coincides with spawning season. In an Illinois stream, flow was an important factor that limited immigration of fish in fall (Schlosser 1982a).

Disconnections Caused by Changes in Water Quality. There is increasing concern about the effects of chemicals in our environment and on the endocrine systems of fish, wildlife, and humans (Folmar et al. 1996; Harries et al. 1996; Jobling et al. 1998; Colborn and Thayer 2000). At least 45 chemicals have been identified as potential endocrine-disrupting contaminants (Colborn et al. 1993). The chemicals in question–including pesticides, PCB’s, plasticizers, and petrochemicals–have been known to cause fish to change sex. Decreased fertility (fewer gametes), hatchability, viability (less robust gametes), altered sex ratios in gametes, and altered sexual development and behavior are among the reproductive injuries reported to date (Colborn and Clement 1992). The endocrine disruptors enter rivers concentrated in point-source discharges or more diffusely in nonpoint source runoff (Harries et al. 1996).

Temporal discontinuity may also be occurring between generations of fish. For example, fish affected by endocrine disruption from organic contaminants may be unable to interact with older fish that are not affected. Downstream of large cities, sewage treatment effluent containing detergent metabolites (i.e., nonyphenols and surfactants), alkylphenols ethoxylates APE’s, and human estrogen and birth control pills (17a-ethynylestradiol) has been implicated in endrocrine disruption in fishes (Purdom et al. 1994; Jobling et al. 1998; Barber et al. 2000). Biomarkers, like egg protein in males (vitellogenin), are being used to determine if fish are affected by water quality changes traceable to endocrine disruptors such as steroid hormones, 17B-estradiol-female, and 11-ketotesterone. The use of these and other biomarkers of potential endocrine disruption will be important for detecting and monitoring adverse effects of environmental contaminants on aquatic organisms (Goodbred et al. 1997).

The tie between contaminant levels, the occurrence of endocrine disruption, and water discharge has important implications for instream flow practitioners, particularly those who work on river systems with large municipal wastewater treatment facilities. Organic contaminants released from treated municipal wastewater systems may effectively disconnect different segments of the river system spatially by segregating populations according to water quality and the physiological health of the aquatic community. Dilution of treated sewage effluent through increases in discharge has been offered as an explanation for a reduced effect of exogenous estrogens on trout held in cages at increasing distances below the plant outflow (Harries et al. 1996). Still the problem is likely to be widespread: reconnaissance assessment of carp from U.S. streams indicates that fish in some streams within all regions studied may be experiencing some degree of endocrine disruption (Goodbred et al. 1997).

The degree of dilution and disconnectivity is a function of flow. Increasing flows to provide dilution can transport pollutants downstream and ultimately lead to deposition and impacts elsewhere. Practitioners must realize that flow recommendations for water quality that traditionally focused on assimilation of sewage, now must also account for the presence of estrogenic chemicals. Because these chemicals are very persistent, their removal is not accomplished solely by increased flow and is unlikely to occur for some time. Prescriptions must be made in the context of what is currently possible. Because national standards for endocrine-disrupting chemicals are not currently in place, the practitioner is relegated to considering dilution as the only available solution. Still, walking away from a problem after prescribing a flow regime does not ensure successful natural resource management; in fact, it may lead to failure to fulfill public stewardship responsibilities if the other elements are ignored.

Estuarine Production. Estuaries, where lotic systems terminate in marine systems, are highly productive for fish and wildlife (Benson 1981; Cross and Williams 1981). Productivity and the form of estuarine habitats are affected by the rate of flow entering estuaries (Nixon 1981). Flow rate, sediment transport, and deposition are major factors that control the form of the estuary and the distribution of salinities. The level of salinity controls trophic interactions and community composition by selectively limiting species distribution according to salinity tolerance. For example, certain bivalve mollusks can tolerate lower salinities than their primary gastropod predators, thereby optimizing oyster growth in a predator-free zone (Livingston et al. 1997; Rodriguez et al. 2001).

Estuarine habitat includes main channel, distributary channels, and flats, which are dominated by seagrasses, marsh grasses (including sedges and rushes), or sediment. Flats are locations of high primary and secondary productivity, but they are inundated only during higher tides or streamflows. As tides recede, some of the nutrients and material produced on the flats is flushed through steep-banked tidal channels. Fish feed in these channels and use the channels as routes to feeding excursions onto the flats during high water periods. Low inflows can leave tidal channels dewatered.

The amount of estuarine aquatic habitat varies with flow and tide, which interact to control water surface elevation, thus determining how much habitat is inundated. In most coastal areas there are two high tides and two low tides each day, although along parts of the Gulf of Mexico there is only a single high and a single low tide each day. As tide rises, it pushes saltwater upstream into the river channel, raising the overlying freshwater surface. Fish and crustaceans follow the tides onto inundated areas to feed, then retreat to deeper water as water recedes. Water depth is a result of tide height plus stream height in estuarine zones between lowest and highest tide, with the contribution to water depth or stage being greatest from streamflow at the upstream limit of high tide and greatest from tide at the low tide line.

Fish production and migration in estuaries and adjacent marine waters are correlated to pulses of fresh water and associated nutrients (Copeland 1966; Day et al. 1977; Meeter et al. 1979; Sheridan and Livingston 1979; White et al. 1979; Yin et al. 1997). Wharton et al. (1982) reviewed literature relating river pulse delivery of different nutrients to estuaries and concluded that specific methods to evaluate riverine connectivity must entail data collection and review of empirical relations rather than the use of formulas for recommending flows.

ECOLOGICAL CONSIDERATIONS FOR HABITAT AND SCALE

Physical habitat conditions must be tied to a broad understanding of ecosystem processes. The five riverine components help practitioners address the whole ecosystem when making instream flow prescriptions. It is necessary to keep these factors in mind when using assessment methods such as the IFIM. Models in the IFIM are based on an analysis of habitat and do not directly predict animal populations. The primary advantages of the IFIM models are that historical patterns of physical habitat structure and the effects of project operating schemes can be quantified in terms of time and space. These scales are extremely important parts of any flow recommendation or watershed management plan.

Spatial Scales

A management or study reach is that part of a stream system where instream flow analysis or management occurs. It is the point of reference for geographic scale discussion. Spatial scales range from global to micro. River scale is a nested hierarchy; the smaller spatial scales, including micro-, meso-, and macrohabitats, are nested within larger landscape features, such as reach, stream segment, watershed (Naiman et al. 1992). The relative importance of controlling factors changes with the spatial scale.

The Global Scale. For migratory fish--whether white sturgeon (*Acipenser transmontana*), American eel (*Anguilla rostrata*), American shad (*Alosa sapidissima*), chinook salmon (*Oncorhynchus tshawytscha*), and many others, including those with less extensive migration areas--the proper spatial scale for consideration is global. Even fish that spend their entire lives in a single pool are in some way affected by global changes such as temperature and precipitation patterns because these factors influence all ecosystems and populations (e.g., see Jager et al. 1999 for a discussion of climate change effects on fish, particularly salmonids). For these reasons, even resource agencies that have little ability to influence global scale phenomena should consider global trends when making management decisions. Important questions to ask are whether instream flow prescriptions will be adequate to meet objectives if climate changes the timing or magnitude of flows in the system, and if water will maintain an acceptable temperature if the air temperature increases.

The Watershed Scale. Watershed, catchment, or river basin refers to a scale at which state and provincial agencies have more management control. Often management at this scale is achieved by subdivision of major basins, such as the St. Lawrence, Mississippi, Rio Grande, Colorado, Sacramento-San Joaquin, Columbia, Fraser, Yukon, Mackenzie, or Saskatchewan-Nelson. In these large systems, looking at subdivisions is more practical because instream flow management decisions generally influence a sub-basin scale watershed more directly and information at the subbasin scale is more easily understood.

Conditions of a watershed directly affect the channel form and the timing and magnitude of flow in the management reach (Hill et al. 1991). Watershed interacts with climate, topography, and geology to influence vegetation, stream channel, groundwater, and streamflow. Vegetation influences the channel through erosion and deposition patterns and rates. The effects of fire illustrate the connection of watershed, stream, and fish populations (Gresswell 1999). That connection is evident in the way that land use activities--such as urban or suburban development, road building, agriculture, and forestry--modify vegetation, erosion, and sedimentation, as well as the temporal relation between precipitation and streamflow. Watershed conditions such as migration barriers may limit movement of fish into or out of a management reach. Types of downstream habitat might allow or preclude a species' use of a management reach (e.g., sockeye salmon [*Oncorhynchus nerka*] are unlikely to use a stream reach that is not accessible from a lake). Watersheds that contain lakes and wetlands modify hydrology and store and release water somewhat more gradually than in watersheds without lakes (Leopold 1994).

The Stream Segment Scale. Many instream flow analyses are based on stream segments in which flow, gradient, and channel form a consistent mosaic throughout the study area. In defining a stream segment, tributaries that change flow by ≥10%, geological boundaries, gradient changes, or other features that modify channel form and valley form provide typical segment boundaries (Bovee and Milhous 1978). Instream flow analyses often entail sampling a series of adjacent stream reaches and riparian and floodplain zones within each segment.

Many stream fishes were long believed to reside throughout their lives in a single stream segment or perhaps even a smaller habitat unit (Gerking 1950, 1959). However, recent evidence of the variety of movement patterns has emerged (Gowan et al. 1994). Because fish are now known to move in and out of stream reaches, it is essential--as part of the stream segment scale--that the spatial and temporal distribution for all life stages of each species of interest be understood and stream sampling stratified accordingly.

The Macrohabitat Scale. Geomorphologists have coined the term “hydraulic biotope” to describe the flow-dependent abiotic environment of a community or species assemblage (Wadeson and Rowntree 1998). These occur at different levels such as macro-, meso-, and microhabitat. Macrohabitat includes many reach and larger scale phenomena, primarily dealing with abiotic habitat conditions (such as channel morphology and chemical or physical properties of water) that control the longitudinal distribution of aquatic organisms. The mix of mesohabitats (see below), such as the ratio of pools to riffles, is determined by macrohabitat. Macrohabitat is determined by long-term geological setting, climate interaction with geology, vegetation, and the shorter term influence of land use superimposed on the preceding processes. It includes such factors as net rate of sediment transport and type of sediments transported, as well as abundance and distribution of sediment, large woody debris, and boulders. Infrequent high flows are also a major influence on macrohabitat. Flows that form channels, floodplains, and valleys are discussed by Hill et al. (1991) and Whiting (1998).

The Mesohabitat Scale. Mesohabitat refers to a combination of pools, riffles, runs, cascades, waterfalls, and off-channel habitats within a reach (Bisson et al. 1988; Kershner and Snider 1992; Hawkins et al. 1993; Vadas and Orth 1998). At least at low flows, certain combinations and ranges of depth and velocity are associated with different mesohabitats (Vadas and Orth 1998). Relative proportions of different mesohabitats appear to vary with flow as depth and velocity distributions change (Vadas and Orth 1998; Hildebrand et al. 1999). However, work by others (Rowntree and Wadeson 1998; Wadeson and Rowntree 1998) suggested that geomorphic-defined units do not change with discharge. Certain life stages of certain fish species are associated with particular mesohabitats (Bisson et al. 1988).

The connectivity between mesohabitats is often flow-dependent. A connection among habitats at certain times is critical to the life history of some fishes. Passage through or around migration barriers, such as shallow riffles, cascades, and waterfalls depends on flow (Smith 1973; Powers and Orsborn 1985).

The Microhabitat Scale. Microhabitat refers to depth, velocity, substrate, and cover at specific points in a stream (Bovee 1982). Many commonly used instream flow methods focus on microhabitat. One of those is the PHABSIM component of the IFIM, which allows analysis of the distribution of microhabitat at different flows (Bovee and Milhous 1978; Bovee 1982; Bovee et al. 1998). The microhabitat variables provide a reasonable within-reach description of hydraulic features selected and avoided by fish at different flows within a reach (Orth and Maughan 1982; Beecher et al. 1993, 1995; Shuler and Nehring 1993; Thomas and Bovee 1993; Shuler et al. 1994; Gallagher and Gard 1999). Although PHABSIM results are useful for identifying how the hydraulic features of microhabitat vary with flow, units of microhabitat must be sufficiently large or contiguous to support the species and life stages of interest (Gallagher and Gard 1999).

The Temporal Scales. Streams are dynamic systems, changing over time. Yet a fundamental problem in the development of a general model of system response to river alteration is the failure to consider changes within an appropriate time-scale (Petts 1984). For example, models such as PHABSIM assume that the channel has remained stable during data collection and analysis, but data collection and analysis may take several months or even years.

The present status of a watershed reflects its history, expressed in the volume, stratification, and slope of deposits, all of which affect the present dynamics of the channel. Moreover, as climate, discharge, and sediment change, the geomorphologic characteristic of a river also changes (Amoros et al. 1987) and different components of the system respond at different rates (Petts 1987). In watersheds undisturbed by human activity, all these factors usually operate in a dynamic equilibrium. Human actions can change process rates by several orders of magnitude, disrupting the equilibrium. The minimum time required for system adjustment to a new set of conditions is dependent on those variables that require the longest time to achieve a stable structure. The relative importance of controlling factors changes with the spatial scale, which is inversely related to the time scale of potential persistence. Microhabitats may change daily; mesohabitats may change annually; stream reaches may change with the occurrence of landslides, log inputs or washouts, dam building, and the like; and the watershed may change through tectonic uplift, subsidence, glaciation, or climate shifts (Frissell et al. 1986).

Petts (1987) demonstrated the length of time required for channel morphology to adjust to impoundment and regulation of flow by dams in the United Kingdom. For instream flow analysis and water management, relevant time scales range from geological effects (10^6 to 10^9 years) to single floods (minutes or hours). Patterns of variation over time range over similar scales. Hydrologic events are stochastic, with shorter and extreme events less predictable than averages and some trends, but extreme events can have great significance to stream functions, processes, and channel forms. In recent years, increased attention has focused more or less on extreme events such as channel-forming, channel-maintaining, and flushing flows (Wesche et al. 1987; Reiser et al. 1989; Kondolf 1998; Whiting 1998). These flows may have low frequencies of occurrence--with recurrence intervals measured in years, decades, or longer—but their effect on maintaining long-term ecological processes is critical.

LESSONS FROM STREAM ECOLOGY

The Importance of Flow Variability

The importance of the natural hydrograph to stream resource stewardship has been demonstrated by the outcomes from earlier water developments (Karr 1991; Hughes and Noss 1992; Stalnaker 1994; Castleberry et al. 1996; Frissell and Bayles 1996; Rasmussen 1996; Poff et al. 1997; Richter et al. 1997; Bovee et al. 1998; Hardy 1998; Ward 1998; Goldstein 1999; Potyondy and Andrews 1999; Ward et al. 1999). The lesson is that those developments somehow altered the variability of the system to the detriment of the ecological system. Poff et al. (1997) pointed out that “the natural flow regime of virtually all rivers is inherently variable and that this variability is critical to ecosystem function and native biodiversity.” Year-to-year variation in flow drives processes that periodically reset physical, chemical, and biological functions essential to the ecosystem. Some species do well in wet years and other species do well in dry years. For this reason, *providing a single flow value (minimum, optimal, or otherwise) cannot simultaneously meet the requirements for all species or maintain a fishery.* To ensure sustained biological diversity and dynamic ecosystem functions, both intra- and interannual flow regimes and natural functions must be maintained or provided.

Flows that vary over time create and maintain dynamic channel and floodplain conditions, create essential habitats for aquatic and riparian species (Figure 1), and directly regulate numerous ecological processes. High flows--as a result of snow melt or rain--sort and transport sediments, create discrete distributions of different-sized particles, move bed material, provide a sediment balance, control submerged, emergent, and streamside vegetation, influence the structural stability of stream banks, and prevent vegetation encroachment into the active channel. Floods import particulate organic matter and woody debris into the channel thereby creating habitat and providing food sources for some species. Ice formation processes have similar functions. All of these benefits may be disrupted by flow and temperature regimes that do not mimic the seasonality of unregulated streams.

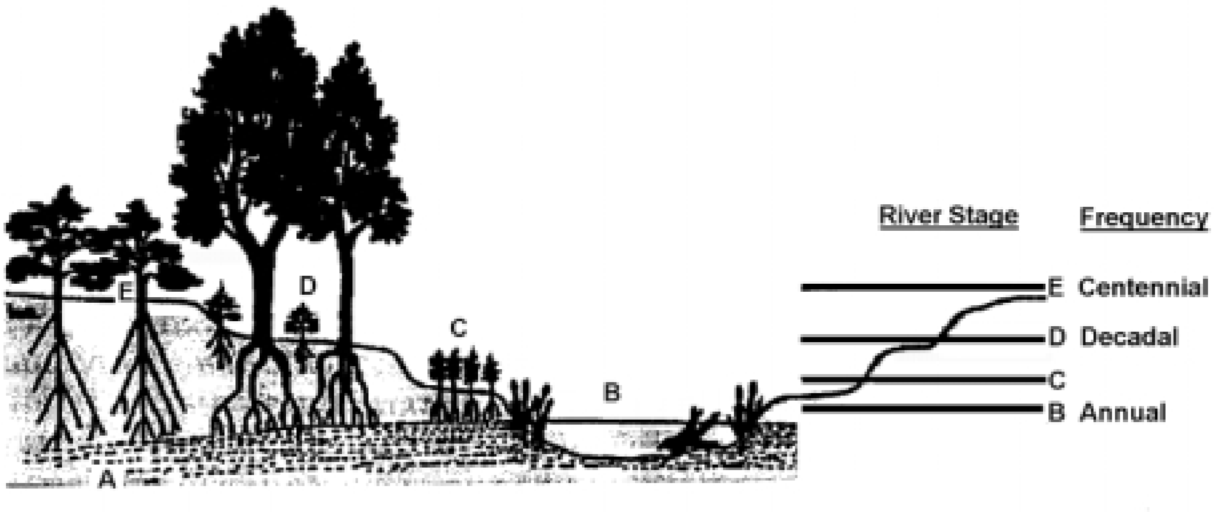

FIGURE 1. *Geomorphic and ecological functions provided by different levels of flow. Water tables that sustain riparian vegetation and that delineate in-channel base flow habitat are maintained by groundwater inflow and flood recharge (A). Floods of varying size and timing are needed to maintain a diversity of riparian plant species and aquatic habitat. Small floods occur frequently and transport fine sediments maintaining high benthic productivity and creating spawning habitat for fishes (B). Intermediate-size floods inundate low-lying floodplains and deposit entrained sediment, allowing for the establishment of pioneer species (C.) These floods also import accumulated organic material into the channel and help to maintain the characteristic form of the active stream channel. Larger floods that recur on the order of decades inundate the aggraded floodplain terraces, where later successional species establish (D). Rare large floods can uproot mature riparian trees and deposit them in the channel, creating high-quality habitat for many aquatic species (E)* (From Poff et al. 1997).

Life cycles of many aquatic and riparian species are timed to either avoid or exploit flows of variable magnitudes. Predictable high and low streamflows provide cues for certain life cycle events (e.g., spawning movements, egg hatching, rearing, movement into and out of floodplain areas and upstream and downstream movement). Seasonal access to floodplain wetlands for spawning and rearing is essential for certain riverine fishes to spawn and rear young fish to larger size. When access to floodplains is reduced due to the alteration of high flow events (or other land management activities), such species may become reduced or eliminated (Robinson et al. 1998; Wydoski and Wick 1998; Muth et al. 2000). Many riparian plants also have life cycles that are adapted to the seasonal timing of natural flow regimes. Seasonal sequences of flowering, seed dispersal, germination, and seedling growth are timed to natural flow events. The scouring of the floodplain by these high flows rejuvenates habitat for some types of plant species. Seasonal variation in flow, including drought, can prevent the successful establishment of nonnative species with specific moisture requirements or inundation tolerances.

The rate of change, or flashiness, in flow conditions can influence species persistence and coexistence. In some areas, natural flow can change abruptly. Nonnative species generally are not adapted to such situations and lack the behavioral and physiological adaptations to survive. However, if the flow regime is altered to become more stable, they may out-compete native species (Hawkins et al. 1997; Tyus et al. 2000). On the other hand, rapid flow increases often serve as spawning cues for native species whose rapidly developing eggs are either broadcast into the water column (e.g., Taylor and Miller 1990) or attached to submerged structures as floodwaters recede. More gradual, seasonal rates of change in flow conditions also regulate the persistence of many aquatic and riparian species. In the case of cottonwoods, the rate of floodwater recession is critical to seedling germination because seedling roots must remain connected to a receding water table as they grow downward (Rood and Mahoney 1990).

The Need for Ecosystem-Level Management

All watersheds are complex webs of interrelated physical, chemical, and biological components (Calow and Petts 1992, 1994) that have been affected by human activities. These activities have degraded stream ecosystems by altering food (energy) source, water quality, habitat structure, flow regime, and biotic interactions (Karr 1991) (Figure 2). Ecosystem degradation is manifested as lost biological diversity when humans disturb watersheds by removing permanent vegetation (for agricultural purposes or urban development), building dams that store and/or divert water, and physically modifying channels. Biological diversity and ecological integrity refer to the variety of life at the genetic, taxonomic, and ecosystem levels, and include function, processes, structure, and naturalness (Hocutt 1981; Karr and Dudley 1981; Pimm 1984; Hughes and Noss 1992; Goldstein 1999)(Figure 3). Degradation often leads to at least localized shifts in species community or even the loss of some species.

Place Figure 2 here

FIGURE 2. *An example of how human activity can affect ecological function (From Karr 1991).*

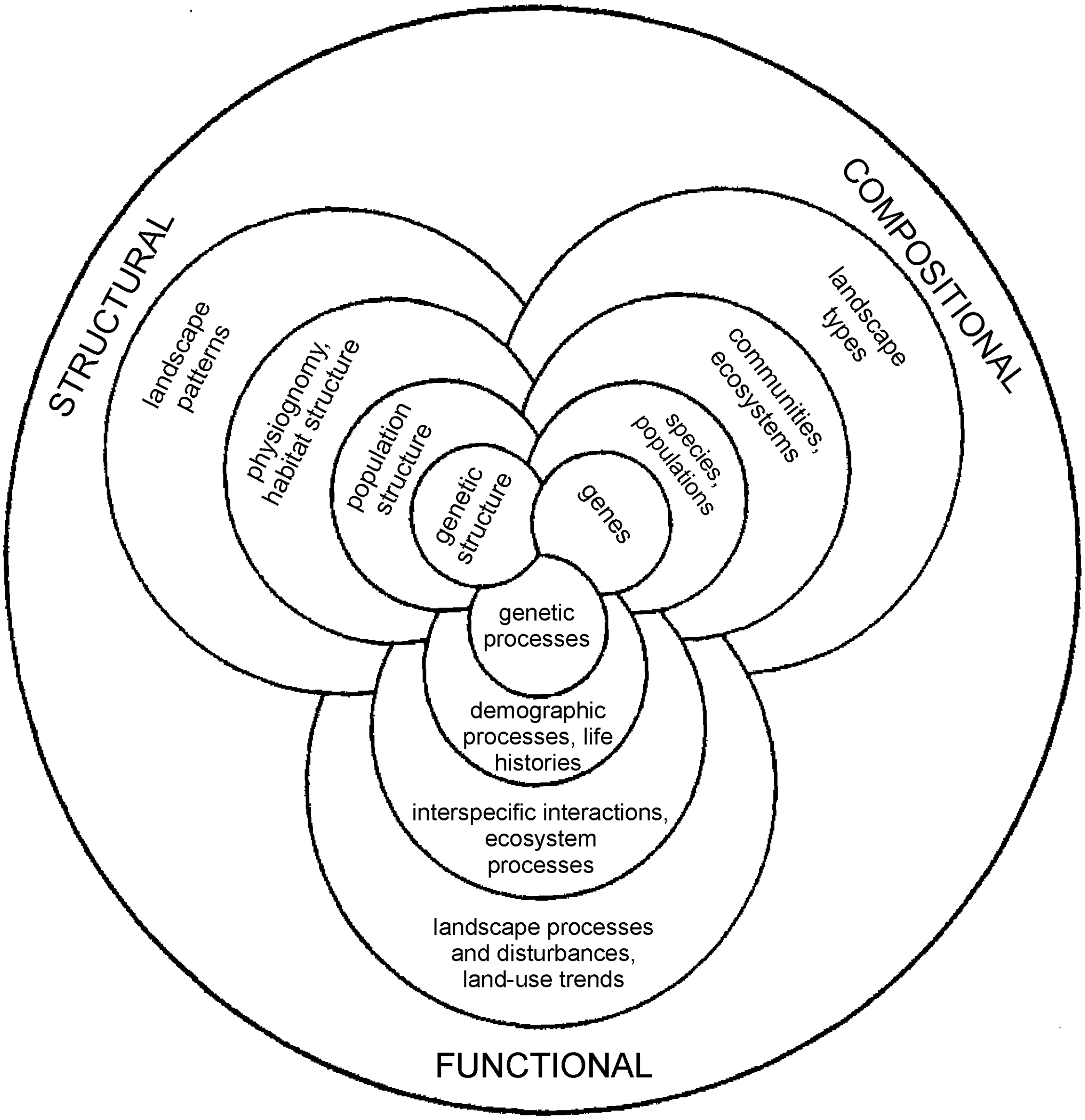

FIGURE 3. *An example of how ecosystem structure, function, and process affect biological diversity and ecological integrity (From Noss 1990).*

Historically, most land use decisions have been made with little understanding or regard for their effect on the interconnectedness of river and landscape (Schlosser 1991). Long-term solutions in natural resource management depend on a holistic view of the river system, including the geology, hydrology, fluvial dynamics, biological interactions with habitat, and water quality. To achieve this perspective for rivers, it is necessary to identify major interactive pathways, hierarchical structure, and temporal dynamics by making full use of our knowledge while recognizing its limitations. This requires that water management decisions extend beyond the needs of a single species or recreational use. Such complex issues must be addressed through interdisciplinary studies that involve hydrologists, geomorphologists, water quality specialists, aquatic biologists, and riparian ecology experts.

This philosophy reflects the emerging consensus endorsed by the IFC that river managers should assess riverine flow management needs over the entire range of natural flows (Stalnaker 1994; Rasmussen 1996; Poff et al. 1997; Bovee et al. 1998; Potyondy and Andrews 1999) and make flow recommendations that are related in some fashion to the physical, biological, and chemical processes embodied in the natural flow regime. The first step for state and provincial natural resource managers working on instream flow issues is to proceed by defining goals based on ecosystem objectives.