Final EPA-USGS Technical Report: Protecting Aquatic Life from Effects of Hydrologic Alteration

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USGS Scientific Investigations Report 2016–5164

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Cover. Redfish Lake Creek, Stanley, Idaho. (Photo by Daniel Hart, U.S. Environmental Protection Agency)

Final EPA-USGS Technical Report: Protecting Aquatic Life from Effects of Hydrologic Alteration

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Foreword

This report, developed collaboratively by the U.S. Environmental Protection Agency (EPA) and the U.S. Geological Survey (USGS), provides scientific and technical support for efforts by states and Tribes to advance the protection of aquatic life from the adverse effects of hydrologic alterations in streams and rivers. The report presents: a literature review of the natural flow regime and description of the potential effects of flow alteration on aquatic life (Section 4); examples of narrative criteria that some states have developed to support the natural flow regime and maintain healthy aquatic biota (Section 5); and a flexible, non-prescriptive framework that can be used by states, Tribes, and territories to quantify targets for flow regime components that are protective of aquatic life (Section 6).

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The USGS and the EPA have made every effort to ensure the accuracy of the technical information in this document. Depending on individual circumstances, the general descriptions provided here may not apply to a given situation. Interested parties are free to raise questions and objections about the substance of this document and the appropriateness of the application of the information presented to a specific situation. This document does not make any judgment regarding any specific data collected or determinations made as part of a state or tribal water-quality program. State and tribal decision makers retain the discretion to adopt approaches on a case-by-case basis that differ from the approaches described in this report.

The USGS, in accordance with its mission to collect and disseminate reliable, impartial, and timely scientific information that is needed to understand the Nation's water resources, collaborated with the EPA on Sections 1-4, 6, and Appendix B only.

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Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
meter (km)	3.2808	foot (ft)
kilometer (km)	0.6213	mile (mi)
	Area	
square meter (m^2)	0.00025	Acre
square kilometer (km^2)	0.3861	square mile (mi^2)
hectare (ha)	2.4710	Acre
	Volume	
cubic meter (m^3)	35.3147	cubic foot (ft^3)
cubic meter (m^3)	0.00026	million gallon (gal)
	Flow rate	
cubic meter per second per square kilometer [$(m^3/s)/km^2$]	91.47	cubic foot per second per square mile [$(ft^3/s)/mi^2$]
cubic meter per second (m^3/s)	22.8244	million gallons per day (Mgal/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Acronyms

Acronym/Abbreviation	Definition
CADDIS	Causal Analysis/Diagnosis Decision Information System
CFR	Code of Federal Regulations
CWA	Clean Water Act
ELOHA	Ecological Limits of Hydrologic Alteration
EPA	U.S. Environmental Protection Agency
ERA	Ecological Risk Assessment
GCM	General Circulation Model
GIS	Geographic Information System
HSP	Healthy Streams Partnership
IBI	Index of Biotic Integrity
IPCC	Intergovernmental Panel on Climate Change
MS4	Municipal Separate Storm Sewer System
NHD	National Hydrography Dataset
NID	National Inventory of Dams
NPDES	National Pollutant Discharge Elimination System
STORET	EPA Storage and Retrieval Data Warehouse
TCEQ	Texas Commission on Environmental Quality
TMDL	Total Maximum Daily Load
USGS	U.S. Geological Survey
WQS	Water Quality Standards

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1 Abstract

The natural flow regime of a water body, defined as its characteristic pattern of flow magnitude, timing, duration, frequency, and rate of change, plays a critical role in supporting the chemical, physical, and biological integrity of streams and rivers and the services they provide[1]. Human-induced alteration of the natural flow regime can degrade a stream's physical and chemical properties, leading to loss of aquatic life and reduced aquatic biodiversity. Protecting aquatic life from the effects of flow alteration involves maintaining multiple components of the flow regime within their typical range of variation. This report was developed[2] (1) to serve as a source of information for states, Tribes, and territories on the natural flow regime and potential effects of flow alteration on aquatic life and (2) to provide a flexible, nonprescriptive framework that can be used to quantify targets for flow regime components that are protective of aquatic life. As a supplementary resource, Appendix A was added to provide examples where states and Tribes have applied Clean Water Act (CWA) tools to protect aquatic life from altered flow.

Anthropogenic landscape change and water management activities are modifying flood flows, base flows, peak-flow timing, and other flow characteristics in streams and rivers throughout the United States. Under natural conditions, a stream's flow regime is determined by hydrologic properties at two scales, the upstream drainage area (catchment) and the local, reach scale. At the catchment scale, climate determines patterns of water and energy input over time, whereas physical characteristics like soils, geology, and topography

[1] The objective of the Clean Water Act (CWA) is to "restore and maintain the chemical, physical and biological integrity of the Nation's waters" (Section 101(a)).

[2] The two sections of the CWA related to the development of the information presented in this report are CWA Sections 304(a)(2) and 304(f). CWA Section 304(a)(2) generally requires EPA to develop and publish information on the factors necessary to restore and maintain the chemical, physical, and biological integrity of navigable waters. Section 304(a)(2) also allows EPA to provide information on the conditions necessary for the protection and propagation of shellfish, fish, and wildlife in receiving waters and for allowing recreational activities in and on the water. CWA Section 304(f) requires EPA to issue information to control pollution resulting from, among other things, "changes in the movement, flow, or circulation of any navigable waters."

determine pathways, rates of runoff, and routing through the stream network. Reach-scale factors such as local groundwater dynamics further influence natural flow regime characteristics. Human activities that alter the natural flow regime also occur at both the catchment and reach scales and include impoundments, channelization, diversions, groundwater pumping, wastewater discharges, urban development, thermoelectric power generation, and agricultural practices. Many of these activities alter hydrologic processes like infiltration, groundwater recharge, channel storage, or routing and lead to flow conditions outside the natural range of variation. Others directly add or remove water from a stream such that flows are uncommonly high or low over long periods of time. Occurring in conjunction with these activities is climate change. Climate trends observed in recent decades and future projections (for example, rising ambient air temperatures, increasing frequency of heavy precipitation events, reductions in the thickness of snow pack and ice) may magnify the effects of other anthropogenic processes on the natural flow regime.

Alteration of the natural flow regime can have cascading effects on the physical, chemical, and biological properties of riverine ecosystems. Effects on physical properties include altered channel geomorphology (channel incision, widening, bed armoring, etc.), reduced (or augmented) riparian and flood-plain connectivity, and reduced (or augmented) longitudinal (upstream-downstream) and vertical (surface water/groundwater) connectivity. Effects on water quality can also result from altered flow magnitudes. For example, salinity, sedimentation, and water temperature can increase when flow volumes are reduced, whereas erosion and sediment transport can increase with amplified flow volumes. These changes to a stream can in turn lead to the degradation of aquatic life as a result of the loss and disconnection of high-quality habitat. Furthermore, altered flows can fail to provide the cues needed for aquatic species to complete their life cycles and can encourage the invasion and establishment of non-native aquatic species. The ability of a water body to support aquatic life is tied to the maintenance of key flow-regime components.

Efforts to implement strategies to protect aquatic life from flow alteration will be most effective if numeric targets are identified for flow-regime components that equate to intact and healthy aquatic communities. This report presents a flexible framework that can be used to quantify flow targets that incorporate U.S. Environmental Protection Agency Guidelines for Ecological Risk Assessment (ERA) and concepts from contemporary environmental flow literature. The framework consists of eight steps that begin with identifying biological goals and assessment endpoints and end with an evaluation of effects on aquatic life under varying degrees of flow alteration. The framework does not prescribe any particular analytical approach (for example, statistical or mechanistic modeling methodology), but rather focuses on the process and information needed to evaluate relations between flow and aquatic life and the development of narrative or numeric flow targets.

2 Introduction

Healthy aquatic ecosystems provide an array of services to individuals and society, including clean drinking water, irrigation supplies, and recreational opportunities (U.S. Environmental Protection Agency, 2012c). Sound and sustainable management of aquatic ecosystems is an integral part of managing water resources to meet the needs of society and the goals of the Clean Water Act (CWA; see Box A).

Box A. Goals of the Clean Water Act

In 1972, with the objective of protecting lakes, rivers, streams, estuaries, wetlands, coastal waters, oceans, and other water bodies, the U.S. Congress enacted the Clean Water Act (CWA). The overall objective of the CWA is to "restore and maintain the chemical, physical and biological integrity of the Nation's waters" (Section 101(a)). In addition, the CWA establishes as an interim goal "water quality which provides for the protection and propagation of fish, shellfish and wildlife and provides for recreation in and on the water," wherever attainable (Section 101(a)(2)).

Freshwater aquatic ecosystems are the most altered ecosystems globally; they exhibit declines in biodiversity that far outpace those of terrestrial or marine ecosystems (Dudgeon and others, 2006; Strayer and Dudgeon,

2010). Although discharge of contaminants ranks as a top threat to aquatic biodiversity, other important sources of stress include urbanization, agriculture practices, and engineered structures used for water-resource development (Vörösmarty and others, 2010). These factors directly and indirectly alter the natural hydrology of a catchment and can have cascading effects on aquatic organisms (Poff and others, 1997). Today's water-resource managers face a common challenge: balancing the needs of a growing human population with the protection of natural hydrologic regimes to support aquatic life, ecosystem health, and services of crucial importance to society (Annear and others, 2004; Postel and Richter, 2003). Further complicating this challenge are expected changes to historic hydrologic conditions as a result of climate change, which add complexity to the task of estimating acceptable levels of hydrologic variation (Milly and others, 2008).

The natural flow regime, defined as the characteristic pattern of flow magnitude, timing, duration, frequency, and rate of change, plays a critical role in supporting the ecological integrity of streams and rivers and the services they provide (Figure 1). Human-induced alteration of the natural flow regime can degrade the physical, chemical, and biological properties of a water body (Annear and others, 2004; Bunn and Arthington, 2002; Naiman and others, 2002; Poff and others, 1997; Poff and Zimmerman, 2010; and many others). For example, an increase in the duration and frequency of high flows can degrade aquatic habitat through scouring and streambank erosion. More frequent low-flow conditions can degrade water quality through elevated concentrations of toxic contaminants resulting from decreased dilution, increased temperatures, or a decrease in dissolved-oxygen concentration. Lower flows can reduce sensitive taxa diversity and abundance, alter life cycles, cause mortality in aquatic life, and promote the expansion of invasive plants and animals (Bunn and Arthington, 2002; Poff and Zimmerman, 2010).

Hydrologic alteration (also referred to as "flow alteration" in this document) can be a primary contributor to the impairment of water bodies that are designated to support aquatic life. Addressing flow conditions can

contribute to a comprehensive approach to managing and protecting water quality, improving aquatic restoration efforts, and maintaining designated and existing uses (for example, aquatic life, cold-water or warm-water fisheries, economically or recreationally important aquatic species). As the science of flow ecology has uncovered aquatic life needs across the full spectrum of the flow regime (base flows, high flows, etc.), water resource-managers are starting to recognize that protecting aquatic life from the adverse effects of flow alteration involves maintaining multiple components of the flow regime within their typical range of variation. This perspective requires an understanding of natural flow variability over space and time and the many ways in which biota respond to varied flow conditions.

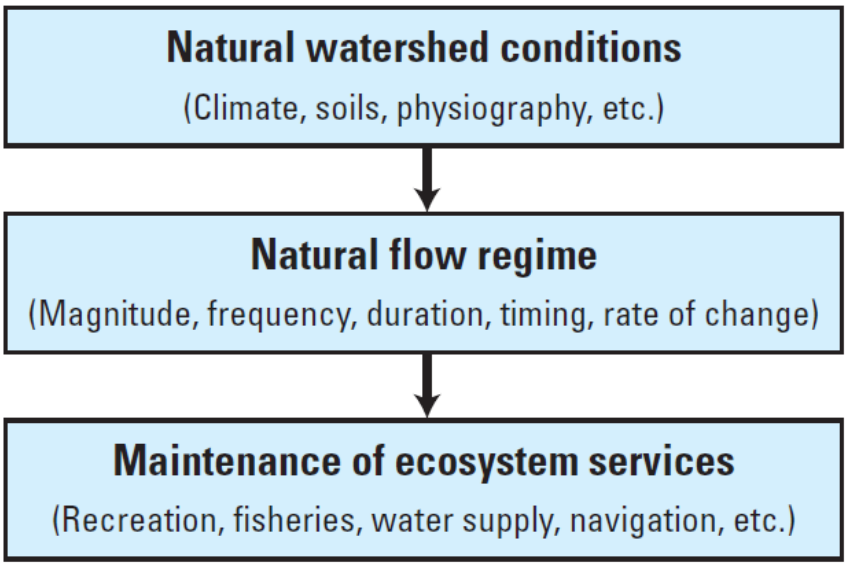


Figure 1. Schematic diagram depicting the interaction between the natural flow regime, natural watershed conditions and the many ecosystem services it helps to maintain.

3 Purpose, Scope, and Overview

3.1 Purpose and Scope

The purpose of this report is threefold. First, it describes the effects of flow alteration on aquatic life designated uses in streams, rivers, and other natural flowing water bodies. Second, it gives examples of states and Tribes that have narrative flow standards. Third, it provides a flexible, nonprescriptive framework that can be used to quantify flow targets to protect aquatic life from the effects associated with flow alteration. As a supplementary resource, Appendix A was added to provide examples where states and Tribes have applied CWA tools to protect aquatic life from altered flow. Non-flowing waters (lakes or wetlands, for example) and non-freshwater systems (estuaries, tidal waters) are not discussed in this report, nor are other designated uses such as recreation or drinking water, although they also can be affected by hydrologic alteration and can benefit from measures to maintain or restore hydrologic conditions.

This report was developed by the U.S. Environmental Protection Agency (EPA) in collaboration with the U.S. Geological Survey (USGS) in response to evidence that flow alteration has adversely affected the biological integrity of water bodies throughout the United States (Bunn and Arthington, 2002; Carlisle and others, 2010; Poff and Zimmerman, 2010). The information presented is drawn from the Guidelines for Ecological Risk Assessment (U.S. Environmental Protection Agency, 1998), relevant environmental flows literature (for example, Bunn and Arthington, 2002; Petts, 2009; Poff and Zimmerman, 2010), and the experience of states and Tribes that have adopted narrative flow criteria to protect aquatic life uses in their waters.

3.2 Overview

Section 4 is a summary of available scientific information about the effects of flow alteration on ecosystems, including the role of climate change, which can exacerbate the stresses that result from flow alteration. Section 5 provides examples of states and Tribes that have established narrative flow standards and Section 6 presents a flexible, nonprescriptive framework that can be used to quantify targets for flow regime

components that are protective of aquatic life. Section 6 includes examples of quantification to support states, authorized Tribes, and territories (hereinafter, “states”) that wish to adopt flow criteria to protect aquatic life designated uses in their Water Quality Standard regulations. This section also describes the potential role of using narrative criteria as a tool to manage flow to restore and maintain aquatic ecosystems. Appendix A contains examples where states and Tribes have applied CWA tools to protect aquatic life from altered flow.

Climate change is one category among a range of stressors that is likely to increase the vulnerability of rivers and streams to flow alteration and affect the ecosystem services they provide (see Section 4.3.6). Given the inherent difficulties associated with climate change assessment, many natural-resource management agencies will likely encounter increasing challenges as they work to protect and restore the health of aquatic ecosystems. Appendix B provides examples of vulnerability assessments of freshwater aquatic life and environmental flows related to climate change.

3.3 Who Can Use This Information?

This report presents scientific information that can help water-resource managers improve the protection of flow for aquatic life uses. Additionally, it serves as a source of information for a broad stakeholder audience involved in water-resource management and aquatic life protection.

4 Effects of Altered Flow on Aquatic Life

This section describes the scientific principles of the natural flow regime, hydrologic alteration, and ecological responses to altered flows and presents a general conceptual model of the effects of flow alteration on aquatic life. Potential causes of various types of hydrologic change are outlined and pathways to degraded biological conditions are discussed.

4.1 Conceptual Model of the Biological Effects of Flow Alteration

In Ecological Risk Assessment (Box B, below), a conceptual model consists of a written description and diagram of the relations and pathways between human activities (sources), stressors, and direct and indirect effects on ecological entities (U.S. Environmental Protection Agency, 1998). A conceptual model links one or more stressors to ecological assessment endpoints that are important for achieving management goals. Under the CWA, management goals are established by states as designated uses of waters (for example, to support aquatic life) and criteria to protect those uses.

Box B. Ecological Risk Assessment

Ecological Risk Assessment (ERA) provides a framework for evaluating the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors (U.S. Environmental Protection Agency, 1998). It can apply to a range of environmental problems associated with chemical, physical, and biological stressors, including evaluating the risk posed to aquatic life by flow alteration. A key step in the first phase of the ERA process, problem formulation, is the development of a conceptual model that explicitly demonstrates the hypothesized relations between ecological entities and the stressors to which they may be exposed.

The flow alteration conceptual model (Figure 2) describes in a general way how various stressors can alter the natural flow regime, how flow alteration affects the chemical and physical conditions of an aquatic ecosystem,

and how those changes may ultimately reduce the ability of a stream to support aquatic life. The general model is intended only to provide a foundation for detailed regional or catchment models; for a specific area, specific types of flow alteration and biological responses should be identified.

The general conceptual model of the biological effects of flow alteration presented in this report (Figure 2) is a broad framework relating hydrologic alteration and its sources to degraded aquatic life. The model is constructed around the following concepts and relations.

- A stream's natural flow regime is primarily a function of climate and physical catchment-scale properties, and is further affected by local, reach-scale conditions.
- The natural flow regime supports the integrity of aquatic life by maintaining habitat of sufficient size, character, diversity, and connectivity by supporting natural sediment, organic material, water temperature, and water chemistry regimes and by providing cues for spawning, migration, and other life-history strategies.
- A variety of human activities that change pathways and rates of runoff, modify channel storage and dimensions, or directly add water to or remove water from streams can alter the natural flow regime.
- Alteration of the natural flow regime leads to changes in water temperature and chemistry and (or) the physical properties of streams and adjacent riparian areas and flood plains. Feedback between altered flow and altered physical properties can further modify flow characteristics. Changes to stream chemical and physical condition following flow alteration can lead to the reduction, elimination, or disconnection of optimal habitat for aquatic biota.
- Biological responses to flow-mediated changes in stream chemistry and physical habitat can have cascading effects across trophic levels and aquatic communities, which may result in degraded aquatic life as determined by measures of effect (for example, survival, growth, and reproduction of aquatic biota).

The following sections describe the components of the general conceptual model. A detailed conceptual model of flow alteration with explicit directional relations is provided in Section 6.4. For detailed conceptual models developed for the EPA Causal Analysis/Diagnosis Decision Information System (CADDIS), see U.S. Environmental Protection Agency (2012a), https://www3.epa.gov/caddis/.

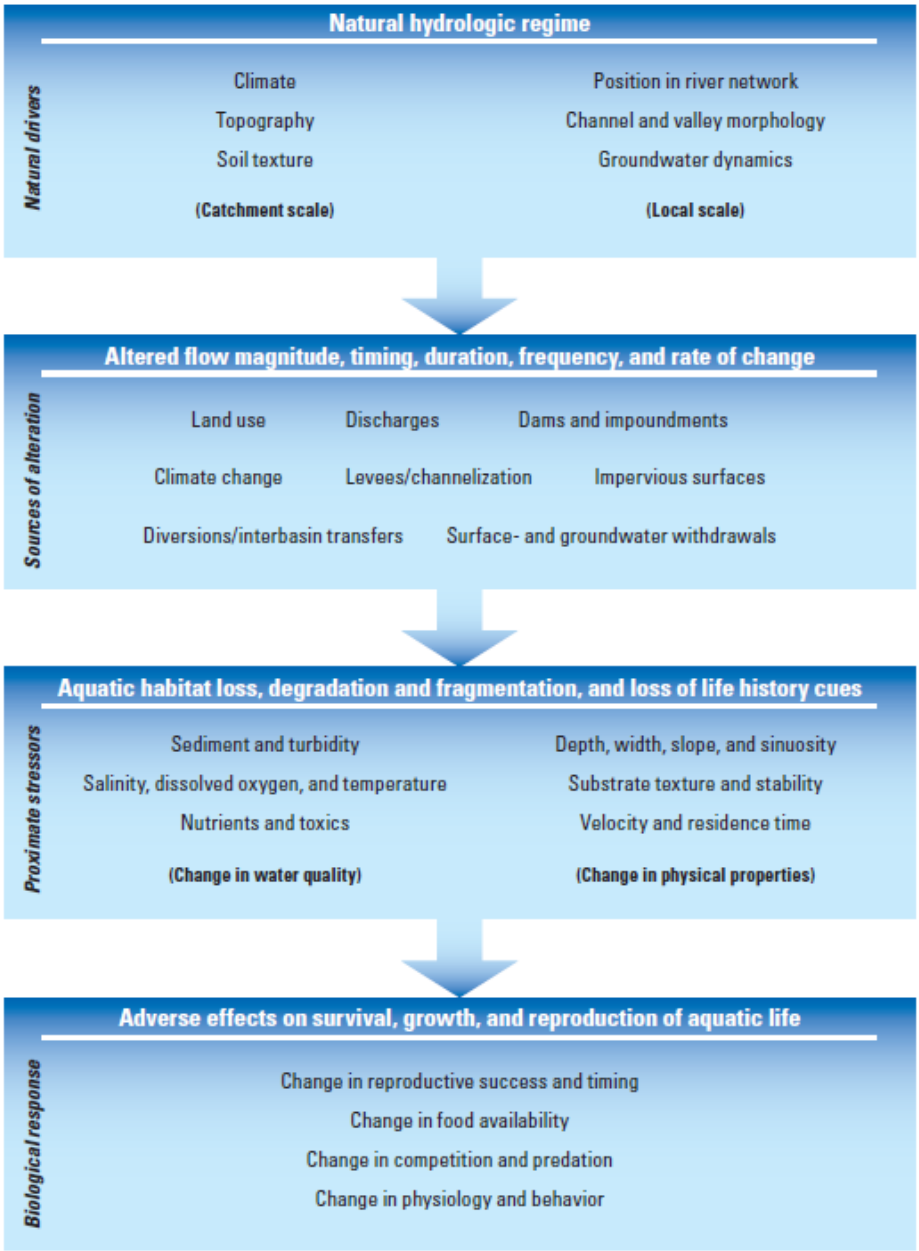


Figure 2. Schematic diagram illustrating a generalized conceptual model of the biological effects of flow alteration.

4.2 Drivers of the Natural Flow Regime

The natural flow regime is the characteristic pattern of flow in a stream under natural conditions. Poff and others (1997) present five components of the natural flow regime that are critical to aquatic ecosystems:

- the *magnitude* of flow over a given time interval (for example, average flow rate [reported in either cubic feet per second or cubic meters per second] during the month of April, or the spring season);
- the *frequency* with which flow is above or below a threshold value (for example, the number of times that flow exceeds the long-term average in one year);
- the *duration* of a flow condition over a given time interval (for example, the number days in a year during which the flow exceeds some value);
- the *timing* of a flow condition (for example, the date of the annual peak flow); and
- the *rate of change* of flow (for example, how rapidly flow increases during a storm event).

A stream's natural flow regime is largely a function of the climate and physical properties of its unique upstream drainage area (catchment[3]). Climate determines patterns of water and energy input over time, whereas physical catchment characteristics such as soils, geology, vegetation, and topography determine infiltration pathways (surface or subsurface) and rates of runoff and routing of streamflow through the drainage network. For example, a large proportion of rainfall in a catchment dominated by steep slopes and poorly-permeable soils will be converted to surface runoff that is quickly routed through the channel network. The flow regime of a stream in such a catchment would be characterized by high peak flows relative to average conditions, high rates of hydrologic change during and after storm events, and relatively low dry-

[3] The term "catchment" throughout this report refers specifically to the unique drainage area upstream from a stream reach of interest. Although the term "watershed" also fits this definition, catchment is used in this report because managers use the term "watershed" to describe larger geographic or planning units within a state or region.

weather flows. In contrast, in a catchment dominated by well-drained soils and abundant natural vegetation, peak flows would more closely match average flows as a result of higher rates of infiltration and groundwater routing to the stream channel.

Although the natural flow regime is driven primarily by catchment-scale properties, flow characteristics are also affected by local-scale drivers specific to individual stream reaches and the location of the reach within the river network. Heterogeneity of local topography and geology, for example, can result in variable groundwater inputs among reaches with similar catchment-scale properties. Other potential local-scale drivers of the natural flow regime include channel morphology and riparian vegetation, although such characteristics are themselves affected by the flow regime.

4.3 Sources of Flow Alteration

The natural flow regime is driven by both catchment and local properties; human activities that alter the natural flow regime also occur at both of these scales. Changes to water quantity (flow volume) may result in loss of the designated use, such as when perennial streams or rivers are anthropogenically dewatered or intermittent streams are dewatered permanently or well beyond their natural variability. This section describes the major potential sources of flow alteration and their typical effects on the natural flow regime. Other sources of flow alteration (for example, artificial perennialization of intermittent streams [see Section 4.3.4]) may need to be considered depending on local or regional circumstances.

Recent assessments indicate that hydrologic alteration is pervasive in the Nation's streams and rivers. In a national assessment, the USGS found that human alteration of waterways has affected the magnitude of minimum and maximum streamflows in more than 86 percent of monitored streams (Carlisle and others, 2013). In addition, human-caused depletion of minimum and maximum flows was associated with a twofold

increase in the likelihood of effects on fish and macroinvertebrate communities[4] (Carlisle and others, 2011). Sources of such effects may include groundwater and surface-water withdrawals, new and existing dams, impoundments and reservoirs, interbasin transfers, altered channel morphology, impervious cover, culverts, stream crossings and water diversions. Human adaptations to increased drought, including expansion of surface- and groundwater uses, may compound these effects by decreasing the magnitude of low flows and increasing the frequency and duration of low flows in streams and rivers. Alterations in high flows can affect use; for instance, an increase in impervious surface area may cause an increase in flow, resulting in deleterious alterations to habitat or the biological community. The following sections describe potential stressors in more detail.

4.3.1 Dams and Impoundments

Dams and impoundments (for example, reservoirs) are designed to control and store streamflow for various purposes and can provide multiple societal benefits through increased recreation opportunities, flood attenuation, hydroelectric power, irrigation, public water supply, and transportation (Collier and others, 1996). However, dams are also a cause of flow alteration throughout the United States, as only about 40 large rivers (defined as longer than 200 kilometers) remain free-flowing (Benke, 1990). At a national scale, when interregional flow variation before and after dam construction is compared, streams below dams can be subject to reduced high and low flows, augmented low flows, reduced seasonal variation, and other changes relative to predam conditions, resulting in a regional homogenization of the flow regime (Poff and others,

[4] Carlisle and others (2011) use the term “impairment” to describe this effect on the aquatic community, defining it as occurring when the value of the ratio of the observed condition to the expected reference condition (O/E) was less than that at 90 percent of reference sites within the same region. The aquatic community at a site was considered “unimpaired” when the O/E did not meet this condition. Although the term “impairment” is used in the original publication, the term “affected” is used for the purposes of this report to avoid confusion with the specific use of the term “impaired” in CWA programs.

2007). At a finer scale, however, within a more homogenous hydroclimatic region, dams can create new flow regimes (McManamay and others, 2012). The ecological costs of controlling natural flows can have wide-ranging effects on the chemical, physical, and biological integrity of streams and rivers (Collier and others, 1996; Dynesius and Nilsson, 1994; Magilligan and Nislow; 2005; Poff and others, 2007; Wang and others, 2011; Zimmerman and others, 2010). The various types of effects are highly dependent on dam purpose, size, and release operations (Poff and Hart, 2002).

As of 2013, more than 87,000 dams were represented in the U.S. National Inventory of Dams (NID) (U.S. Army Corps of Engineers, 2013). Not included in this total are small impoundments for farm ponds, fishing ponds, community amenities that fragment stream networks (for example, impoundments less than 2 meters [m] high), and larger dams that have not yet been included in the national database. New geographic information system (GIS) and remote-sensing tools are used to identify the extent and number of small impoundments, which may be in the tens of thousands per state. For example, a study in the Apalachicola-Chattahoochee-Flint River Basin in the southeastern United States identified the presence of more than 25,362 impoundments (Ignatius and Stallins, 2011), whereas the NID database recognized 1,415 (fewer than 6 percent of the reported total) in the same basin. The extensive presence of dams on United States waterways in the NID (U.S. Army Corps of Engineers, 2013) is shown in Figure 3. Estimates made by Poff and Hart (2002), identify more than 2,000,000 dams across the country, which includes small and large sized dams.

Studies have shown that dam reoperation (when operational guidelines for the dam are modified to address environmental management concerns about downstream fisheries, riparian habitats, recreation, flow, etc.) and removal of obsolete dams have the potential to restore ecological function downstream of dams (Watts and others, 2011). Although the ability to modify operations varies on the basis of the type and purpose of the dam (that is, hydropower, flood control, irrigation, etc.), virtually all dams, regardless of size, have the potential to be modified (Arthington, 2012). Since 2000, large-scale flow experiments have become an

important component of water-management planning, with considerably more than 100 large-scale flow experiments documented worldwide, including 56 in the United States alone (Olden and others, 2014). Alterations to dam operations, including changes in the magnitude, frequency, and duration of high-flow events; changes to minimum releases; and alteration of reservoir drawdown regimes or restoration of flows to bypassed reaches; can result in ecological benefits, including recovery of fish and shellfish, improved water quality, reactivation of flood-plain storage, and suppression of non-native species (Konrad and others, 2011; Olden and others, 2014; Richter and Thomas, 2007; Poff and Schmidt, 2016; Kennedy and others, 2016.). Key components of successful dam reoperation include clearly articulating objectives and expectations prior to beginning reoperation, inclusion of a process to monitor or model the short -and long-term effects of proposed release operations, and the ability to adaptively manage the dam operations (Konrad and others, 2011; Richter and Thomas, 2007). Similar to the benefits noted for dam reoperation, restoration of stream and river flows through removal of obsolete dams may re-establish natural habitat connectivity for aquatic life, expose shoal and riffle habitat, restore water quality (for example, dissolved oxygen, pH, temperature and ammonia), and re-establish sediment transport dynamics and downstream sediment deposition (Poff and Hart, 2002; Kornis and others, 2015; Pess and others, 2014; Tuckerman and Zawiski, 2007).

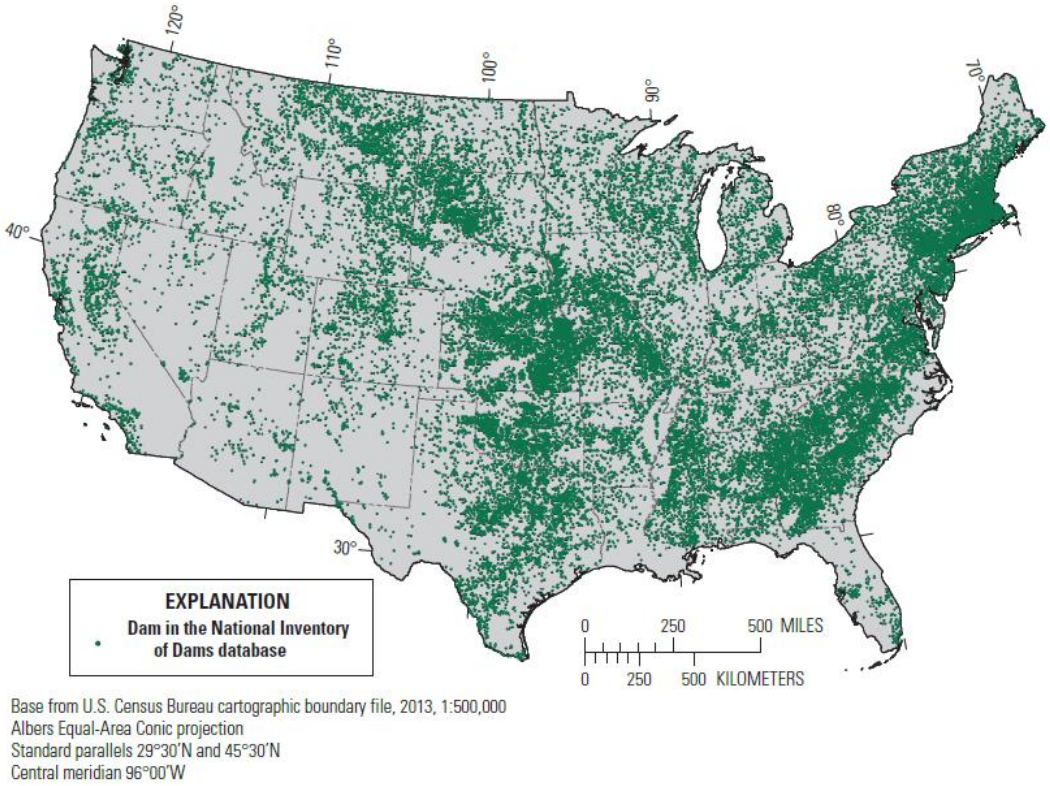


Figure 3. Map showing dams in the conterminous United States listed in the National Inventory of Dams (NID) (U.S. Army Corps of Engineers, 2013).

The NID database contains the most comprehensive set of dam information in the United States and lists dams with at least one of the following criteria: high hazard classification, significant hazard classification, equals or exceeds 25 feet in height and exceeds 15 acre-feet in storage, and (or) equals or exceeds 6 feet in height and exceeds 50 acre-feet in storage.

4.3.2 Diversions

Diversions remove a specified volume of flow from a stream channel; direct diversions respond directly to demands for water, which are usually highest during the dry season, and storage diversions can transport water during any flow, often intended to be released at a later time for future water needs. Diversions include permanent or temporary structures and water pumps designed to divert water to ditches, canals, or storage structures; storage diversions are commonly coupled with reservoirs. Diverted waters are used for hydropower, irrigation, recreational, municipal, industrial, and other purposes. Permanent infrastructure to convey diverted waters (pipelines, canals, ditches, etc.) exists throughout the United States; a large number of these structures are found in certain areas of the country (Figure 4).

The effects of diversions on the flow regime depend on the quantity and timing of the diversion (for example, see Figure 5) (Bradford and Heinonen, 2008). Although the largest diversions by volume occur during storm events, a greater proportion of flow is generally removed during low-flow periods, when plants and wildlife are already under stress. Although diversions result in an immediate decrease in downstream flow magnitude, some of the diverted water may eventually return to the stream as irrigation return flow or point-source discharge (see Section 4.3.4). This is not the case, however, for interbasin water transfers, a distinct class of diversion in which water is transported out of one basin and used in another, affecting both donor and receiving streams. Regardless of the fate of the water, the quantity and timing of the diversion can alter the natural flow regime.

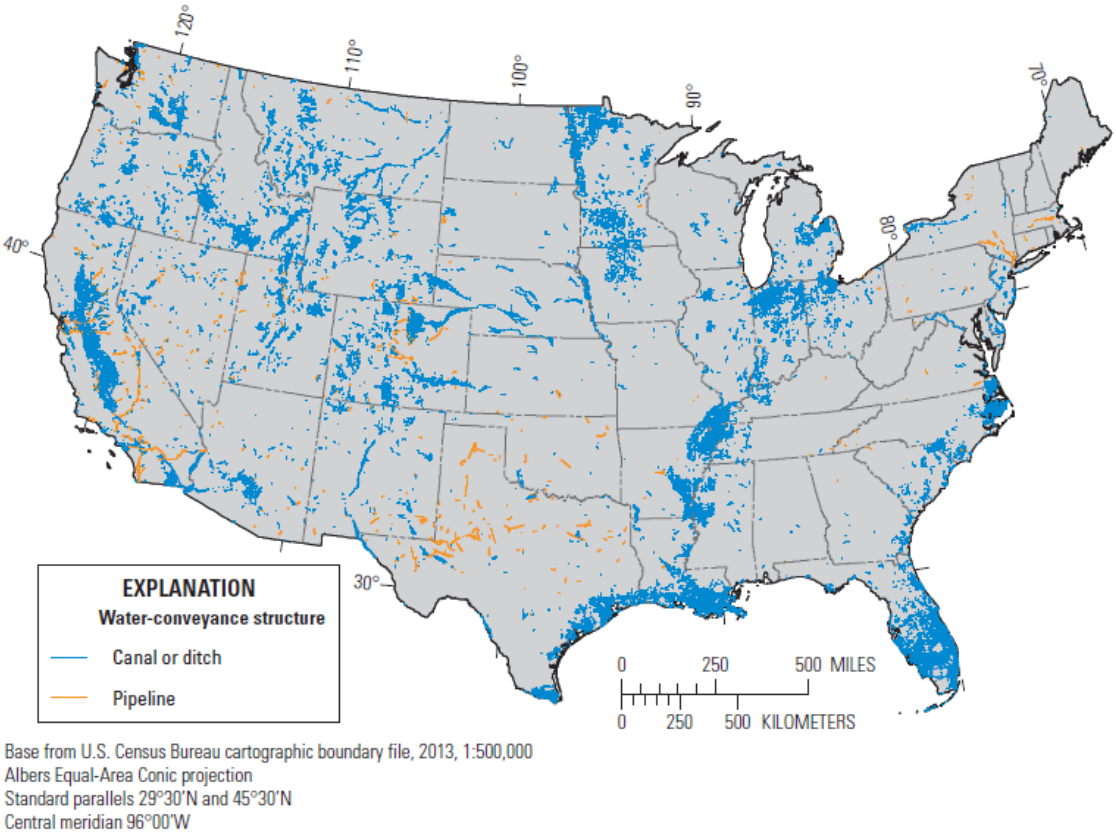


Figure 4. Map showing location of water-conveyance structures in the medium-resolution National Hydrography Dataset (NHD) (U.S. Geological Survey, 2012), illustrating the widespread extent of canals, ditches, and pipelines in the conterminous United States.

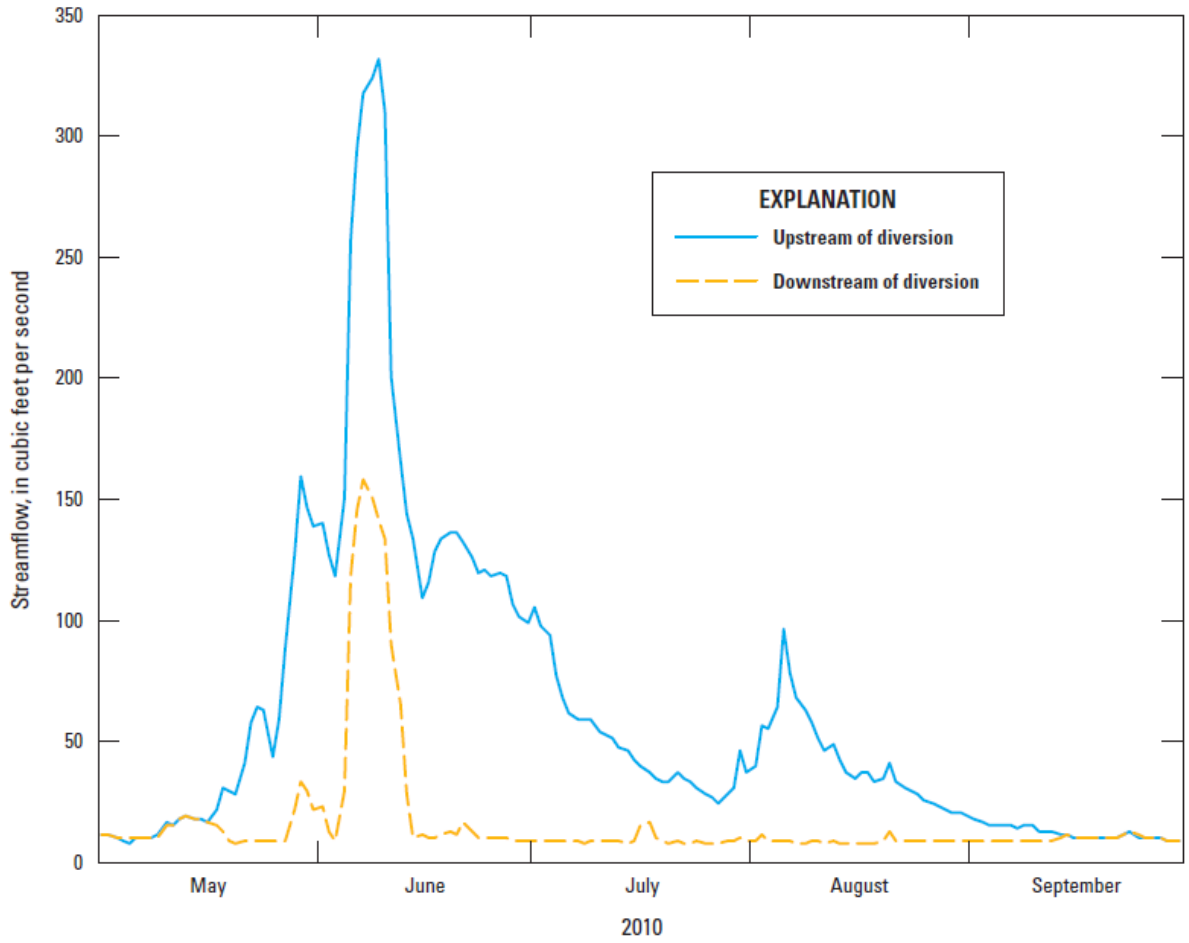


Figure 5. Graph showing streamflow at Halfmoon Creek, Colorado (U.S. Geological Survey station number 7083000), May–September, 2010.

(Streamgages are located upstream and immediately downstream from the diversion structure. Diverted water is stored in a nearby reservoir for irrigation.)

4.3.3 Groundwater Withdrawals

Most surface-water features interact with shallow groundwater, serving as points of discharge or recharge to local and regional aquifers. In many parts of the United States, groundwater contributes to streamflow and is the primary natural source of water during periods without substantial precipitation and runoff. Groundwater is also a major source of water for irrigation, public water supplies, industrial, and other uses (Maupin and others, 2014). Once thought to be limited to the arid West, groundwater depletion has been identified throughout the United States. The rate of groundwater depletion continues to increase and has been

recognized globally as a threat to sustainability of water supplies (Konikow, 2013). Groundwater withdrawals can lower the water table, resulting in reduced discharge to streams (Barlow and Leake, 2012; Reeves and others, 2009; Winter and others, 1998; Zarriello and Ries, 2000; Zorn and others, 2008; Wahl and Tortorelli, 1997). In some cases, particularly where wells are located close to a stream, the water table can be lowered to such a degree that the hydraulic gradient at the stream-aquifer boundary is reversed, and streamflow is induced to flow into the aquifer (Barlow and Leake, 2012). Some of the important factors that affect the timing of groundwater-withdrawal impacts on streamflow are the distance of individual wells from streams, the hydraulic properties of the aquifer and streambed materials, and the timing of withdrawals (Barlow and Leake, 2012). Groundwater withdrawals for irrigation increase during drought, when the only source of streamflow may be base flows from groundwater. The ecological effects of reduced groundwater contributions to streamflow, like those of other reductions in stream base flows, include the desiccation of aquatic and riparian habitat, reduced velocities and increased sedimentation, increased water temperature, and reduced connectivity of the stream network (discussed in Sections 4.4 and 4.5). These effects are exacerbated by groundwater demand, which spikes at times of the year when adequate flows are needed to support important biological behaviors and processes (for example, in summer when certain fish migrate and reproduce). Wahl and Tortorelli (1997) provide an example of the long-term impacts on streamflow due to groundwater withdrawals in a basin in western Oklahoma.

4.3.4 Effluents and Other Artificial Inputs (Discharges)

In contrast to diversions, surface- and groundwater withdrawals, and other human activities that remove water from streams, effluents, and other artificial inputs add water to streams but can also alter natural flow patterns. Examples of discharges and other artificial inputs include industrial facilities, municipal wastewater-treatment facilities, tile drainage systems, agriculture return flows, pumping and drainage from stormwater

control structures and others. The effects on streamflow from these additions are amplified when they consist of water that is not part of the natural water budget of the stream, such as deep groundwater or water derived from other basins, as in the case of interbasin transfers (Jackson and others, 2001). Such exogenous contributions shift the hydrograph upward and may be especially noticeable during natural low-flow periods as well as during flood flows resulting from storm events (Figure 6). This flow augmentation distorts the flow-sediment balance characteristic of undisturbed catchments, leading to effects such as channel downcutting and bank erosion as the stream strives to attain a new balance between water and sediment flux (as discussed in Section 4.4.1). In many arid environments, streamflow during dry seasons is composed almost entirely of treated effluent from wastewater-treatment facilities (Brooks and others, 2006). These inputs can cause a change in the stability of natural systems by artificially raising the water level during low-flow periods.

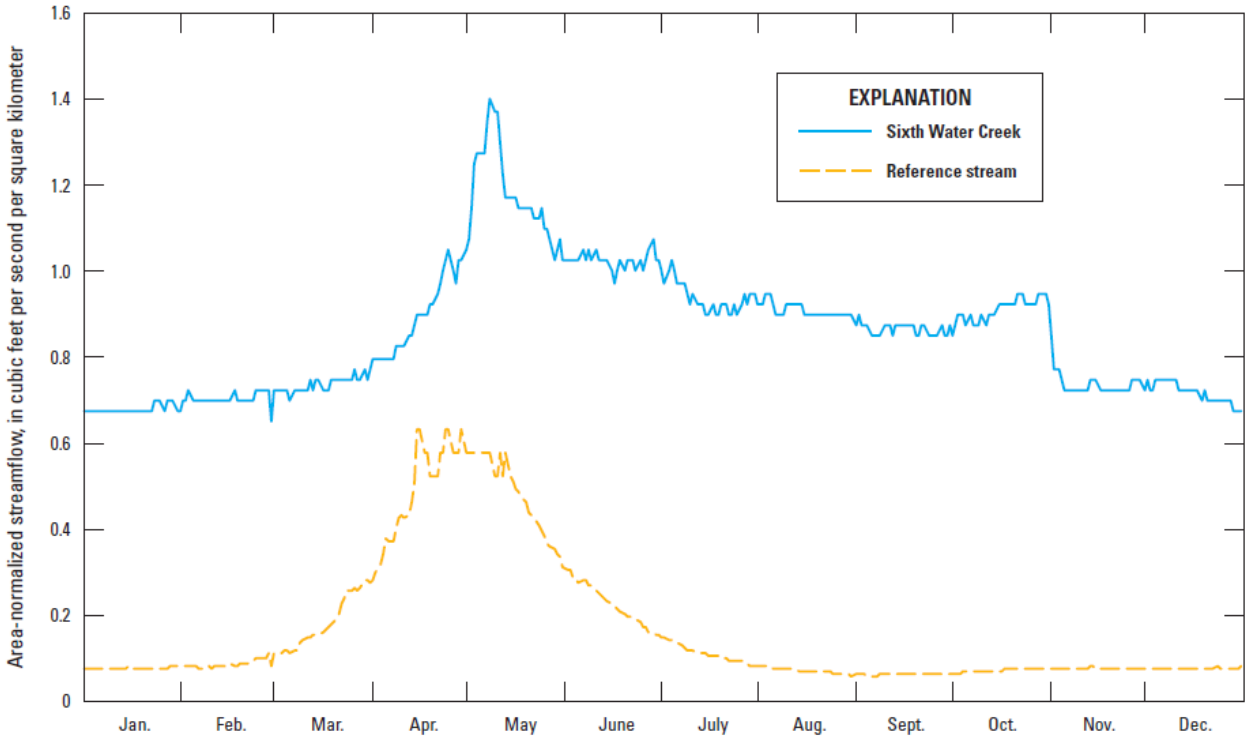


Figure 6. Graph showing artificially augmented daily streamflow at Sixth Water Creek, Utah (U.S. Geological Survey station number 10149000), January–December, 2000.

4.3.5 Land-Cover Alteration (Land Use)

The alteration of natural land cover for agricultural, forestry, industrial, mining, or urban use can modify several hydrologic processes that govern the amount and timing of runoff from the land surface, as well as other important processes and characteristics (for example, sediment dynamics, temperature). Such land-cover alterations may involve the removal of or change in vegetation cover, construction of impervious surfaces (for example, parking lots and rooftops), land grading, stream-channel alteration, or construction of engineered drainage systems. These changes reduce the potential for precipitation to be stored in shallow depressions and soils (Blann and others, 2009; Konrad and Booth, 2005) and allow a greater fraction of precipitation to enter stream channels through surface runoff, rather than infiltrate into the ground or evaporate. Moreover, engineered drainage systems (for example, municipal stormwater systems) and road networks can directly route runoff to receiving waters, increasing the rate of change to streamflow during a storm event. As a result, streams in developed areas exhibit extreme flashiness, characterized by a rapid rise in flow during storm events to a high peak-flow rate followed by rapid recession of flow after precipitation ceases (Dunne and Leopold, 1978; Walsh and others, 2005a, 2005b).

In addition, impervious surfaces may reduce base flow in the days, weeks, or even months after a storm event as a result of reduced infiltration and groundwater recharge. In agricultural areas, the opposite effect is observed with subsurface drainage structures (or tile drains), which discharge groundwater that would otherwise be held in storage or lost through evapotranspiration. However, agricultural drainage systems can reduce base flow, particularly when drainage lowers the water table and decreases groundwater recharge (Blann and others, 2009). During prolonged drought, differences in low-flow conditions between developed and natural streams generally are less pronounced than during average or high-flow conditions because developed areas tend to have a smaller effect on the deep groundwater recharge that supports flow during

drought conditions than on the shallow groundwater and runoff that contribute water to a stream when precipitation is more plentiful (Konrad and Booth, 2005).

Urban and agricultural land uses can accompany water-use and management practices such as interbasin transfers, irrigation and other surface-water withdrawals, on-site wastewater disposal, impoundment, and groundwater pumping. Each of these practices affects the direction and magnitude of flow alteration in urban and agricultural streams and can compound hydrologic effects, as discussed previously.

The effects of mining on streamflow depend on the size and type of mining, subsidence of underground mines, catchment characteristics and vegetative cover, the geology of the mine and degree of valley fills, the extent of underground mine pools and sediment ponds, the amount of soil compaction and infiltration, and type and timing of reclamation. For example, valley fills resulting from surface mining have been found to increase peak flows, unless other transport pathways, such as substantial connections to underground mines, intercept the stormwater discharges to streams (Messinger, 2003).

Finally, other management activities can cause flow alteration. Improperly sized road stream crossings may cause flooding, erosion, and sedimentation modifying the flow regime (Hoffman and others, 2012). Timber harvesting in forested areas generally increases peak flows and base flows as a result of decreased evapotranspiration and increased snowpack resulting from decreased canopy interception (Harr and others, 1982; Hewlett and Hibbert, 1961). The magnitude and duration of the effects are dependent on the size and type of harvest and the rate of vegetation regeneration.

4.3.6 Climate Change

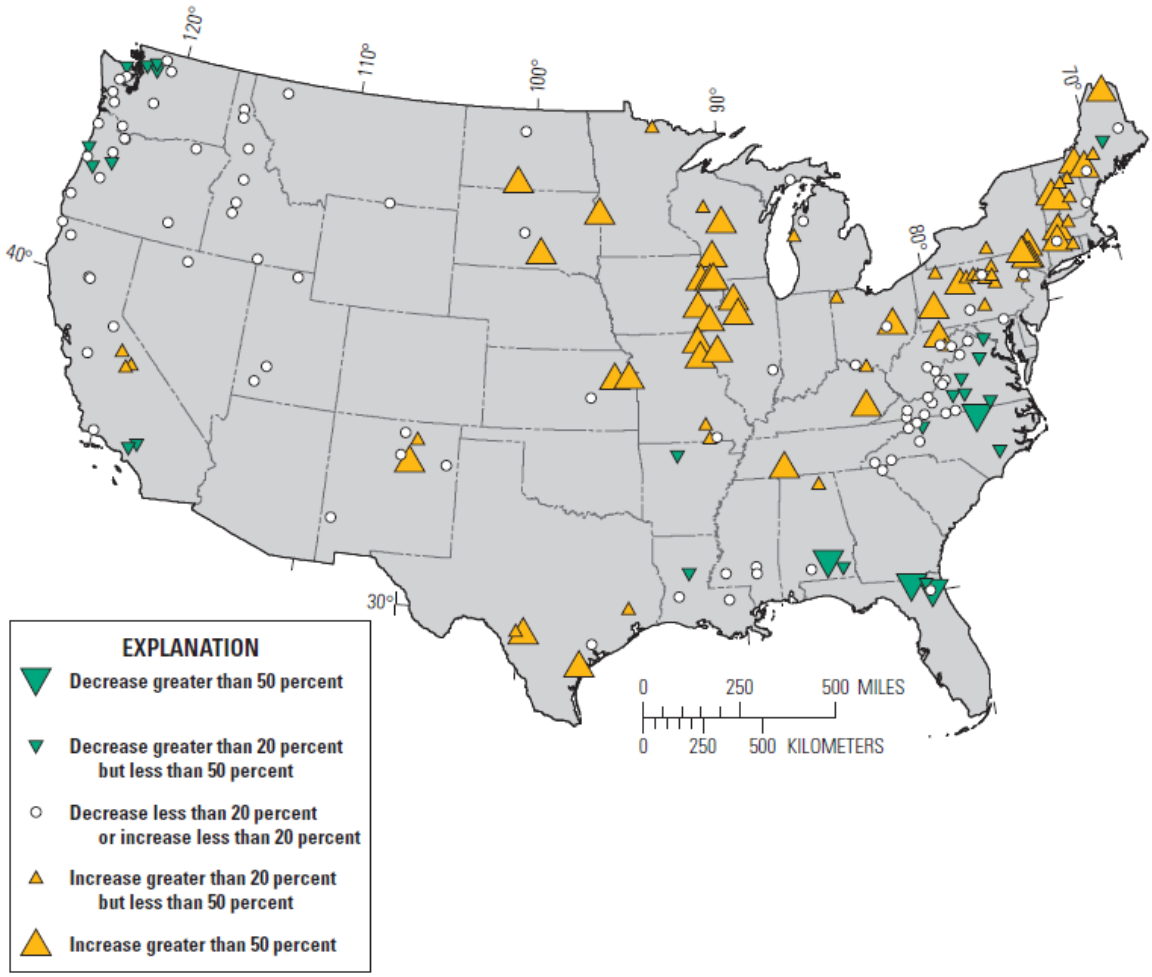
Climate change is an important and complex source of flow alteration because of the broad geographic extent of its effects and the lack of management options for direct mitigation at the watershed scale. Recent climate trends have included rising ambient air and water temperatures, increased frequency of extreme weather such as heavy precipitation events, increased intensity of droughts, altered fire regimes, longer growing

seasons, and reductions in snow and ice, all of which are expected to continue in the coming years and decades (Karl and others, 2009). Some of these changes have occurred or are projected to occur throughout the United States, such as increases in the frequency of very heavy precipitation events during the 20th century (Melillo and others, 2014). Increasing terrestrial disturbances from climate change (for example more frequent wildfires, debris flows, biological invasions, and insect outbreaks) can alter terrestrial inputs to streams (for example hydrologic runoff, sediment, and large wood) thereby affecting the flow regime (Davis and others, 2013). Other changes have been or are projected to be limited to certain regions, such as a projected increase in winter and spring precipitation in the northern United States and a decrease in winter and spring precipitation in the southwestern United States (Melillo and others, 2014).

Each of these aspects of climate change can substantially alter historic flow patterns. Projected nationwide increases in the frequency of heavy storm events and summer droughts have the potential to result in more frequent flooding and extreme low flows in streams and rivers across the United States. Specific effects on streamflows, however, will vary by region on the basis of regional climate change and hydrologic regimes. For example, observed trends in the magnitude of 7-day low flows at streamgages with minimal landscape effects vary across the United States, with some regions exhibiting a trend of decreasing low flows (longer dry spells) and others trending toward higher low flows (Figure 7) (U.S. Environmental Protection Agency, 2014b). Anthropogenic alterations that reduce streamflow may be further exacerbated by this climate-change trend. In areas where flow regimes are strongly affected by snowmelt, observations show a trend toward earlier timing of spring high flows (Figure 8) that corresponds to declines in the spring snowpack and earlier snowmelt (Melillo and others, 2014). These examples demonstrate the exposure of aquatic ecosystems to climate-driven flow alteration. Exposure analysis is an essential part of an assessment of the vulnerability of aquatic life to climate change. Additional discussion and examples of climate-change vulnerability assessments related to altered flow and aquatic life are included in Appendix B.

Climate change is occurring in conjunction with other anthropogenic stressors related to population increase and land-use change and may magnify the hydrologic and biological effects of those existing stressors (Intergovernmental Panel on Climate Change, 2007; Karl and others, 2009; Kundzewicz and others, 2008; Palmer and others, 2009; Pittock and Finlayson, 2011). For example, the combination of earlier spring snowmelt and increased water withdrawals can reduce summer flows to levels that would not otherwise occur in response to either stressor alone and that reduce the survival of aquatic biota. An additional example is the compounding effect of increased storm intensity on flood frequency in areas where impervious cover already drives flood flows at a frequency that degrades stream habitat (Intergovernmental Panel on Climate Change, 2007). These and other changes to the flow regime may further benefit invasive species to the detriment of native species (Rahel and Olden, 2008).

Adaptive capacity, or the ability of a stream ecosystem to withstand climate-driven stresses, may be seen in rivers whose flow patterns more closely resemble the natural flow regime. These rivers may be buffered from the harmful effects of climate-related disturbances on aquatic life (Palmer, 2009; Pittock and Finlayson, 2011). Understanding and enhancing adaptive capacity, along with an assessment of climate-change vulnerability, is a key part of climate-change adaptation planning.



Base from U.S. Census Bureau cartographic boundary file, 2013, 1:500,000
Albers Equal-Area Conic projection
Standard parallels 29°30'N and 45°30'N
Central meridian 96°00'W

Figure 7. Map showing trends in the magnitude of 7-day low streamflows in the United States, 1940-2009.

(Minimum streamflow is based on data from 193 long-term U.S. Geological Survey streamgages over the 70-year period whose drainage basins are only minimally affected by changes in land use and water use. Modified from U.S. Environmental Protection Agency, 2014b)

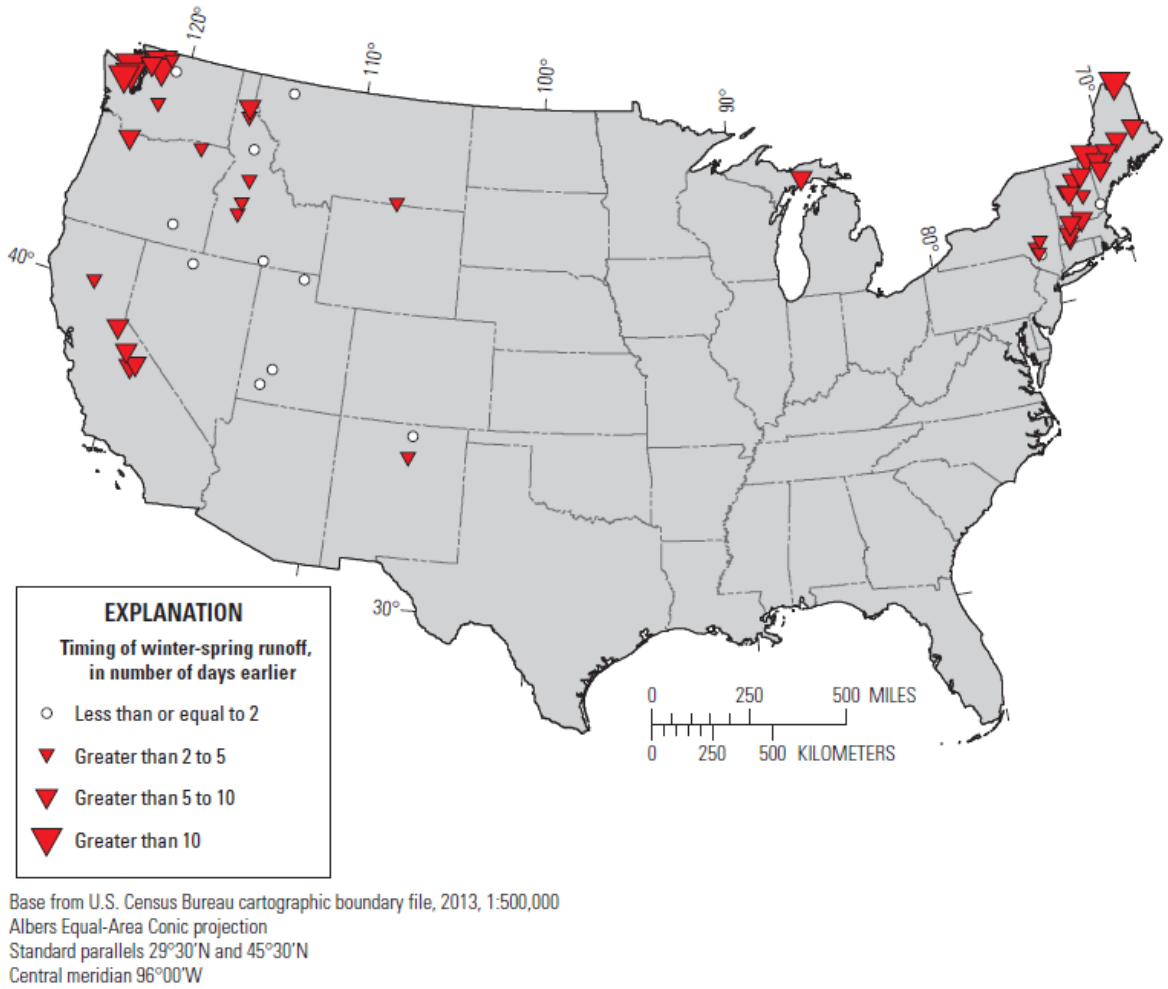


Figure 8. Map showing trends in the timing of winter-spring runoff in the United States, 1940-2009.

(Streamflow trends are based on data from 193 long-term U.S. Geological Survey streamgages over the 70-year period whose drainage basins are only minimally affected by changes in land use and water use. Modified from U.S. Environmental Protection Agency, 2014b).

4.4 Physical and Chemical Effects of Flow Alteration

Changes to the natural flow regime resulting from land-use and water-management practices can affect physical and chemical properties of riverine ecosystems, including geomorphology, connectivity, and water quality (Annear and others, 2004). This section provides an overview of the effects of flow alteration on each of these properties.

4.4.1 Effects on Geomorphology

The natural geomorphology of stream channels and flood plains is shaped largely by watershed hydrology and resulting flow patterns. Geomorphology is the expression of the balance between flow strength (for example, flow magnitude, slope) and flow resistance and sediment supply (for example, grain size, vegetation, sediment load), with a tendency toward channel erosion and degradation when flow strength increases and a tendency toward channel deposition and aggradation when flow resistance and sediment supply increase. Channel geometry, bed substrate, and the presence of geomorphic features such as oxbow lakes, point bars, or riffle-pool sequences vary according to the frequency of bankfull flows, the magnitude of floods, and other flow characteristics (Trush and others, 2000). Research has uncovered a variety of geomorphic responses to flow alteration, with specific effects depending on the type and severity of hydrologic change. These effects can include channel incision, narrowing, or widening; increased deposition of fine sediment or bed armoring (coarsening of the surface of gravel bed rivers relative to the subsurface); and reduced channel migration (Poff and others, 1997).

A primary mechanism for geomorphic change is a shift in energy and sediment dynamics following flow alteration. For example, increased peak flows resulting from urban land use can increase bed erosion and drive channel incision or widening. In contrast, reduced flooding as a result of dam regulation can lower the distribution of nutrient-bearing sediments to flood plains, starve downstream channel and coastal areas of needed sediment, and increase sedimentation upstream from the dam (Syvitski and others, 2005). These

processes can lead to simplified channels that are disconnected from their natural flood plains. Natural mosaics of geomorphic features serve as important habitats for a range of aquatic and flood-plain species, and the loss of habitat diversity following hydrologic alteration can have adverse effects on the health of biological communities.

4.4.2 Effects on Connectivity

Hydrologic connectivity is the water-mediated transfer of matter, energy, and (or) organisms within or between elements of a hydrologic system (Pringle, 2003). In aquatic ecosystems, it encompasses longitudinal connectivity of the stream network and specific habitat types, as well as lateral connectivity among stream channels, riparian zones, flood plains, and wetlands. The vertical connection between surface water and groundwater is a third dimension of connectivity along the various flow paths that connect points of recharge (beginning at the water table) to points of discharge (for example, a river or stream) (Ward, 1989).

Longitudinal, lateral, and vertical connectivity naturally vary spatially and temporally with climate, geomorphology, groundwater dynamics, and other factors. Longitudinal connectivity, for example, may be continuous from headwaters to lower reaches in one catchment but interrupted by intermittent or ephemeral reaches in another (Larned and others, 2010a, 2010b, 2011). Lateral connectivity is restricted to short-duration flooding of narrow riparian areas in headwater reaches, whereas meandering and braided lower reaches are subject to longer periods of inundation over broader flood plains (Ward and Stanford, 1995). Aquatic biota have adapted to connectivity patterns through space and time, with life-history traits such as migration and spawning closely linked to the timing, frequency, and duration of upstream-downstream and channel/flood-plain connections (Junk and others, 1986; U.S. Environmental Protection Agency, 2015).

Hydrologic alteration can affect connectivity in several ways. Longitudinal connectivity of the stream network is disrupted by dams, weirs, diversions, culverts, stream crossings and other manmade structures that obstruct upstream-downstream passage by fish and other organisms. For instance, culverts can affect the movement of

fish species during critical life stages due to outlet drops, increased velocity or reduced flows (Diebel and others, 2015). Longitudinal connectivity is also disrupted by fragmentation of aquatic habitat without manmade barriers. For example, an increase in the frequency of zero-flow conditions in a stream reach as a result of water withdrawals can cause the disconnection of upstream areas from the rest of the stream network (U.S. Environmental Protection Agency, 2015). Lateral connectivity among the stream channel, riparian areas, flood plains, and wetlands is reduced as a result of the decreased frequency of high flows and floods caused by geomorphic change (for example, channel incision) or of direct modification of stream channels (channelization, levee construction, etc.). Vertical connectivity is altered directly and indirectly through practices that alter infiltration and runoff (for example, impervious surface), which can affect recharge to groundwater and outflow to surface water. Other activities (for example, drainage) can alter surface-runoff rates and potentially reduce recharge and contribute to flooding. Other practices may cause a rise in the water table and, subsequently, the base level of a stream (for example, reservoirs) (Winter and others, 1998). For systems characterized by an absence of connectivity, flow alterations such as stream channelization, irrigation, and impervious surface area can increase flashiness and increase connectivity (U.S. Environmental Protection Agency, 2015).

4.4.3 Effects on Water Temperature and Chemistry

The water quality effects of flow alteration are varied and can include changes in water temperature, salinity (which is measured by specific conductance), dissolved-oxygen concentration, pH, nutrient concentrations, and other parameters. For example, dilution of dissolved salts or toxic contaminants are reduced because of a decrease in flow magnitude when water is diverted or groundwater is pumped (Caruso, 2002; Olden and Naiman, 2010; Sheng and Devere, 2005). Stream temperature is also closely linked to flow magnitude (Cassie, 2006; Gu and Li, 2002; Wehrly and others, 2006); artificially low flows can result in increased water temperatures as a result of reduced depths and (or) reduced input of cool groundwater. Low flows also

increase the likelihood of stagnant water with a low dissolved-oxygen concentration. In contrast, dam tailwaters can become supersaturated with gases and harm aquatic life (Weitkamp and Katz, 1980). Additionally, dam tailwaters, particularly those drawing water from the depths of stratified reservoirs, show elevated levels of nutrients and metals, low dissolved-oxygen concentrations, and altered temperature relative to downstream waters (Arnwine, 2006; De Jalon and others, 1994; McCartney, 2009; Olden and Naiman, 2010; Poff and Hart, 2002; Preece and Jones, 2002; Sherman and others, 2007; Vörösmarty and others, 2003). Thermal regime modifications can include an increase in temperatures when warm water is released from the reservoir surface (common in smaller dams and diversions), or lower temperatures when water is released from beneath a reservoir's thermocline (Olden and Naiman, 2010). In urban areas, stream temperatures are elevated during high-flow conditions (constituting an increase in the rate of change) as a result of the input of runoff that has come in contact with warm impervious surfaces. Moreover, runoff from developed lands can transport nutrients, organic matter, sediment, bacteria, metals, and other contaminants to streams (Grimm and others, 2005; Hatt and others, 2004; Morgan and Good, 1988; Mulholland and others, 2008; Paul and Meyer, 2001). Effects may differ among water-body types (for example, lentic and lotic waters).

4.5 Biological Responses to Flow Alteration

The combined physical and chemical effects of flow alteration (summarized in the previous section) may result in the degradation, loss, and disconnection of ecological integrity within a stream system. Moreover, flow modification can eliminate hydrologic cues needed to stimulate spawning or flow volume and timing needed to aid seed dispersal, resulting in a mismatch between flow and species' life-history needs, and can encourage the invasion and establishment of non-native species (Bunn and Arthington, 2002). The ability of a water body to support healthy aquatic life is therefore tied to the maintenance of key flow-regime components.

Specific biological effects of a given type of flow alteration vary by location and degree of alteration; however, some generalities can be made. Literature summarizing biological responses to altered flows, compiled and reviewed by Bunn and Arthington (2002) and Poff and Zimmerman (2010), includes studies showing overall reductions in the abundance and diversity of fish and macroinvertebrates, excessive growth of aquatic macrophytes, reduced growth of riparian vegetation, and shifts in aquatic and riparian species composition. Similarly, a meta-analysis of research in the South Atlantic United States noted consistently negative ecological responses to anthropogenically induced flow alterations, with fish tending to respond negatively and algae positively, while macroinvertebrates and riparian vegetation often responded negatively, but were more inconsistent (McManamay and others, 2013). These changes are tied to altered habitat. For example, the stabilization of flow downstream of dams tends to reduce habitat diversity and, therefore, species diversity. Reduced longitudinal connectivity of habitat types can reduce the survival of migratory fish species, and reduced lateral connectivity between stream channels and flood-plain wetlands limits access to important reproduction and feeding areas, refugia, and rearing habitat for native and resident fishes. Reduced lateral connectivity can reduce the availability of habitat needed for aquatic life stages of macroinvertebrates and amphibians, and can reduce the potential for gene flow (mixing individuals from different locations). Altered flows may disrupt the cues needed for gametogenesis and spawning and result in loss of habitat occurring during all life stages of freshwater mollusks. Fish spawning is disrupted by changes to the natural seasonal pattern of flow. For some fish species, spawning is triggered by rising flows in the spring; therefore, a shift in the timing of high flows can result in aseasonal reproduction during periods when conditions for larval survival are suboptimal. In addition, changes in species abundance and richness, ecosystem functions such as contaminant removal and nutrient cycling rates, can degrade in the environment due to flow alteration (Palmer and Febria, 2012; Poff and others, 1997; Vaugh and Taylor, 1999).

The relations among variables such as flow, temperature, habitat features, and biology are key in controlling species distribution (for example, Zorn and others, 2008). Water temperature is an associated hydrologic characteristic and has a particularly strong effect on aquatic organisms in summer months, when streamflows are lowest and temperatures are highest (Brett, 1979; Elliot, 1981; Wehrly and others, 2003). Increases in water temperature that result from alterations such as withdrawals, especially during critical summer low-flow periods, have detrimental biological effects. Dam operations can have diverse effects on biology through modifying the thermal regime, and these modifications depend on the size, purpose, and release operations of the dam. For example, depressed spring and summer temperatures due to dam releases from the deep, cool layer in a stratified reservoir, may result in delayed or reduced spawning of fish species or extirpation of native warm-water biological communities in favor of cool- and cold-water assemblages (Olden, 2006; Preece and Jones, 2002). Dam releases in the winter result in warmer water temperatures, which may eliminate developmental cues and increase growth, leading to earlier aquatic insect emergence. These changes in temperature can create a mismatch between life-history stages and environmental conditions that may increase mortality as a result of high-flow events, predation, reduction in resource availability earlier in the season, and other stresses (Olden and Naiman, 2010; Vannote and others, 1980; Ward and Stanford, 1982).

The result of these hydrologic alterations may be impairment of a water body due to the physical, chemical, or biological effects discussed above. The most severe of alterations, the complete dewatering of a perennial stream or river, will result in complete extirpation of aquatic species in those water bodies. In addition to directly contributing to impairments through ecologically deleterious physical changes (that is, hydrologic, geomorphic, and connectivity change), hydrologic alteration may also be the underlying source of other impairments such as low dissolved oxygen, modified thermal regimes, increased concentrations of sediment, anoxic byproducts (such as downstream of dams), and nutrients or toxic contaminants. While the focus of this report is primarily on those direct physical factors (for example, geomorphic and hydrologic) that can affect

biological communities, addressing these hydrologic alterations may also help to mitigate the effects of contaminants such as those mentioned above.

5 Examples of States that have Adopted Narrative Flow Standards

This section provides examples of states and Tribes that have used the CWA tools to address the effects of altered flows on aquatic life. Figure 9 illustrates how water-quality management programs are based on Water Quality Standards (WQS) under the CWA.

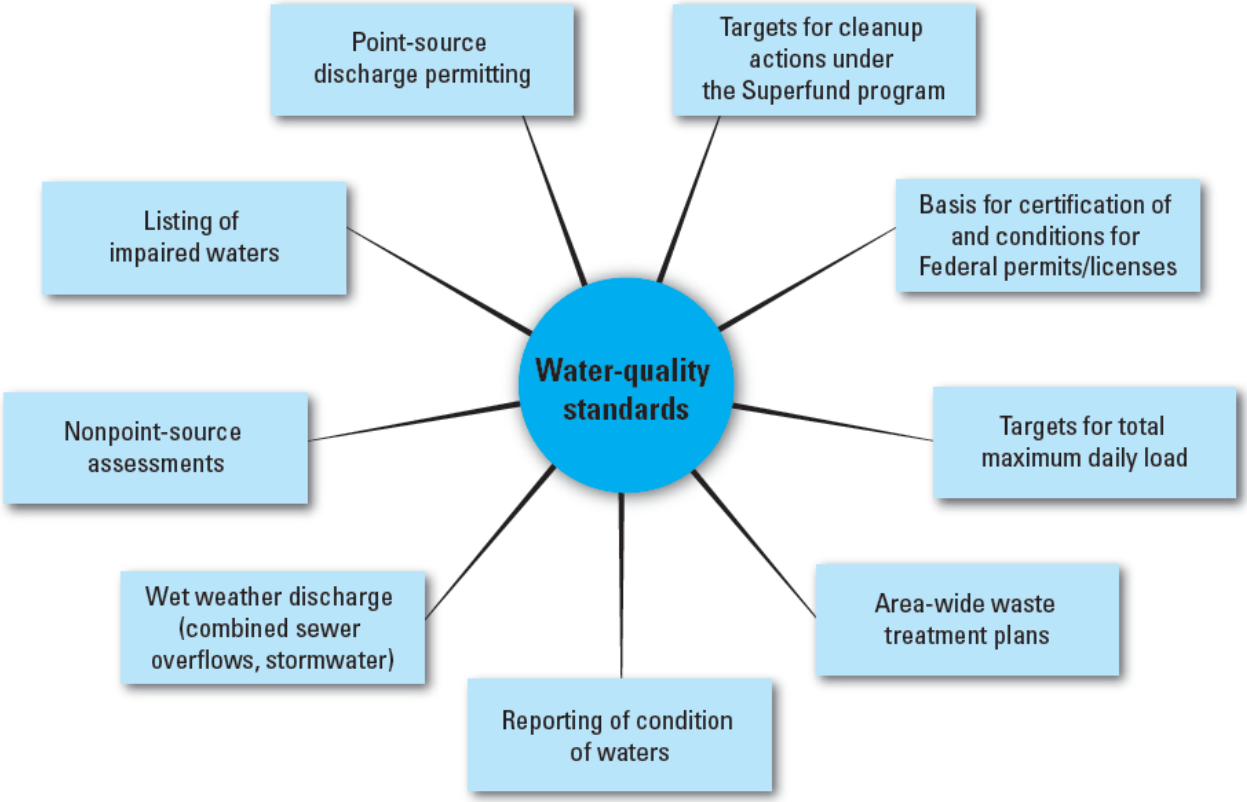


Figure 9. Schematic diagram illustrating environmental management programs utilizing water quality standards developed under the Clean Water Act.

5.1 Narrative Criteria in State and Tribal Water Quality Standards

One set of CWA tools that some states and Tribes have used to address the effects of hydrologic alteration on aquatic life is water quality standards (WQS), which include designated uses, criteria, and antidegradation requirements. The goals and provisions of the CWA and corresponding EPA regulations provide for states to adopt narrative and (or) numeric chemical-specific criteria, as well as criteria that address the physical and biological integrity of the Nation's waters (see CWA sections 101 and 303(c); see also Title 40 of the Code of Federal Regulations (40 CFR) part 131.11(b)). Table 1 of this section presents examples of narrative flow criteria that some states and Tribes have developed.

Table 1. Examples of states and Tribes that have adopted narrative flow criteria for the protection of aquatic life.

[Key terms are shown in bold for emphasis; see U.S. Environmental Protection Agency (2014e) for complete text of individual criteria; %, percent; 7Q10, the 7-day, 10-year annual low-flow statistic; WMT, Water Management Type]

State/Tribe	Water Quality Standard description of protected resource and corresponding goal
Kentucky	Section 4. "Aquatic Life. (1) Warm water aquatic habitat. The following parameters and associated criteria shall apply for the protection of productive warm water aquatic communities, fowl, animal wildlife, arboreous growth, agricultural, and industrial uses:…(c) Flow shall not be altered to a degree which will adversely affect the aquatic community."
Missouri	"Waters shall be free from physical, chemical, or **hydrologic changes** that would impair the natural biological community."
New Hampshire	"**surface water quantity** shall be maintained at levels adequate to protect **existing and designated uses**" "These rules shall apply to any person who causes point or nonpoint source discharge(s) of pollutants to surface waters, or who undertakes hydrologic modifications, such as dam construction or water withdrawals, or who undertakes any other activity that affects the beneficial uses or the level of water quality of surface waters."
New York	Classes N and AA-special fresh surface waters … "There shall be **no alteration to flow** that will impair the waters for their **best usages**." Classes AA, A, B, C, D, and A-special waters…."**No alteration** that will impair the waters for their **best usages**."
Rhode Island	"**quantity** for protection of… **fish and wildlife**…adequate to protect **designated uses**" "For activities that will likely cause or contribute to flow alterations, streamflow conditions must be adequate to support **existing and designated uses.**"
Tennessee	Rule 0400-40-03-.03, Criteria for Water Uses: Section (3) The criteria for the use of Fish and Aquatic Life are the following, subsection (n) Habitat—"The quality of stream habitat shall provide for the development of a **diverse aquatic community** that meets regionally-based biological integrity goals. Types of habitat loss include, but are not limited to: channel and substrate alterations….stream **flow** changes….for wadeable streams, the instream habitat within each subecoregion shall be generally similar to that found at **reference streams**. However, streams shall not be assessed as impacted by habitat loss if it

State/Tribe	Water Quality Standard description of protected resource and corresponding goal
	has been demonstrated that the biological integrity goal has been met." Subsection (o) Flow—"Stream or other waterbody **flows shall support the fish and aquatic life criteria**." "Section (4) The criteria for the use of Recreation are the following: Subsection (m) Flow—Stream **flows** shall support **recreational uses."**
Vermont	Class A(1)—"Changes from **natural flow regime** shall not cause the natural flow regime to be diminished, in aggregate, by more than 5% of 7Q10 at any time;" Class B WMT 1 Waters—"Changes from the **natural flow regime**, in aggregate, shall not result in **natural flows** being diminished by more than a minimal amount provided that **all uses** are fully supported; and when flows are equal to or less than 7Q10, by not more than 5% of 7Q10." Class A(2) Waters and Class B Waters other than WMT1—"Any change from the **natural flow regime** shall provide for maintenance of flow characteristics that ensure the **full support of uses** and comply with the applicable water quality criteria."
Virginia	"**Man-made alterations in stream flow** shall not contravene designated uses including protection of the propagation and growth of **aquatic life**."
Bad River Band of the Lake Superior Tribe of Chippewa Indians	"**Water quantity** and quality that may limit the growth and propagation of, or otherwise cause or contribute to an adverse effect to wild rice, wildlife, and other flora and fauna of cultural importance to the Tribe shall be prohibited." "**Natural hydrological conditions** supportive of the **natural biological community**, including all flora and fauna, and physical characteristics naturally present in the waterbody shall be protected to prevent any adverse effects." "Pollutants or human-induced changes to Tribal waters, the sediments of Tribal waters, or area hydrology that results in changes to the natural biological communities and wildlife habitat shall be prohibited. The migration of fish and other aquatic biota normally present shall not be hindered. **Natural daily and seasonal fluctuations of flow** (including naturally occurring seiche), level, stage, dissolved oxygen, pH, and temperature shall be maintained."
Seminole Tribe	"Class 2-A waters shall be free from activities....that....impair the **biological community** as it naturally occurs....due to....**hydrologic changes.**"

State/Tribe	Water Quality Standard description of protected resource and corresponding goal
of Florida	

Table 1 demonstrates that narrative flow criteria are written in various ways. However, the language commonly addresses two general components: (1) a description of the resource or attribute to be protected and (or) protection goal; and (2) one or more statements describing the hydrologic condition needed to be maintained to achieve the protection goal. The resource to be protected generally is an explicit reference to aquatic life designated uses or general language that targets the protection of a suite of designated and (or) existing uses (for example, “propagation and growth of aquatic life,” “biological community as it naturally occurs,” “diverse aquatic community,” etc.). For most existing narrative flow criteria, the flow condition to be maintained is written in general terms (for example, “There shall be no alteration to flow....,” “natural daily and seasonal fluctuations in flow,” etc.). The addition of language that references specific aquatic life endpoints, such as migration or other life-cycle events, may serve as important reminders of biological goals to guide the selection of assessment endpoints, measures of effect (biological and flow indicators), and flow targets to meet aquatic life needs taking into account both near-field and downstream impacts. These concepts are discussed in detail in Section 6.

More complete examples from New Hampshire and Rhode Island narrative flow criteria are as follows and illustrate additional attributes these states chose to emphasize, such as broad applicability across all surface waters:

“Unless flows are caused by naturally occurring conditions, surface water quantity shall be maintained at levels adequate to protect existing and designated uses.” (New Hampshire Code of Administrative Rules Env-Wq 1703.01 (d)). “These rules shall apply to any person who causes point or nonpoint source discharge(s) of pollutants to surface waters, or who undertakes hydrologic modifications, such as dam construction or water withdrawals, or who undertakes any other activity that affects the beneficial uses or the level of water quality of surface waters.” (New Hampshire Code of Administrative Rules Env-Wq 1701.02 (b)).

“General Criteria—The following minimum criteria are applicable to all waters of the State, unless criteria specified for individual classes are more stringent:….(h). For activities that will likely cause or contribute to flow alterations, streamflow conditions must be adequate to support existing and designated uses.” (Rhode Island Department of Environmental Management Water Quality Regulations (2010) Rule 8(D)(1)(h)).

Although the narrative examples in Table 1 may be useful tools to help states make informed decisions about their water resources, they do not explicitly describe the specific components of the natural flow regime (that is, magnitude, duration, frequency, rate of change, and timing) to be maintained to protect aquatic life uses. The framework presented in Section 6 can help guide a state through a process to determine which of these components are most important to protect the designated use. Box C describes the physical and biological importance of considering the specific components of the natural flow regime in the development of environmental flow targets rather than relying on a more general minimum flow magnitude to protect aquatic life.

Box C. Addressing Flow Regime Components

It is critically important to maintain extremes (floods and droughts) within the bounds of the natural flow regime to support the ecological structure and function of streams and rivers. However, alterations in low or high flows that are human-induced, affect and can control many ecosystem patterns, such as habitat extent and condition, water quality, connectivity, and material and energy exchange. These patterns can in turn affect many ecosystem processes, including biological composition, distribution, recruitment of biota, and ecosystem production (Rolls and others, 2012).

Although low flows serve a critical role in ecosystem function, current scientific research indicates that flow criteria ideally should support the natural flow regime as a whole, and that criteria for minimum flow alone (that is, a single minimum discharge value or a minimum passing flow) are not sufficient for maintaining ecosystem integrity (Annear and others, 2004; Bunn and Arthington, 2002; Poff and others, 1997). Minimum flow criteria do not address the full range of seasonal and interannual variability of the natural flow regime in most rivers and streams.

The natural fluctuation of water volume and levels in rivers and streams is critical for maintaining aquatic ecosystems because aquatic biota have developed life-history strategies in response to these fluctuations (Hill and others, 1991; Lytle and Poff, 2004; Mims and Olden, 2012, 2013; Postel and Richter, 2003; Stalnaker, 1990). Comprehensive flow criteria not only identify flow needs (that is, magnitude) but may also address the rate, frequency, timing, and duration of streamflow required to support ecosystem health (Poff and others, 2010). The Instream Flow Council (a non-profit organization working to improve the effectiveness of instream flow programs and activities: http://www.instreamflowcouncil.org/) recommends developing criteria that incorporate natural patterns of intra- and interannual variability in a manner that maintains and (or) restores riverine form and function to effectively maintain ecological integrity (Annear and others, 2004). Therefore, narrative hydrologic criteria and their implementation ideally should address several flow-regime components

(frequency, duration, timing, rate of change) in addition to flow magnitude. The components necessary are determined on a case-by-case basis, depending on which values are most ecologically relevant.

Minimum flow statistics such as the 7Q10 design flow (the minimum 7-day average flow likely to occur in a 10-year period) are recommended by the U.S. Environmental Protection Agency for the derivation of water quality-based effluent limits in the National Pollutant Discharge Elimination System permitting program, but, although they include magnitude, duration, and frequency components, they were not derived to support the hydrologic requirements of aquatic ecosystems (Annear and others, 2004). The main purpose of these design flows is to determine pollutant discharge values (or limits) rather than to support the flow requirements of aquatic ecosystems (see U.S. Environmental Protection Agency, 1991).

6 Framework for Quantifying Flow Targets to Protect Aquatic Life

The adoption of narrative flow criteria in WQS is a mechanism to address the effect of flow alteration on aquatic life. Narrative criteria are qualitative statements that describe the desired water quality condition needed to protect a specified designated use (for example, aquatic life uses). The adoption of explicit narrative flow criteria allows for a clear link between the natural flow regime and the protection of designated uses. Moreover, the adoption of narrative flow criteria ensures that flow conditions are considered under various other CWA programs (for example, CWA Section 401 certifications, monitoring and assessment, and permitting under CWA Sections 402 and 404).

The effectiveness of narrative flow criteria depends, in part, on the establishment of scientifically defensible methods to quantitatively translate and implement the narrative. Quantitative translation of narrative flow criteria requires an understanding of the principles of the natural flow regime, hydrologic alteration, and ecological responses to altered flows (Knight and others, 2012; Knight and others, 2014). (The term "quantitative translation" encompasses the qualitative approaches described further in this section.)

A fundamental goal of any effort to translate narrative flow criteria is to establish scientifically sound, quantitative flow targets that are readily implemented in State water quality management programs. This section describes a framework (illustrated in Figure 10) for developing quantitative flow targets for protection of aquatic life uses that incorporates elements of the EPA Guidelines for Ecological Risk Assessment (ERA) (U.S. Environmental Protection Agency, 1998), recent environmental flow literature (Arthington, 2012; Kendy and others, 2012; Poff and others, 2010), and procedures outlined in EPA guidance documents (U.S. Environmental Protection Agency 2000a, 2000b, 2001, 2008, 2010b). The framework is intended to be flexible; decisions regarding whether and how each step is applied depend on project-specific goals and resources.

The framework presented in this section is organized into eight discrete steps that integrate science and policy (Figure 10). Steps 1 through 4 correspond to the "problem formulation phase" of the EPA ERA framework;

Steps 5 through 7 represent the “analysis phase”; and Step 8 incorporates concepts from the “risk characterization” phase as an “effects characterization”. Throughout the process, opportunities for public and stakeholder involvement should be considered. Certain steps within this framework are particularly well suited for public participation (see discussion of Steps 1 and 8). The benefits of public involvement are two-fold. First, public input can help strengthen the study design by incorporating suggested methods or addressing deficiencies identified in proposed approaches. Second, public involvement can foster a sense of support and ownership in the resulting flow targets, leading to streamlined implementation (Annear and others, 2004; Locke and others, 2008).

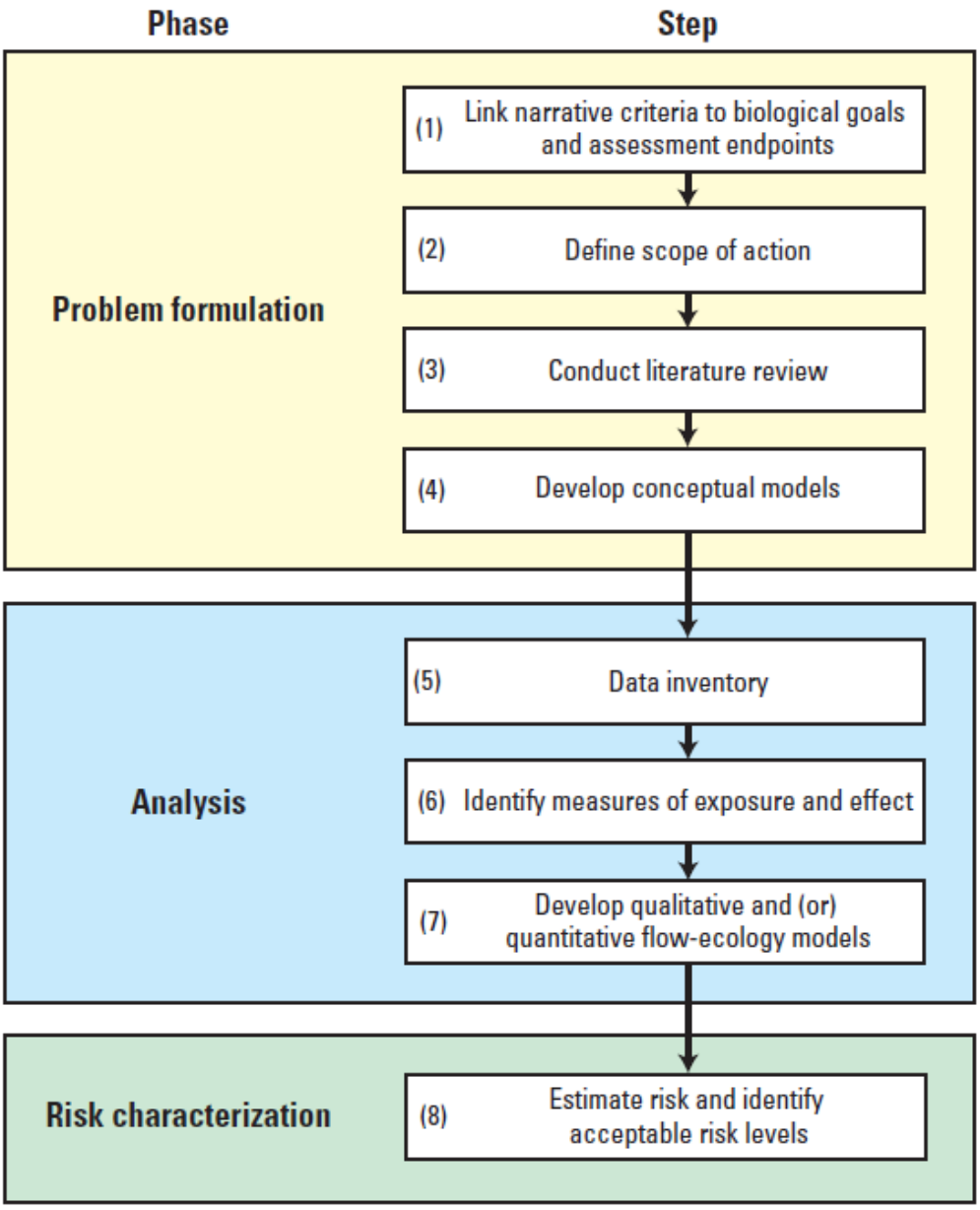


Figure 10. Flow diagram illustrating a framework for quantifying flow targets to protect aquatic life. (Adapted from EPA Guidelines for Ecological Risk Assessment; http://www.epa.gov/sites/production/files/2014-11/documents/eco_risk_assessment1998.pdf)

6.1 Link Narrative Criteria to Biological Goals and Assessment Endpoints

As described in Section 4, narrative flow criteria (see Table 1) are generally composed of (1) a description of the resource to be protected and the protection goal, and (2) statements describing the flow condition needed to be maintained to achieve the protection goal.

The first step in the framework for quantifying flow targets is to link narrative flow criteria to biological goals and assessment endpoints for the purpose of directing subsequent steps. A biological goal is a specific type of management goal that focuses on the biological characteristics of an aquatic system, such as fish or macroinvertebrate populations. Biological goals clearly state the desired condition of biological attributes relevant to flow target development (for example, “restore and maintain cold-water fisheries”). In most cases, a narrative flow criterion will already provide or suggest biological goals for a particular community or species that are tied to aquatic life designated uses. For narrative criteria worded in general terms, biological goals are derived through interpretation of narrative statements or are based on existing biological criteria to protect aquatic life designated uses. Examples of linking narrative flow criteria to biological goals are provided in Section 6.9.

Assessment endpoints are “explicit expressions of the actual environmental value that is to be protected” (U.S. Environmental Protection Agency, 1998). Whereas biological goals describe the desired condition of aquatic biota and communities, assessment endpoints specify which biological attributes are used to evaluate whether goals are met. If, for example, a biological goal was to “maintain a cold-water fishery,” assessment endpoints could include spawning success rate and adult abundance for one or more cold-water fish species. Assessment endpoints use “neutral phrasing” in that they do not call for any desired level of achievement. The EPA document “Guidelines for Ecological Risk Assessment” (U.S. Environmental Protection Agency, 1998) outlines three main criteria for selecting assessment endpoints: (1) ecological relevance; (2) susceptibility to known or potential stressors; and (3) relevance to management goals. Selection of assessment endpoints can

take into consideration available methods for measuring biological conditions, although endpoints without standard measurement protocols may be selected. Additional discussion of biological measures for quantitative analysis is provided in Section 6.6, and example endpoints are listed in Table 2.

Biological goals and assessment endpoints defined during this step may be shared with the public for comment. Soliciting feedback at this step can improve public awareness of a state's intent to quantitatively translate narrative flow criteria and promote transparency at the onset of the process, both of which are crucial to the successful development and implementation of flow targets.

6.2 Identify Target Streams

Flow targets are quantified for a single stream, all streams within a geographic area (for example, a catchment or a state), or a subset of streams that satisfy a set of selection criteria. The second step in the framework for quantifying flow targets is to clearly define the spatial extent of the project and the target stream population.

When multiple streams over a large area are the subject of study, it is advantageous to classify target streams according to their natural flow, geomorphic properties, temperature regimes, and other attributes. The purpose of stream classification is to identify groups of streams with similar characteristics so that data for each group are aggregated and extrapolated (Archfield and others, 2013; Arthington and others, 2006; Olden and others, 2011; Poff and others, 2010; Wagener and others, 2007). It is a key step described in EPA's "Biological assessment program review" (U.S. Environmental Protection Agency, 2013a), the EPA technical guidance for developing numeric nutrient criteria for streams (U.S. Environmental Protection Agency, 2000a) and the Ecological Limits of Hydrologic Alteration (ELOHA) framework for developing regional flow standards outlined in Poff and others (2010). Stream classification based on flow, geomorphology, or other attributes should not be confused with the definition of stream condition classes that may serve as the basis of tiered biological thresholds or effects levels [see Section 6.8]. Additionally, although stream classification offers

several benefits (Box D), it is not a requirement for successful development of quantitative flow targets (Kendy and others, 2012).

Box D. Fundamentals of Stream Classification

Stream classification is the grouping of multiple streams into a smaller number of classes on the basis of shared hydrologic, physical, chemical, and (or) biological attributes. Stream classification is a valuable tool for quantifying flow targets because (1) data from multiple streams are pooled for analysis, and (2) conclusions drawn for a given class are reasonably applied to all streams in that class. A general goal of stream classification is to systematically arrange streams of the study area into groups that are unique in key attributes for environmental flow research and management (for example, catchment size and temperature regime, as in example Scenario A described in Section 6.9). The process requires compiling observed and modeled data for the streams of interest, identifying metrics to serve as the basis of classification, and determining appropriate breakpoints for these metrics. Statistical methods such as correlation analysis, principal component analysis, regression, and cluster analysis are used to select metrics for classification and determine stream groupings. Important considerations include the types of data and attributes such as the number of classes, analytical methods, approaches to data gaps and uncertainty, and methods for evaluating results. As an example, a simple classification scheme may reflect the dependence of flow characteristics on catchment size and would require a database of stream drainage areas and the definition of drainage-area breakpoints for stream-size classes (for example—small, less than 50 square miles [mi^2]; medium, 50–100 mi^2; large, greater than 100 mi^2). A comprehensive review of stream classification to support environmental flow management is provided in Olden and others (2011) and Melles and others (2012). Example approaches are found in Seelbach and others (2006), Kennard and others (2010b), Kennen and others (2007), Reidy Liermann and others (2012), Melles and others (2012), and Archfield and others (2013).

6.3 Conduct Literature Review

A review of existing literature provides a foundation for understanding how the natural flow regime supports aquatic life and the biological effects of flow alteration in target streams. The literature review can include any published or unpublished journal articles, reports, presentations, and other documents that are relevant to the target streams. The literature review ideally should identify the most important aspects of flow regimes that are vital to support aquatic life and include both direct and indirect connections between flow variables and ecological response (Richter and others, 2006). Studies that characterize natural flow and biological conditions are valuable even if they do not specifically address flow alteration (Mims and Olden, 2012; McMullen and Lytle, 2012; Rolls and others, 2012). For example, studies of the historical and current biological condition of target streams, the physical and chemical conditions that support aquatic life, and the life-history strategies of aquatic species are all relevant for subsequent analysis steps. Literature reviews are aided by existing databases of flow-ecology literature for the region of interest (for example, McManamay and others, 2013, Southeast Aquatic Resources Partnership—Flow-ecology literature compilation, and The Nature Conservancy, 2015, ELOHA bibliography). Global-scale literature reviews, such as Bunn and Arthington (2002) or Poff and Zimmerman (2010), may also help to identify candidate sources of flow alteration, and the relevance of these potential effects are evaluated on the basis of local information.

The literature review can help to identify data gaps that could be filled through subsequent studies. It can provide a set of references for characterizing the types and sources of flow alteration in target streams. Past studies may provide detailed descriptions of observed flow modifications below dams and diversions or in urbanized catchments. Studies of observed and projected climate change may be reviewed, particularly those conducted at the state or regional scale. Information on climate-mediated changes in flow will be most valuable for subsequent steps; however, historical and projected trends in climate variables (precipitation, temperature, etc.) may be used to model flow regime changes for a state.

6.4 Develop Conceptual Models

The literature review is used to guide the development of one or more conceptual models that depict hypothesized relations between biological conditions and flow alteration in target streams. A conceptual model consists of a diagram and accompanying narrative describing hypothesized cause-and-effect relations. Poff and others (2010) recommend that these hypotheses focus on process-based relations between a particular flow-regime component and ecological change. The conceptual models, therefore, ideally depict how a specific change in a flow-regime component is believed to drive one or more biological responses. The pathways leading to indirect biological responses to flow alteration (that is, those mediated by habitat or water-quality change) are clearly depicted. Conceptual models developed as part of this process are therefore much more detailed than the general model presented in Section 4 (Figure 2).

The EPA Causal Analysis/Diagnosis Decision Information System (CADDIS) Web site includes a conceptual diagram of potential biological responses to several types of flow alteration (Figure 11) that may serve as a useful starting point for conceptual model development; other existing conceptual diagrams can be considered. Although this example does not include climate change as a source of flow alteration, climate effects on flow and biota can be conceptualized to more accurately reflect climate as a dynamic component of the ecosystem. Relations among climate, flow, and aquatic life might already be apparent from past studies, particularly if a state has undertaken a climate-change vulnerability assessment. (See Appendix B for additional discussion and examples of climate-change vulnerability and assessments.) Where information on climate change effects does not already exist, available climate, hydrologic, and biological literature may be synthesized to infer potential types of flow alteration and potential biological responses.

The conceptual models resulting from this step of the framework are used to guide subsequent analysis of flow targets, including the selection of biological and flow variables and analysis methods. In general, conceptual models created for flow target development contain a similar structure, but focus on stressors and

responses specific to the streams of study. Biological responses to flow-mediated changes in water chemistry and temperature can be included which are not explicitly depicted in Figure 11. A detailed conceptual model may also identify alternative pathways (that is, other than flow alteration) to a given biological response. This approach also facilitates identification of potential confounding variables for consideration in flow-ecology modeling. The topic of confounding variables is discussed further in Section 6.6.

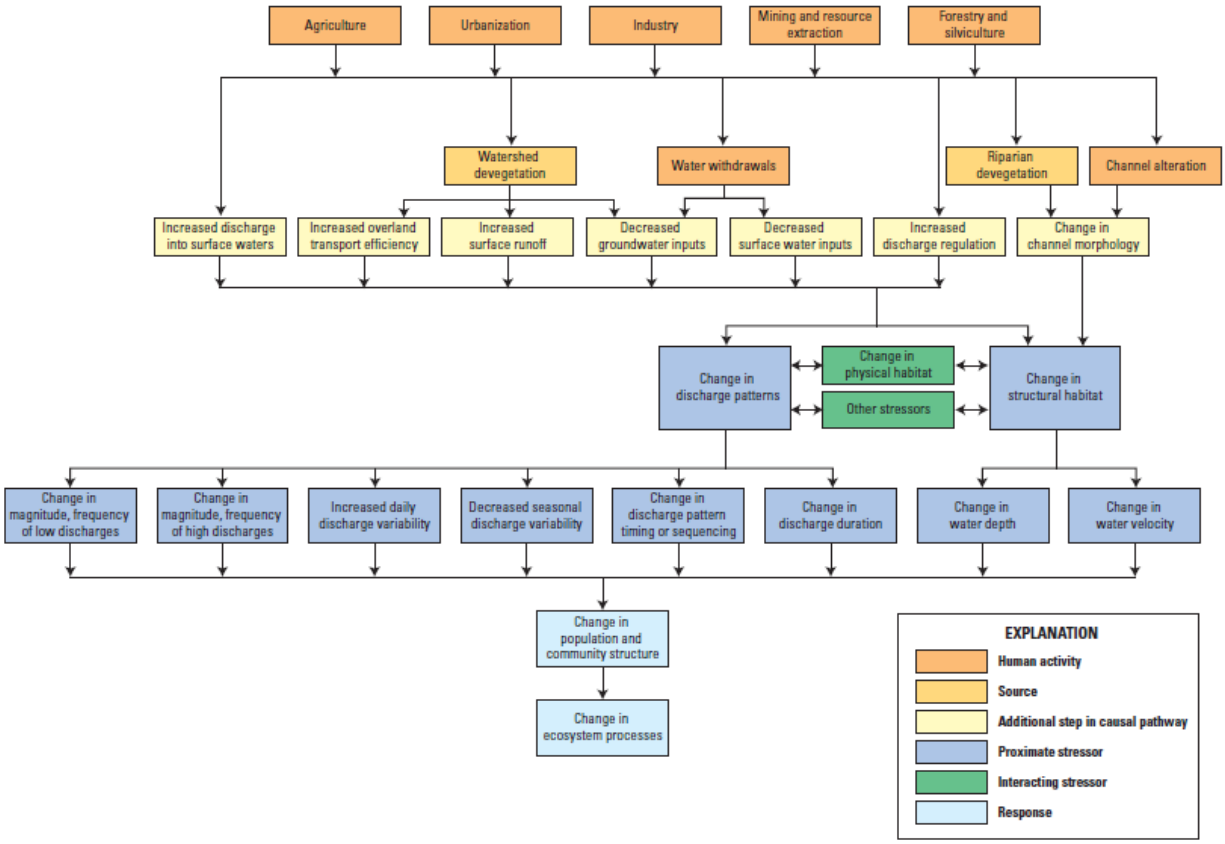


Figure 11. Example conceptual diagram illustrating the ecological effects of human-induced flow alteration from the U.S. Environmental Protection Agency Causal Analysis/Diagnosis Decision Information System (CADDIS).

(Modified from CADDIS Volume 2: Sources, Stressors and Responses, http://www3.epa.gov/caddis/ssr_flow4s.html).

6.5 Perform Data Inventory

Existing streamflow and ecological data from target streams ideally are compiled, inventoried, and reviewed for use in quantifying flow targets. Data quality objectives are determined and the data inventory may reveal that more data needs to be collected before proceeding. A common source of streamflow data is the USGS National Water Information System database (http://waterdata.usgs.gov/nwis), in which catchment attributes for many streams monitored by the USGS have been compiled in geographic information system (GIS) datasets (Falcone and others, 2010; Falcone, 2011). Existing mechanistic or statistical models of streamflow can provide continuous flow estimates, estimates of historical summary statistics, or estimates of flow under projected future climate scenarios (for example, Archfield and others, 2010; Holtschlag, 2009; Stuckey and others, 2012).

Potential sources of biological data include the EPA Wadeable Streams Assessment program (http://water.epa.gov/type/rsl/monitoring/streamsurvey/web_data.cfm), the USGS BioData retrieval system (https://aquatic.biodata.usgs.gov/landing.action), and databases maintained by the U.S. Forest Service, the Bureau of Land Management, the National Fish Habitat Partnership[5], or state agencies. Sampling methods, including the attributes measured, timing, equipment used, habitat type sampled, and taxonomic classification, are reviewed for each biological dataset. These and other sampling protocols are important for evaluating whether and how data from multiple sources are synthesized. A thorough discussion of potential data compatibility issues is provided in Cao and Hawkins (2011) and Maas-Hebner and others (2015).

The literature and data review will likely reveal information gaps that hinder the quantification of flow targets. Common issues include a lack of biological data for streams with long-term flow data or a lack of reference

[5] The National Fish Habitat Partnership data are available at http://www.tandfonline.com/doi/full/10.1080/03632415.2011.607075#.VPc9VGjF-4I. The fish data are available at .

biological or flow data with which to evaluate alteration. Depending on the scope of the effort, additional monitoring or modeling may be required to fill such gaps.

6.6 Identify Flow and Biological Indicators

Streamflow and biological indicators are specific measures that are used to analyze the relations between flow alteration and biological response (termed "flow-ecology" relations). Flow indicators correspond to "measures of exposure" in the EPA ERA framework, whereas biological indicators correspond to "measures of effect." Biological indicators reflect narrative flow criteria and can include various measures of the diversity, abundance, or specific life-history traits of fish, macroinvertebrates, mollusks and aquatic vegetation. Many flow indicators have been proposed to characterize the flow regime; these indicators describe the magnitude, timing, frequency, duration, and rate of change of various flow conditions. They are calculated from long-term daily flow datasets, and software tools are available to automate this process (for example, Henriksen and others, 2006; The Nature Conservancy, 2009; and the USGS EflowStats "R" package, which is available at https://github.com/USGS-R/EflowStats. Example flow and biological indicators that have been used in past studies of flow-ecology relations are listed in Table 2. These examples are only a small subset of the full universe of indicators that could be considered for a target-setting effort.

The biological indicators selected for analysis ideally are consistent with narrative flow criteria and the biological goals and assessment endpoints developed under Step 1 of this framework. Ideally, the biological indicators selected directly reflect the biological attributes of concern described by assessment endpoints (for example, fish diversity). In cases where assessment endpoints cannot be directly measured or have limited observational data for flow-ecology modeling, surrogate biological indicators are linked to assessment endpoints through additional analysis. For example, if an assessment endpoint involves a rare fish species with few monitoring records, a surrogate biological indicator is selected by identifying a data-rich species with

similar life-history traits. (See Merritt and others [2010] or Mims and Olden [2012, 2013] for examples of methods for grouping biota by life-history strategies.)

The flow and biological indicators selected for analysis should be consistent with the conceptual models developed as part of Step 4 of this framework. Biological indicators (that is, measures of effect) may include measurements along the scales of ecological organization, but they should be quantitatively related to survival, reproduction, or growth, as indicated in the general conceptual model presented in Figure 2. In most cases, the ability to analyze each and every hypothesized relation will be prohibited by data limitations and the project schedule and resources. Moreover, multiple flow indicators may be relevant to a particular relation. For example, analysis of a hypothesized relation between peak flow magnitude and fish-species diversity could use one of several peak-flow indicators (peak daily flow, peak 7-day flow, etc.). It may therefore be beneficial to establish a set of guidelines for flow indicator selection. Guidelines proposed in Apse and others (2008) include the use of flow indicators that are readily calculated, replicated, and communicated. Also recommended by Apse and others (2008) is the use of nonredundant flow indicators (that is, those that are not strongly correlated with one another). Olden and Poff (2003) and Gao and others (2009) describe the use of principal component analysis to identify nonredundant indicators and Archfield and others (2013) used a subset of fundamental daily streamflow statistics to capture the stochastic properties of the streamflow signal while minimizing the potential for redundancy. Other studies have addressed redundancy by investigating the correlation between pairs of potential flow indicators and discarding one indicator from highly correlated pairs (U.S. Army Corps of Engineers and others, 2013). The uncertainty associated with potential flow indicators and attempt to select indicators with low measurement uncertainty can be considered (Kennard and others, 2010a). Finally, identification of flow indicators that are most sensitive to sources of flow alteration can be attempted. For example, if climate change is considered to be an important source of flow alteration, available climate-vulnerability information to identify flow indicators that are

sensitive to observed and projected climate trends and that are amenable to management changes can be evaluated (See Appendix B for additional discussion of climate-change vulnerability).

Table 2. Example flow and biological indicators used to evaluate relations between streamflow characteristics and aquatic assemblage response.

Flow component	Flow indicators (measures of exposure)	Biological component	Biological indicators (measures of effect)	Reference
Magnitude	Mean June–July flow; Mean August flow	Fish	Fish density; Fish abundance	Peterson and Kwak (1999); Zorn and others (2008)
Magnitude	Spring maximum flow; Summer median flow	Fish	Fish abundance; Fish-assemblage composition	Freeman and others (2001)
Magnitude	Magnitude of 10-year low-flow event	Fish	Fish Index of Biotic Integrity; Fish-species richness	Freeman and Marcinek (2006)
Magnitude	Mean annual flow; Base-flow index	Macroinvertebrates	Macroinvertebrate abundance; Macroinvertebrate assemblage; composition	Kennen and others (2014); Castella and others (1995)
Magnitude	Maximum flow; Ratio of maximum to minimum flow	Macroinvertebrates	Macroinvertebrate Index of Biotic Integrity; Macroinvertebrate species richness	Morley and Karr (2002)
Magnitude	Magnitude of 1-, 2-, 5-, 10-, and 20-year flood events	Macroinvertebrates	Macroinvertebrate O/E (ratio between the observed and expected) scores; Macroinvertebrate-assemblage	Nichols and others (2006)

Flow component	Flow indicators (measures of exposure)	Biological component	Biological indicators (measures of effect)	Reference
			composition	
Magnitude	Summer diversion magnitude	Macroinvertebrates	Macroinvertebrate abundance	Wills and others (2006)
Timing	Date of annual maximum flow; Date of annual minimum flow	Fish	Fish abundance; Fish-assemblage composition	Koel and Sparks (2002)
Frequency	Number of days above mean annual flow; Number of events above 75% exceedance flow value	Macroinvertebrates	Macroinvertebrate Index of Biotic Integrity; Macroinvertebrate richness	Booth and others (2004); Kennen and others (2010)
Frequency	Number of flood events; Number of low-flow events	Riparian vegetation	Riparian tree abundance	Lytle and Merritt (2004)
Duration	Duration of high-flow events; Duration of low-flow events	Fish	Fish abundance; Fish-assemblage composition	Koel and Sparks (2002)
Rate of change	Mean rise rate; Mean fall rate	Fish	Fish abundance; Fish-assemblage composition	Koel and Sparks (2002)

6.7 Develop Qualitative or Quantitative Flow-Ecology Models

A flow-ecology model is a specific type of stressor-response model that describes the relation between a flow indicator and a biological indicator in absolute terms (for example, fish diversity as a function of annual peak flow magnitude) or relative to reference conditions (for example, the percent change in fish diversity as a function of the percent change in annual peak flow magnitude).

Guided by the conceptual model, quantitative flow-ecology models are developed by using statistical methods and used to predict the value of a biological indicator under a variety of flow conditions (Figure 12). Quantitative flow-ecology models take the form of linear or nonlinear regression equations, but other approaches, such as regression tree analysis or change point analysis, also are available. Their development is guided by a variety of exploratory data analysis techniques to characterize individual indicator datasets (their range, average, distribution, etc.), evaluate potential relations, and determine appropriate modeling methods. A thorough review of statistical methods to employ for stressor-response modeling is provided in the report "Using stressor-response relations to derive numeric nutrient criteria" (U.S. Environmental Protection Agency, 2010b). An example approach to flow-target development using quantitative modeling is described in Section 6.9 (see Table 3 and Figure 13).

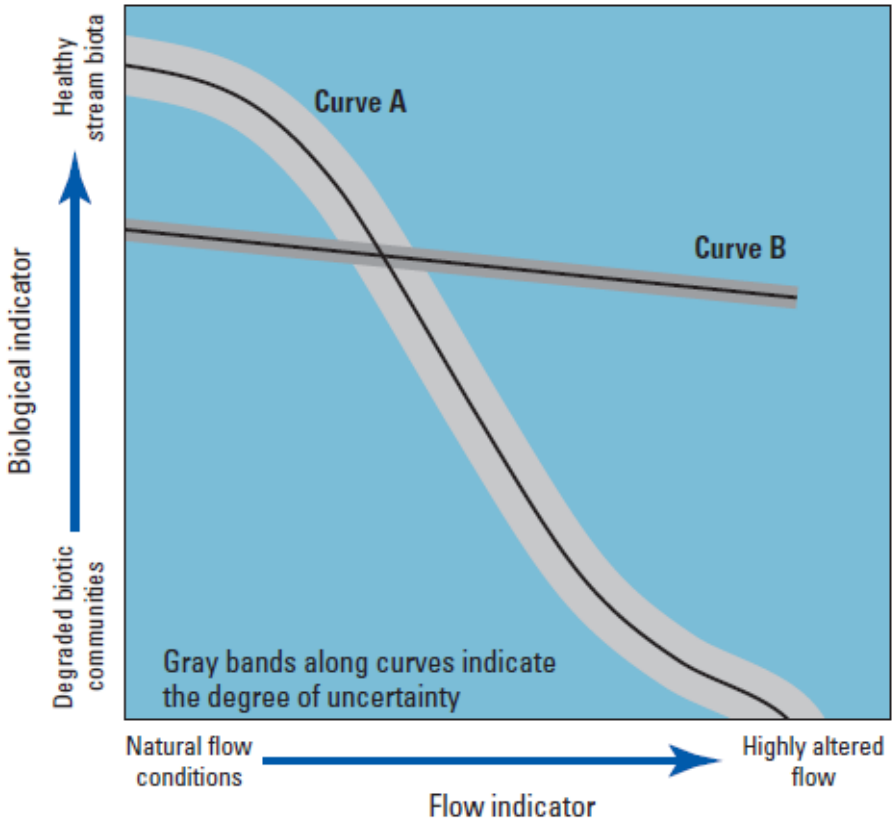


Figure 12. Example flow-ecology curves illustrating quantitative relations between flow and biological indicators.

(Quantitative models provide continuous predictions of biological responses to flow alteration. Curve A depicts a flow-ecology relation with higher sensitivity but greater uncertainty than those associated with Curve B.)

As introduced in Section 4.5, confounding variables are associated with alternative stressors and pathways (that is, other than flow alteration) to a given biological response. The presence of confounding variables at biological monitoring sites can limit the strength of causal inferences about the association between altered streamflow and biological indicators (U.S. Environmental Protection Agency, 2010b). Where feasible, confounding variables should be factored into the development of quantitative flow-ecology models. In practice, researchers have dealt with this issue by explicitly including possible confounding variables in

preliminary models (for example, Carlisle and others,. 2010), by using modeling approaches that implicitly assume the presence of other confounding factors (for example, Konrad and others, 2008; Kennen and others, 2010), or, at a minimum, acknowledging that potential confounding factors were not included in modeling efforts, but that other evidence indicates that their influence likely was minimal (for example, Merritt and Poff, 2010).

Available data may be insufficient to support quantitative flow-ecology modeling, or that data or analytical limitations result in quantitative relations with a low level of statistical significance. In such cases, qualitative flow-ecology modeling is a practical alternative. Qualitative modeling does not attempt to uncover precise numerical relations between flow and biological indicators. Rather, the objective is to describe relations between variables based on hypothesized cause-effect associations using any available evidence. Qualitative modeling can help identify the direction of flow-ecology relations, and possible thresholds for degraded conditions, in data-limited environments.

The conceptual models discussed in Sections 4.1 and 6.4 are examples of qualitative models; however, it may be useful to reformulate conceptual models in terms of the flow and biological indicators selected for analysis. Qualitative models can incorporate numerical flow alteration and biological response thresholds reported in relevant literature, and (or) available data on reference flow and biological conditions. Such models are sometimes referred to as semiquantitative because they include numeric values but, unlike quantitative models, do not allow for precise predictions across the full spectrum of flow alteration. Qualitative modeling can incorporate a set of decision rules for combining and weighting conclusions from existing studies that used inconsistent study designs and data (Webb and others, 2013). An example approach to flow-target development using qualitative modeling is described in Section 6.9 (see Table 3 and Figure 14).

6.8 Estimate Effects and Identify Acceptable Levels

After modeling flow-ecology relations, dividing lines between acceptable and unacceptable flow alteration to select numeric flow targets can be determined. Effects estimation can guide this process. In general, effects estimation involves estimating effects levels that correspond to increasing magnitudes of a stressor. Effects estimation can define the likelihood that biological goals will not be achieved given a certain magnitude of flow alteration. Effects estimates are categorical (low, medium, high) or numeric (the probability of not meeting a certain biological condition). Effects estimation integrates quantitative or qualitative flow-ecology models, biological goals, and other available evidence.

In cases where quantitative flow-ecology models are available, effects estimation may be centered on the numerical relations between flow and biological indicators and their uncertainty. For example, descriptive effects levels are assigned to incremental flow-indicator values on the basis of predicted effects on stream biota and the degree of uncertainty associated with those predictions (for example, narrative effects statements based on the Biological Condition Gradient [Davies and Jackson, 2006] may provide useful examples). When quantitative models are not available, effects estimates are generated from qualitative flow-ecology models, results of past observational studies, information on current and expected levels of flow alteration, and any other lines of evidence. For more detailed information on characterization and estimation, see, “Guidelines for Ecological Risk Assessment” (U.S. Environmental Protection Agency, 1998) and “Risk Characterization Handbook” (U.S. Environmental Protection Agency, 2000c).

Effects estimation can be guided by threshold values or range of biological indicators, concentration of the stressor magnitude response, etc. that correspond to attainment or non-attainment of biological goals. For some biological indicators, point thresholds may be readily apparent from past studies or known reference conditions, or may be defined by existing biological criteria (for example, Index of Biotic Integrity = 90).

Alternatively, available evidence may point to a range of biological-indicator values as a suitable threshold (for example, Index of Biotic Integrity between 80 and 90).

After generating effects estimates, numeric flow targets are determined by identifying acceptable levels toward attainment of biological goals. For example, if flow-indicator values are divided into high, medium, or low effects ranges, the decision to set the flow target to the high-medium effects breakpoint, the low-medium breakpoint, or some alternative level is made. The process of identifying acceptable effects levels offers an opportunity to further incorporate uncertainty (for example, uncertainty caused by natural temporal and spatial variability of biological and hydrologic processes, sampling, etc.) in flow-ecology models and is helpful for soliciting and incorporating feedback from stakeholders and the public. The utility of feedback received at this step will likely be maximized if stakeholders have been kept informed and involved throughout the completion of prior steps. Decisions on whether and how to act on suggested modifications to acceptable effects levels and proposed numeric flow targets are weighed according to the strength of scientific support for the change and implications for meeting biological goals.

After acceptable effects levels have been identified and flow targets have been quantified, planning for implementation is enhanced by several key activities. Peer review can be used to evaluate the strength of flow-target values and highlight areas for improvement. Targeted monitoring or modeling can support validation of the ability of flow targets to achieve desired goals. Finally, an adaptive management approach allows flow targets to be periodically evaluated and adjusted to ensure that the desired goals are achieved. The adaptive management approach is continually informed and updated by results of monitoring, research, and experimentation to address specific uncertainties. (See Richter and others [2003] and Konrad and others [2011] for specific examples.)

6.9 Example Applications of the Flow-Target Framework

Two hypothetical efforts to quantify flow targets to protect aquatic life (referred to as Scenario A and Scenario B) are described in Table 3. Each scenario represents one potential application of the framework discussed in this section to quantitatively translate the following narrative flow criterion: Changes to the natural flow regime shall not impair the ability of a stream to support characteristic fish populations. The two scenarios differ in their approach to several framework steps. These scenarios are not intended to convey recommended methods, but rather describe example approaches for each step and demonstrate the adaptability of the framework to project-specific goals and available resources.

Scenario A is a case in which a state incorporates existing numeric biological condition criteria and an ample hydrologic and biological dataset for quantitative flow-ecology modeling, in which the resulting flow-ecology curves are used as a focal point for estimating effects, identifying acceptable effects levels, and selecting numeric flow targets. In Step 1, biological goals and assessment endpoints are selected from state WQS, which define minimum acceptable values of fish Index of Biotic Integrity (IBI) scores for attaining designated uses. In Step 2, statewide stream classification is undertaken to assign stream segments to one of 10 classes on the basis of catchment size and temperature regime (cold headwater, warm large river, etc.). In Step 3, the literature review uncovers extensive evidence for the effect of summer base-flow depletion on fish diversity and abundance. Conceptual models are developed in Step 4 to demonstrate pathways between anthropogenic sources of summer base-flow depletion and effects on fish populations. Data compiled in Step 5 include fish-survey results, flow-monitoring records, and modeled streamflow data for ungaged stream segments. In Step 6, fish IBI score and the percent reduction in August median flow are determined to be appropriate indicators for flow-ecology modeling because they reflect biological goals and sufficient data are available for analysis. Regression modeling is undertaken in Step 7 by using paired biological and flow data to generate response curves that quantify relations between fish IBI score and reduced August median flow.

Separate response curves are developed for each of the 10 stream classes defined for the project so that selected targets are transferable between stream segments within each class. In Step 8, fish response curves are used to guide discussions with stakeholders to identify appropriate targets for August median flow that are consistent with meeting the IBI scores for attaining designated uses identified in Step 1.

In Scenario B, qualitative flow-ecology models are generated and integrated with other lines of evidence to identify a set of flow indicators that, if altered, present an unacceptable effect to aquatic communities. In Step 1, the state's WQS do not include biological criteria that establish assessment endpoints defining biological goals, so the state takes appropriate actions, and includes stakeholder input, to identify specific biological goals that are consistent with its designated aquatic life uses. This effort identifies specific fish species and functional groups that are key to ensuring attainment of the state's designated aquatic life uses and, in turn, establishes the goals for interpreting the state's narrative flow criteria. In Step 2, the decision is made to include all streams in the state in the effort and opt not to address stream classification until after the literature review of flow-ecology relations is complete. Literature reviewed in Step 3 demonstrates clear links between fish health and a broad range of flow components. Because documented relations are consistent across stream size and ecoregion, stream classification is not pursued. The conceptual models developed in Step 4 summarize known and hypothesized flow needs of fish, organized by fish species/functional group, season, and flow characteristic. Data compiled in Step 5 focus on streamflow, with long-term records used to calculate reference and affected values of more than 50 flow metrics to evaluate the sensitivity of each metric to anthropogenic sources of flow alteration. On the basis of this analysis and evidence for biological sensitivity, a subset of flow metrics is selected in Step 6. A lack of biological data is determined to prohibit quantitative flow-ecology modeling; therefore, qualitative modeling is undertaken in Step 7 to reframe conceptual models in terms of the subset of flow indicators identified during Step 6. In Step 8, participating agencies review available evidence to estimate effects associated with increasing levels of hydrologic change and, with public

input, use effects estimates to set targets that express the maximum allowable deviation from reference conditions for each flow indicator.

Although the examples in Scenarios A and B are largely hypothetical, components were drawn from real-world examples. Table 3 below provides an example where one indicator of many biological indicators and flow attributes is used to illustrate the potential relationship between stream flow processes and ecological response. Many more case studies of flow-target quantification can be found in Colorado Division of Water Resources and Colorado Water Conservation Board (2009), Cummins and others (2010), DePhilip and Moberg (2010), Kendy and others (2012), Kennen and others (2013), Richardson (2005), and Zorn and others (2008).

Table 3. Example applications of the framework to quantitatively translate the following narrative flow criterion: "Changes to the natural flow regime shall not impair the ability of a stream to support characteristic fish populations."

Framework Step	Scenario A: Quantitative Example	Scenario B: Qualitative Example
(1) Link narrative criteria to biological goals and assessment endpoints	Numeric biological goals are defined from existing biological condition criteria, expressed as minimum acceptable values of fish Index of Biotic Integrity (IBI) scores.	Narrative biological goals that are consistent with the designated aquatic life use are defined through interpretation of the narrative flow criterion with stakeholder input. Each biological goal identifies a specific fish species or functional group to protect. Example biological goal: to maintain the abundance of riffle obligate species.
(2) Define scope of action: identify target streams	Statewide stream classification is undertaken that builds on prior stream mapping and fish-ecology research. Individual stream segments are assigned to one of 10 stream classes according to catchment size and water-temperature regime, characteristics known to affect fish distributions. Example stream class: cold headwater.	All streams in the state are included in the effort to develop flow targets. As a result of data and resource constraints, the need for stream classification following the literature review is evaluated.
(3) Conduct literature review	Literature is reviewed to identify flow-regime changes that most affect the condition of fish communities. Relevant literature points to summer base-flow depletion as a factor in reduced fish diversity and abundance throughout the state.	Literature is reviewed to highlight flow-dependent life history and habitat traits of fish species/functional groups referenced in Step 1. Relevant literature demonstrates the importance of a wide range of flow conditions on the health of fish communities in the state, with consistent relations identified across stream size and ecoregion. On the basis of these findings, a systematic stream classification is not needed.

Framework Step	Scenario A: Quantitative Example	Scenario B: Qualitative Example
(4) Develop conceptual models	Conceptual models depict pathways between anthropogenic sources of summer base-flow depletion and effects on fish populations. Important relations include reduced food availability for both benthic and water-column taxa as a result of reduced wetted-channel perimeter and water depth.	Conceptual models summarize known and hypothesized flow needs of fish, organized by fish species/functional group, season, and flow characteristic.
(5) Conduct data inventory	A database of existing flow and fish-survey records is prepared. Observed data are augmented with predictions from previous hydrologic modeling efforts. Modeled data include reference and present-day values of median monthly streamflow for every stream segment in the state.	Long-term daily flow records, land-use information, and water-use data are compiled. Reference streams (those with minimal flow alteration) and affected streams are identified. Flow records for these sites are used to calculate reference and affected values of 50 or more flow metrics. The sensitivity of each flow metric to anthropogenic sources flow alteration is quantified by comparing reference and affected values.
(6) Identify flow and biological indicators to serve as measures of exposure and effect	Steps 6 and 7 are iterated to examine relationships between potential indicators and flow responses identified in Steps 3-5. Two indicators are selected for quantitative flow-ecology modeling: fish IBI score and the percent reduction in August median flow (relative to reference conditions).	A subset of the flow metrics quantified in Step 5 is selected for flow-target development. Metrics are evaluated according to their sensitivity to anthropogenic sources flow alteration and evidence of biological relevance. Flow indicators describe magnitude and frequency characteristics of high/flood flows, seasonal/average flows, and low/drought flows.
(7) Develop flow-ecology models	Regression modeling is undertaken by using monitoring and modeling data from sites with paired flow and biological data. Final models	Qualitative flow-ecology models are developed by reframing conceptual models in terms of the flow indicators selected in Step 6 (Figure 14).

Framework Step	Scenario A: Quantitative Example	Scenario B: Qualitative Example
	(termed "fish response curves"; see Figure 13) quantify the relation between fish IBI scores and reduced August median flow. Fish response curves are generated for each of the 10 stream classes defined in Step 2.	
(8) Estimate effects and identify acceptable levels	Fish response curves are shared with stakeholders to guide discussion of acceptable flow targets for each stream class that are consistent with meeting the fish IBI scores. Targets are expressed as a maximum allowable percentage reduction in August median flow by stream type.	Participating agencies review available evidence to estimate effects associated with increasing levels of hydrologic change. For some flow indicators, past studies indicate the likelihood of high effect of biological degradation under any magnitude of flow change. For others, healthy biotic communities are observed under moderate flow change and are determined to pose a lower effect if altered. This information is shared with stakeholders to further refine effects estimates and levels of flow alteration presenting unacceptable effects to stream biota. The outcome of these discussions is a set of targets expressing the maximum allowable deviation from reference conditions for each flow indicator that will protect the aquatic life use.
Follow-up and adaptive management	Participating agencies continue to collect flow and fish-community data. A plan is developed to assess flow targets every 5 years by analyzing new and historic data for evidence of their effectiveness.	Participating agencies continue to collect flow and fish-community data. A plan is developed to assess flow targets every 5 years by analyzing new and historic data for evidence of their effectiveness.

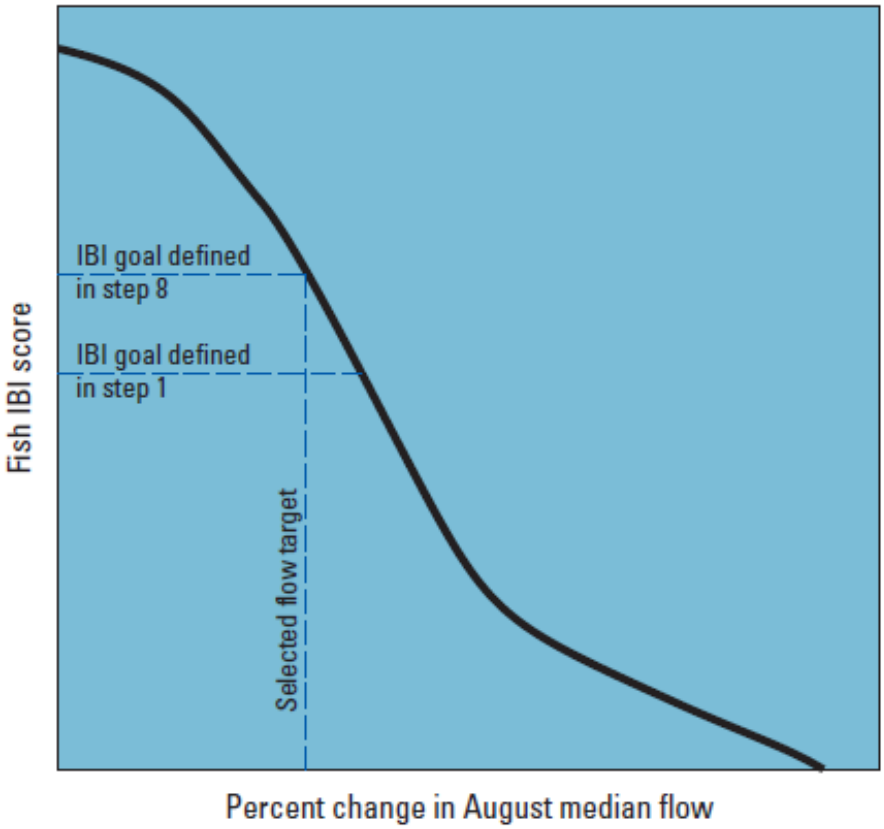


Figure 13. Example fish response curve from Scenario A generated through regression modeling.

(In this scenario, fish response curves depict the relation between altered August median flow and fish-community condition; IBI, Index of Biotic Integrity)

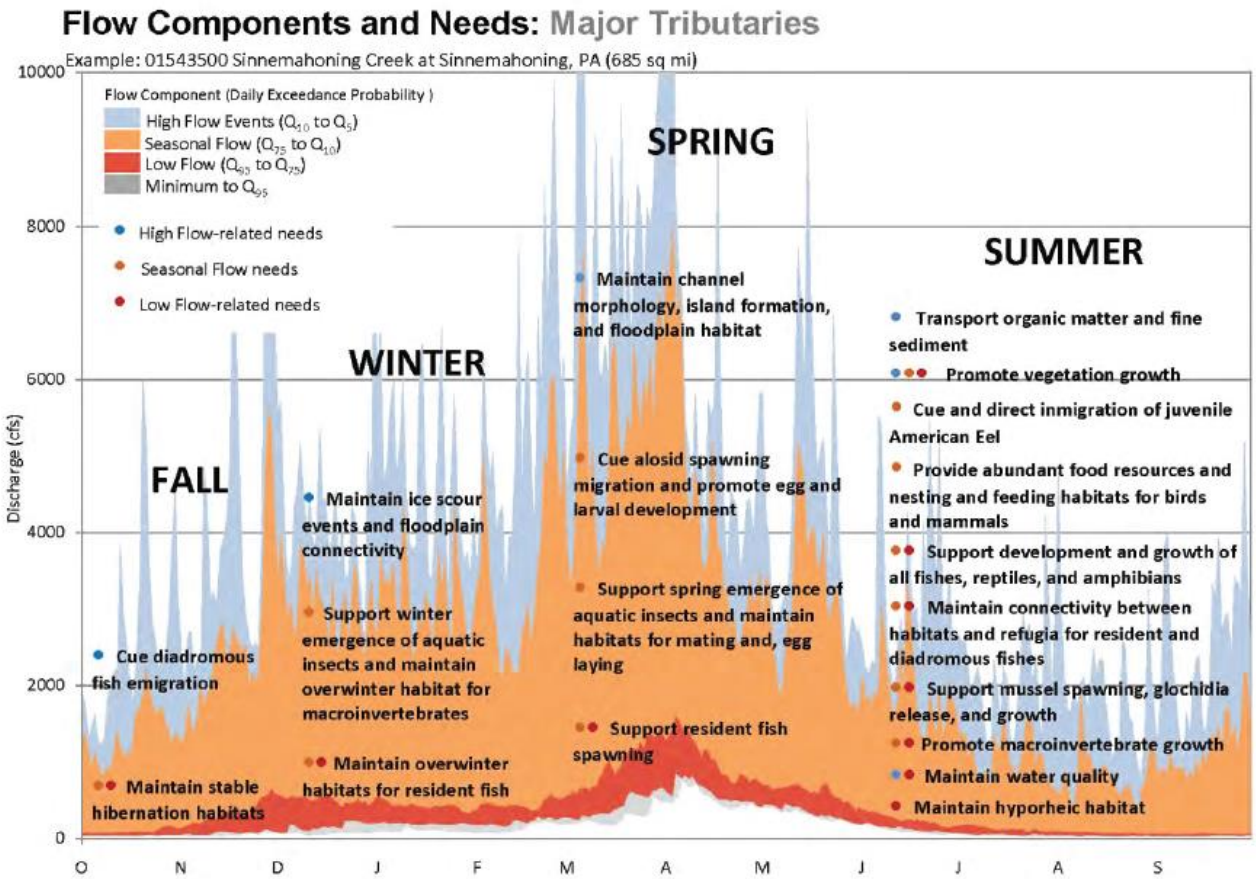


Figure 14. Conceptual diagram illustrating hypothesized flow needs of fish and other aquatic biota by season in major tributaries of the Susquehanna River Basin, northeastern United States.

(Example hydrograph shown is from U.S. Geological Survey station 01543500, Sinnemahoning Creek at Sinnemahoning, Pennsylvania [drainage basin 685 square miles]; as described in Scenario B, conceptual diagrams are used in conjunction with information on natural flow variability, flow alteration, and biological response thresholds to quantify candidate flow targets.) (From DePhilip and Moberg, 2010)

7 Conclusions

The flow regime plays a central role in supporting healthy aquatic ecosystems and the ecological services they provide to society. A stream's natural flow regime is determined by climate and other catchment- and reach-scale properties that affect hydrologic processes such as infiltration, groundwater recharge, or channel storage. Human activities can alter the flow regime by modifying streamflow-generation processes (for example, infiltration, overland flow, etc.), altering the physical properties of stream channels (for example, channelization), or through direct manipulation of surface water and groundwater (dams or water withdrawals). Climate change effects on patterns of water and energy inputs to streams may further exacerbate these effects of flow alteration on aquatic ecosystems.

Alterations to the natural flow regime can contribute to the degradation of biological communities by reducing habitat quality, extent, and connectivity and by failing to provide cues needed for aquatic species to complete their life cycles. Flow alteration can prevent water bodies from supporting aquatic life designated uses defined by state water-quality standards. This report was cooperatively developed to serve as a source of information for states, Tribes, and territories that may want to proactively protect aquatic life from the adverse effects of flow alteration. To that end, the report provides background information on the natural flow regime and potential effects of flow alteration on aquatic life, examples of states and Tribes with narrative criteria, a flexible, nonprescriptive framework to quantify targets for flow regime components that are protective of aquatic life, and Appendix A, which provides illustrative examples of CWA tools that states and Tribes have used to protect aquatic life from altered flow.

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Appendix A. Examples where States and Tribes have applied Clean Water Act (CWA) Tools to Protect Aquatic Life from Altered Flows or that Account for Variations in the Flow Regime

A.1 Monitoring, Assessing, and Identifying Waters Impaired as a Result of Flow Alteration

States ensure Water Quality Standards (WQS) are met through implementation of technology and water quality-based controls, monitoring to assess use attainment status, reporting on use attainment and identifying impaired waters, and implementing appropriate restoration measures where waters are impaired. Waters are classified and states report on their condition to support use attainment decisions under Sections 303(d) and 305(b). States use their monitoring and assessment programs to identify and report to the public those waters that have impairments from pollution, defined under the CWA as "the man-made or man-induced alteration of the chemical, physical, biological, and radiological integrity of water" (Section 502(19)), including the effects of altered flow regimes or hydromodification (U.S. Environmental Protection Agency, 1997, 2003, 2005, 2016). Attainment of designated uses is evaluated through monitoring and assessment of indicators that reflect state WQS, including narrative or numeric criteria, or evaluating other data or information (U.S. Environmental Protection Agency, 1991). Accurately identifying the impairment status of these waters allows states to engage stakeholders on appropriate restoration strategies. The state of the science for restoring waters impaired by hydrologic alteration has evolved considerably, including, for instance, dam re-operation and improved methods for surface- or groundwater withdrawals.

States can record and evaluate flow information even when routine monitoring cannot occur as a result of extreme (high or low) flow conditions. This evaluation could include analytical hydrologic tools such as the USGS StreamStats (a Web application that provides users with access to stream network tools for water-resources planning purposes: http://water.usgs.gov/osw/streamstats/) or qualitative visual observations of streams. Such data or information could be used for making attainment decisions. For instance, the absence of

water from a perennial stream could demonstrate that the aquatic life designated use is not being attained, and a state may conclude that the designated use is impaired. Texas provides an example: for each visit to nontidally influenced freshwater streams or rivers, the Texas Commission on Environmental Quality (TCEQ) monitoring procedures require that a "flow-severity" field (with a value of no flow, low flow, normal flow, flood flow, high flow, or dry) be recorded, even if it is not possible to quantitatively measure flow or conduct sampling during a visit (see Box E).

Box E. Procedures for Capturing Flow Information in the State of Texas

The publication "Surface water quality monitoring procedures, Volume 1: Physical and chemical monitoring methods" (Texas Commission on Environmental Quality [TCEQ], 2012) describes how Texas monitors all flow conditions and captures flow information in its State database. Parameter codes for data uploads to the U.S. Environmental Protection Agency (EPA) Storage and Retrieval Data Warehouse (STORET), a repository for water monitoring data, are provided for each type of data collected. In addition to describing methods for capturing quantitative flow information, the document describes how to capture qualitative flow information with the "flow-severity" field:

- "Record a flow-severity value for each visit to freshwater streams or rivers (nontidally influenced) and report the value to the TCEQ central office. Do not report flow severity for reservoirs, lakes, bays, or tidal streams. It should be recorded even if it was not possible to measure flow on a specific sampling visit. See the Surface water quality monitoring data management reference guide for detailed information on data reporting." (Texas Commission on Environmental Quality, 2013)
- "No numerical guidelines are associated with flow severity, an observational measurement that is highly dependent on the water body and the knowledge of monitoring personnel. It is a simple but useful piece of information when assessing water quality data. For example, a bacteria value of 10,000 with a flow severity of 1 would represent something entirely different than the same value with a flow severity of 5."

Table 3.2 of Texas Commission on Environmental Quality (2012) provides photographs of each "flow-severity" category and the following descriptions, which can be found at https://www.tceq.texas.gov/assets/public/comm_exec/pubs/rg/rg415/rg-415_chapter3.pdf (accessed February 4, 2016):

- "No Flow. When a flow severity of 1 is recorded for a sampling visit, record a flow value of 0 ft^3/s (using parameter code 00061) for that sampling visit. A flow severity of 1 describes situations where the stream has water visible in isolated pools. There should be no obvious shallow subsurface flow in sand or gravel beds between isolated pools. —No flow not only applies to streams with pools, but also to long reaches of streams that have water from bank to bank but no detectable flow."
- "Low Flow. When streamflow is considered low, record a flow-severity value of 2 for the visit, along with the corresponding flow measurement (parameter code 00061). In streams too shallow for a flow measurement where water movement is detected, record a value of < 0.10 ft3/s. In general, at low flow the stream would be characterized by flows that don't fill the normal stream channel. Water would not reach the base of both banks. Portions of the stream channel might be dry. Flow might be confined to one side of the stream channel."
- "Normal Flow. When streamflow is considered normal, record a flow severity value of 3 for the visit, along with the corresponding flow measurement (parameter code 00061). What is normal is highly dependent on the stream. Normality is characterized by flow that stays within the confines of the normal stream channel. Water generally reaches the base of each bank."
- "Flood Flow. Flow-severity values for high and flood flows have long been established by the EPA and are not sequential. Flood flow is reported as a flow severity of 4. Flood flows are those that leave the confines of the normal stream channel and move out onto the floodplain (either side of the stream)."

- “High Flow. High flows are reported as a flow severity of 5. High flow would be characterized by flows that leave the normal stream channel but stay within the stream banks.”
- “Dry. When the stream is dry, record a flow-severity value of 6 for the sampling visit. In this case the flow (parameter code 00061) is not reported, indicating that the stream is completely dry with no visible pools.”

An example of a reporting option that helps clearly delineate and address waters impaired as a result of streamflow alteration is described in Box F, which illustrates the use of Category 4F in Vermont.

Box F. Vermont Addresses Hydrologically Altered Waters

Vermont first adopted narrative criteria into its water quality standards (WQS) for Clean Water Act purposes for flow or hydrologic condition in 1973 (for full text, see http://www2.epa.gov/sites/production/files/2014-12/documents/vtwqs.pdf [accessed February 4, 2016] or Vt. Code R. 12 004 052, http://www.vtwaterquality.org/wrprules/wsmd_wqs.pdf [accessed February 4, 2016]). Although hydrologic alteration is listed under integrated reporting guidance as Category 4c (impairments due to pollution not requiring a Total Maximum Daily Load), Vermont does address flow-related exceedance of the WQS through the Vermont Priority Waters List. This list includes waters assessed as "altered" using the state's assessment methodology (Vermont Department of Environmental Conservation, 2014: http://www.vtwaterquality.org/mapp/docs/mp_assessmethod.pdf [accessed February 4, 2016]). Part F of the Priority Waters List is water bodies that do not support one or more designated uses as a result of alteration by flow regulation (primarily from hydroelectric facilities, other dam operations, or industrial, municipal, or snowmaking water withdrawals). This list includes a description of the problem, current status or control activity, and the projected year the water-body segment will come into compliance with WQS. Creating a new category for hydrologic alteration helps separate it from other causes of pollution effects that would be reported in Category 4.

A.2. Development of Total Maximum Daily Loads

A total maximum daily load (TMDL) is a calculation of the maximum amount of a pollutant that a water body can receive and still meet WQS, and an allocation of that load among the various sources of those pollutants. Quantity of flow and variation in flow regimes are important factors in the fate and transport of pollutants (for example, sediment, pathogens, and metals), and therefore flow is considered when calculating TMDLs. A common source of streamflow data is the USGS National Water Information System. Several EPA TMDL technical documents discuss the role of flow in the context of methods and models to develop loadings and

load and waste-load allocations. These include the EPA document on developing TMDLs based on the load-duration curve approach (U.S. Environmental Protection Agency, 2007) and the EPA protocol for developing sediment TMDLs (U.S. Environmental Protection Agency, 1999).

A.3 Consideration of Flow Alteration in Issuing 401 Certifications

Under CWA Section 401 states and authorized Tribes have the authority to grant, condition, or deny certification for a Federal permit or license (see CWA Section 401(a)(1)) to conduct any activity that may result in any discharge into navigable waters. Before issuing a CWA Section 401 certification, a state or Tribe would ensure that any discharge to navigable waters from the activity to be permitted or licensed will be consistent with, among other things, the state's WQS and any other appropriate requirement of state law (see CWA Section 401(d)).

Box G. 401 Certifications, Sufficient Flow, and Water Quality Standards

South Carolina Board of Health and Environmental Control Negotiates New Commitments for Recertification

In 2009, South Carolina denied a 401 certification of a hydroelectric project license renewal (involving 11 dams), stating, "[t]he Board finds that the WQ Certification does not provide sufficient flow to protect classified uses, the endangered shortnose sturgeon and adequate downstream flow….to provide reasonable assurance….that WQS will be met." As a result of that action, negotiations were held that resulted in an agreement in 2014 and granting of the 401 certification. The agreement conditions committed the energy company to operating its dams to improve conditions for the sturgeon, protect flow conditions during spawning periods, and provide periodic flood-plain inundation mimicking ecologically important natural floods and recessions.

A.4 Consideration of Flow Alteration in Issuing 404 Permits

CWA Section 404 regulates[6] discharge of dredged or fill material into waters of the United States, and some proposed projects may result in loss of the conditions necessary for survival of aquatic life, including, for example, lotic species (species that depend on flowing water for survival).

Examples of projects involving discharge of dredged or fill material that affect hydrology include the construction of new water withdrawal or storage systems (for example, reservoirs); valley fills and waste disposal areas for resource extraction; expansion of existing withdrawal or storage systems; diversions and construction of projects such as drinking-water or flood-control reservoirs, impoundments for energy generation, and fishing reservoirs or amenity ponds (an impoundment developed for recreation and (or) aesthetic purposes). Impoundments alter streamflows, and operation of dams to manage releases largely determines how closely downstream flows resemble the natural hydrograph.

Activities proposed for Section 404 permits (issued by the U.S. Army Corps of Engineers) are reviewed by resource agencies (Federal and state) and are subject to Section 401 certification. Permits issued by a state that has assumed the Section 404 program (as of 2015, only Michigan and New Jersey have approved Section 404 programs), or issued by a state or Tribe implementing a programmatic general permit issued by the U.S. Army Corps of Engineers, consider the potential effects of a project on attainment of WQS, including antidegradation requirements.

[6] The responsibility for administering and enforcing CWA Section 404 is shared by the U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency. For more information on these responsibilities, see http://www.epa.gov/cwa-404/laws-regulations-executive-orders and http://www.epa.gov/cwa-404/policy-and-guidance

A.5 Consideration of Flow Alteration in Issuing National Pollutant Discharge Elimination System (402) Permits

National Pollutant Discharge Elimination System (NPDES) permits are generally required for point-source discharges of pollutants. Many NPDES permits depend on streamflow data for pollutant discharge limit calculations. Permits issued under CWA Section 402 use critical low-flow values such as the 7Q10 (7-day, 10-year annual low-flow statistic) or regulated low flows to calculate a permittee's discharge limits so that permitted values will be protective of aquatic life under the most critical conditions. Many rivers and streams across the United States have experienced trends in low flows since the 1940s–with increases generally in the Northeast and Midwest, and decreases (streams carrying less water) in the Southeast and the Pacific Northwest (Figure 7). Permit writers use the most up-to-date critical low-flow information for the receiving water and, where historical flow data are no longer representative, use current low-flow data to calculate effluent permit limits to protect for the new critical low flow (see the EPA Water Quality Standards Handbook [U.S. Environmental Protection Agency, 1994, Chapter 5.2]).

Box H. Stormwater and West Virginia Department of Environmental Protection Municipal Separate Storm Sewer Systems (MS4) Permit Language

The West Virginia Department of Environmental Protection issued a small MS4 permit including the language below for new and redevelopment projects to reduce effects from stormwater runoff at permitted sites:

"Performance Standards. The permittee must implement and enforce via ordinance and/or other enforceable mechanism(s) the following requirements for new and redevelopment: [....]"

"Site design standards for all new and redevelopment that require, in combination or alone, management measures that keep and manage on site the first one inch of rainfall from a 24-hour storm preceded by 48 hours of no measurable precipitation. Runoff volume reduction is achieved by canopy interception, soil amendments, evaporation, rainfall harvesting, engineered infiltration, extended filtration, and/or evapotranspiration and any combination of the aforementioned practices. This first one inch of rainfall must be 100% managed with no discharge to surface waters."

For a full compendium of this and other examples, see U.S. Environmental Protection Agency (2014c).

For additional examples of stormwater-related permits and their analysis, see U.S. Environmental Protection Agency (2012b).

A.6 Further Considerations

The discussion above is not meant to be a comprehensive assessment of all CWA tools that may address flow and the protection of aquatic life uses. In addition to the approaches mentioned above, other non-CWA mechanisms exist that may protect aquatic ecosystems from alteration of flow. Although many of these programs may provide a method to specifically address these altered-flow effects, others may lack specified frameworks and (or) established methods to quantify targets to address the impacts of flow on aquatic life

uses, allowing room for supplemental considerations or the application of methods considered the “best available science.”

Appendix B. Climate-Change Vulnerability and the Flow Regime

Climate change is one category of stressors among many (see Section 4.3) that increase the vulnerability of rivers and streams to flow alteration and affect the ecosystem services they provide. Changes in global temperature and shifts in precipitation are superimposed on local stressors such as water contamination, habitat degradation, exotic species, and flow modification (Dudgeon and others, 2006). Given the challenges posed by climate change, many natural-resource management agencies likely will find protecting and restoring the health of aquatic ecosystems increasingly challenging. For example, projected changes in temperature and precipitation due to climate change are expected to increase the departures from historic conditions. This means that using the past envelope of variability as a guide for the future is no longer a reliable assumption in water-resources management (Milly and others, 2008). Observed streamflow trends since about 1940 indicate regional changes in low flows, high flows, and timing of winter/spring runoff (U.S. Environmental Protection Agency, 2014b). However, there is much uncertainty about the future effect of climatically driven changes on streamflow. Even though knowledge of national and regional climate-change effects are useful at a coarse scale, water scientists need to move from generalizations of climate-change effects to more regional and (or) place-based effects to develop approaches relevant to the scale of management (Palmer and others, 2009). Global, national, and regional effects are described comprehensively elsewhere (Intergovernmental Panel on Climate Change, 2007; Field and others, 2014; Georgakakos and others, 2014; Karl and others, 2009).

Resilience is the ability of a system to recover after disturbance and the capacity of that system to maintain its functions in spite of the disturbance (Turner and others, 2003; Walker and others, 2004). Restoring or maintaining a natural flow regime can increase system resilience to climate-change effects and help avoid or reduce intensification of historical stresses (Beechie and others, 2013; Palmer and others, 2008, 2009; Pittock

and Finlayson, 2011; Poff and others, 2012). Therefore, defining and protecting environmental flows is not only a way to protect and restore rivers and streams from anthropogenic stressors, but it may also be a means of adapting to climate-change.

Not all rivers and streams are equally vulnerable to the effects of climate change. An assessment of climate-change vulnerability can help identify locations and hydrologic and ecological attributes that are most vulnerable to altered climate conditions. A climate-change vulnerability assessment, at a minimum, will supply specific information on the type of climate change expected across the assessed area. Depending on the scope of the effort, a climate-change vulnerability assessment may also translate projected changes in climate into effects on flow and (or) aquatic biota. This information is valuable for planning and implementation of Clean Water Act program strategies to support the resilience of aquatic life to a changing climate. Furthermore, flow and biological projections are incorporated into efforts to quantify flow targets that are protective of aquatic life under both historic and projected future climate conditions.

Approaches for assessing climate-change vulnerability are evolving and becoming more robust (Dawson and others, 2011). This appendix describes the components of vulnerability (Box I) and presents two examples from studies in California (Box J) and the Pacific Northwest (Box K) that illustrate the ways in which regional climate-change effects are being incorporated into vulnerability studies of the flow regime and the potential resulting effects on aquatic life (Box J).

Box I. Components of Climate-Change Vulnerability

The paragraphs that follow briefly describe the primary components of climate-change vulnerability that may be included in climate vulnerability assessments: exposure, sensitivity, and adaptive capacity. An in-depth discussion of these components is available in Glick and others (2011) and Poff and others (2012). Generalized case examples available in Glick and others (2011) demonstrate assessment approaches for climate vulnerability assessments across various ecosystems and species, both aquatic and terrestrial. Examples that focus on watershed vulnerability and aquatic resources are included in Furniss and others (2013). An additional resource (U.S. Environmental Protection Agency, 2014a) is a workbook for organizations managing environmental resources that provides a two-part process to carry out vulnerability assessments and develop effects-based adaptation plans for strategic climate-change plans.

Exposure: Exposure generally refers to the character, magnitude, and rate of climatic changes (Glick and others, 2011). Results of climate model simulations such as regional climate projections or downscaled climate projections, though accompanied by uncertainty, can help to estimate the range and location of potential climate change. Identifying sources of increased past variability may also be helpful (for example, paleoclimate records of tree-rings). Those changes that are ecologically significant (for example, those that affect an assessment endpoint) are considered as exposure metrics (for example, snowpack vulnerability, winter water temperature, aridity index, monthly precipitation, winter peak flows, freeze and thaw days, etc.) Additional examples of exposure metrics used in case studies are given in Furniss and others (2013).

Sensitivity: Climate sensitivity is the degree to which a system, habitat, or species is (or is likely to be) altered by or responsive to a given amount of climate change (in this case, climate-induced hydrologic changes in particular) (Glick and others, 2011). Sensitivity factors can include intrinsic attributes of a watershed, aquatic ecosystem, or organism, as well as the existing condition owing to anthropogenic factors. For example, the hydrology in a snowmelt-dominated watershed (and the ecosystem that is adapted to this hydrologic regime)

may be more sensitive to climate changes that reduce the proportion of precipitation from snow than that in a rainfall-dominated watershed (see the Beechie and others [2013] example in Box K). Many of the intrinsic attributes at the landscape level (for example, geology, soil, topography) affect the sensitivity of the aquatic ecosystem to any stressor. For example, the rate at which shifts in stream temperature can occur is driven by variables such as stream slope and interannual variability—so the rate at which temperature gradients shift are variable, even within a given basin, and statistically significant signals may not be detected for decades (Isaak and Reiman, 2013). The intrinsic factors that affect sensitivity at the population scale may include environmental tolerance range (for example, thermal tolerances), mobility, genetic adaptation, and range or population size.

Adaptive Capacity: Adaptive capacity is the ability of a species or system to cope with or adjust to climate-change effects with minimal disruption (Glick and others, 2011). It is also a subset of system resilience and can help managers assess vulnerability for use in decision making. Ecosystems and aquatic organisms can cope with climate change in different ways; for example, they may migrate, shift to more suitable microhabitats, or persist in place (for example, phenotypic plasticity) (Dawson and others, 2011). On a landscape scale, some vulnerability assessment approaches include landscape/river connectivity under this component. Many adaptive capacity factors may be those pre-existing conditions that future management conditions can address (for example, reducing fragmentation of a water body, thereby preventing mobility to more suitable conditions, such as cooler temperatures) (Glick and others, 2011). The Pacific Northwest salmon restoration case study (Box K) provides some examples of restoration practices Beechie and others (2013) identified as adaptive activities that may ameliorate some of the expected climate changes and increase habitat diversity and salmon population resilience.

Box J. California's Climate-Change Vulnerability Index

The goal of the California Integrated Assessment of Watershed Health (U.S. Environmental Protection Agency, 2013b) was to identify and better protect healthy watersheds by integrating data and making them available to planning agencies for improved coordination of monitoring and prioritization of protection efforts. The primary partners included the U.S. Environmental Protection Agency (EPA) and the Healthy Streams Partnership (HSP), an interagency workgroup of the California Water Monitoring Council. The assessment partners identified and integrated 23 indicators of watershed health, stream condition, and watershed vulnerability to characterize relative watershed health and vulnerability across California. The indicators used in this assessment reflect the reality that multiple ecological attributes and anthropogenic effects play a role in watershed and stream health, and need to be considered together.

The integrated watershed vulnerability index used in the assessment of watershed health is a composite of four vulnerability indices that may change from 2010 to 2050 (land cover, wildfire severity, water use, and climate change). The composite climate-change vulnerability index, in turn, is composed of seven component metrics of estimated climate-change parameters using projections from Cal-Adapt, a collaboration of several institutions that modeled downscaled hydrologic response across California by using temperature and precipitation projections produced from global general circulation models (GCMs). The interagency partners used the modeled outputs to evaluate the relative response of watersheds in California to future climate change, but the models did not explicitly simulate effects on ecosystem health or watershed processes (although they are certainly related to the modeled inputs), nor was the sensitivity of those watersheds to such changes a focus of this screening-level assessment. Rather, the vulnerability index is meant to be assessed with the composite indices of stream health and watershed condition to help prioritize protection opportunities.

The HSP used annual precipitation, mean base flow, mean surface runoff, and snowpack (as snow water equivalent) as the hydrologic responses to projected climate change because they were identified as the primary indicators affecting stream hydrology. It also identified annual temperature maximum, minimum, and mean as climate variables that may affect future watershed vulnerability. The interagency partners calculated the percent difference between projected values of these indicators (that is, component metrics of exposure) from 2050 and 2010.

The composite results of the vulnerability assessment (Figure B-1) illustrate the climate exposure primarily in terms of its effects on temperature and hydrology-related parameters in this example. Overall, the climate vulnerability component of this assessment identified the greatest vulnerability for northern California as a result of a combination of expected temperature increases and changes in snowpack, surface runoff, and base flow.

This screening-level assessment is an instructive example that may help inform the protection of healthy watersheds based on climate-change vulnerability. However, the assessment combined other vulnerability indices—land cover, water use, and fire-regime class (which can affect surface erosion, sediment deposition, and stream temperature)—with climate change as characteristics that could modify (exacerbate or ameliorate) overall vulnerability. Additionally, this assessment not only sought to develop priorities based on ecosystem vulnerability, but also a comprehensive understanding of the overall status of the aquatic ecosystem. For the entire assessment, stream condition, watershed health, and vulnerability were considered.

For more information, see U.S. Environmental Protection Agency (2013b) (http://www.epa.gov/sites/production/files/2015-11/documents/ca_hw_report_111213_0.pdf).

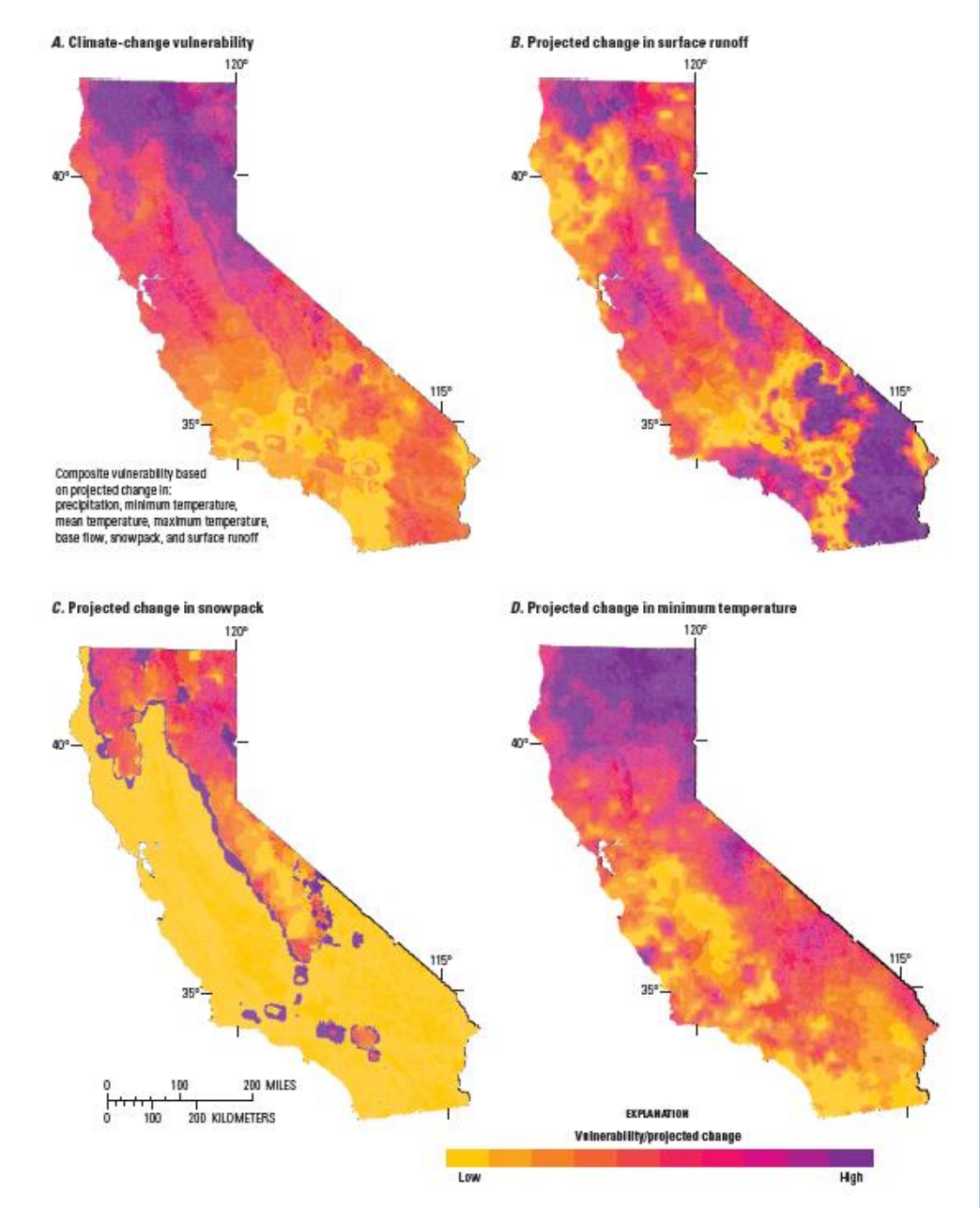

Figure B-1. (a) Composite results of the vulnerability assessment illustrating the combined changes in the seven component metrics of projected climate-change parameters, three of which are shown: (b) surface runoff, (c) minimum temperature, and (d) snowpack. (Additional component metrics including projected change in precipitation, mean temperature, maximum temperature, and base flow are shown in U.S. Environmental Protection Agency [2013b], available at http://water.epa.gov/polwaste/nps/watershed/integrative_assessments.cfm.)

Box K. Addressing Regional Climate-Change Effects on Salmon Habitat in the Pacific Northwest: Examples for Prioritizing Restoration Activities

Salmon habitat restoration is a prominent issue in the Pacific Northwest; however, a need exists to better understand whether current restoration activities and priorities will be effective under future climate conditions. Beechie and others (2013) sought to address this issue by providing insight into ways in which a restoration plan might be altered under various climate-change scenarios.

The authors developed a decision support system to adapt salmon recovery plans to address climate-mediated stream temperature and flow changes in order to both ameliorate climate effects and increase salmon resilience. To guide the effort, the researchers mapped scenarios of future stream temperature and flow and performed a literature review of current restoration practices.

The authors modeled stream temperature and flow from a multimodel average of daily gridded precipitation and air temperature. By using the variable infiltration capacity (VIC) model, the inputs were used to predict daily runoff, runoff routing, and stream temperature and flow. (Additional information on the specifics of the development of these parameters is found in Beechie and others [2013].) The scenario mapping exercise compared historical baseline (1970–99) water temperature and flow conditions to those projected for the periods 2000–29, 2030–69, and 2070–99. The researchers modeled mean monthly flows, calculating the change in magnitude and timing of maximum monthly flows between the future period and the historical baseline for each stream cell. They modeled and mapped stream temperature directly. The results indicated lower summer flows (35–75 percent lower), higher monthly maximum flows (10–60 percent higher), and higher air and stream temperatures (maximum weekly mean temperature 2–6 ºC [degrees Celsius] higher). Snowmelt-dominated hydrologic regimes across the region almost entirely disappeared by the 2070–99 time period, and transitional (rain-snow mix) hydrologic regimes contracted substantially as well. By the final 2070–

99 time period, most of the region was characterized by a rainfall-dominated hydrologic regime. The authors compared the projected stream-temperature changes to the known thermal thresholds and seasonal flows needed during different salmonid life stages (Figure B-2).

Beechie and others (2013) carried out a literature review to identify restoration practices that could ameliorate expected changes in streamflow (base-flow decrease and peak-flow increase) and stream temperature, and increase habitat diversity and population resilience. The primary activities most likely to do so include restoring flood-plain connectivity, restoring streamflow regimes, and reaggrading incised stream channels.

This Pacific Northwest salmonid restoration example combines projected climate-exposure information and known ecological sensitivities of salmonid species to improve understanding of potential vulnerability to climate change. This knowledge can help inform management plans to prioritize restoration practices that are more likely to be effective under projected climate scenarios.

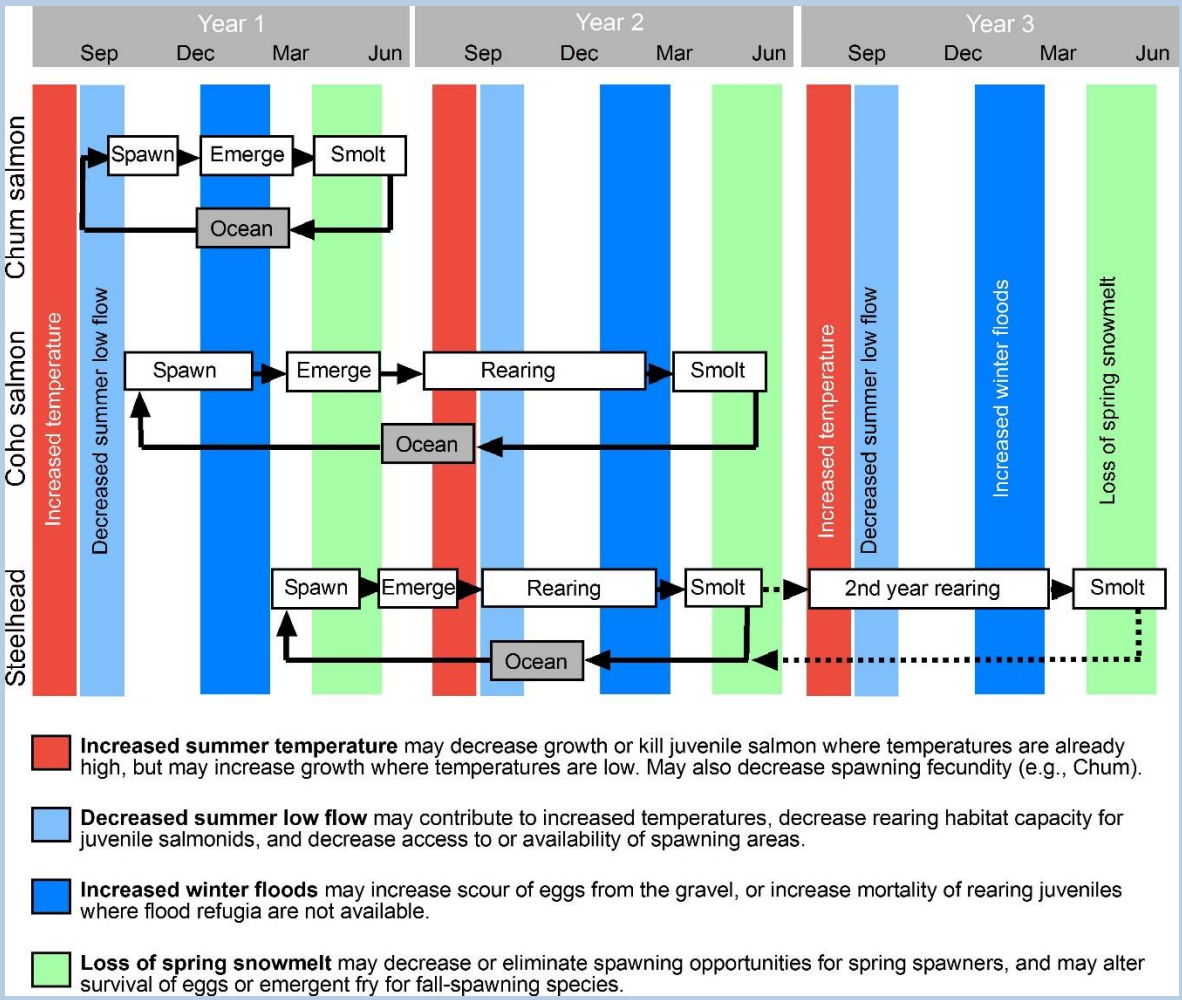

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Figure B- 2. Diagram showing effect of climate change on life stages of salmonids through time, by season. (Modified from Beechie and others, 2013; white rectangles represent the freshwater life-history stage of salmonids, gray boxes represent the ocean stage, and stippled lines indicate an alternate life-history)

The science of incorporating climate change into environmental flow assessments is young and complex. Considerations for incorporating climate change into the framework for developing flow targets to protect aquatic life discussed in Section 6 and illustrated in Figure 10 are presented above. This information can help identify which ecologically significant flow indicators may be most affected by climate change (as determined from the observed trends and projections). These examples can help elucidate relative climate effects (that is, vulnerability) related to flow targets and the aquatic life uses they are designed to protect. States and Tribes

can more effectively prioritize limited resources and identify new management actions more strategically to increase aquatic-ecosystem resilience. This framework is meant to be a qualitative assessment to rank relative effects, which may help in identifying and ranking adaptive management actions in later steps. In a resource-constrained environment, managers also need to evaluate the importance of projected climate change on key hydrologic variables compared to that of hydrologic alteration from other anthropogenic sources. The ranking of effects below can assist in this process to optimize management of limited resources.

Table B1. Incorporating climate-change considerations into the framework for quantifying flow targets.

Framework component	Potential climate-change considerations
(1) Formally link narrative criteria to biological goals	May not be applicable to Step 1 unless climate changes affect biological expectations.
(2) Identify target streams	Consider which elements, if any, in the classification of target streams are climate dependent.
(3) Conduct literature review	Consider all potential climate-change-related effects that could eventually threaten the target streams. Identify available climate-change reports relevant to the region or state water resources. Identify potential changes in ecologically relevant flow components from both observed trends and projected changes. It may be helpful to create broad categories of effects and list specific stressors by type for consideration in conceptual model development.
(4) Develop conceptual models	Include climate change in development of conceptual models. Consider how climate-related stressors can affect biological goals from various pathways, building on the findings obtained from the literature review. The level of detail should be commensurate with the level of detail for planning or screening.
(5) Inventory data	Identify which of the available observed hydrologic, climatic, and biological data may be affected by climate-related stress identified in preceding steps. Consider observed data/projected information to identify the already or potentially affected biological indicators and (or) flow indicators/flow-regime components. Rate them considering the following qualitative categories: **consequences (low, medium, high); likelihood (low, medium, high); spatial extent (site, watershed, region); time until problem begins (decades, within next 15 to 30 years, already occurring/likely occurring**). Consider sensitivity: Do some characteristics of the catchment increase or decrease sensitivity to these climate stressors (for example, north-facing aspect or high elevations may reduce sensitivity of snowmelt or water temperature to increased air temperature, whereas south-facing aspect or low elevations may increase sensitivity).

Framework component	Potential climate-change considerations
(6) Identify biological and flow indicators	Identify which biological and flow indicators may be most affected by climate change. Rate them by considering the qualitative categories previously mentioned (consequence, likelihood, spatial extent, time until problem begins).
(7) Develop qualitative or quantitative flow-ecology models	Climate change considerations may not be applicable to Step 7.
(8) Identify acceptable biological condition goals/effects levels	Compare range of potential likely climate changes to the potential flow targets.
(9) Select candidate flow targets	Compare range of potential likely changes to the actual selected flow target. Identify management adaptation actions and determine which of them are most appropriate given the likely effect to flow targets/biological goals.
(10) Monitor, evaluate, and periodically refine flow targets	Assess observed climate and hydrologic data for any emerging climate-change related trends in variability of magnitude, frequency, duration, timing, and rate of change of flow. Identify and assess new or updated climate-change projections. Are the updated projections consistent with observed trends and (or) other existing projected information? How are the updated projections ecologically significant? Do the updated climate change projections merit reassessment of acceptable effects levels and the ability to meet environmental flow targets under current management practices?

As discussed in this appendix, climate change may challenge the management of aquatic resources because past variability is no longer a reliable assumption for the future. However, protection of environmental flows can serve as an adaptation tool, increasing resilience so that a system is more likely to recover from the effects

of climate change. Climate-change vulnerability assessments can help managers strategically address water-resource protection in spite of uncertainty. Climate-change vulnerability assessment approaches are highly diverse; the two presented here illustrate only two of the many possible approaches. The California example (Box J) describes a screening-level assessment in which climate-change exposure is the focus, whereas the Pacific Northwest example (Box K) additionally accounts for potential effects of climate exposure on assessment endpoints, in large part on the basis of the sensitivity of the biota and their life stages. The information developed during a climate-change vulnerability assessment can help managers identify differential effects to aquatic resources and understand the reasons that their resources are at risk so they can set priorities and develop appropriate management responses.

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