

# Analyzing the Impacts of Dams on Riparian Ecosystems: A Review of Research Strategies and Their Relevance to the Snake River Through Hells Canyon

Jeffrey H. Braatne · Stewart B. Rood ·  
Lori A. Goater · Charles L. Blair

Published online: 28 November 2007  
© The Author(s) 2007

**Abstract** River damming provides a dominant human impact on river environments worldwide, and while local impacts of reservoir flooding are immediate, subsequent ecological impacts downstream can be extensive. In this article, we assess seven research strategies for analyzing the impacts of dams and river flow regulation on riparian ecosystems. These include spatial comparisons of (1) upstream versus downstream reaches, (2) progressive downstream patterns, or (3) the dammed river versus an adjacent free-flowing or differently regulated river(s). Temporal comparisons consider (4) pre- versus post-dam, or (5) sequential post-dam conditions. However, spatial comparisons are complicated by the fact that dams are not randomly located, and temporal comparisons are commonly limited by sparse historic information. As a result, comparative approaches are often correlative and vulnerable to confounding factors. To complement these analyses, (6) flow or sediment modifications can be implemented to test causal associations. Finally, (7) process-based modeling represents a predictive approach incorporating hydrogeomorphic processes and their biological consequences. In a case study of Hells Canyon, the

upstream versus downstream comparison is confounded by a dramatic geomorphic transition. Comparison of the multiple reaches below the dams should be useful, and the comparison of Snake River with the adjacent free-flowing Salmon River may provide the strongest spatial comparison. A pre- versus post-dam comparison would provide the most direct study approach, but pre-dam information is limited to historic reports and archival photographs. We conclude that multiple study approaches are essential to provide confident interpretations of ecological impacts downstream from dams, and propose a comprehensive study for Hells Canyon that integrates multiple research strategies.

**Keywords** Environmental impact analysis ·  
Riparian ecology · River damming

## Introduction

Rivers have been dammed and diverted for millennia and river damming is one of the most prominent human impacts on fresh water ecosystems (Graf 1999; Naiman and others 2005; Nilsson and others 2005). With damming, the flooded zone upstream undergoes an abrupt, dramatic transition from river valley to reservoir (Nilsson and Berggren 2000; Naiman and others 2005). In addition, river damming and flow regulation also impact downstream ecosystems and these downstream impacts often influence longer river reaches than the segments that are inundated (Williams and Wolman 1984; Johnson 1998; Rood and others 2005).

Downstream ecological impacts often follow from three environmental alterations (Rood and others 2005): changes to the quantity and timing of downstream water flow

---

J. H. Braatne  
Department of Fish and Wildlife Resources, University of Idaho,  
Moscow, ID 83844, USA

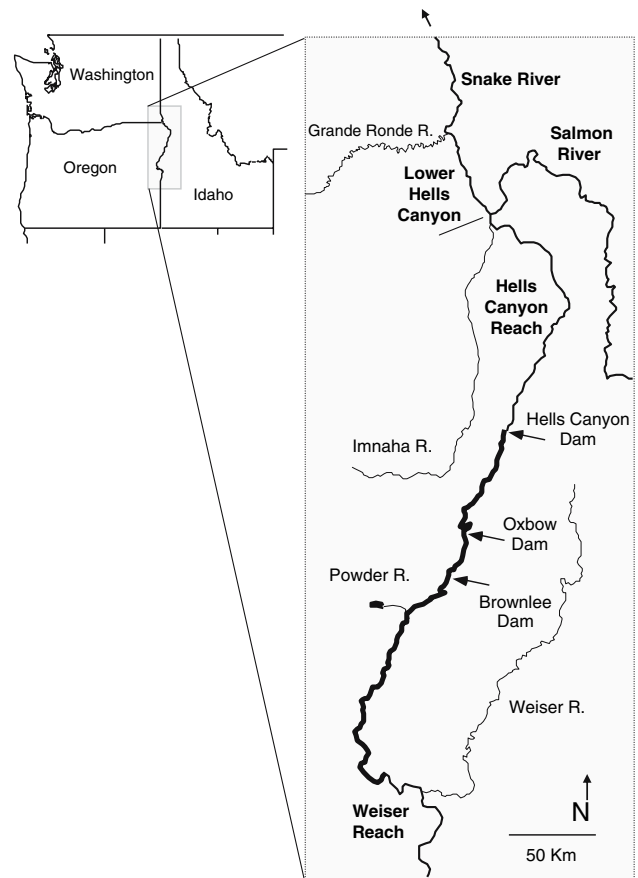
S. B. Rood (✉) · L. A. Goater  
Department of Biological Sciences, University of Lethbridge,  
T1K 3M4 Lethbridge, AB, Canada  
e-mail: rood@uleth.ca

C. L. Blair  
CH2M HILL, Boise, ID, USA

(Williams and Wolman 1984; Rood and Mahoney 1990; Magilligan and others 2003), reduced passage of alluvial materials and particularly suspended sediments (Ligon and others 1995; Kondolf 1997), and the fragmentation of the river corridor, with interruptions in downstream and even upstream passage of biota (Ward and Stanford 1995a, 1995b; Jansson and others 2000). Alterations to the water flow regime are determined by dam operations, while sediment trapping and interruption to corridor connectivity are largely unavoidable consequences of major dams and reservoirs.

Many prior studies have investigated the ecological impacts downstream from specific dams and there have also been integrative reviews of some environmental impacts by Petts (1984), Williams and Wolman (1984), Ligon and others (1995), Friedman and others (1998), Grant and others (2003) and others. Conversely, there are few analyses of the research strategies to investigate downstream impacts. A systematic analysis of prospective research strategies is of interest for three reasons. First, relative to the broader understanding of ecosystem function, river systems are especially dynamic (Poff and others 1997; Naiman and others 2005; Schumm 2005) and this provides conceptual and practical challenges in resolving human impacts that are superimposed on natural spatial and temporal variation (Underwood 1994; Stewart-Oaten and Bence 2001). Second, relative to an understanding of fundamental river processes, each dam represents a major perturbation and the investigation of the physical and biological consequences can provide insight into the functioning of aquatic (instream) and riparian (streamside) ecosystems (Williams and Wolman 1984; Nilsson and Berggren 2000). Third, there is a need to develop rigorous study designs for environmental analyses of new dams that are being implemented, especially in China and India, and for relicensing applications of existing dams, particularly in North America and Europe (Johnson and others 1995; Trush and others 2000; Hughes and Rood 2003). Prior dams were generally implemented without comprehensive environmental assessment and the relicensing phase provides the opportunity to analyze and even mitigate some environmental impacts (Richter and Richter 2000; Rood and others 2005).

Consequently, in this study we reviewed and categorized the different research strategies and, as an illustrative case-study, we considered how these approaches might apply in the analysis of environmental impacts downstream from a sequence of three major dams and reservoirs along the Snake River, the largest tributary of the Columbia River (Palmer 1991). The dams are located at the upstream end of Hells Canyon, a spectacular river reach that provides the border between Oregon and Washington, and Idaho (Fig. 1). Brownlee, Oxbow and Hells Canyon dams were



**Fig. 1** Map of the study region showing rivers and dams of the Hells Canyon Complex

completed in 1958, 1961, and 1967, respectively, and are collectively referred to as the Hells Canyon Complex (HCC).

## Methods

The study commenced with a literature survey of reports analyzing ecological impacts downstream from dams and especially studies investigating riparian zones along bed-rock-dominated river canyons of western North America (Table 1). We categorized the research strategies relative to their conceptual approach and study design, and considered scientific strengths and weaknesses, including confounding factors. The relevant studies often involved multidisciplinary approaches, with integrative analyses of river hydrology, fluvial geomorphology, and riparian ecology.

Following categorization, we considered the prospective applicability of the research strategies for the Hells Canyon reach of the Snake River. The suitability of spatial comparisons was considered by observing biophysical

**Table 1** Recent studies that include multiple comparisons for investigating ecological impacts from dams above river canyons of western North America (north to south) and the Snake River

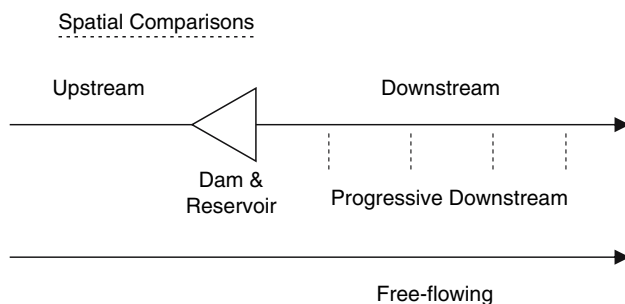
| Author (year)  | River(s)   | Location      | 1. Upstream versus downstream | 2. Progressive downstream | 3. Dammed versus free-flowing | 4. Pre- versus post-dam | 5. Sequential post-damming | 6. Flow modification | 7. Process-based modeling |
|--|--|---------------|-------------------------------|---------------------------|-------------------------------|-------------------------|----------------------------|----------------------|---------------------------|
| Rood and others (1995); Rood and Mahoney (2000); Rood and others (2005) <sup>a</sup>   | St. Mary River through Box Canyon                | Alberta       | X                             | X                         | X                             | X                       | X                          | X                    |                           |
| Andrews 1986; Schmidt and others (1995); Andersen & Cooper (2000); Merritt & Cooper (2000); Grams & Schmidt (2002); Cooper and others (2003); Adair and others (2004) <sup>a</sup> | Green and Yampa rivers through Dinosaur Monument | Colorado      |                               | X                         | X                             | X                       | X                          |                      |                           |
| Schmidt and others (1995, 2001); Stevens and others (1995); Webb (1996); Collier and others (1997); Patten and others (2001) <sup>a</sup>  | Grand Canyon of the Colorado River               | Arizona       | X                             | X                         | X                             | X                       | X                          | X                    | X                         |
| Johnson and others (1995); Dixon & Johnson (1999)  | Snake River, upstream of Hells Canyon            | Idaho         |                               |                           |                               |                         | X                          |                      | X                         |
| Schmidt and others (1995)  | Snake River, Hells Canyon                        | Idaho, Oregon |                               | X                         |                               |                         | X                          |                      |                           |
| Proposed composite study   | Snake River, Hells Canyon                        | Idaho, Oregon | X                             | X                         | X                             | X                       | X                          | ?                    | X                         |

<sup>a</sup> additional relevant articles are cited within the articles in this group

conditions along (1) the 93 km Hells Canyon reach of the Snake River versus (2) the 35 km upstream Weiser reach of the Snake River, (3) the adjacent 107 km reach of the Lower Salmon River Gorge below White Bird, Idaho, and (4) the 32 km reach of the Snake River below the Salmon River confluence to the Grande Ronde River (Fig. 1).

River channel and valley characteristics were assessed by field visits and float trips along all of these reaches and from 1:24,000 scale USGS quadrangle topographic maps. From these maps, channel widths were measured at 1.6 km intervals from the left to right bank and incorporated islands if present. Longitudinal profiles were determined from elevational contours and calculated as both river and valley gradients. Historic hydrologic data were accessed from regional USGS gauges along the Snake and Salmon Rivers. Statistical comparisons of the river channel characteristics were undertaken with Kruskal-Wallis non-parametric comparisons with JMP 5.0 (SAS Institute Inc., Cary, North Carolina).

Following from the consideration of different research strategies, we compared the different spatial and temporal study approaches relative to the similarity of the proximal, or local, rivers and landscapes, and the distal, headwater environments. We considered: (1) climate and hydrology and especially the seasonal river flow pattern; (2) aspects of fluvial geomorphology, with the geomorphic context for the local comparison, and sediment inputs for the distal comparison; and (3) biological aspects and especially the composition of the riparian vegetation communities. We applied a quartile scaling with: 0 = very different; 0.25 = different; 0.5 = somewhat different; 0.75 = very similar; or 1.0 = same. The local environment was considered most critical for riparian vegetation and, consequently, we doubled the weighting of this component and subsequently added the proximal and distal scores to produce the comparability index that could range from 0 (entirely different) to 4 (identical).



**Fig. 2** Schematic showing general spatial comparisons to analyze environmental impacts downstream from dams. Triangles represent dams and reservoirs

## Results

Previous studies investigating ecological impacts downstream from major dams in western North America (Table 1) have applied research strategies that may be broadly classified into three categories: (1) comparative studies, (2) manipulative experiments, and (3) process-based biophysical modeling. Comparative studies have been most common and are generally correlative in nature. These can be divided into studies involving spatial comparisons or temporal comparisons and we have sub-divided these into five comparative research strategies (Table 2). For each of these, we present the conceptual approach, followed by consideration of its applicability to Hells Canyon.

### Spatial Comparisons

Spatial comparisons involve assessments of different reaches along a particular river or comparisons with nearby reaches of different rivers. Scientific interpretation is based on the general assumption that regional river reaches will demonstrate ecological similarities because they often share hydrologic and geomorphic contexts, have similar climatic regimes, and at least prior to damming, share some ecosystem communities. Correspondingly, the strength of comparison within or across rivers relies on environmental similarity without damming.

### Upstream Versus Downstream

*Concept* – Probably the most obvious spatial comparison contrasts river reaches upstream versus downstream from a dam and reservoir (Fig. 2, Tables 1 and 2). This comparison is based on the expectation that sequential reaches along a river will experience similar but gradually changing ecological conditions and processes, an expectation consistent with the river continuum concept (Vannote and others 1980). The dam and reservoir separate the upstream versus downstream reaches, which subsequently experience different physical and biological influences (Ward and Stanford 1995a, 1995b). Although upstream and downstream reaches are both impacted by some alterations such as fragmentation of the river corridor (Jansson and others 2000), the upstream reach is unaltered relative to the fundamental fluvial processes of hydrology and sediment flux. There is, consequently, an expectation that the upstream reach will continue to function in a natural manner, similar to the condition without the dam. In contrast, the downstream reach is impacted by aspects such as sediment depletion (Kondolf 1997) and hydrologic changes that

**Table 2** Research strategies to analyze ecological impacts downstream of dams and their suitability for the Snake River through Hells Canyon

| Research strategy                                  | Study design   | Consideration / complexity  | Suitability for Hells Canyon  |
|--|--|---|---|
| <b>I. Comparative studies</b>                      |  |   |   |
| <b>A. Spatial comparison</b>                       |  |   |   |
| 1. Upstream versus downstream                      | Paired comparison:<br>upstream = control,<br>downstream = treatment  | Dams are not randomly<br>situated and are often at<br>geomorphic transitions                          | Low - an extreme geomorphic<br>transition exists  |
| 2. Progressive downstream                          | Quantitative comparison<br>suitable for pattern analysis   | Inflowing tributaries can<br>mitigate impacts of<br>damming but also introduce<br>system complexity   | Medium - the inflow of the Salmon<br>River provides considerable<br>system recovery                                       |
| 3. Dammed versus free-flowing                      | Paired or multiple comparison:<br>free-flowing = control<br>or reference, dammed = treatment                             | Although regional rivers have<br>biophysical similarities, each<br>river is somewhat unique           | High - in biophysical condition,<br>the Salmon River Gorge is very<br>similar to Hells Canyon                             |
| <b>B. Temporal comparison</b>                      |  |   |   |
| 4. Pre- versus post-dam                            | Paired comparison:<br>pre-dam = control,<br>post-dam = treatment   | Comprehensive biophysical<br>inventories were seldom<br>undertaken prior to damming                   | Medium - historic descriptions and<br>archival photographs are<br>available   |
| 5. Sequential post-damming                         | Multiple comparison that may<br>be suitable for pattern analysis   | Other coincidental changes<br>complicate interpretation   | Medium - sequential aerial<br>photographs permit comparison<br>of large-scale features                                    |
| <b>II. Manipulative experiments</b>                |  |   |   |
| 6. Flow or sediment<br>modification or dam removal | Pre-determined paired<br>or multiple comparison  | A specialized post-damming<br>comparison that may test<br>causal association                          | Uncertain - following recent<br>relicensing, there may be slight,<br>but probably not major, changes<br>in dam operations |
| <b>III. Biophysical modeling</b>                   |  |   |   |
| 7. Process-based modeling                          | Quantitative modeling with<br>hydrogeomorphic foundation<br>(i.e., hydrology & geomorphology<br>→ vegetation → wildlife) | Requires defined and<br>deterministic relationships<br>but some processes remain<br>poorly understood | High - the physically rigid<br>landscape simplifies<br>hydrogeomorphic modeling and<br>riparian vegetation is limited     |

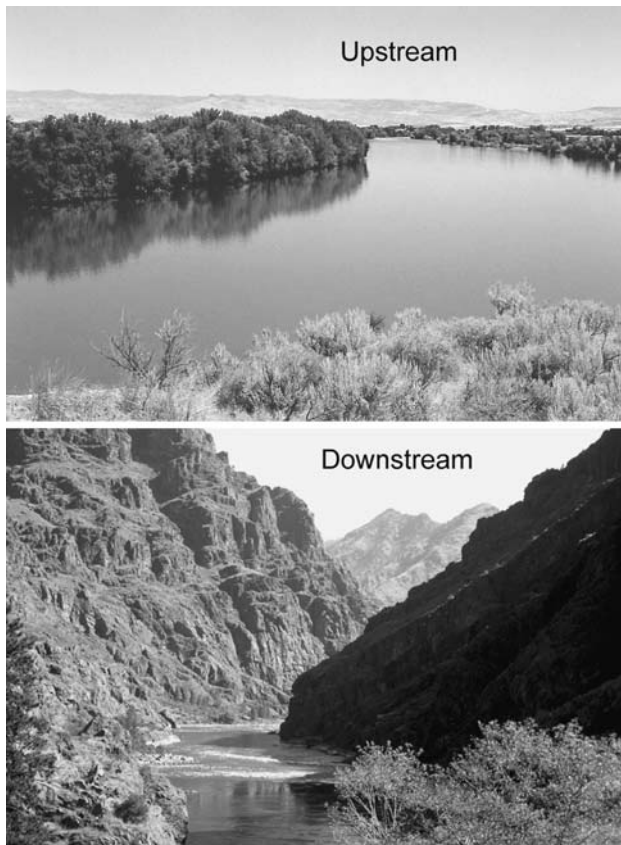
reflect the pattern of dam operation. Thus, the upstream versus downstream comparison represents a paired comparison whereby the upstream reach provides the control and the downstream reach represents the treatment condition (Table 2).

While upstream versus downstream comparison is a common study approach there is frequently a confounding factor. Dams are not randomly situated but are instead positioned at strategic locations that may involve valley narrowing. These sites are often at geomorphic transitions that are naturally associated with ecological change. Consequently, natural differences in river reaches commonly exist upstream versus downstream from dam sites. In addition, the upstream environments can also be altered by damming. For example, dams can interrupt the upstream movement of marine-derived nutrients contributed by carcasses of anadromous salmonids (Naiman and others 2005).

*Application* – The reaches of the Snake River upstream versus downstream from the HCC differ dramatically in their natural geomorphic setting (Fig. 3). The upstream reach near Weiser, Idaho flows through a broad, 3 km wide

river valley (Fig. 4) with extensive floodplain zones and terraces dominated by agricultural development. The river channel averages about 300 m in width (Fig. 4), with frequent islands. The longitudinal gradient is shallow, averaging about 0.27 m/km (Fig. 4) and consequently, stream velocities are typically slow. The river banks and floodplain consist of alluvial deposits without bedrock exposure or confinement. Thus, the channel would be relatively dynamic over the time period of decades or a few centuries that correspond to the life spans of native riparian shrubs and trees such as the locally abundant sandbar willow (*Salix exigua* L.) and black cottonwood (*Populus trichocarpa* Torrey & Gray) that require a dynamic floodplain environment (Polzin and Rood 2006).

In contrast to the alluvial reach upstream, Hells Canyon below the HCC is an exceptionally erosion-resistant, bedrock-dominated canyon landscape (Fig. 3). The Snake River has probably been flowing through Hells Canyon for 2 to 6 million years and the deep canyon was considerably scoured during the draining of Lake Idaho about 2 million years ago (Vallier 1998). Progressive river incision has compensated for gradual uplifting of the mountainous

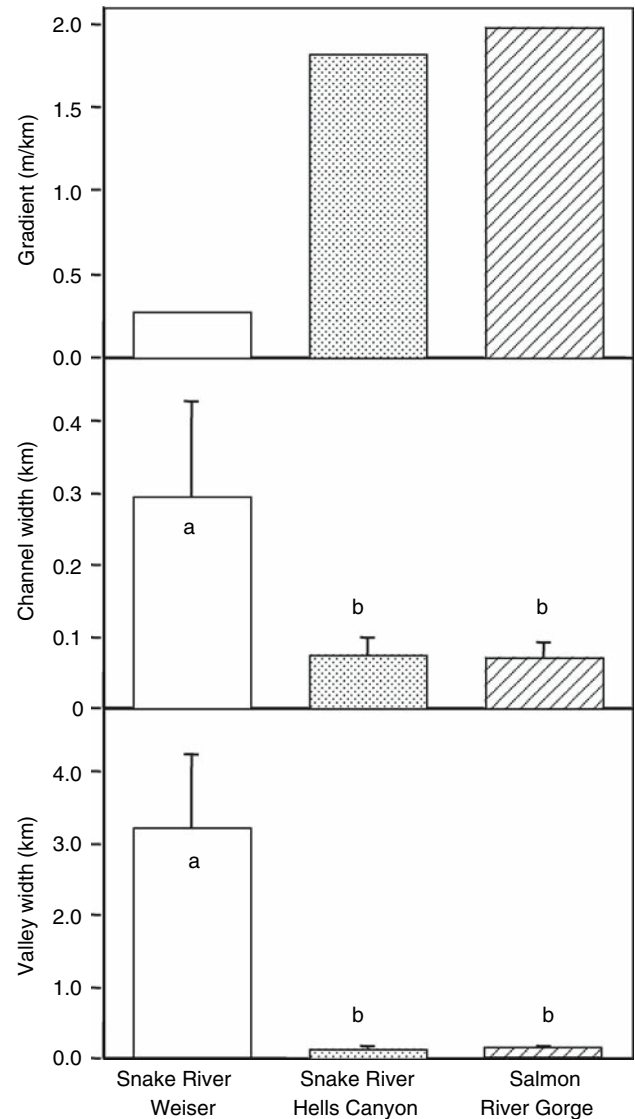


**Fig. 3** Typical views of the Snake River upstream (top, near Weiser, July 1997) and downstream (bottom, below Hells Canyon Dam, July 1997) from the Hells Canyon Complex of three dams and reservoirs

region to create the present, exceptionally deep (reaching 2100 m) V-shaped valley canyon. While slight changes in specific channel configuration have occurred, the general river valley form has probably been only slightly altered over the past 100,000 years (Malde 1991; Vallier 1998).

Through Hells Canyon below the HCC, the Snake River has a typical width of about 75 m, about one-quarter of the channel width of the upstream Weiser reach (Fig. 4). Basalt bedrock exists as a dominant surface material in the riparian zones, along with large, jagged colluvial boulders that have fallen from the hill-slope bedrock due to physical weathering (Fig. 3). Given the prominence of erosion-resistant bedrock and massive boulders, the position of the river channel and banks would be almost static over the life span of riparian plants.

With the steep cross-section of the canyon extending down to the valley floor and into the river, alluvial floodplain development is minimal along the Hells Canyon reach. The typical river valley width is about 130 m, only 55 m wider than the river channel and about 1/25<sup>th</sup> of that of the upstream Weiser reach (Fig. 4). The longitudinal gradient of the river channel through Hells Canyon is 6.7–fold steeper than the gradient along the upstream Weiser



**Fig. 4** Comparisons of channel slopes (longitudinal gradients) and channel and valley widths for the Weiser reach of the Snake River upstream of the Hells Canyon Complex ( $n = 22$ ), for the Hells Canyon reach downstream of the dams ( $n = 58$ ), and for the adjacent lower gorge of the Salmon River ( $n = 67$ ). Different letters indicate significantly different ( $p < 0.05$ ) widths

reach. As a result, the upstream versus downstream reaches differ significantly, complicating this spatial comparison (Table 2).

#### *Progressive Downstream*

**Concept** – The progressive downstream research strategy investigates biophysical conditions along consecutive reaches of the dammed river, and thus represents another within-river longitudinal comparison (Fig. 2, Tables 1 and 2). Instead of an upstream control reach, observations are

made along the segments downstream from a dam to investigate progressive change. The longitudinal patterns provide insight into the nature of the environmental influences and may resolve impacts due to water flow regulation versus sediment change (Rood and others 2005). Impacts from sediment trapping would be most severe in the tail-water zone directly below the dam and would initially be less severe downstream (Williams and Wolman 1984; Kondolf 1997). In contrast, ecological consequences of flow alteration could be more uniform along the downstream reach. For both water- and sediment-associated impacts there is some recovery with tributary inflows that contribute water, sediments, and other materials (Andrews 1986; Cooper and others 1999).

While the upstream versus downstream comparison represents a paired comparison, the progressive downstream or synoptic comparison involves a sequence of river segments to reveal quantitative patterns that are suitable for regression or other trend analyses. The progressive downstream approach also overlaps with temporal comparison because impacts such as sediment depletion may extend downstream over time.

*Application* – The Hells Canyon reach of the Snake River is fairly uniform with respect to riparian vegetation and over the past half-century the zone of sediment depletion has extended through the full reach downstream to the Salmon River (Schmidt and others 1995). However, there are numerous dams above the HCC, including those along the Boise and Payette rivers that formerly provided extensive sands originating from the Idaho Batholiths, and it is thus difficult to differentiate some of the physical impacts of the HCC from impacts due to the upstream dams (Parkinson and others 2003).

Within Hells Canyon, tributary inflows are quite minor, except for the free-flowing Imnaha River shortly upstream from the Salmon River junction (Fig. 1). There is little evidence of sediment or vegetation response due to the Imnaha inflow because the downstream Snake River segment is in a severely confined canyon zone dominated by steep bedrock walls rising directly from the river. In contrast, accompanying the inflow of the Salmon River there is an abrupt change in the riverine environment. Along the Lower Hells Canyon reach (downstream from the Salmon River inflow), sandy beaches are abundant as are interstitial sands sifted between alluvial cobbles and colluvial boulders. In contrast to the Hells Canyon reach, sandbar willow is prolific below the confluence of the Snake and Salmon Rivers, particularly at the fringes of sandbars and in other zones with interstitial sand.

However, the Snake River valley also widens with the inflow of the Salmon River and valley wall slopes are shallower. Further, the Salmon River drains a geologically different catchment, dominated by the Idaho Batholiths

that provide extensive sand sources. Consequently, the change in riparian conditions along the Snake River below the Salmon River partly reflects a natural transition in the physical landscape. Despite this transition, the general river valley landscape is quite similar through Hells Canyon above and below the Salmon River inflow, and the riparian vegetation communities are very similar. Consequently, comparison between reaches above and below the Salmon River should provide a useful study approach (Fig. 2, Table 2).

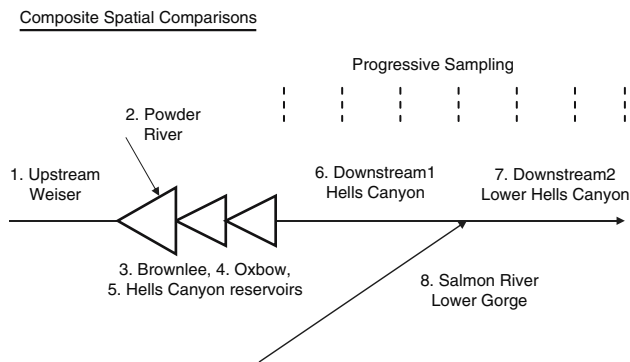
#### *Dammed Versus Free-Flowing Rivers*

*Concept* – Another commonly applied spatial comparison involves the assessment of a river reach downstream from a dam versus a reach(es) along a nearby river(s) that is free-flowing or has experienced a different history of damming and flow regulation (Fig. 2, Tables 1 and 2). This scientific comparison is based on the expectation that adjacent rivers will experience similar climates and regional-scale geologic and geomorphic conditions. As a result, adjacent rivers often support similar aquatic and riparian ecosystems. Consequently, impacts due to damming and flow regulation could result in differences between the flow-regulated versus free-flowing river reaches. The free-flowing river thus provides the study control or reference reach and the dammed river reach provides the treatment condition.

However, each river is somewhat unique and while there are similarities across regional rivers, there are also some differences in hydrology, geomorphology, and aquatic and riparian biology (Naiman and others 2005). Processes along river reaches also reflect impacts and characteristics of the upstream watershed that also vary across rivers. Thus, an effective comparison of a dammed versus an adjacent free-flowing reach must consider watershed influences as well as the local conditions along the comparative study reaches (Hewlett and others 1969).

*Application* – As previously noted, Hells Canyon is a particularly distinctive landscape with a large, steep-gradient river in a deep, bedrock-dominated V-shaped valley. The Lower Salmon River Gorge has a biophysical context very similar to Hells Canyon. Both river canyons are deeply incised, producing narrow, V-shaped valley canyons with minimal floodplains (Fig. 5). Exposed bedrock and angular colluvia dominate both landscapes and steep bedrock walls flank the valleys of both river reaches that share a common climate and support sparse vegetation.

The physical similarities of Hells Canyon and the Lower Salmon River Gorge are confirmed by channel and valley characteristics (Fig. 4). River channel and valley widths



**Fig. 5** Schematic showing the proposed spatial comparisons to analyze environmental impacts downstream from the Hells Canyon Complex of dams

are almost identical and the longitudinal gradients are also very similar (Fig. 4). While their channel geometry is very similar, the associated hydrology differs considerably (Table 3). The annual discharge of the Snake River is about twice that of the Salmon River but the Salmon River has about 1/3 greater peak flows. The Salmon River has a much smaller watershed that receives greater precipitation and provides fairly synchronous snowmelt-dominated seasonal flow.

Although these adjacent river reaches are very similar, their headwater reaches vary substantially with respect to both natural and human influences. The Snake River originates in western Wyoming and then flows in a wide arc across the Snake River Plain of southern Idaho, a region with a combination of erosion-resistant lava beds with minimal soil cover and limited sediment input and agricultural landscapes with greater sediment inputs. Immediately upstream of the Hells Canyon reservoirs, five major tributaries (Boise, Malheur, Owyhee, Payette, and Weiser rivers) double the drainage area of the Snake River (Fig. 1).

The Snake and Salmon rivers also vary considerably in accessibility and the extent of human impact. The Snake River corridor has been the focus for agricultural

development and human settlement in Idaho. In contrast, much of the Salmon River flows through the Frank Church River of No Return Wilderness Area, one of the least developed areas of the contiguous United States. Only about 150 km of the Salmon River flows through lands with developed agriculture and these areas are minor compared to agricultural developments along the Snake River. Because virtually all land uses within a watershed impact hydrology, sediment and nutrient fluxes, the different human histories of the watersheds would result in different inputs into the Snake versus Salmon River systems.

Also related to human history, the Snake and Salmon Rivers represent an extreme contrast with respect to river damming. The Salmon River is nondammed, although it was briefly impounded by the small Sunbeam Dam in its headwaters near Stanley, Idaho. The Salmon River is one of the last large free-flowing rivers in the contiguous United States, whereas the Snake River is one of the most extensively dammed and diverted rivers in North America (Palmer 1991). Damming commences in the headwater region of Grand Teton National Park with Jackson Lake Dam that elevates a natural lake. It is followed by Palisades Dam, a sequence of weirs near Idaho Falls, and substantial dams at American Falls, Minidoka, Milner, Shoshone Falls, Twin Falls, Upper Salmon, Lower Salmon, Bliss, CJ Strike, and Swan Falls, upstream of the HCC. There are also 41 major dams along the tributaries of the Snake River upstream from Hells Canyon. These dams and reservoirs would considerably modify the flow regime and trap sediment above the HCC.

These assessments provide mixed conclusions relative to comparing the Hells Canyon reach of the Snake River with the Lower Salmon River Gorge. The local river valley landscapes and riparian vegetation communities are very similar, but there are considerable differences in the watersheds and major differences in upstream damming. Analyses of the Hells Canyon reach of the Snake River versus the Lower Salmon River Gorge should thus provide

**Table 3** Hydrological characteristics of river reaches in the Hells Canyon region

| River gauge <sup>a</sup>                    | Years of record | Drainage area (km <sup>2</sup> ) | Mean annual discharge (m <sup>3</sup> /s) |      |     | Annual peak discharge (m <sup>3</sup> /s) |      |     |
|---|-----------------|----------------------------------|---|------|-----|---|------|-----|
|   |                 |                                  | Ave                                       | Max  | Min | Ave                                       | Max  | Min |
| Snake River at Murphy                       | 1914–1998       | 108,521                          | 314                                       | 543  | 191 | 706                                       | 1339 | 306 |
| Major tributaries above Weiser <sup>b</sup> | 1914–1998       | 70,707                           | 198                                       | 488  | 48  | 593                                       | 1053 | 116 |
| Snake R. at Weiser                          | 1914–1998       | 179,228                          | 513                                       | 1031 | 239 | 1299                                      | 2393 | 422 |
| Snake R. at Hells Canyon Dam <sup>a</sup>   | 1965–1997       | 189,847                          | 585                                       | 1035 | 276 | 1356                                      | 2777 | 578 |
| Salmon R. at Whitebird                      | 1914–1998       | 35,095                           | 316                                       | 506  | 165 | 1798                                      | 3681 | 617 |

<sup>a</sup> Hells Canyon Dam data were provided by Idaho Power Corp. and data for other gauges were derived from USGS gauging stations

<sup>b</sup> Owyhee, Boise, Malheur, Payette, and Weiser rivers. The associated peak flow values are estimates based on data from Weiser and Murphy gauges



a useful but somewhat confounded spatial comparison (Table 2).

### Temporal Comparisons

Temporal comparisons involve sequential analyses of the same river reach(es) and may involve comparative field measurements at different time periods, consideration of indirect records, such as ground or aerial photographs, or the analyses of ecological elements that provide chronosequences, such as progressive arcuate bands of vegetation or tree rings (studies cited in Table 1). The focus of temporal comparisons is on the river reach downstream from a dam, but simultaneous study of other reaches along the same river or an adjacent river(s) would reveal broader regional patterns upon which the impacts of damming are superimposed (Table 1).

Temporal comparisons are common for ecological analyses following environmental disturbance (Underwood 1994; Stewart-Oaten and Bence 2001), and are based on the assumption that a particular region should demonstrate ecological consistency over time. Consequently, observed changes following damming may be interpreted to reveal impacts of damming and flow regulation (Williams and Wolman 1984; Ligon and others 1995; Friedman and others 1998). However, river systems are naturally dynamic, with considerable seasonal and interannual variations in hydrology, including periodic disturbance, particularly from floods, that can produce major ecological change (Junk and others 1989; Naiman and others 2005; Rood and others 2007). Thus, the scientific challenge in interpreting temporal patterns is to resolve the impacts due to damming and flow regulation from the natural variations of these physically-dynamic fluvial systems.

#### *Pre- Versus Post-Dam*

*Concept* – The analysis of sequential change along a particular river reach following damming may provide the most direct approach for analyzing ecological impacts downstream from dams. However, rigorous temporal comparisons are hindered due to the history of river damming projects and the nature of research funding. Relative to project history, many dams were implemented in the twentieth century following geotechnical and hydrologic studies but with minimal pre-project biophysical study. Neither the values nor the vulnerabilities of river ecosystems were generally appreciated and many of the major dams in western North America were situated in remote locations and were implemented with limited public interest in environmental consequences. Because these

dams were undertaken before comprehensive environmental impact analyses were required, ecological attributes were often neglected and pre-dam ecological conditions were rarely inventoried.

The second impediment is the nature of research funding. Because funding is generally limited in duration, it is more practical to seek funding for a limited-term project with a short-term “deliverable” than for a long-term study, potentially with an uncertain duration and outcome. The nature of academic study also favors a shorter-term comparison because research projects often involve two or three-year intervals to suit graduate student and post-doctoral projects.

Due to these practical limitations, temporal comparisons have often relied upon archival materials such as ground-level and aerial photographs (studies cited in Table 1). Ground-level photographs were seldom based on pre-determined sampling strategies for ecological investigation but were instead generally taken for human interest. The sites of historic photographs are often biased towards locations with ease of access or for atypical landscape features that are dramatic or scenic. Aerial photographs provide more systematic coverage, but are insufficient to reveal small-scale features such as plant species and community types. Comparisons involving both ground-level and aerial photographs are often complementary because the two approaches partially compensate for the prospective weaknesses.

*Application* – The pre- versus post-dam comparison has considerable merit relative to Hells Canyon but pre-dam information particularly regarding riparian vegetation is sparse. Hells Canyon is remote and sparsely inhabited and very few photographs exist from the pre-dam period. In contrast, Hells Canyon is now one of the world’s most highly regarded recreational river trip destinations. The spectacular landscape provides a prime attraction and consequently the river valley has been extensively, but not systematically, photographed in recent decades.

#### *Sequential Post-Damming*

*Concept* – Similar to pre- versus post-dam comparisons, the sequential post-damming comparison provides a temporal approach that focuses on the specific river reach below a dam. It involves two or more observation or sampling periods after the dam is implemented and, especially with multiple observations, it can reveal quantitative patterns that may enable future forecasting (Dixon and Johnson 1999). This approach may also be more practical than pre- versus post-damming comparisons due to the deficiency of pre-dam inventory. Additionally, remote sensing inventories have become more common through

the twentieth century and aspects such as aerial photographs and more recently, digital multispectral imagery, are now available with repetitive coverage for many landscapes (Lorang and others 2005).

For sequential temporal comparison, an appropriate time-frame must be considered relative to the dam project and the environmental components of interest. Some responses occur within a few years, while others require decades or even centuries for change (Williams and Wolman 1984; Church 1995). As a composite study, the combination of pre-project inventory followed by sequential post-dam study can strengthen the analysis since this overlaps the two temporal study approaches.

*Application* – For the Hells Canyon reach of the Snake River, the sequential post-damming comparison is enabled by periodic aerial photographs. These commenced when the first dam was under construction and have been repeated at about one to two decade intervals thereafter. Early photographs were black and white and more recent photographs are often in true-color or false-color, infra-red. The resolution of aerial photographs limits the scale of landscape feature that can be assessed and those for Hells Canyon are only suitable for large physical features such as river channel position and the extent of major sand bars. Through the interpretation of sequential aerial photographs, Schmidt and others (1995) previously interpreted post-damming depletion in sand bars along the Hells Canyon reach of the Snake River, particularly in the first two decades after damming.

Long-lived woody plants also enable investigations of riparian landscape chronology. In Hells Canyon netleaf hackberry and sandbar willow are abundant small trees and shrubs that are appropriate to investigate distribution and population age structure and hence, prospective impacts of damming and flow regulation on recruitment, expansion and mortality (Rood and others 1995).

#### *Flow Modification*

*Concept* – Comparative study approaches yield correlative data, including abundances in ecological attributes, such as woodland groves or sandbars, that may change following damming. This reveals correlative pattern but not causal association. The deliberate modification of flow or sediment regime provides an experimental manipulation that can confirm causal association (Rood and Mahoney 2000; Patten and others 2001; Schmidt and others 2001; Rood and others 2003b). Flow modification may follow comparative investigations and enable testing of hypotheses arising from observed responses. Although deliberate flow modification may provide the most definitive study approach, its implementation is restricted by practical

considerations. There have been relatively few instances in which dam operations have been deliberately altered in response to ecological considerations but following some initial successes (Rood and others 2005) modifications may increase in future.

*Application* – The HCC has recently undergone an environmental review in association with the Federal Energy Regulatory Commission relicensing process. Following from that review it is possible that dam operations will remain relatively unchanged. However, if dam operations are altered, appropriate ecological investigations should be undertaken to assess the environmental consequences and to capitalize on the research opportunities.

#### *Process-Based Biophysical Modeling*

*Concept* – Process-based modeling relies on systematic relationships between underlying physical components of hydrology and geomorphology, and subsequent biological responses, such as the establishment, survival, and growth of riparian plants (Auble and others 1994; Johnson and others 1995; Springer and others 1999; Mahoney and Rood 1998; Richter and Richter 2000). This modeling considers stochastic patterns and assumes deterministic relationships that are predictably quantitative and represents a relatively new approach for analyzing ecological impacts downstream from dams.

Relative to riparian ecology, modeling requires an understanding of the life history strategies of different riparian plants, including both native and nonnative species (Shafroth and others 2002; Karrenberg and others 2002; Rood and others 2003a). Life history defines the phenology (timing) of seed release and other developmental events, as well as aspects of the physiological water relations that underlie flood and drought tolerance (Tyree and others 1994; Mahoney and Rood 1998; Nilsson and Svedmark 2002). Modeling involves hydrologic analysis of river stage in conjunction with discharge patterns since it is the water elevation that determines the moistening or inundation of riparian zones critical to seedling (or clonal) colonization (Auble and others 1994; Scott and others 1996; Rood and others 2003b). The modeling requires analyses of riparian substrate and particularly sediment textures since this influences erosion resistance and moisture retention that also contributes to seedling survival (Mahoney and Rood 1990; Polzin and Rood 2006). The modeling involves multiple year simulations to account for the natural variation in inflows and the multiple-year life cycle of perennial plants (Auble and others 1994; Scott and others 1996). The modeling may emphasize the large, woody plants that are especially important for wildlife

habitat as these provide “structure” through vertical development of woodland groves (Rood and others 2003b).

*Application* – The Hells Canyon reach of the Snake River is well-suited for process-based modeling. The bedrock dominated landscape is static relative to the longevity of the riparian plants, reducing the need to account for the dynamic channel changes along alluvial river reaches. The hydrology may also be simpler than along other rivers because the major inflow originates from dam release and only small tributaries occur along the Hells Canyon reach. With a very dry regional climate in the valley bottom, local precipitation and ground-water contribution are also limited, strengthening the linkage between river regulation and riparian soil moisture. With the prominent bedrock and minimal floodplain zones, associated vegetation are relatively limited in both extent and species diversity, thus reducing the range of plants needed to be considered in hydrogeomorphic modeling. Additionally, with a xeric upland landscape, adjacent vegetation is naturally sparse and this would reduce some complexity due to competition and other biological interactions. On the basis of these considerations, the Hells Canyon reach of the Snake River could provide an ideal study system for the development or refinement of process-based hydrogeomorphic models (Auble and others 1994; Mahoney and Rood 1998) similar to those implemented for the Middle Snake River (Johnson and others 1995).

#### Comparative Validity Across Study Approaches

The semi-quantitative comparison of the different comparative strategies indicated that for the Hells Canyon reach: (1) pre- versus post-dam comparison would provide a valid study approach (Table 4), (2) spatial comparison of the Hells Canyon reach versus the Lower Salmon River Gorge would also be useful, particularly due to the biophysical similarities of the adjacent canyon environments, and (3) an upstream versus downstream comparison is

complicated by the natural geomorphic transition. A combination of all three comparisons would provide the most comprehensive approach since this could account for natural and anthropogenic differences in both the proximal (local) and distal (watershed) landscapes.

#### Discussion

In this study, we reviewed and categorized various research strategies that researchers have used to analyze ecological impacts in riparian zones downstream from dams in western North America (Table 1). Similar research strategies have been used for dams in other regions worldwide and many of the fundamental considerations are universal (Petts 1984; Williams and Wolman 1984; Ligon and others 1995; Lytle and Poff 2004). We also provided qualitative analyses of the suitability of these approaches for Hells Canyon (Table 2) and provided a semi-quantitative consideration of validity (Table 4). However, these research strategies are prone to a number of potentially confounding factors (Table 2). With respect to comparative studies, responses are correlative in nature and some effects may not be caused by the dam or the associated alteration to downstream flows. As a result, the following factors should be considered: natural variation, coincidental influences, cumulative and sequential impacts, threshold effects, and latent effects.

#### Natural Variation

Riparian zones are naturally extremely dynamic reflecting river flows that vary seasonally across years (Trush and others 2000; Naiman and others 2005; White and others 2005). Occasional floods provide powerful agents of erosion and deposition and can immediately have dramatic impacts on aquatic and riparian zones. Floods often enable bursts of recruitment by riparian plants and some other

**Table 4** Assessment of different comparison studies for analyzing impacts of damming and flow regulation on the Snake River through Hells Canyon

|   | Proximal score (P) local landscape (weight = 2) | Distal score (D) watershed conditions (weight = 1) | Comparability index = P + D |
|---|---|--|-----------------------------|
| Upstream vs. downstream (Weiser vs. Hells Canyon) | Different (0.5)                                 | (almost the) Same (1)                              | 1.5                         |
| Dammed vs. free-flowing (Hells Canyon vs. Salmon) | Very similar (1.5)                              | Different (0.25)                                   | 1.75                        |
| Pre- vs. post-dam (Hells Canyon)                  | Same (2)  | Very similar (0.75)                                | 2.75                        |

We applied a quartile scaling of: 0 = very different; 0.25 = different; 0.5 = somewhat different; 0.75 = very similar; or 1.0 = same; and multiplied this value by the weight to produce the P and D score

biota and thus, the initial “destruction” may be followed by ecosystem rejuvenation, a sequence of events consistent with the flood pulse concept (Junk and others 1989; Scott and others 1996).

In contrast to natural floods, droughts lead to natural declines in some riverine biota such as riparian vegetation, due to drought-induced mortality (Tyree and others 1994). Following particular wet or dry years or multiple-year wet and dry cycles, aquatic and riparian populations naturally experience episodes of decline and recovery. These natural cycles provide a variable baseline upon which impacts of damming and flow-regulation are superimposed.

#### Coincidental Influences

Aquatic and riparian ecosystems are influenced by many natural and anthropogenic factors (Naiman and others 2005), which may temporally or spatially coincide with river damming. For example, exotic weeds have progressively migrated through the western United States and in some areas their expansion coincides with periods of extensive river damming. Within remote landscapes, such as Hells Canyon, major dam projects introduce roads and utility corridors that facilitate many human uses and impacts that further alter riverine environments.

#### Cumulative and Sequential Impacts

Like many other rivers in North America and worldwide (Graf 1999; Nilsson and others 2005), the Snake River is extensively dammed and diverted (Palmer 1991). The combined impacts from the various water resource projects make it very difficult to isolate those effects specifically related to the Hells Canyon Complex. With respect to river environments, we suggest that cumulative impacts be viewed as those effects that accumulate spatially along the longitudinal corridor whereas sequential impacts are those that accumulate over time. Some of these impacts may be additive while other response functions may be more complex and more difficult to resolve or model.

#### Threshold Effects

Threshold effects are related to cumulative and sequential impacts. For threshold effects, the ecosystem or component may remain relatively unaltered up to a point at which a substantial response occurs. Threshold effects are particularly relevant to physiological stresses that are tolerable within a specific range of environmental conditions. For example, cold water fish may be unaffected until aquatic

conditions exceed particular thresholds in temperature and oxygen levels (Ruckelshaus and others 2002). Similarly for riparian plants, water stress due to instream flow reduction may have minor impact until the xylem cavitation threshold is reached which can lead to abrupt mortality (Tyree and others 1994). Thus, threshold effects reflect nonlinear ecosystem dynamics that confound analyses such as instream flow needs (IFN) calculations.

#### Latent Effects

Latent effects are those in which the timing of a response is delayed, thus complicating temporal comparisons. For example, an alteration in stream flow pattern may eliminate fish spawning or vegetation recruitment, but if monitoring is focused on the population of mature fish or trees, the impact may not be revealed until a substantial fraction of the life cycle passes. Alternately, higher-order members of a riverine ecosystem may not be affected by a negative impact until the lower-order prey base is substantially diminished (Power and others 1995).

#### Multiple Comparisons

Due to the limitations of individual study approaches and the range of confounding factors, simple comparisons involving specific spatial or temporal comparison are vulnerable (Stewart-Oaten and Bence 2001). Conversely, integrative comparisons among multiple river reaches over several time intervals (Table 2) would enhance data interpretation and subsequent study conclusions. In the ideal case, several comparative approaches would be used although this is rarely practical (Table 1).

For Hells Canyon, the Schmidt and others (1995) interpretation of aerial photographs provided a form of sequential post-damming comparison. This study would be complemented by further research to reveal the range of dam-related impacts on the riparian ecosystem along the Hells Canyon corridor (Table 1).

#### A Composite Study Strategy for Hells Canyon

The analysis of different comparisons (Table 4) suggests that the pre- versus post-dam analysis would provide a particularly valid single study approach for the Hells Canyon reach of the Snake River. However, pre-dam information is limited to a few historic descriptions and archival photographs with limited spatial coverage. Comparisons of the historic descriptions and photographic views with contemporary conditions would be useful and

may especially reveal changes in vegetation that would complement Schmidt and others' (1995) study of sand bars. Subsequently, current vegetation and sediment conditions could be more thoroughly investigated through a composite spatial analysis (Fig. 5). Further, vegetation analyses could also be linked to habitat studies to assess prospective influences on wildlife (Blair and others 2002), and reveal the extent of invasive weeds which are increasingly problematic in riparian zones (Naiman and others 2005). When coupled with detailed analyses of hydrology, these data could provide a confident foundation for hydrogeomorphic modeling of the plant species and communities.

This composite study design would thus involve overlapping all three spatial comparisons (Fig. 5) to compliment and calibrate a process-based modeling approach (Tables 1 and 2). This study design would also provide a dam operator with information to assist in the management of large dams for multiple benefits, including environmental conservation along the downstream river reach (Richter and Richter 2000; Rood and others 2005). The development and implementation of this comprehensive study design would also provide an informative case study that would be relevant for other rivers impacted by dams and regulated flows.

Although the upstream versus downstream comparison is confounded by a natural geomorphic transition, we propose to initiate this composite study along the Weiser reach upstream from the HCC (Fig. 5). Sampling could continue along each of the three sequential reservoirs (Fig. 1), with more intensive sampling downstream from Hells Canyon Dam. Sequential sampling would also extend below confluence of the Salmon River (Fig. 5). Complementary sampling along the Lower Salmon River Gorge would enable spatial comparisons between a free-flowing river and the dammed Hells Canyon reach of the Snake River. To complement longitudinal (downstream) sampling, transverse (upslope from the river) patterns in vegetation and substrate would also be inventoried to provide yet another form of spatial analysis, revealing correspondence between water-levels, substrate, and vegetation.

As a final component of the composite study design, we propose the extension and implementation of process-based modeling (Johnson and others 1995). The proposed field sampling strategy would be extensive and as indicated, we consider that the exceptionally static, bedrock-dominated Hells Canyon landscape may be particularly well suited for hydrogeomorphic model development. In contrast to alluvial rivers with frequently shifting channels and banks, changes in river channel position along Hells Canyon are minimal within a time frame corresponding to the life cycle of riparian plants. Additionally, the hot and dry climate restricts the number of local plant species further

simplifying this system. Thus, despite the vast scale and remote situation of this dramatic landscape, we consider that Hells Canyon presents an ideal opportunity to advance process-based models to analyze functional interactions in this riparian ecosystem and to refine research strategies used to analyze ecological impacts downstream of dams.

**Acknowledgments** This research was supported by a contract from Idaho Power Company (IPC), funding to S. Rood from the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Alberta Ingenuity Centre for Water Research (AICWR). We extend sincere thanks to Bob Simons of Simons & Assoc., Colorado, Gary Holmstead, Anthony Holthuijzen, Frank Edelman and Allan Ansell of IPC for their insightful discussions about river damming and the environments along the Snake River, Andrea Kalischuk for research assistance, and to Drs. Michael Church, Frank Magilligan, Duncan Patten, Jack Schmidt, and three anonymous reviewers for their thoughtful reviews.

**Open Access** This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

## References

- Adair ED, Binkley D, Andersen DC (2004) Patterns of nitrogen accumulation and cycling in riparian floodplain ecosystems along the Green and Yampa rivers. *Oecologia* 139:108–116
- Andersen DC, Cooper DJ (2000) Plant-herbivore-hydroperiod interactions: effects of native mammals on floodplain tree recruitment. *Ecological Applications* 105:1384–1399
- Andrews ED (1986) Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. *Geological Society of America Bulletin* 97:1012–1023
- Auble GT, Friedman JM, Scott ML (1994) Relating riparian vegetation to present and future streamflows. *Ecological Applications* 4:544–554
- Blair C, Braatne JH, Rood SB, Simons RK (2002) Effects of Construction and Operating the Hells Canyon Hydroelectric Complex on Wildlife Habitat. Technical Appendix Vol. 12, Technical Report E.3.2–44, in New License Application Hells Canyon Hydroelectric Project, Idaho Power Company, Boise, Idaho
- Church M (1995) Geomorphic response to river flow regulation: case studies and time-scales. *Regulated Rivers: Research & Management* 11:3–22
- Collier MP, Webb RH, Andrews ED (1997) Experimental flooding in the Grand Canyon. *Scientific American* 276:82–89
- Cooper DJ, Merritt DM, Andersen DC, Chimner RA (1999) Factors controlling the establishment of Fremont cottonwood seedlings on the upper Green River, USA. *Regulated Rivers: Research & Management* 15:419–440
- Cooper DJ, Anderson DC, Chimner RA (2003) Multiple pathways for woody plant establishment on floodplains at local to regional scales. *Journal of Ecology* 91:182–196
- Dixon MD, Johnson WC (1999) Riparian vegetation along the middle Snake River, Idaho: Zonation, geographical trends, and historical changes. *Great Basin Naturalist* 59: 18–34
- Friedman JM, Osterkamp WR, Scott ML, Auble GT (1998) Downstream effects of dams on channel geometry and bottomland

- vegetation: regional patterns in the Great Plains. *Wetlands* 18:619–633
- Graf WL (1999) Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research* 3:1305–1311
- Grams PE, Schmidt JC (2002) Stream flow regulation and multi-level flood plain formation: channel narrowing on the aggrading Green River in the eastern Unita Mountains, Colorado and Utah. *Geomorphology* 44:337–360
- Grant GE, Schmidt JC, Lewis SL (2003) A geological framework for interpreting downstream effects of dams on rivers. in 'A Unique River' *Water Science and Application* 7, American Geophysical Union, Washington, DC. pp. 209–225
- Hughes FMR, Rood SB (2003) The allocation of river flows for the restoration of woody riparian and floodplain forest ecosystems: a review of approaches and their applicability in Europe. *Environmental Management* 32:12–33
- Jansson R, Nilsson C, Renofalt B (2000) Fragmentation of riparian floras in rivers with multiple dams. *Ecology* 81:899–903
- Johnson WC, Dixon MD, Simons R, Jenson S, Larson K (1995) Mapping the response of riparian vegetation to possible flow reductions in the Snake River, Idaho. *Geomorphology* 13:159–173
- Johnson WC (1998) Adjustment of riparian vegetation to river regulation in the great plains, USA. *Wetlands* 18:608–618
- Junk WJ, Bayley PF, Sparks RE (1989) The flood pulse concept in river-floodplain systems. *Can Spec Publ Fish Aquat Sci* 106:110–127
- Kareiva P, Marvier M, McClure M (2000) Recovery and management of spring/summer Chinook salmon in the Columbia River Basin. *Science* 290:977–979
- Karrenberg S, Edwards PJ, Kollman J (2002) The life history of *Salicaceae* living in the active zone of floodplains. *Freshwater Biology* 47:733–748
- Kondolf GM (1997) Hungry water: effects of dams and gravel mining on river channels. *Environmental Management* 21:533–551
- Ligon FK, Dietrich WE, Trush WJ (1995) Downstream ecological effects of dams: a geomorphic perspective. *BioScience* 45:183–192
- Lorang MS, Whited DC, Hauer FR, Kimball JS, Stanford JA (2005) Using airborne multispectral imagery to evaluate geomorphic work across floodplains of gravel-bed rivers. *Ecological Applications* 15:1209–1222
- Lytle DA, Poff NL (2004) Adaptation to natural flow regimes. *Trends in Ecology and Evolution* 19:94–100
- Magilligan FJ, Nislow KH, Graber BE (2003) Scale-independent assessment of discharge reduction and riparian disconnectivity following flow regulation by dams. *Geology* 31:569–572
- Mahoney JM, Rood SB (1998) Stream flow requirements for cottonwood seedling recruitment - an integrative model. *Wetlands* 18:634–645
- Malde HE (1991) Quaternary geology and structural history of the Snake River Plain, Idaho and Oregon. In Morrison RB (ed), 'Quaternary nonglacial geology; conterminous U.S.', Vol. K-2 of *The Geology of North America*, Geological Society of America, Boulder, CO. pp. 252–281
- Merritt DM, Cooper DJ (2000) Riparian vegetation and channel change in response to river regulation: A comparative study of regulated and unregulated streams in the Green River Basin, USA *Regulated Rivers: Research & Management* 16:543–564
- Naiman RJ, Décamps H, McClain ME (2005) *Riparia - Ecology, Conservation, and Management of Streamside Communities*. Elsevier Acad. Pr., Amsterdam, 430 pp
- Nilsson C, Berggren K (2000) Alteration of riparian ecosystems caused by river regulation. *BioScience* 50:783–792
- Nilsson C, Reidy CA, Dynesius M, Revenga C (2005) Fragmentation and flow regulation of the world's large river systems. *Science* 308:405–408
- Nilsson C, Svedmark M (2002) Basic principles and ecological consequences of changing water regimes: riparian plant communities. *Environmental Management* 30: 468–480
- Palmer T (1991) *The Snake River: Window to the West*. Island Press, Washington D.C. 320 p
- Parkinson S, Anderson K, Conner J, Milligan J (2003) Sediment transport, supply, and stability in the Hells Canyon Reach of the Snake River. Technical Report Appendix E.1-1, of Idaho Power Company submission: Hells Canyon Complex, FERC No. 1971. Boise, ID., 262 pp
- Patten DT, Harpman DA, Voita MI, Randle TJ (2001) A managed flood on the Colorado River: Background, objectives, design, and implementation. *Ecological Applications* 11:635–643
- Petts GE (1984) *Impounded Rivers: Perspectives for Ecological Management*. John Wiley and Sons, Chichester, UK, 326 pp
- Poff NL, Allan JD, Bain MB, Karr JR, Prestegard KL, Richter BD, Sparks RE, Stromberg JC (1997) The natural flow regime: a paradigm for river conservation and restoration. *BioScience* 47:769–784
- Polzin ML, Rood SB (2006) Effective disturbance: seedling safe sites and patch recruitment of riparian cottonwoods after a major flood of a mountain river. *Wetlands* 26:965–980
- Power ME, Sun A, Parker G, Dietrich WE, Wootton JT (1995) Hydraulic food-chain models: an approach to the study of food-web dynamics in large rivers. *BioScience* 45:159–167
- Richter BD, Richter HE (2000) Prescribing flood regimes to sustain riparian ecosystems along meandering rivers. *Conservation Biology* 14:1467–1478
- Rood SB, Braatne JH, Hughes FMR (2003a) Ecophysiology of riparian cottonwoods: stream flow dependency, water relations and restoration. *Tree Physiology* 23:1113–1124
- Rood SB, Goater LA, Mahoney JM, Pearce CM, Smith DG (2007) Floods, fire and ice: disturbance ecology of riparian cottonwoods. *Canadian Journal of Botany* (in press)
- Rood SB, Gourley C, Ammon EM, Heki LG, Klotz JR, Morrison ML, Mosley D, Scopettone GG, Swanson S, Wagner PL (2003b) Flows for floodplain forests: successful riparian restoration. *BioScience* 53:647–656
- Rood SB, Mahoney JM (1990) Collapse of riparian poplar forests downstream from dams in western prairies: probable causes and prospects for mitigation. *Environmental Management* 14:451–464
- Rood SB, Mahoney JM (2000) Revised instream flow regulation enables cottonwood recruitment along the St. Mary River, Alberta, Canada. *Rivers* 7:109–125
- Rood SB, Mahoney JM, Reid DE, Zilm L (1995) Instream flows and the decline of riparian cottonwoods along the St. Mary River, Alberta. *Canadian Journal of Botany* 73:1250–1260
- Rood SB, Samuelson GM, Braatne JH, Gourley CR, Hughes FMR, Mahoney JM (2005) Managing river flows to restore floodplain forests. *Frontiers in Ecology and the Environment* 3:193–201
- Ruckelshaus MH, Levin P, Johnson JB, Kareiva PM (2002) The Pacific Salmon Wars: what science brings to the challenge of recovering species. *Annual Review of Ecology and Systematics* 33:665–706
- Schmidt JC, Grams PE, Webb RH (1995) Comparison of the magnitude of erosion along two large regulated rivers. *Water Resources Bulletin* 31:617–631
- Schmidt JC, Parnell RA, Grams PE, Hazel JE, Kaplinkski MA, Stevens LE, Hoffnagle TL (2001) The 1996 controlled flood in Grand Canyon: flow, sediment transport, and geomorphic change. *Ecological Applications* 11:657–671

- Schumm SA (2005) River variability and complexity. Cambridge Univ. Pr., Cambridge UK, 234 pp
- Scott ML, Auble GT, Friedman JM (1996) Fluvial process and the establishment of bottomland trees. *Geomorphology* 14:327–339
- Shafroth PB, Stromberg JC, Patten DT (2002) Riparian vegetation response to altered disturbance and stress regimes. *Ecological Applications* 12:107–123
- Springer AE, Wright JM, Shafroth PB, Stromberg JC, Patten DT (1999) Coupling groundwater and riparian vegetation models to assess effects of reservoir releases. *Water Resources Research* 35:3621–3630
- Stevens LE, Schmidt JC, Ayers TJ, Brown BT (1995) Flow Regulation, geomorphology and Colorado-River marsh development in the Grand-Canyon, Arizona. *Ecological Applications* 5:1025–1039
- Stewart-Oaten A, Bence JR (2001) Temporal and spatial variation in environmental impact assessment. *Ecological Monographs* 71:305–339
- Trush WJ, McBain SM, Leopold LB (2000) Attributes of an alluvial river and their relation to water policy and management. *Proceedings of the National Academy of Sciences USA* 97:11858–11863
- Tyree MT, Kolb KJ, Rood SB, Patino S (1994) Vulnerability to drought-induced cavitation of riparian cottonwoods in Alberta - a possible factor in the decline of the ecosystem. *Tree Physiology* 14:455–466
- Underwood AJ (1994) On beyond BACI – sampling designs that might reliably detect environmental disturbances. *Ecological Applications* 4:3–15
- Vallier T (1998) Islands & Rapids, The Geologic Story of Hells Canyon. Confluence Press, Lewiston ID. 151 p
- Vannote RL, Minshall GW, Cummins KW, Sedell JR, Cushing CE (1980) The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37:130–137
- Ward JV, Stanford JA (1995a) Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers: Research & Management* 11:105–119
- Ward JV, Stanford JA (1995b) The serial discontinuity concept: extending the model to floodplain rivers. *Regulated Rivers: Research & Management* 10:159–168
- Webb RH (1996) Grand Canyon, a century of change. University of Arizona Press, Tuscon AZ. 290 p
- White MA, Schmidt JC, Topping DJ (2005) Application of wavelet analysis for monitoring the hydrologic effects of dam operation: Glen Canyon Dam and the Colorado River at Lees Ferry, Arizona. *River Research and Applications* 21:551–565
- Williams GP, Wolman MG (1984) Downstream effects of dams on alluvial rivers. U.S. Geological Survey Professional Paper 1286, 83 p