Chapter 4
River Hydrology, Flow Alteration, and Environmental Flow

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"The water runs the river." This chapter focuses on the river flow as the fundamental process determining the size, shape, structure, and dynamics of riverine ecosystems. We briefly introduce hydrological regimes as key characteristics of river flow. Hydrological regimes are then linked to habitats and biotic communities. The effects of flow regulation as a result of human activities such as water abstraction (irrigation and hydropower), river channelization, land use, and climate change are demonstrated. Finally, methods to assess the environmental flow, the flow that is needed to maintain the ecological integrity, are described, and examples of successful flow restoration presented.

4.1 The Water Cycle and Hydrological Regimes

In temperate zones water received via precipitation is either stored in ice and snow during winter or infiltrates into the groundwater and is released into rivers during summer. Water cycles through stages of evaporation, water storage in the atmosphere, precipitation, (sub)surface runoff, and storage in the ocean. The water cycle and climatic conditions form the boundary conditions for the *hydrological regimes* that define distinct seasonal and daily flow patterns. High altitude rivers receive water mainly from glacial melt during summer with distinct diurnal melting peaks following air temperature warm-up (*glacial regime*) (Fig. 4.1). At lower elevations snow melting in spring causes seasonal peaks (*nival regime*), while periods of high flow and floods due to rainfall can occur at any time of the year (*pluvial regime*).

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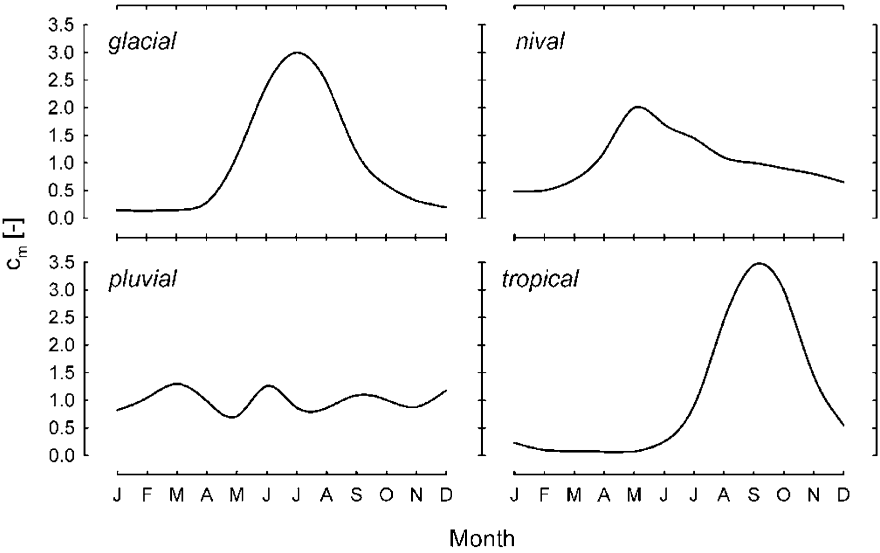

Fig. 4.1 Simple hydrological regimes (glacial, River Ötztaler Ache; nival, River Mur; pluvial, River Stiefing; and tropical, River Niger). The monthly discharge coefficient (c_m) is defined by the ratio of the average monthly discharge and the mean discharge (hydrograph data over several years)

Tropical rivers are characterized by distinct flow cycles related to dry and wet seasons. The *tropical regime* is similar to the pluvial regime, e.g., drought in the dry season and abundant rainfall in the wet season. Depending on the local conditions and position within the catchment, observed flow may represent a mixture of hydrological regimes. Flow regimes are very important to understand the key functions and processes of riverine ecosystems.

Catchments are hydrological units defined as the area collecting the water within a given drainage divide or watershed (a drainage divide is the line that separates neighboring drainage basins). All the catchments for all the tributaries of a river are lumped together to form a *river basin* (e.g., Danube River Basin). The so-called *water balance* of a given catchment or basin is calculated from water gains (precipitation) and losses (evapotranspiration and runoff) including storage phases (soil water, groundwater, ice, snow). The observed discharge (m^3/s) at distinct locations within the catchment is determined based on meteorological and biogeophysical factors (see Table 4.1).

The river flow determines the dynamics of the four-dimensional river system (Ward 1989). Sediment and nutrient transport is closely linked to the longitudinal dimension of flow. Floodplain dynamics depend on the lateral hydrological connectivity and flood pulses (Junk et al. 1989). River groundwater interaction represents the vertical dimension of flow dynamics and determines groundwater recharge and groundwater contribution to river flow. The longitudinal, lateral, and vertical flow pattern varies over time representing the fourth dimension of the four-dimensional river system.

Table 4.1 Meteorological and biogeophysical factors determining river flow

Meteorological factors	Biogeophysical factors
– Type of precipitation (rainfall, snow) – Rainfall amount, intensity, duration, and distribution over the drainage basin – Precipitation that occurred earlier and resulting soil moisture – Meteorological conditions that affect evapotranspiration and infiltration	– Drainage area – Elevation – Topography, terrain slope – Basin shape and drainage network patterns – Soil type, land use, and vegetation – Ponds, lakes, reservoirs, sinks, etc. in the basin, which prevent or delay downstream runoff

4.2 Flow Determines Habitats and Biotic Communities

River flow determines processes that shape and organize the physical habitat and associated biotic communities. Flow variability is a fundamental feature of river systems and their ecological functioning (Poff et al. 1997). The natural flow of a river varies on time scales of hours, days, seasons, years, and longer. Many years of observation from a streamflow gauge are generally needed to describe the characteristic pattern of a river's flow quantity, timing, and variability (Poff et al. 1997). River flow regimes show regional patterns that are determined largely by river size and by geographic variation in climate, geology, topography, and vegetative cover.

The widely accepted natural flow paradigm (*sensu* Poff et al. 1997), where the flow regime of a river, comprising the five key components of variability, i.e., *magnitude*, *frequency*, *duration*, *timing*, and *rate of change*, is recognized as central to sustaining biodiversity and ecosystem integrity (Poff and Ward 1989; Karr 1991; Richter et al. 1997; Rapport et al. 1998; Rosenberg et al. 2000). These components can be used to characterize the entire range of flows and specific hydrologic phenomena, such as floods or low flows, which are critical to the integrity of river ecosystems.

The natural flow regime organizes and defines river ecosystems. In rivers, the physical structure of the environment and, thus, of the habitat is defined largely by physical processes, especially the movement of water and sediment within the channel and between the channel and floodplain. The physical habitat of a river includes sediment size and heterogeneity, channel and floodplain morphology, and other geomorphic features. These features form as the available sediment, woody debris, and other transportable materials are moved and deposited by flow. Thus, habitat conditions associated with channels and floodplains vary among rivers in accordance with both flow characteristics and the type and the availability of transportable materials. Within a river, different habitat features are created and maintained by a wide range of flows (Poff et al. 1997).

Generally, the shaping of hydro-morphological channel and floodplain features (e.g., river bars and riffle-pool sequences) happens continuously. But the dominant, shaping processes occur in episodes of bank-full discharges (see Chap. 3). It is important that these flows are able to move bed or bank sediment and occur frequently enough to continually modify the river channel (Wolman and Miller 1960).

The diversity of instream and floodplain habitat types has stimulated the evolution of species that use the habitat mosaic created by hydrologic variability. For many riverine species, completion of the life cycle requires an array of different habitat types, whose availability over time is regulated by the flow regime (Greenberg et al. 1996).

Aquatic organisms have evolved life history strategies primarily in direct response to natural flow regimes (Bunn and Arthington 2002). The physical, chemical, and biological characteristics of rivers are primarily affected by flow variation as a “master variable.” Changes in discharge are a form of disturbance, but a moderate level of hydrological variability enhances biological diversity (*sensu* Connell 1978; Ward and Stanford 1983; Bunn and Arthington 2002). River biota have evolved adaptive mechanisms to cope with habitat changes that result from natural flow variation, and indeed many species rely on regular or seasonal changes in river flows to complete their life cycles (Poff et al. 1997). For detailed discussions of the ecological effects (and knock-on social and economic implications) of hydrological alterations on riverine ecosystems, with impacts ranging from genetic isolation through habitat fragmentation to declines in biodiversity, floodplain fisheries, and ecosystem services, see Ward (1982), Petts (1984), Lillehammer and Saltveit (1984), Armitage (1995), Cushman (1985), Craig and Kemper (1987), Gore and Petts (1989), Calow and Petts (1992), Boon et al. (1992, 2000), Richter et al. (1998), Postel (1998), Snaddon et al. (1999), Pringle (2000), World Commission on Dams (2000), Bergkamp et al. (2000), and Bunn and Arthington (2002).

Bunn and Arthington (2002) propose that the relationship between biodiversity and the physical nature of the aquatic habitat is likely to be driven primarily by large events that influence channel form and shape (principle 1) (Fig. 4.2). However, droughts and low-flow events are also likely to play a role by limiting overall habitat availability. Native biota have evolved in response to the overall flow regime. Many features of the flow regime influence life history patterns, especially the seasonality and predictability of the overall pattern, but also the timing of particular flow events (principle 2). Some flow events trigger longitudinal dispersal of migratory aquatic organisms, and other large events allow access to otherwise disconnected floodplain habitats (principle 3). Catchment land-use change and associated water resource development inevitably lead to changes in one or more aspects of the flow regime resulting in declines in aquatic biodiversity via these mechanisms. Invasions by introduced or exotic species are more likely to succeed at the expense of native biota if the former are adapted to the modified flow regime (principle 4).

4.3 Flow Regulation

The global increase in water demand has resulted in a conflict between using rivers as water and energy sources and the need to conserve rivers as intact ecosystems (Dynesius and Nilsson 1994; Abramovitz 1995; Postel 1995; McCully 1996; World Commission on Dams (2000). This ongoing conflict has stimulated a growing field

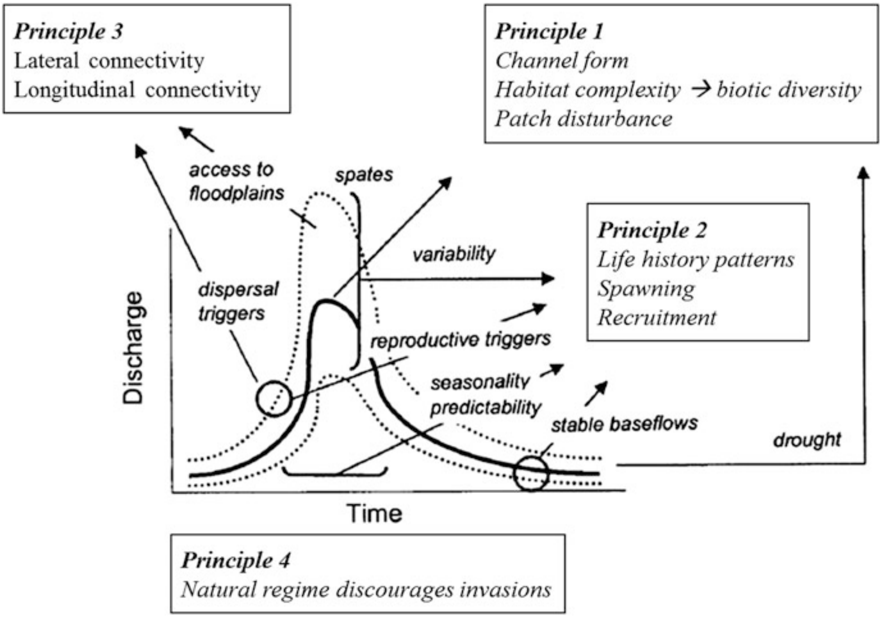

Fig. 4.2 The natural flow regime of a river influences aquatic biodiversity via several interrelated mechanisms that operate over different spatial and temporal scales. The relationship between biodiversity and the physical nature of the aquatic habitat is likely to be driven primarily by large events that influence channel form and shape (principle 1). However, droughts and low-flow events are also likely to play a role by limiting overall habitat availability. Many features of the flow regime influence life history patterns, especially the seasonality and predictability of the overall pattern, but also the timing of particular flow events (principle 2). Some flow events trigger longitudinal dispersal of migratory aquatic organisms, and other large events allow access to otherwise disconnected floodplain habitats (principle 3). The native biota have evolved in response to the overall flow regime. Catchment land-use change and associated water resource development inevitably lead to changes in one or more aspects of the flow regime resulting in declines in aquatic biodiversity via these mechanisms. Invasions by introduced or exotic species are more likely to succeed at the expense of native biota if the former are adapted to the modified flow regime (principle 4) (Bunn and Arthington 2002) (© Environmental management, Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity, 30, 2002, p. 493, Bunn SE, Arthington AH. With permission of Springer.)

of research dedicated to assessing the requirements of rivers for their own water, to enable satisfactory tradeoffs in water allocation among all users of the resource and the resource base itself (the river) (Tharme 2003).

More than half of the world's accessible surface water is already appropriated by humans, and this is projected to increase to 70% by 2025 (Postel 1998). Water resource developments such as impoundments, diversion weirs, interbasin water transfers, run-of-river abstraction, and exploitation of aquifers, for the primary uses of irrigated agriculture, hydropower generation, industry, and domestic supply, are responsible for unprecedented impacts to riverine ecosystems, most of which result from alterations to the natural hydrological regime (Rosenberg et al. 2000). Almost all large river basins are already impacted by large dams (Nilsson et al. 2005).

About 60% of the world's rivers are estimated to be fragmented by hydrologic alteration, with 46% of the 106 primary watersheds modified by the presence of at least one large dam (Revenga et al. 1998, 2000). Dynesius and Nilsson (1994) calculated that 77% of the total discharge of the 139 largest river systems in North America, Europe, and the republics of the former Soviet Union is strongly or moderately affected by flow-related fragmentation of river channels. Moreover, they observed that large areas in this northern third of the world entirely lack unregulated large rivers. EU member countries regulate the flow of around 65% of the rivers in their territories, while in Asia, just under 50% of all rivers that are regulated have more than one dam (World Commission on Dams 2000). Flow regulation through impoundment represents the most prevalent form of hydrological alteration with over 45,000 large dams in over 140 countries (World Commission on Dams 2000); a further 800,000 small dams are estimated to exist worldwide (McCully 1996). The top five dam-building countries (China, United States, India, Japan, Spain) account for close to 80% of all large dams worldwide, with China alone possessing nearly half the world total (World Commission on Dams 2000, cited in Tharme 2003). Dam development is expected to continue, with more than 3700 large hydropower dams alone currently planned or under construction worldwide (Zarfl et al. 2014).

4.4 Human Alteration of Flow Regimes

Human alteration of flow regime changes the established pattern of natural hydrologic variation and habitat dynamics. Modification of natural hydrologic processes disrupts the dynamic balance between the movement of water and the movement of sediment that exists in free-flowing rivers (Dunne and Leopold 1978).

Typical sources of alteration of flow regimes are (after Poff et al. 1997):

- Dam
- Water diversion
- Urbanization, sealing, drainage
- Levees and channelization
- Groundwater pumping

Dams, which are the most obvious direct modifiers of river flow, capture both low and high flows for flood control, electrical power generation (Fig. 4.3), irrigation and municipal water needs, maintenance of recreational reservoir levels, and navigation. Dams capture sediments moving down a river, with many severe downstream consequences (e.g., erosion of fine sediment in the downstream section). The coarsening of the streambed can, in turn, reduce habitat availability for aquatic species living in or using interstitial spaces (Chien 1985). Beside flow regulation as a consequence of dam construction, rivers get fragmented and loose its natural connectivity (see Chap. 6).

Dams also lead to reduction of the magnitude and frequency of high flows, leading to deposition of fines and sealing in gravel and channel stabilization and

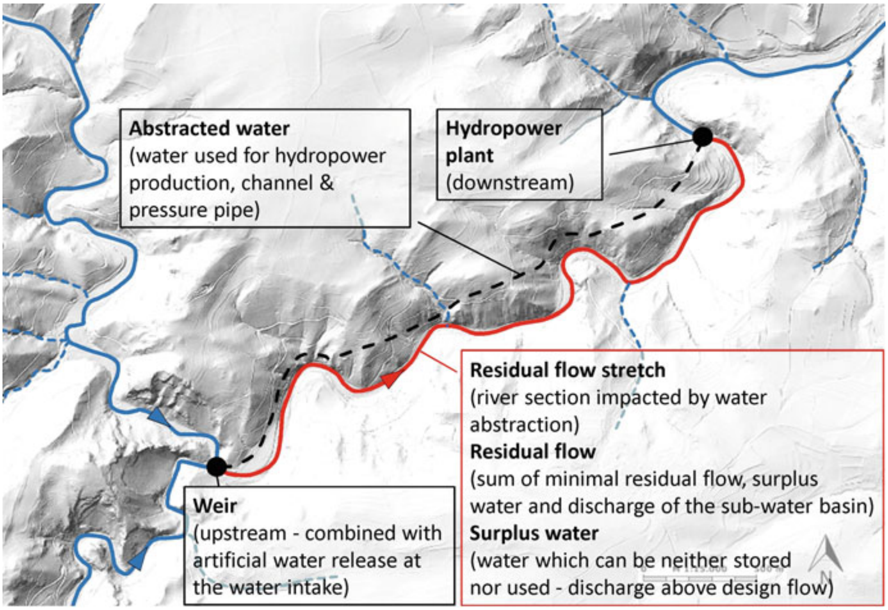

Fig. 4.3 Scheme of a diversion power plant and residual flow stretch (hydropower plant Hohenstein at the River Krems, Austria). Main river (blue solid line), small tributaries (blue dashed line), residual flow stretch (red solid line), and diversion channel (black dashed line)

narrowing. Sealing and land drainage increase the magnitude and frequency of high flows, leading to bank and riverbed erosion and floodplain disconnection. Furthermore, reduced infiltration into soil reduces base flows. Levees and channelization reduce overbank flows, leading to floodplain deposition and channel restriction, causing downcutting and restraining channel migration and formation of secondary channels. Groundwater pumping lowers water table levels and further reduces plant growth. The loss of vegetation leads to streambank stability erosion and channel downcutting.

4.5 Ecological Responses to Altered Flow Regime

In a comprehensive review, Poff and Zimmerman (2010) reported that almost all published research found negative ecological changes in response to a variety of flow alteration (Table 4.2). Only in few instances did values for ecological response metrics increase, indicating shifts in ecological organization, such as increase in non-native species or non-woody plant cover on dewatered floodplains. This also confirms earlier summaries of ecological response to flow regime alterations (Poff et al. 1997; Bunn and Arthington 2002; Lloyd et al. 2003).

Table 4.2 Alterations in flow components and common ecological response (modified after Poff et al. 1997; Poff and Zimmerman 2010)

Flow component	Alteration	Ecological response	
Magnitude	Flow stabilization (loss of extreme high and/or low flows)	(a)	Reduced diversity Loss of sensitive species Altered assemblages and dominant taxa Reduced abundance Increase in non-natives
		(r)	Seedling desiccation Ineffective seed dispersal Terrestrialization of flora Lower species richness Encroachment of vegetation into channels Increased riparian cover Altered assemblages
	Greater magnitude of extreme high and/or low flows	(a)	Life cycle disruption Reduced species richness Altered assemblages and relative abundance of taxa Loss of sensitive species
Frequency	Decreased frequency of peak flows	(a)	Aseasonal reproduction Reduced reproduction Decreased abundance or extirpation of native fishes Decreased richness of endemic and sensitive species Reduced habitat for young fishes
		(r)	Shift in community composition Reductions in species richness Increase in wood production
Duration	Decreased duration of floodplain inundation	(a)	Decreased abundance of young fish Change in juvenile fish assemblage Loss of floodplain specialists in mollusk assemblage
		(r)	Reduced growth rate or mortality Altered assemblages Terrestrialization or desertification of species composition Reduced area of riparian plant or forest cover
	Prolonged low flows	(a)	Concentration of organisms Downstream loss of floating eggs
		(r)	Reduction or elimination of plant cover Diminished plant species diversity Desertification of species composition
	Prolonged inundation	(a)	Loss of riffle habitat
		(r)	Change in vegetation functional type Tree mortality

(continued)

Table 4.2 (continued)

Flow component	Alteration	Ecological response	
Timing	Shifts in seasonality of peak flows	(a)	Disruption of spawning cues Decreased reproduction and recruitment Change in assemblage structure
	Increased predictability	(a)	Change in diversity and assemblages structure Disruption of spawning cues Decreased reproduction and recruitment
	Loss of seasonal flow peaks	(a)	Disruption of migration cues Loss of accessibility to wetlands and backwaters Modification of food web structure
		(r)	Reduced riparian plant recruitment Invasion of exotic riparian plant species Reduced plant growth and increased mortality Reduction in species richness and plant cover
Rate of change	Rapid changes in river stage	(a)	Drift (washout) and stranding
	Accelerated flood recession	(r)	Failure of seedling establishment

Taxonomic identity of organisms: aquatic (a) and riparian (r)

Taxonomic groups, e.g., fish, macroinvertebrates, and riparian vegetation, show biota-specific responses (abundance, diversity, and demographic parameters) to flow alteration depending on the flow components affected (magnitude, frequency, duration, timing, rate of change). Most of the studies on ecological changes report responses to altered flow magnitude associated with flow stabilization due to water abstraction or water withdrawals for irrigation. For the most part instream taxa react negatively to alteration of flow magnitude. Alterations in flow frequency, referring mainly to decreases in frequency of floods, resulted in negative ecological responses by macroinvertebrates and fish. Riparian communities usually decline in response to flow frequency alteration; but also some increases are indicated (e.g., wood production). Alterations in flow duration, mostly in the form of changes in the duration of floodplain inundation, are primarily associated with decreases in both instream and riparian communities. Similarly, changes in the timing of flows due to loss of seasonal flow peaks reduce both aquatic and riparian communities (Poff et al. 1997; Poff and Zimmerman 2010). The rate of change is an important component of the natural flow regime, commonly altered by hydropeaking, which causes detrimental effects on instream and riparian communities (see Chap. 5).

Fish respond negatively to changes in flow magnitude, whether the flows increase or decrease. Fish metrics decrease sharply in response to reduced flows (see Figs. 4.4, 4.5 and 4.6). Diversity shows a clear decline, especially where changes in flow magnitudes exceed 50%. Therefore, fish are sensitive indicators of flow alteration. Compared to this, macroinvertebrates or riparian species are not such reliable indicators, since they do not consistently respond to changes in flow magnitude. Riparian

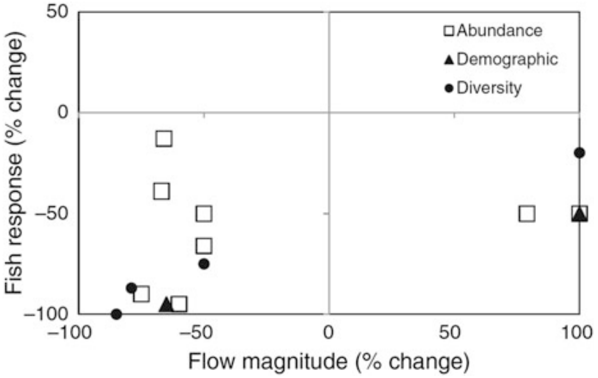

Fig. 4.4 Percent change in fish abundance, demographic parameters, and species diversity (and/or richness) with respect to percent alteration of flow magnitude. Percent change for both fishes and flow magnitude represents alteration relative to a pre-impact or "reference" condition. Alteration in flow magnitude includes changes in peak flow, total or mean discharge, baseflow, or hourly flow (Poff and Zimmerman 2010) (source: Poff and Zimmerman (2010). Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshwater Biology, 55(1), 194–205, reproduced with permission of John Wiley & Sons, Ltd., © 2009 Blackwell Publishing Ltd, Freshwater Biology, 55, 194–205)

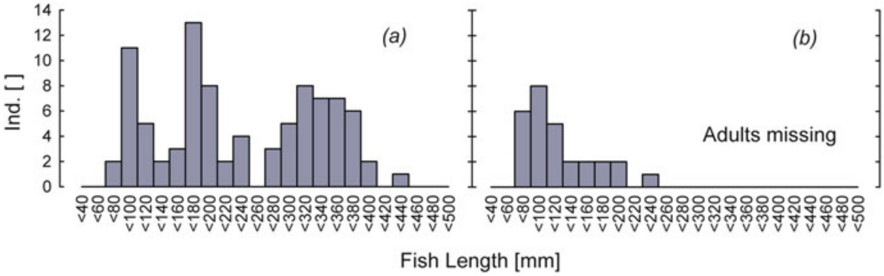

Fig. 4.5 Length distribution of brown trout at River Unrechttraisen (**a**) full water section and (**b**) residual flow section (adapted from Zeiringer 2008b)

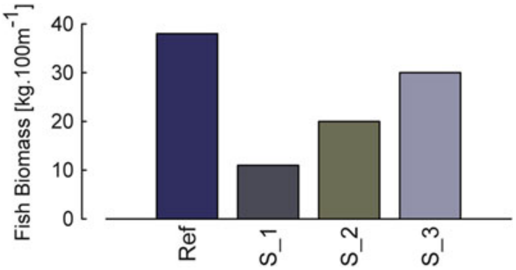

Fig. 4.6 Biomass of brown trout in River Ybbs in full flow section (reference) and residual flow sections, ordered along the river course (adapted from Zeiringer et al. 2010)

Fig. 4.7 Encroachment of vegetation into river channel, example residual flow stretch River Gölsen

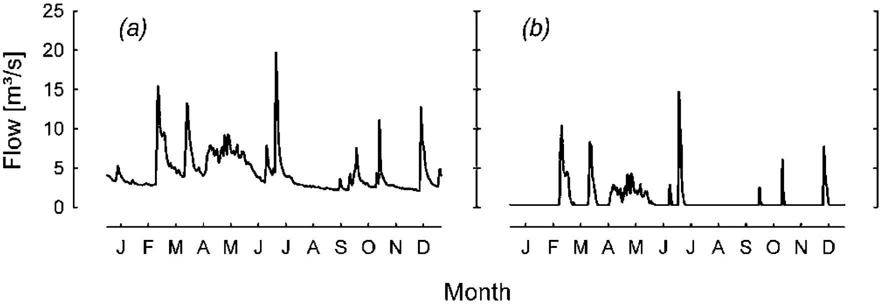

Fig. 4.8 Hydrological effects of water abstraction, (**a**) natural hydrograph, and (**b**) reduced and moderated flow in the residual flow section at the HPP Reichenau/River Schwarza (adapted from Zeiringer 2008a)

responses can be associated with decreases in flood peaks, leading to reduction or elimination of overbank flooding (Poff and Zimmerman 2010) (Fig. 4.7).

Aquatic and riparian species respond to multiple hydrologic drivers, and overlap in their occurrence and impacts often confounds analysis (Poff and Zimmerman 2010). Changes in magnitude of high flows are often accompanied by changes in frequency, and either or both of these may influence biological response (Fig. 4.8). Additionally, other environmental characteristics, like water temperature (Fig. 4.9) or sediment regime (Fig. 4.10), may affect biota independently or in association with flow alteration.

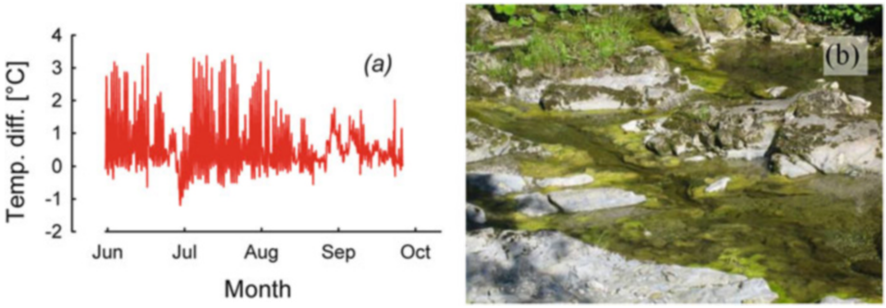

Fig. 4.9 Change of water quality due to water abstraction (**a**) water temperature increase River Mur during summer (adapted from Zeiringer et al. 2008) and (**b**) algae bloom River Lassing

Fig. 4.10 Morphological effects of water abstraction, e.g., reduction of flow velocity and shear stress, change of flow and substrate patterns, silting up of interstitial (clogging), reduced water depth, and reduced wetted width (**a**) River Aschbach and (**b**) and (**c**) River Mur

Poff and Zimmerman (2010) mentioned that there are no studies reported that focus primarily on ecosystem functional responses (e.g., riparian production, nutrient retention), even though many ecological processes are clearly flow dependent (Hart and Finelli 1999; Doyle et al. 2005, cited in Poff and Zimmerman 2010). They emphasized that this absence points to an obvious research gap in the environmental flows research.

4.6 Environmental Flow

Environmental flow (EF) is the quantity or volume of water required over time to maintain river health in a particular state, where the state has to be predetermined or agreed upon based on a trade-off with other considerations (Acreman and Dunbar 2004). Such quanta are captured by a variety of terms, including the environmental flow (regime), instream flow, environmental allocation, or ecological flow requirement, to distinguish these from compensation flows (Gustard et al. 1987, cited in Acreman and Dunbar 2004). The latter have been set for other purposes, such as downstream human uses (e.g., irrigation, hydropower), pollutant dilution, or navigation. The first approaches to quantifying EFs only focused on minimum flow, based on the idea that all river health problems are associated with low flows.

Although there is no generally agreed definition or term (IWMI 2005), it is widely accepted (e.g., Poff et al. 1997; Karr 1991; Bunn and Arthington 2002; Postel and Richter 2003; Annear et al. 2004) that not only the quantity of discharge is decisive but that also the timing and discharge dynamics are key factors for sustaining and conserving native species diversity and ecological integrity of rivers.

4.6.1 The Concept and Definitions of Environmental Flow

The concept of EF historically was developed as a response to the degradation of aquatic ecosystems caused by overuse of water. In this context EF may be defined as the amount of water that is left in an aquatic ecosystem, or released into it, for the specific purpose of managing the condition of that ecosystem (Arthington et al. 2006; Brown and King 2003). Despite the fact that the concept of EF has existed for over 40 years (including other terminology, such as instream flows), there is still no unified definition for it (Moore 2004). This lack of uniform agreement for a definition of EF can be illustrated by looking at a sample of the ways in which it has been defined in the literature by researchers and organizations involved in assessing and implementing the concept all around the world over the last decades. In these definitions of environmental flows, there are always two key aspects of the concept included: the flow regime that should be considered and the level of conservation for the ecosystem that is intended.

Selected definitions of EF:

- Arthington and Pusey (2003) define the objective of environmental flows as maintaining or partially restoring important characteristics of the natural flow regime (i.e., the quantity, frequency, timing, and duration of flow events, rates of change, and predictability/variability) required to maintain or restore the biophysical components and ecological processes of instream and groundwater systems, floodplains, and downstream receiving waters.
- Brown and King (2003) state that environmental flows is a comprehensive term that encompasses all components of the river, is dynamic over time, takes cognizance of the need for natural flow variability, and addresses social and economic issues as well as biophysical ones.
- Dyson et al. (2003) in the IUCN guide on environmental flows define the concept as the water regime provided within a river, wetland, or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated.
- Tharme (2003) defines an environmental flow assessment (EFA) as an assessment of how much of the original flow regime of a river should continue to flow down

it and onto its floodplains in order to maintain specified, valued features of the ecosystem.
- Gupta (2008) defines EFs as discharges of a particular magnitude, frequency, and timing, which are necessary to ensure that a river system remains environmentally, economically, and socially healthy.
- Environmental flows can be described as "the quality, quantity, and timing of water flows required to maintain the components, functions, processes, and resilience of aquatic ecosystems which provide goods and services to people" (Hirji and Davis 2009).

EF is a management concept, and thus it should vary in response to actions or processes that are used and understood by management. Generally, certain human activities create a water demand that requires the development of infrastructure (diversion weirs, dams, etc.). The presence and operation of this infrastructure produces modifications of the natural flow regimes that affects the biophysical conditions of ecosystems. Environmental flows can help to restrict water use, to define the maximum limits of hydrological alteration to maintain a certain biological condition and may appear as a basic tool for the recovery of certain species affected by the modification of aquatic habitats (Navarro and Schmidt 2012). A combination of Arthington and Pusey and Tharme definitions (2003) might consider the most basic and relevant aspects of the concept of environmental flows: environmental flow is the proportion of original flow maintaining or restoring biophysical components, ecological processes, and services of instream and groundwater systems, floodplains, and downstream receiving waters.

4.6.2 Assessing and Implementing Environmental Flows

In many countries a variety of approaches for assessing EF were developed with varying complexity, e.g., look-up tables (preliminary assessment level), desktop analyses and functional analyses (intermediate assessment level), and finally hydraulic habitat modeling (comprehensive assessment level), which we describe in more detail below (see also Table 4.3). Some address just parts or the river system, while others are more holistic (Tharme 2003; Acreman and Dunbar 2004). Currently, there exist at least 200 environmental flow methods classifiable in four major categories according to focus, complexity, and cost and time effectiveness: (1) hydrological methods, (2) hydraulic rating, (3) habitat simulation models, and (4) holistic methodologies (Dyson et al. 2003; Tharme 2003; Arthington et al. 2004; Richter et al. 2006; King et al. 2008).

Hydrological Analyses (also called desktop analyses) are mostly based on simple minimum flow thresholds derived from hydrographs (e.g., mean annual flows, monthly flows, high/low flows, and Q95%) (Barker and Kirmond 1998). For example, the Tennant or Montana method (Tennant 1976) defines EF values as percentage of the average daily discharge or mean annual flow (MQ) with 10% MQ

Table 4.3 Different methods and characteristics of setting environmental flows and choice of method (modified after Acreman and Dunbar 2004; European Commission 2015; Theodoropoulos and Skoulikidis 2014)

Method type	Application range				Pros and cons	Assessment level
Look-up table	Scoping study, regional planning	Basin-scale planning			Rapid, cheap, not site specific	Preliminary
Desktop			Impact assessment (multi-site)		Site specific, limited new data collection, long time series required, use existing ecological data	Intermediate
Functional analysis				Impact assessment (single-site); River restauration (multi- and single-site)	Flexible, robust, more focused on whole ecosystem, expensive to collect all relevant data and wide range of experts	
Habitat modeling					Replicable, predictive, expensive to collect hydraulic and ecological data	Comprehensive

considered as minimum flow and 60–00% MQ considered the flow range necessary to provide optimal habitat conditions. More complex hydrological indices are the indicators of hydrologic alteration (IHA) (Richter et al. 1996), the range of variability approach (RVA) (Richter et al. 1997), and the indicators of hydrologic alteration in rivers (IAHRIS) (Martinez and Fernandez 2010). RVA, for example, uses 32 hydrological parameters (their range and variation) as indicators of hydrological alteration (IHA; Richter et al. 1996) to characterize ecologically relevant attributes of the local flow regime and to translate them into defined flow-based management targets. The method suggests a natural flow paradigm including the full range of natural intra- and interannual variation of hydrological regimes and associated characteristics of timing, duration, frequency, and rate of change as critical factors to sustain the integrity of the riverine ecosystem (Richter et al. 1997). Hydrological methods rely primarily on historical hydrological data, requiring flow measurements over long time periods. Although hydrological data collection is resource demanding, the application of such methods itself is time- and cost-effective and simple. Although such methods consider flow dynamics, they only indirectly address requirements of aquatic biota. Therefore, they are not considered appropriate as stand-alone methods, but often are used as initial desktop analyses to assist more complex environmental flow methodologies (Theodoropoulos and Skoulikidis 2014). In fact, these methods lack ecological relevance and sensitivity to individual rivers and are considered as inadequate to provide the data needed to sustain ecological integrity.

Hydraulic Rating methods use simple hydraulic variables and propose EF through the quantifiable relationship between water discharge and instream habitats (Trihey and Stalnaker 1985). Hydraulic rating methods try to incorporate channel-discharge relationships. The generic wetted perimeter method (Reiser et al. 1989, cited in Tharme 2003) is the most applied hydraulic rating approach worldwide. River integrity is directly related to the quantity of wetted perimeter. The modeled relationship between wetted perimeter and discharge is used to determine minimum or preservation flows. The flow events method (FEM; Stewardson and Gippel 2003) evaluates the frequency of hydraulically relevant flow indices (selected by experts) under alternate flow regimes (Acreman and Dunbar 2004). It consists of five steps: After preparing a list of ecological factors affected by flow variation, different flow events and their distribution in time are analyzed. Then hydraulic parameters (e.g., wetted perimeter) at these different flow events are modeled. A comparison and evaluation of different flow management scenarios with regard to ecological consequences leads to the specification of certain flow rules (Stewardson and Gippel 2003). However, these methods have been currently replaced by more sophisticated hydraulic/habitat simulation methods (described below).

Habitat Simulation methods combine flows with habitat availability for selected indicator species and life stages. Waters (1976) invented the concept of weighted usable area (WUA), which was used by the US Fish and Wildlife Service to develop the computer model PHABSIM (Physical Habitat Simulation model, Bovee 1982). Available habitat is weighted by its suitability for certain species under different flow scenarios (Acreman and Dunbar 2004). PHABSIM is embedded into the Instream Flow Incremental Methodology (IFIM; Bovee and Milhous 1978; Reiser et al. 1989) providing a tool for calculating suitable EF. Physical habitat (flow velocity, water depth, substrate) is monitored in the field and/or modeled using mainly 1-D or 2-D hydraulic models or habitat modeling software, such as TELEMAC (Galland 1991), PHABSIM (USGS 2001), CASiMiR (Schneider et al. 2010), and RIVER 2D (Steffler and Blackburn 2002). Habitat preferences for target organisms are retrieved from field observations or literature, and habitat availability is then calculated through the modeling software for different discharges (for more details, see Chap. 7).

Holistic Methodologies require multidisciplinary input and expertise (Tharme 1996, 2000; King et al. 2008; Arthington 1998), address flow requirements of multiple ecosystem components (fish, benthic fauna, macrophytes, riparian vegetation) at various spatial temporal scales, and target a flow regime going beyond simple minimum flow definitions. Examples are the building block methodology (BBM) (Tharme and King 1998; King et al. 2008), the downstream response to imposed flow transformations (DRIFT) (King and Brown 2006), and the ecological limits of hydrologic alteration (ELOHA) (Poff et al. 2010). Field data on a monthly basis are required to construct a flow regime from scratch (bottom-up approaches, BBM, and ELOHA). In contrast, top-down approaches (e.g., DRIFT) are generally scenario based, defining environmental flows as acceptable degrees of divergence from the natural/reference flow regime, being less susceptible to any omission of critical flow characteristics or processes than their bottom-up counterparts (Bunn 1998). More detailed, the building block methodology states that aquatic organisms rely on basic elements (i.e., building blocks) of the flow regime (e.g., low flows, medium flows, and floods). In this method EF is assessed by an expert-based combination of building blocks. The expert panel assessment method (Swales and Harris 1995), the scientific panel approach (Thoms et al. 1996), or the benchmarking methodology (Brizga et al. 2002) tries to evaluate how much a flow regime can be altered before the integrity of the aquatic ecosystem is altered or seriously affected. Also ELOHA is based on the premise that increasing degrees of flow alteration enforce increasing ecological change. The evaluation of the relationship relies on the testing of plausible hypotheses stated by experts. Ecological response variables are most suitable if they react to flow alterations, allow validation using monitoring data, and are esteemed by society (e.g., for fishery) (Poff et al. 2010).

Several modified approaches have also been proposed and implemented, e.g., trying to shift the assessment scale from the micro- to meso-habitat (e.g., Parasiewicz 2007), but their general concept is based on one of the four principles mentioned above. Although progress in environmental flow methodologies is fast and becoming very sophisticated, there still remains a critical need for greater understanding of flow-ecological response relationships and enhanced modeling capacity to support river flow management and ecosystem conservation (Arthington et al. 2010).

While (1) current EF determinations are often prescriptive and not negotiable (i.e., consequences of noncompliance are not discussed) and (2) socioeconomic impacts are not adequately considered (cost-benefit of water resource developments), the DRIFT method (King et al. 2003) tries to incorporate all aspects of the river ecosystem as well as socioeconomic aspects on the basis of scenario assessments. It consists of four modules:

- The biophysical module evaluates changes of the ecosystem (e.g., hydrology, hydraulics, geomorphology, water quality, riparian vegetation, aquatic plants, organisms, etc.) in response to altered flow.
- The socioeconomic module covers all relevant river resources.
- The scenario-building module optimizes flow.
- The economic module considers compensation costs of each scenario.

DRIFT is usually used to build scenarios, but can also be used to set flows for achieving specific objective (e.g., optimizing ecological condition through combinations of dam releases; different timings, magnitudes, and durations; Acreman and Dunbar 2004).

Although many different methodologies exist, it is still a challenge to translate the knowledge of hydrologic-ecological principles into specific management rules (Poff et al. 2003). The selection of the appropriate methodology depends on matching the available resources (e.g., time, money, and data) to the question of concern. Environmental flow assessments should be incorporated into the planning phase of any proposed use of river resources that changes flows, especially hydropower plants. Finally, it has to be kept in mind that each EF assessment, whether calculated by a simple rule of thumb or by a holistic method, has to be evaluated with regard to its biological relevance and effectiveness for the specific river to be assessed. Therefore, the selected EF has to be monitored and, if necessary, adapted accordingly.

Recently, environmental flow assessments have been shifted toward more holistic approaches (Arthington and Pusey 2003; Tharme 2003; King et al. 2008), demanding assessment of the requirements of all ecosystem components through judgment from multidisciplinary teams of scientific experts. Furthermore, at the same time habitat modeling techniques have significantly advanced, offering a greater basis to incorporate data-driven approaches, in the holistic perspective. As a result, habitat modeling applications can now be used to assess the flow requirements of various ecosystem components. This concept is also adopted and incorporated in a three-level (preliminary/intermediate/comprehensive) approach proposed in the EFs Guidance Document of the European Commission (2015), highlighting the need for data-driven holistic environmental flow assessments and using habitat modeling for optimum visualization of the information to stakeholders and water managers (see Table 4.3).

Even though there is no simple choice for which method is the most suitable to assess environmental flow, Acreman and Dunbar (2004) suggest that the main driving force for choice of method is the type of issue to be addressed (i.e., scoping, basin planning, impact assessment, and river restoration). Scoping includes large-scale assessment and national auditing, where the focus encompasses many river basins. Therefore, a rapid method, such as a look-up table, would be most relevant. Basin planning involves the assessment of EFs throughout an entire river basin. Such assessment can be started using look-up tables, but increasing the level of detail assessed requires following up with a desktop approach. Environmental flow assessment often involves impact assessment and mitigation of flow modifications (e.g., dams, abstractions). Where the impact is spread over several sites within a river basin, it may be useful to make initial assessments of the impact around the basin using a desktop method before more specific functional analysis or hydraulic habitat modeling is undertaken as part of a holistic approach (Acreman and Dunbar 2004). The holistic approaches allow assessment of the benefits of any restoration activities (e.g., reduced abstractions, release from reservoirs, structural measures, and morphological river restoration). Some pros and cons useful in selecting different approaches are summarized in Table 4.3.

4.7 Conclusions

Nowadays, hydrological processes forming riverine ecosystems are well understood, and the importance of flow for maintaining the ecological integrity is well perceived. Human uses have altered the hydrological regime of running waters and degraded riverine ecosystems. A number of environmental flow assessment methods have been developed ranging from simple hydrological methods over habitat flow models to more comprehensive methodologies including socioeconomic aspects. While much effort has been dedicated to the development of those methods, the biological effectiveness of environmental flow regulations has been evaluated only in few cases. Further research is necessary to better understand the response of biota and riverine ecosystems to flow restoration by holistic assessments including interactions with river morphology, sediment transport, groundwater, and floodplain dynamics.

References

Abramovitz JN (1995) Freshwater failures: the crises on five continents. World Watch 8:27–35

Acreman MC, Dunbar MJ (2004) Defining environmental river flow requirements? A review. Hydrol Earth Syst Sci Discuss 8:861–876

Annear T, Chisholm I, Beecher H (2004) Instream flows for riverine resource stewardship (revised edn). Instream Flow Council, Cheyenne

Armitage PD (1995) Faunal community change in response to flow manipulation. In: Harper DM, Ferguson AJD (eds) The ecological basis for river management. Wiley, Chichester, pp 59–78

Arthington AH, Pusey BJ (2003) Flow restoration and protection in Australian rivers. River Res Appl 19:377–395

Arthington AH, Brizga SO, Kennard MJ (1998) Comparative evaluation of environmental flow assessment techniques: best practice framework. Occasional paper No. 25/98. Land and Water Resources Research and Development Corporation. Canberra

Arthington AH, Tharme R, Brizga SO, Pusey BJ, Kennard MJ (2004) Environmental flow assessment with emphasis on holistic methodologies. In: Welcomme R, Petr T (eds) Proceedings of the second international symposium on the management of large rivers for fisheries, vol II. RAP Publication 2004/17, FAO Regional Office for Asia and the Pacific, Bangkok, pp 37–65

Arthington AH, Bunn SE, Poff NL, Naiman RJ (2006) The challenge of providing environmental flow rules to sustain river ecosystems. Ecol Appl 16:1311–1318

Arthington AH, Naiman RJ, McClain ME, Nilsson C (2010) Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. Freshw Biol 55(1):1–16

Barker I, Kirmond A (1998) Managing surface water abstraction. In: Wheater H, Kirby C (eds) Hydrology in a changing environment, vol 1. British Hydrological Society, London, pp 249–258

Bergkamp G, McCartney M, Dugan P, McNeely J, Acreman M (2000) Dams, ecosystem functions and environmental restoration. WCD thematic review—environmental issues II.1. Final report to the world commission on dams. Secretariat of the World Commission on Dams. Cape Town

Boon PJ, Calow P, Petts GE (eds) (1992) River conservation and management. Wiley, Chichester

Boon PJ, Davies BR, Petts GE (eds) (2000) Global perspectives on river conservation: science, policy and practice. Wiley, Chichester

Bovee KD (1982) A guide to stream habitat analysis using the IFIM. US Fish and Wildlife Service Report FWSIOBS-82I 26. Fort Collins

Bovee KD, Milhous R (1978) Hydraulic simulation in instream flow studies: theory and techniques. Instream flow information paper: No. 5. FWS/OBS-78/33. Fish and Wildlife Service, 156p

Brizga SO, Arthington AH, Choy SC, Kennard MJ, Mackay SJ, Pusey BJ, Werren GL (2002) Benchmarking, a 'top-down' methodology for assessing environmental flows in Australian rivers. In: Proceedings of the international conference on environmental flows for river systems, Southern Waters, University of Cape Town, Cape Town

Brown C, King J (2003) Environmental flows: concepts and methods. In: Davis R, Hirji R (eds) Water resources and environment technical note C.1. The World Bank, Washington

Bunn SE (1998) Recent approaches to assessing and providing environmental flows: concluding comments. In: Arthington AH, Zalucki JM (eds) Water for the environment: recent approaches to assessing and providing environmental flows, Proceedings of AWWA forum. Brisbane, Australia, pp 123–129

Bunn SE, Arthington AH (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ Manag 30:492–507

Calow P, Petts GE (eds) (1992) The rivers handbook. vol. 1: hydrological and ecological principles. Blackwell Scientific, Oxford

Chien N (1985) Changes in river regime after the construction of upstream reservoirs. Earth Surf Process Landf 10:143–159

Connell JH (1978) Diversity in tropical rain forests and coral reefs. Science 199(4335):1302–1310

Craig JF, Kemper JB (eds) (1987) Regulated streams: advances in ecology. Plenum Press, New York

Cushman RM (1985) Review of ecological effects of rapidly varying flows downstream of hydroelectric facilities. N Am J Fish Manag 5:330–339

Doyle MW, Stanley EH, Strayer DL, Jacobson RB, Schmidt JC (2005) Effective discharge analysis of ecological processes in streams. Water Resour Res 41, W11411, https://doi.org/10.1029/2005WR004222

Dunne T, Leopold LB (1978) Water in environmental planning. W. H. Freeman and Co., San Francisco

Dynesius M, Nilsson C (1994) Fragmentation and flow regulation of river systems in the northern third of the world. Science 266:753–762

Dyson M, Bergkamp M, Scanlon J (2003) Flow: the essentials of environmental flows. IUCN, Switzerland

European Commission (2015) Ecological flows in the implementation of the water framework directive. WFD CIS Guidance Document No. 31

Galland J (1991) TELEMAC: a new numerical model for solving shallow water equations. Adv Water Resour 14:138–148

Gore JA, Petts GE (eds) (1989) Alternatives in regulated river management. CRC Press, Florida

Greenberg L, Svendsen P, Harby A (1996) Availability of microhabitats and their use by brown trout (Salmo trutta) and grayling (Thymallus thymallus) in the river Vojman, Sweden. Regul Rivers Res Manag 12:287–303

Gupta AD (2008) Implication of environmental flows in river basin management. Phys Chem Earth 33:298–303

Gustard A, Cole G, Marshall D, Bayliss A (1987) A study of compensation flows in the UK. Institute of Hydrology report 99, Wallingfort

Hart DD, Finelli CM (1999) Physical-biological coupling in streams: the pervasive effects of flow on benthic organisms. Annu Rev Ecol Syst 30:363–395

Hirji R, Davis R (2009) Environmental flows in water resources policies, plans, and projects: findings and recommendations. The World Bank. Environment and Development series

International Water Management Institute (IWMI) (2005) Environmental flows. Planning for environmental water allocation. Water Policy briefing, 15, pp 1–6

Junk WJ, Bayley PB, Sparks RE (1989) The flood pulse concept in river-floodplain systems. Can Spec Publ Fish Aquat Sci 106:110–127

Karr JR (1991) Biological integrity: a long neglected aspect of water resource management. Ecol Appl 1:66–84

King J, Brown C (2006) Environmental flows: striking the balance between development and resource protection. Ecol Soc 11:26

King J, Brown C, Sabet H (2003) A scenario-based holistic approach to environmental flow assessments for rivers. River Res Appl 19(5–6):619–639

King JM, Tharme RE, De Villiers MS (2008) Environmental flow assessments for rivers: manual for the building block methodology. WRC report no TT 354/08, Cape Town, 364p

Lillehammer A, Saltveit SJ (eds) (1984) Regulated rivers. Universitetsforlaget As, Oslo

Lloyd N, Quinn G, Thoms M, Arthington A, Gawne B, Humphries P, Walker K (2003) Does flow modification cause geomorphological and ecological response in rivers? A literature review from an Australian perspective. Technical report 1 / 2004, CRC for freshwater ecology, ISBN 0-9751642-02

Martinez SMC, Fernández Yuste JA (2010) IAHRIS 2.2. Indicators of hydrologic alteration in rivers. Methodological reference manual & user's manual. http://www.ecogesfor.org/IAHRIS_es.html

McCully P (1996) Silenced rivers: the ecology and politics of large dams. ZED books, London

Moore M (2004) Perceptions and interpretations of environmental flows and implications for future water resource management: a survey study. Masters Thesis, Department of Water and Environmental Studies, Linköping University, Linköping

Navarro SR, Schmidt G (2012) Environmental flows as a tool to achieve the WFD objectives. Discussion paper (in the framework of Service contract for the support to the follow-up of the Communication on Water scarcity and Droughts). Version: Draft 2.0, 11 June 2012

Nilsson C, Reidy CA, Dynesius M, Revenga C (2005) Fragmentation and flow regulation of the world's river systems. Science 308:405–408

Parasiewicz P (2007) The Mesohabsim model revisited. River Res Appl 27:893–903

Petts GE (ed) (1984) Impounded rivers: perspectives for ecological management. Wiley, Chichester

Poff NL, Ward JV (1989) Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. Can J Fish Aquat Sci 46:1805–1818

Poff NL, Zimmerman JK (2010) Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshw Biol 55(1):194–205

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC (1997) The natural flow regime. Bioscience 47(11):769–784

Poff NL, Allan JD, Palmer MA, Hart DD, Richter BD, Arthington AH, Rogers KH, Meyer JL, Stanford JA (2003) River flows and water wars: emerging science for environmental decision making. Front Ecol Environ 1:298–306

Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E, Acreman M, Apse C, Bledsoe BP, Freeman MC, Henriksen J, Jacobson RB, Kennen JG, Merritt DM, O'Keeffe JH, Olden JD, Rogers K, Tharme RE, Warner A (2010) The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshw Biol 55(1):147–170

Postel SL (1995) Where have all the rivers gone? World Watch 8:9–19

Postel SL (1998) Water for food production: will there be enough in 2025? Bioscience 48:629–637

Postel SL, Richter B (2003) Rivers for life: managing water for people and nature. Island Press, Washington, DC

Pringle CM (2000) River conservation in tropical versus temperate latitudes. In: Boon PJ, Davies BR, Petts GE (eds) Global perspectives on river conservation: science, policy and practice. Wiley, Chichester, pp 371–384

Rapport DJ, Costanza R, McMichael AJ (1998) Assessing ecosystem health. Trends Ecol Evol 13:397–402

Reiser DW, Wesche TA, Estes C (1989) Status of instream flow legislation and practices in North America. Fisheries 14:22–29

Revenga C, Murray S, Abramowitz J, Hammond A (1998) Watersheds of the world: ecological value and vulnerability. World Resources Institute and Worldwatch Institute, Washington, DC

Revenga C, Brunner J, Henninger N, Kassem K, Payne R (2000) Pilot analysis of global ecosystems: freshwater ecosystems. World Resources Institute, Washington, DC

Richter BD, Baumgartner JV, Powell J, Braun DP (1996) A method for assessing hydrological alteration within ecosystems. Conserv Biol 10:1163–1174

Richter BD, Baumgartner JV, Wigington R, Braun DP (1997) How much water does a river need? Freshw Biol 37:231–249

Richter BD, Braun DP, Mendelson MA, Master LL (1998) Threats to imperiled freshwater fauna. Conserv Biol 11:1081–1093

Richter BD, Warner AT, Meyer JL, Lutz K (2006) A collaborative and adaptive process for developing environmental flow recommendations. River Res Appl 22:297–318

Rosenberg DM, McCully P, Pringle CM (2000) Global-scale environmental effects of hydrological alterations: introduction. Bioscience 50(9):746–751

Schneider M, Noack M, Gebler T, Kopecki I (2010) Handbook for the habitat simulation model CASiMiR, Module CASiMiR-Fish, Base Version. 52 pp. Translated by Tuhtan, J. Available from: http://casimir-software.de/ (accessed 21 September 2015)

Snaddon CD, Davies BR, Wishart MJ (1999) A global overview of inter-basin water transfer schemes, with an appraisal of their ecological, socio-economic and socio-political implications, and recommendations for their management. Water Research Commission Technology Transfer report TT 120/00. Water Research Commission. Pretoria

Steffler P, Blackburn J (2002) River 2D: two-dimensional depth averaged model of river hydrodynamics and fish habitat. Introduction to depth averaged modelling and user's manual. University of Alberta, Canada

Stewardson MJ, Gippel CJ (2003) Incorporating flow variability into environmental flow regimes using the flow events method. River Res Appl 19:459–472

Swales S, Harris JH (1995) The expert panel assessment method (EPAM): a new tool for determining environmental flows in regulated rivers. In: Harper DM, Ferguson AJD (eds) The ecological basis for river management. Wiley, Chichester

Tennant DL (1976) Instream flow regimens for fish, wildlife, recreation and related environmental resources. Fisheries 1(4):6–10

Tharme RE (1996) Review of international methodologies for the quantification of the instream flow requirements of rivers. Water law review final report for policy development for the Department of Water Affairs and Forestry, Pretoria. Freshwater Research Unit, University of Cape Town, Cape Town

Tharme RE (2000) An overview of environmental flow methodologies, with particular reference to South Africa. In: King JM, Tharme RE, De Villiers MS (eds) Environmental flow assessments for rivers: manual for the building block methodology. Water Research Commission Technology Transfer report no. TT131/00. Water Research Commission, Pretoria, pp 15–40

Tharme RE (2003) A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Res Appl 19(5–6):397–441

Tharme RE, King JM (1998) Development of the building block methodology for instream flow assessments, and supporting research on the effects of different magnitude flows on riverine ecosystems. Water Research Commission Report No. 576/1/98, 452p

Theodoropoulos C, Skoulikidis N (2014) Environmental flows: the european approach through the water framework directive 2000/60/EC. Proceedings of the 10th International Congress of the Hellenic Geographical Society (in press)

Thoms MC, Sheldon F, Roberts J, Harris J, Hillman T (1996) Scientific panel assessment of environmental flows for the Barwon-Darling river. New South Wales Department of Land and Water Conservation, Sydney

Trihey EW, Stalnaker CB (1985) Evolution and application of instream flow methodologies to small hydropower developments: an overview of the issues. In: Olson FW, White RG, Hamre RH (eds) Proceedings of the symposium on small hydropower and fisheries. Aurora, CO

USGS (2001) PHABSIM for Windows. User's manual and exercises. Open file report 01-340, U.S. Geological Survey.

Ward JA (1982) Ecological aspects of stream regulation: responses in downstream lotic reaches. Water Pollut Manage Rev (New Delhi) 2:1–26

Ward J (1989) The four-dimensional nature of lotic ecosystems. J N Am Benthol Soc 8:2–8

Ward J, Stanford JA (1983) The intermediate-disturbance hypothesis: an explanation for biotic diversity patterns in lotic ecosystems. In: Fontaine F (ed) Dynamics of lotic ecosystems. Ann Arbor Press, Ann Arbor, pp 347–355

Waters BF (1976) A methodology for evaluating the effects of different stream flows on salmonid habitat. In: Orsborn JF, Allman CH (eds) Instream flow needs. American Fisheries Society, Bethseda, pp 254–266

Wolman MG, Miller JP (1960) Magnitude and frequency of forces in geomorphic processes. J Hydrol 69:54–74

World Commission on Dams (WCD) (2000) Dams and development. A new framework for decision-making. The report of the World Commission on dams. Earthscan Publications, London

Zarfl C, Lumsdon AE, Berlekamp J, Tydecks L, Tockner K (2014) A global boom in hydropower dam construction. Aquat Sci 77(1):161–170

Zeiringer B (2008a) Minimum flow study at the river Schwarza/Reichenau. evn naturkraft, p 49

Zeiringer B (2008b) Minimum flow study at the river Unrechttraisen/Mauthof. evn naturkraft, p 54

Zeiringer B, Unfer G, Jungwirth M (2008) Environmental flow study at the river Mur/Pernegg. VERBUND-Austrian Hydro Power AG (AHP), p 146

Zeiringer B, Hinterhofer M, Unfer G (2010) Environmental flow study at the river Ybbs/Opponitz. WIENERGIE, p 162