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Environmental Flows: a Concept for Addressing Effects of River Alterations and Climate Change in the Andes

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Rivers are dynamic systems and many facets of a river's flow regime—magnitude, timing, frequency, duration, and rate of change—influence the structure and function of aquatic and riparian ecosystems (Poff et al. 1997). Flow shapes physical habitat and biotic composition in rivers; life history strategies of aquatic species have evolved in response to natural flow variability (Bunn and Arthington 2002). On a global scale, flow alterations present a serious and extensive threat to the integrity of aquatic ecosystems and the persistence of freshwater species. Over half of the world's major river systems are presently affected by flow regulation (Nilsson et al. 2005), and climate change is predicted to further modify historical flow patterns in many rivers. The impacts of river alterations manifest themselves in the imperilment of aquatic biota, particularly migratory species (Pringle et al. 2000; Bunn and Arthington 2002; Xenopoulos et al. 2005), and in the reduced ability of rivers to provide valued ecosystem services—sources of water and food, recreation, waste assimilation, flood control (see Anderson et al. Chapter 1, this volume)—upon which humans depend (Postel and Richter 2003; Millennium Ecosystem Assessment 2005).

A response to extensive river alteration in many countries has been an evolving movement to recognize flow needs of ecosystems and allocate freshwater accordingly through determination of environmental flows (Naiman et al. 2002; Tharme 2003; Poff et al. 2010). An environmental flow is a management concept that aims to establish the flow regime needed to sustain ecosystems and the amount of water available for off-channel human uses or storage in reservoirs at different times of the year. To date, the concept has been primarily applied to temperate rivers (e.g., the U.S., South Africa, Australia, Europe), or in tropical countries where water laws and policies recognize the necessity of maintaining specific flow regimes to sustain ecosystems (Tharme 2003). New water laws and policies in some tropical regions (e.g., East Africa) make explicit mention of preserving flows to sustain ecosystems.

Until recently, tropical Andean countries have not applied the concept of environmental flow in management, even though Andean rivers harbor important reserves of freshwater biodiversity and are increasingly subject to flow alterations. Water withdrawals for agriculture and urban populations already substantially affect flow, and hydropower projects impound many Andean rivers (Harden 2006; Buytaert et al. 2006). To address future demands for water and energy of expanding human populations, networks of new dams and water withdrawal projects have been proposed for construction in the next decades (CONELEC 2007; Pelaez-Samaniego et al. 2007). Climate change projections for the Andes also predict substantial flow alterations, with implications for both water supply and freshwater ecosystem integrity (Bradley et al. 2006; Vuille et al. 2008).

A considerable challenge facing Andean countries is finding a way to satisfy growing human demands for water and energy without compromising the biodiversity and ecological function of riverine ecosystems. Given the current pace and intensity of river alterations, there is an urgent need to develop environmental flow management standards that sustain ecosystems, can be effectively applied within a regional context, and that can be adapted to future climate change scenarios. This chapter reviews the concept of environmental flows, discusses regional trends in river alteration and their ecological implications, and outlines research needs for flow management in four Andean countries: Colombia, Ecuador, Perú, and Bolivia.

Environmental Flows: Balancing Water Needs of Humans and Ecosystems

The term environmental flow refers to the quantity, quality, and timing of water flow needed to sustain ecosystems and the services they provide to humans (Dyson et al. 2003; Poff et al. 2010). A distinction should be made between the natural flow regime of a river that would maintain ecosystems in a pristine state and an environmental flow. An environmental flow has the goal of allocating sufficient water to ecosystems to maintain a certain level of ecological integrity based on an appropriate management vision. Environmental flow standards can be restrictive management thresholds—designed to limit water withdrawals—or active management thresholds—designed to control flow releases downstream from dams (Poff et al. 2010).

Since the concept emerged in the mid-20th century, more than 200 methods for estimating environmental flows have been developed globally. These methods can be classified into four approaches (Table 23.1; Tharme 2003). *Hydrology-based methodologies* use historical discharge records to make environmental flow recommendations, usually expressed as a fixed proportion of flow intended to sustain river health (e.g., 10% of average annual discharge). *Hydraulic-rating methodologies* rely on basic hydraulic parameters (e.g., depth, wetted perimeter) that relate to habitat for aquatic biota; environmental flow recommendations are made by plotting acceptable levels of reduction in these parameters against discharge. Hydraulic-rating methodologies preceded more sophisticated *habitat simulation methodologies*, that employ hydrological,

Table 23.1. Examples of common methodologies used to determine environmental flows worldwide (excerpted from Tharme 2003).

Category	**Methodology**	**Brief description**
Hydrology-based	Tennant (Montana) Method (Tennant 1976)	Provides guidelines for flow management based on the percentage of average flow that would maintain biological attributes of a river as optimum (>60%), outstanding (40%), excellent (30%), good (20%), fair, poor, minimum, or degrading (10%).
Habitat simulation	Instream Flow Incremental Methodology (IFIM; Stalnaker et al. 1994)	Uses a model (PHABSIM) to simulate physical habitat and model habitat changes with changing flow, quantifies habitat preferences for selected biota (usually fish) based on hydraulic variables, and then identifies flows at which acceptable habitat is available for target species.
Holistic	Building Block Methodology (BBM; King and Louw 1998; King et al. 2000)	Uses the natural flow regime as a guideline and involves a team of interdisciplinary scientists to examine flow needs for ecological processes. The environmental flow recommendation is presented as a set of flow targets during different months that aim to achieve management goals.
	Downstream Response to Imposed Flow Transformation (DRIFT; King et al. 2003)	Combines data and knowledge from various disciplines to produce flow-related scenarios that can be considered in determining environmental flows. Aims to manage all aspects of flows, including temporal and spatial variability.
	Benchmarking (Arthington 1998; Arthington et al. 2006)	Aims to identify the level of flow alteration at which important ecological and geomorphological changes would begin to be detected through extensive measurements of stream conditions.

hydraulic, and biological response data to quantify suitable instream physical habitat available to target species, usually fish, under different flow regimes. Habitat-discharge curves depicting the range of habitat for biota as a function of flow are then used to determine environmental flow recommendations.

Contemporary advances in scientific understanding have shown that rivers are dynamic ecosystems and that a naturally variable flow regime is required to sustain them (Richter et al. 1997; Poff et al. 1997). *Holistic methodologies* aim to approximate the natural flow regime, and often employ some of the tools of hydrology-based, hydraulic-rating, and habitat-simulation approaches. Environmental flow recommendations can be expressed as a constructed, modified flow regime that varies intra-annually, or defined as acceptable levels of change from natural or reference flow conditions (Tharme 2003). Increased recognition of the services provided by intact freshwater ecosystems has led to the development of holistic methodologies that involve society in setting goals for flow management (King et al. 2000, Arthington et al. 2006). Environmental flow recommendations are designed to help achieve these goals (Table 23.2).

Perspectives on Water Use and River Alteration in the Andes

Human populations in the Andes and adjacent lowlands have long relied on rivers to meet needs for water and energy (Buytaert et al. 2006; Harden 2006). Historically, human impact on Andean landscapes has been most intense at high elevations (>2500 m), but

Table 23.2. An example classification system of management goals for rivers, which are used to guide the environmental flow assessment process. Based on applications of environmental flow methodologies in South Africa (King et al. 2000).

Ecological category	Description
A	Unmodified, natural
B	Largely natural with few modifications. Small changes in natural habitats and biological assemblages. Ecosystem functions are essentially unchanged.
C	Moderately modified. Some loss and change of natural habitat and biological assemblages. Basic ecosystem functions are still intact.
D	Largely modified. Major loss of natural habitat, biological assemblages, and basic ecosystem functions.
E	Seriously modified. Extensive loss of natural habitat, biological assemblages, and basic ecosystem functions.
F	Critical / extremely modified. River alterations have resulted in almost complete loss of natural habitat and biological assemblages. Basic ecosystem functions are destroyed and changes may be irreversible.

*Categories E and F are only used to describe the present state of a river. Management classes are A-D.

increasing colonization at mid and lower elevations (500 – 2500 m) has extended human influence on water resources (Mena et al. 2006; Buytaert et al. 2006). Existing dams and water diversions already have resulted in substantial flow alterations to many Andean rivers. The extent and magnitude of flow alterations are expected to increase in the next decade as a function of human population growth, increasing demands for water and energy, and climate change. Because of limited data, the number of existing and future dams and diversions is difficult to quantify and information availability varies by country. Some general trends are discussed below.

In terms of domestic water usage, several of the region's largest cities depend on Andean páramo streams as their principal source of water supply (Bradley et al. 2006; Vuille et al. 2008). For example, in Quito, Ecuador, approximately 85% of water supply is derived from streams draining Andean páramos (Buytaert et al. 2006). The average water demand of Bogotá, Colombia, is met almost entirely by diverting water from Andean páramo streams (Buytaert et al. 2006; Tellez 2008). Lima and other arid coastal cities in Perú obtain water through a highly engineered system of dams and diversions extending to the headwaters of Andean rivers. Moreover, a growing proportion of coastal cities' water is transferred across the continental divide from Amazon bound rivers (La Touche 1997). La Paz, Cochabamba, and Potosí in Bolivia also rely predominantly on high Andean rivers as a source of water (M. Maldonado, pers. comm.).

Water for irrigated agriculture is the single largest consumptive use of fresh water in Ecuador, Peru, and Bolivia (>80% of surface water withdrawals), and accounts for ~40% of water withdrawals in Colombia (FAO 2003; Jurado 2008). In the Ecuadorian Andes, many rivers are subject to water withdrawals by multiple irrigation projects along their courses, resulting in substantially reduced flows or even zero flows during dry periods (Buytaert et al. 2006). Irrigation efficiency is a concern for water resource use and management. The irrigation potential for Andean countries greatly exceeds the current irrigated area (FAO 2000), thus water withdrawals for agriculture are expected to increase in the future.

Climate and topography have created considerable hydropower potential for Andean rivers. Relatively constant base flow in glacier-fed, high-elevation streams, and annual rainfall in excess of 2 meters at middle and lower elevations guarantees sufficient water for electricity generation across the region; high relief increases the amount of power that can be produced from available water. Regionally, hydropower dams generate ~54% of electricity, although reliance on hydropower varies by country. These trends mirror those reported for neighboring Central America, where hydropower also generates more than half of regional electricity (Anderson et al. 2006). Colombia leads the Andean region in hydropower development, where approximately 50 large (>15 m high) and many smaller dams generate ~80% of electricity (World Commission on Dams 2000; Diez and Burbano 2006; P. Petry, pers. comm.). In Ecuador, ~45% of electricity comes from hydropower, largely generated by a single 1075 MW plant on the Paute River (CONELEC 2007). Other important dams in the Ecuadorian Andes include the Pucara (68 MW), Agoyan (156 MW) and San Francisco (230 MW) plants in the Pastaza River basin (CONELEC 2007). In Perú ~70% of electricity is generated by hydropower dams, including the Santiago Antúnez de Mayolo Dam, one of the country's largest projects (798 MW), and numerous small projects, many <1 MW (Ministerio de Energía y Minas, Peru 2010). In Bolivia's hydropower accounts for ~40% of electricity (US EIA 2009).

Much of the tropical Andean region's hydropower potential remains untapped. Ecuador provides an example: as of 2007, Ecuador had exploited only 15% of its estimated hydropower potential (Pelaez-Samaniego 2007). Regionally, many more dams are proposed and will result in increased fragmentation and flow alteration of rivers. Future hydropower development is motivated by the region's untapped potential but also by other interrelated factors. First, to meet current and future demands for electricity, installed generation capacity in many Andean countries will be increased. In Ecuador, for example, demand for electricity is expected to grow at a rate of 4-6% annually between 2006-2015, and new hydropower dams are viewed as a solution to meet demands (CONELEC 2007; Pelaez-Samaniego 2007). A plan presented by the Consejo Nacional de Electricidad (CONELEC) in 2007 proposed 23 new hydropower projects >100 MW, 76 projects between 10-100 MW, 45 projects between 1-10 MW, and 82 <1 MW (CONELEC 2007). Many of these dams could be located along gradient breaks between 500 – 2000 m elevation in the Napo, Pastaza, and Santiago River Basins. In Bolivia, the hydropower potential of each watershed is being evaluated, and several projects are currently proposed for Andean-Amazon rivers (M. Pouilly, IRD, pers. comm.). A second noteworthy point is the role of the Clean Development Mechanism in promoting new hydropower development in the region. In Peru, many new hydropower dams are being proposed under this framework (Zamora 2008). Finally, the influence of neighboring countries, particularly Brazil, on hydropower development in Andean countries should not be overlooked. Brazil has pursued new hydropower developments on rivers in both Peru and Bolivia. Electricity generated by these projects is largely intended for export to Brazil.

In addition to direct human modifications like dams and water withdrawals, climate change has the potential to substantially alter historical flow patterns of Andean rivers. Current projections suggest temperatures in the Andes may increase by 4.5–5 ºC in the 21st century (Vuille et al. 2008). This warming would cause extensive melt of mountain glaciers and result in an initial increase in runoff followed by abrupt changes in flow regimes of glacier-fed Andean rivers. Glaciers are melting in other tropical regions (e.g., East Africa), but the Andean case is of special concern as there is such heavy reliance on glacier-fed water supplies to meet human demands for water and energy (Bradley et al. 2006; Vuille et al. 2008).

Linking Flows and Aquatic Biodiversity in Andean Rivers

Tropical Andean rivers are extremely diverse, varying from slow-moving, high-elevation streams to fast-flowing, mountain torrents in areas of high relief, and ranging from aseasonal equatorial systems to rivers with marked wet and dry seasons. This natural spatial and temporal heterogeneity in flow has helped shape biological communities and ecological and evolutionary processes. The general ecology of Andean rivers remains understudied (Allan et al. 2006), and even less is known about the specific consequences of flow alterations for Andean freshwater biodiversity. Nevertheless, some predictions can be made based on past research in Andean streams.

Macroinvertebrates (e.g., insects, crustaceans, mollusks, oligochaetes) are a key component of riverine fauna, and the structure and composition of macroinvertebrate assemblages vary widely within and between rivers as a function of flow conditions, geomorphology, and elevation (Jacobsen et al. 1997; Jacobsen 2003; 2004). Flow disturbances (e.g., floods and droughts) and seasonality have been shown to strongly influence the density and diversity of macroinvertebrates present at different times of the year (Flecker and Feifarek 1994; Ríos 2008). Changes in seasonality or changes to timing and magnitude of high and low flow events caused by river alterations could have profound effects on macroinvertebrate distribution and abundance. Flow alterations could affect life history strategies of macroinvertebrates, particularly where periodic water releases from a dam disrupt natural cues for downstream movement (drift), typically linked to high flows (Turcotte and Harper 1982; Ríos 2008). Altered flows could also influence timing of other life history events such as frequency of breeding, time of emergence, and time of reproduction (Jacobsen et al. 2008). In some cases, flow modifications associated with dams and water withdrawals alter a river's thermal regime, which controls many vital processes (Sweeney et al. 1991; Poff et al. 1992; Atkinson 1994; Olden and Naiman 2010).

The tropical Andes are a global center of fish species richness in high-elevation tropical streams, characterized by a highly endemic (estimated at 40% of species), yet poorly studied, fish fauna. Siluriformes (44%) and Characiformes (40%) are the dominant orders, followed by Gymnotiformes, Perciformes, Cyprinodontiformes, and Synbranchiformes. Maldonado-Ocampo et al. (2005) classify Andean fishes into three groups: torrent species that can adhere to hard surfaces and withstand strong currents; fusiform species that inhabit fast-flowing areas and exhibit a hydrodynamic body form; and species found in more still-water environments. Many Siluriformes (catfish) species widely distributed along elevational gradients are considered torrent species and potentially highly susceptible to flow alterations and subsequent changes in habitat (e.g., Astroblepidae, Trichomycteridae, and Loricariidae). Several migratory species of importance to regional fisheries (e.g. *Prochilodus magdalenae*, *P. reticulatus*, *P. nigricans*, *Salminus affinis, Brycon sp., Pseudoplatystoma sp.*) also inhabit Andean rivers (Ortega and Hidalgo 2008). Hydrologic alterations and physical barriers presented by dams impede these species' vital migrations, especially when modifications occur on mainstem rivers (Pringle et al. 2000; Galvis and Mojica 2007). Flow alterations could also affect resource availability and reproduction of Andean fishes in general. Macroinvertebrates are a primary component of the diet of many species and any changes in these communities as a consequence of flow alterations could affect fishes. Evidence suggests that some tropical Andean fishes reproduce during dry periods (Torres-Mejia and Ramírez-Pinilla 2008), thus changes in seasonal flow patterns could thus affect reproductive strategies of these species.

Flow alterations of Andean rivers, as a consequence of dams and water diversions or from climate change, have the potential to affect ecosystems thousands of kilometers downstream. The tropical Andes encompass the headwaters of two of the world's largest and most biologically diverse river basins, the Amazon and the Orinoco, and strongly influence many fundamental characteristics of the geomorphology, biogeochemistry, and ecology of these mainstem rivers (McClain and Naiman 2008). Andean rivers provide an important source of sediments, organic matter, and nutrients, and diverse organisms, particularly fishes, have adapted to the seasonal delivery of water and materials from the Andes to downstream ecosystems (Edmund et al. 1996; Allan et al. 2006; Jepsen and Winemiller 2007; McClain and Naiman 2008). Downstream ecosystems in both the Amazon and the Orinoco depend on unobstructed riverine connectivity between the Andes and the lowlands. By trapping sediments and altering flows, dams on Andean rivers could result in changes to the geomorphology of downstream reaches, affecting aquatic and riparian habitats, and impede movement of the many fish species that migrate along mountain-lowland river corridors (McClain and Naiman 2008).

Sustainable Flow Management in the Andes

In light of existing and future flow alterations of Andean rivers and their potential for wide-ranging consequences, there is a strong need for proactive flow management to sustain freshwater ecosystems and the ecosystem services they provide. The social and ecological value of environmental flows should be recognized, as addressing flow needs of ecosystems typically generates societal benefits (Dyson et al. 2003). Environmental flow assessment remains relatively new in Andean countries and present legal backing and institutional capacity for determining and implementing environmental flows vary by country (Table 23.3).

Scientific research can help guide Andean countries as they move forward in defining policies that support environmental flows. We have identified several research priorities to facilitate more sustainable flow management of Andean rivers:

1. *Maintenance, rehabilitation, and expansion of the network of stream gauges*. Hydrologic records are either incomplete or non-existent for many tropical Andean rivers. Without freely available, scientifically sound gauge data, environmental flows are very difficult to assess.

2. *Investigation of flow-ecology relationships of aquatic and riparian biota and migration patterns of migratory species*. Understanding the flow dependence of freshwater and riparian biota is essential to determination of flows that sustain conditions necessary for their survival. Much aquatic research in the tropical Andes is focused on species distribution. Collection and analysis of quantitative habitat data alongside species surveys would help provide critical information on flow preferences.

3. *Identification of societal goals for river management and acceptable levels of river alteration*. Tropical Andean rivers are more than just a source of water and energy. Loss or replacement of other services (e.g., scenic beauty, recreation, waste assimilation, food) compromised by flow alterations would be costly (Costanza et al. 1997). It is in society's interest to consider the range of benefits that rivers provide when making flow management decisions.

4. *Greater understanding of cumulative effects of multiple water withdrawals and dams on individual river systems, and possible interactions with climate change.* Under present and future scenarios, individual basins in the tropical Andes are subject to multiple dams and water diversions. Many of these are also glacier-fed systems. Understanding which unregulated rivers should be maintained to sustain biota and ecosystem services is crucial to flow management.

5. *Development of new approaches or adaptation of existing environmental flow methodologies to be applicable on a regional scale and adaptive in nature*. The pace of river alteration in the Andes greatly exceeds the time and ability to conduct environmental flow assessments on a river-by-river basis. Methodologies that are regionally appropriate and flow management strategies that can be adapted to deal with changing flow patterns are needed to safeguard rivers amidst existing and future alteration.

Table 23.3. Overview of environmental flow assessments and implementation in the four Andean countries. Sources for this information include: IDEAM 2000; Diez and Burbano 2006; Diez and Ruiz 2007; SENAGUA 2008; Marc Pouilly and Mabel Maldonado (Bolivia) pers. comm. 2009; Lucia Ruiz (Perú) pers. comm. 2009.

Country	Legislative frameworks for environmental flows	Institutional frameworks for environmental flows	Examples of environmental flow related research to date
Colombia	Article 21 of the proposed new Ley de Aguas defines the concept of environmental flow (Ministerio de Ambiente 2006); Ley Ambiental 99/1993 (and modifications), requires an 'environmental license' for hydropower projects.	The Instituto de Hidrología, Meteorología y Estudos Ambientales (IDEAM) is one of the responsible government authorities for determining and implementing environmental flows.	Environmental flow estimation for the Palacé River downstream from a water diversion using habitat simulation and application of the Instream Flow Incremental Methodology (Diez and Ruiz 2007). Pilot project to determine environmental flows for the Chuza River, downstream from reservoir for water supply for Bogotá using holistic methodology similar to Richter et al. 2006 (Tellez 2007). Development of preliminary methodology for estimating environmental flows at water projects that require licenses (Ministerio de Ambiente, Vivienda y Desarrollo Territorial and Facultad de Ingeneria, Universidad Nacional de Colombia, Workshop, October 2008)
Ecuador	The Acuerdo Ministerial No. 155 (Ministerio del Ambiente, 14 March 2007) mentions environmental flows but doesn't provide specific rules for calculation; a new proposed water law also mentions environmental flows. The new Constitution (2008) contains several Articles relevant to water resources management and specifically mentions environmental flows.	The Secretaria Nacional de Agua (SENAGUA) and its basin-level administrative units, the Water Agencies, coordinates with other government authorities to determine and implement environmental flows.	Definition of environmental flows for rivers in the Papallacta system, downstream from water supply reservoirs for the city of Quito using habitat simulation models AndeSim and PHABSIM (Rosero et al. 2007). Determination of environmental flows for rivers of the Pastaza Basin, subject to multiple water diversions and flow alterations, using hydrology-based methods (Moreno and Galárraga 2008; Moreno 2008) and holistic approaches Estimation of environmental flows downstream from a hydropower project on the Topo River using hydrology-based methodologies as part of an environmental impact assessment (ENTRIX 2007)
Peru	The current water law, which dates back to 1969, does not make reference to environmental flows.	The Autoridad Nacional del Agua (ANA), based out of the Ministerio de Agricultura, was recently created and will have a role in determining and implementing environmental flows.	
Bolivia	The current water law does not make reference to environmental flows, but the new constitution indicates the need to avoid damage to freshwater ecosystems.	The Ministerio del Medio Ambiente y Agua (MMyA) will have a role in determining and implementing environmental flows.	Research project on application of PHABSIM to study environmental flow requirements for the Beni River and two other systems (Ibañez 2008)

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