Downstream hydrologic and geomorphic effects of large dams on American rivers

William L. Graf

Department of Geography, University of South Carolina, Columbia, SC, 29208, USA

Abstract

The hydrology and geomorphology of large rivers in America reflect the pervasive influence of an extensive water control infrastructure including more than 75,000 dams. One hundred thirty-seven of the very large dams, each storing 1.2 km^3 (10^6 acre feet) of water or more, alter the flows of every large river in the country. The hydrologic effects of these very large dams emerge from an analysis of the stream gage records of 72 river reaches organized into 36 pairs. One member of each pair is an unregulated reach above a dam, whereas the other is a regulated reach downstream from the same structure. Comparison of the regulated and unregulated reaches shows that very large dams, on average, reduce annual peak discharges 67% (in some individual cases up to 90%), decrease the ratio of annual maximum/mean flow 60%, decrease the range of daily discharges 64%, increase the number of reversals in discharge by 34%, and reduce the daily rates of ramping as much as 60%. Dams alter the timing of high and low flows and change the timing of the yearly maximum and minimum flows, in some cases by as much as half a year. Regional variation in rivers, dams, and responses are substantial: rivers in the Great Plains and Ozark/Ouachita regions have annual maximum/mean flow ratios that are 7 times greater than ratios for rivers in the Pacific Northwest. At the same time, the ratio of storage capacity/mean annual water yield for dams is greatest for Interior Western, Ozark/Ouachita and Great Plains rivers and least for Pacific Northwest streams. Thus, in many cases those rivers with the highest annual variability have the greatest potential impact from dams because structures can exert substantial control over downstream hydrology. The hydrologic changes by dams have fostered dramatic geomorphic differences between regulated and unregulated reaches. When compared to similar unregulated reaches, regulated reaches have 32% larger low flow channels, 50% smaller high flow channels, 79% less active flood plain area, and 3.6 times more inactive flood plain area. Dams also affect the area of active areas, the functional surfaces that are functionally connected to the present regime of the river. Regulated reaches have active areas that are 72 smaller than the active areas of similar unregulated reaches. The geomorphic complexity (number of separate functional surfaces per unit of channel length) is 37% less in regulated reaches. Reductions in the size of hydrologically active functional surfaces are greatest in rivers in the Great Plains and least in Eastern streams. The largest differences in geomorphic complexity are in interior western rivers. The shrunken, simplified geomorphology of regulated large rivers has had direct effects on riparian ecology, producing spatially smaller, less diverse riparian ecosystems compared to the larger, more complex ecosystems along unregulated reaches of rivers.

1. Introduction

Writing half a century ago in *Man's Role in Changing the Face of the Earth*, Leopold (1956, p. 646) predicted

that dams would someday become so numerous on American rivers that they would be the primary factor in controlling the characteristics of river channels. His prediction is now becoming true for large American rivers, where dams are ubiquitous features that make these waterways a partly natural, partly artificial fluvial system. More than 75,000 dams, generally 2 m (6 ft) high or higher, impound portions of every river basin in the country, and every major river includes long reaches controlled to some degree by dams. A total of 137 very large structures (defined as capable of storing 10^9 m^3 or 10^6 ac ft or more) regulate, to varying degrees, the flow of the largest streams (see Graf, 2005, for a size classification of dams and an accounting with data from U.S. Army Corps of Engineers, 1996). The installation of these artificial controls in the 20th century was coincidental with far-reaching ecological changes in the river systems (Fig. 1).

During the same period, dramatic changes also occurred in riparian habitat and associated wildlife (Fig. 2). Losos et al. (1995) found that water development, mostly related to dams and diversions, contributed to the declines of more threatened and endangered species than any other resource-related activity. Representative examples include riparian obligate avian species from seemingly dissimilar parts of the country. Willow flycatchers that breed along southwestern rivers, whooping cranes that use Great Plains for migration stop-overs, and red cockaded woodpeckers inhabiting old-growth riparian forests of the southeast have suffered similar population declines. Large dams now control the rivers upon which they depended, and the pre-dam riparian habitats along the streams have changed in ways that imposed substantial limitations on the species (U.S. Fish and Wildlife Service, 2001; U.S. Fish and Wildlife Service and U.S. Bureau of Reclamation, 2004). The primary purpose of this paper is to specify the nature of the downstream hydrologic and geomorphic effects of large dams on American rivers at a continental scale, and thereby outline the general physical changes that have played themselves out in the riparian ecosystems and ultimately affected wildlife populations.

Riparian habitats are closely connected to the hydrology and geomorphology of the associated rivers (Bennett and Simon, 2004; Wohl, 2004). A general construct of the interactions among hydrology, geomorphology, and ecology illustrates the importance of dams in the processes of the fluvial and riparian systems (Fig. 3). This conceptualization of the fluvial system of a large river begins with inflow to the reservoir. The physical characteristics and operating rules of the dam determine the hydrology of releases from the structure. The dam and reservoir create local upstream effects that are not the subject of this paper, as well as more far-reaching effects downstream that alter hydrology, geomorphology, and ecology within the constraints imposed by general valley conditions. This paper limits its exploration to the downstream effects on hydrology and geomorphology
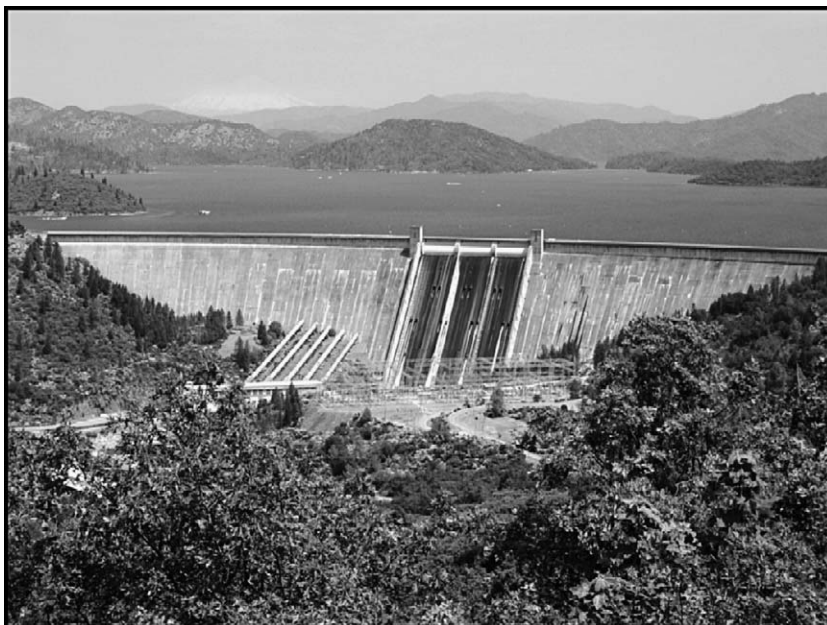

Fig. 1. Shasta Dam on the American River of Northern California exemplifies the very large dams analyzed in this paper. The dam, completed in 1945, has a storage capacity of 5.6 km^3 (4,550,000 ac ft), allowing it to exert considerable control over downstream flows. Source: 2003 image by author.

Fig. 2. Two reaches of the Marias River of northern Montana show the reduction in the extent and complexity of habitats related to dams. Upper image: 1991 aerial photograph of a 5.7 km reach of the river upstream from Tiber Dam, showing an unregulated portion of the stream with a substantial active area and complex functional surfaces. Lower image: 1991 aerial photograph of a similar 7.2 km reach of the river downstream from Tiber Dam showing deactivated flood-plain areas and a simple suite of functional surfaces. Tiber Dam, built in 1956, has a storage capacity 1.6 km^3 (1,424,000 ac ft); the river has an annual yield of 0.8 km^3 (611,700 ac ft). Source: U.S. Geological Survey, EROS Data Center, Souix Falls, S.D.

of large dams to the following questions: (1) what changes do large dams bring about in the hydrology of the rivers, and (2) how do those hydrologic adjustments play themselves out in changing the downstream geomorphology of the streams? Data from most regions of the continental United States provide a nation-wide perspective. The study does not include Hawaii, Alaska, and Puerto Rico, areas that do not have very large dams.

The significance of an improved understanding of the downstream hydrologic and geomorphic effects of very large dams is that such understanding is essential for the restoration of the rivers and for the preservation of endangered species designed under the Endangered Species Act of 1973. The Clean Water Act of 1977 makes restoration of rivers a national goal, but a goal that cannot be approached without addressing the effects of dams. The water, landforms, and materials of the aquatic and riparian habitats of the rivers provide the physical foundation for biological restoration, and it seems unlikely that restoration of altered systems will be successful without an understanding of the dam-related alterations that created the present situation. Whereas it is not likely that the nation will be able (or would want) to return its rivers to entirely natural pre-dam conditions, it may be possible to create systems that are more natural than those that have led to catastrophic declines in some wildlife populations (Postel and Richter, 2003).

After a brief review of previous work, the following narrative explains the specific Methods and Results for investigating the downstream effects of large dams first on hydrology, and then on geomorphology. A Discussion section addresses regional variation of hydrology and geomorphology as affected by dams, and explores the ecologic implications of downstream influence of
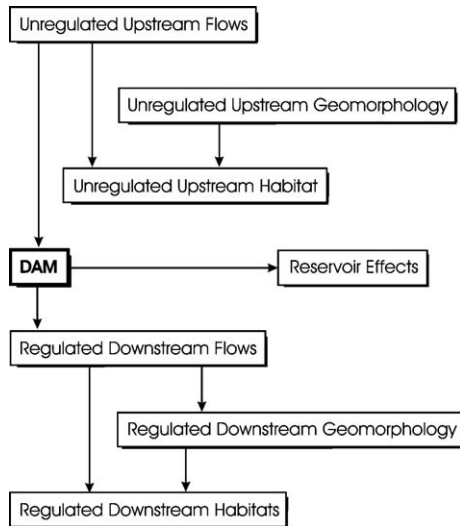
Fig. 3. A simplified construct shows the relationship among upstream unregulated components of the fluvial system and those that are regulated downstream. Source: author.

dams, while the final section is a distilled statement of Conclusions.

2. Previous research

The present paper is the seventh publication in a coordinated series on dams and American rivers. The objective of the series has been to provide a nation-wide perspective in defining physical downstream changes related to dams with likely ecosystem implications. Graf (1999) provided a census of dams in the United States with an analysis of the distribution and relationship to the overall water budget. Graf (2001) outlined the connection between the installation of dams and changes in the physical integrity of rivers. Heinz Center (2002) and Graf (2003) examined the reverse circumstance, the likely outcomes on downstream fluvial and biological systems when dams are removed. Graf (2002) assessed the connections between dams and a specific endangered species in the Southwest as a case example. Graf (2005) provided the scientific, social, and economic context for investigations into the geomorphic effects of dams on American rivers, and the present paper specifies hydrologic and geomorphic adjustments downstream from dams.

2.1. Background for ecological connections

In riverine environments, the geomorphic system forms the indispensable physical framework for the more general ecosystem. In many cases, interest in the

biological component of the more general ecosystem is the imperative that drives restoration of the river, particularly so in the case of threatened or endangered species. Successful restoration of the river for wildlife benefits depends on an understanding of the physical changes wrought by dams and their operation, and an understanding of the implications of the physical changes for wildlife habitat. A sound plan for the restoration of at-risk wildlife populations associated with rivers, therefore, relies first on restoring lost physical characteristics of the system.

This paper focuses on the hydrologic and geomorphic changes; the connection of these physical attributes to the habitats and organisms of riverine ecosystems has been firmly established by others. As demonstrated by Bennett and Simon (2004), the association between geomorphic surfaces is a product of inundation frequency and duration. The physical processes that construct and deconstruct the channel and its associated features create conditions for specific vegetation communities. The intimate connections among physical processes, the forms and materials they influence, and the resulting plant communities lies at the heart of Howard and Mitchell's (1985) conception of phytogeomorphology. This conceptual basis for environmental survey, management, and planning at a variety of scales (including the relatively local scale of analysis in the present paper) defines land units as landscape components of up to a few km^2 in extent. Each land unit has geomorphic processes, forms, and biological communities that are recognizably different from other adjacent land units. In a landscape ecology perspective, the units are patches that are distinct landscape elements with internally consistent physical and biological processes and forms (Forman and Godron, 1981, 1986).

For river landscapes, substantial previous research connects the forms and processes of the physical landscape with particular biological associations. Malanson's (1993) general review explains the connections between fluvial forms and biological communities as operating through processes of disturbance driven by hydraulic processes of the river. He makes the general case for the connection between the geography of river processes and the geography of riparian plant communities. Malanson (1993, p. 80 and 114–119) specifically identifies flooding as a major control for the biological parts of aquatic and riparian systems, and he specifically identifies the controls exerted by dams as a significant factor in riparian ecology. Investigations collated by Anderson et al. (1996) demonstrate such connections for specific cases involving flood plains. Fisher et al. (2004) extend the explanation for the fluvial-habitat connection

by introducing the addition process connection of nutrient dynamics related to flowpaths, and by arguing for a landscape orientation (rather than strictly an aspatial ecosystem approach) that accounts for spatial variation in processes, forms, and nutrient behavior (Fisher et al., 2001).

The present paper examines the connection between the hydrology-sediment regime and the resulting suite of functional surfaces, and explores how dam installation and operation change the hydrology-sediment regime and the surfaces they maintain in aquatic and riparian ecosystems. Benke and Cushing (2005) provide an encyclopedic source for examples of previous research that have explored the connection between functional surfaces and the dependent biological communities. The present paper extends previous work by providing detail about the process connection between hydrology-sediment regimes and the river landscape, and by using two geographic metrics (geomorphic complexity and standard active area) that may aid in establishing a firm process connection between the functional surfaces of the river landscape and the biological components of the aquatic and riparian ecosystem.

2.2. Downstream hydrologic and geomorphic effects of dams

Modern investigations into the downstream effects of dams emerge from more than two centuries of scientific concern about the deleterious effects of the structures in the United States. Small dams inhibited the migration of diadromous fishes along the east coast during colonial times, an issue raised as early as 1784, and that become increasingly important during the 19th century (U.S. Fish and Wildlife Service et al., 2001). In the early 20th century, investigators raised similar issues of fish passage regarding rivers in the Great Lakes region and in the Pacific Northwest. The completion of Roosevelt Dam on the Salt River of Arizona in 1911 introduced an era of installation of very large dams capable of storing large amounts of water and sediment. These very large structures went far beyond posing mere barriers to fish migration. They have been able to affect downstream processes and forms over great distances because they altered the basic hydrologic regimes of the rivers (Fig. 4). In some of the earliest investigations of these effects, Lawson (1925) and Fiock (1931) explained the role of Elephant Butte Dam on the Rio Grande as the instigator of substantial hydrologic change in downstream flows that resulted in remarkable channel adjustments. Within a decade of the closure of the structure, the channel had become choked with sediment from tributaries that the reduced flows in the main-channel were unable to transport.

In the decades immediately following Lawson's and Fiock's pioneering work, researchers paid relatively little attention to the downstream hydrology and geomorphology related to very large dams. Projects installed all of
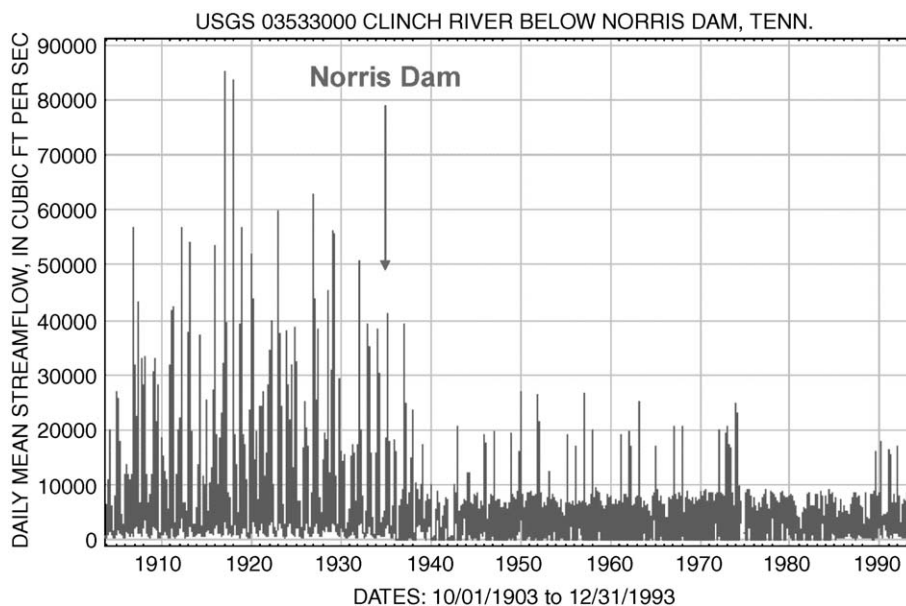

Fig. 4. The gage record of daily discharges on the Clinch River of eastern Tennesee shows the effect of the 1936 installation of Norris Dam with its 3.1 km^3 (2,552,000 ac ft) storage capacity. The annual yield of the river is 3.4 km^3 (2,910,000 ac ft). Source: U.S. Geological Survey.

these structures in the river systems during the period 1935–1975, but the decade of the 1960s, when 44 of the 137 such dams were finished, was the most prominent dam-building era. Because the purpose of the dams was to alter downstream hydrology, including efforts to suppress floods, raise water levels for navigation, and to generate hydropower, the changes in downstream flows were immediately obvious. Increasingly sophisticated and complicated release schedules became highly individualized, tailored to suit the requirements of laws, policy, and management for each structure. As a result, at the scale of the individual dam, the downstream hydrology was no mystery, because it was highly controlled. By the 1990s it was clear that this altered hydrology produced downstream changes that included the decline of previously healthy ecosystems (Ligon et al., 1995). The issue was particularly obvious in the Grand Canyon downstream from Glen Canyon Dam, where the connections among dam operations, downstream hydrology, geomorphology, and biology were the objects of numerous investigations (Carothers and Brown, 1991). Researchers began to realize that, in a general sense, the highly controlled discharges were changing the physical properties of the rivers downstream from the dams.

The number of publications pertaining to downstream hydrologic and geomorphic changes has become so large that an exhaustive review within the confines of this paper is not possible. The broad outlines of the body of work for hydrology, however, are simple: investigations have provided a picture of the changes in flow a variety of specific rivers below dams, but broad generalizations are scarce. The most well-known example is the Colorado River downstream from Glen Canyon Dam, where hydrologic studies have been under way for more than two decades by numerous researchers (summarized by Dawdy, 1991). Other locations of hydrologic investigations include the Green River of Wyoming, Colorado, and Utah (Andrews, 1986), Gunnison River of Colorado (Elliott and Parker, 1997), and the Rio Grande of New Mexico (Molles et al., 1998). The general outcomes from site-specific studies are that dams reduced flood peaks, often increased low flows, and altered the timing of peak and low flows. These studies, however, did not establish the broader, general applicability of the lessons from individual reaches of the rivers. Two recent studies are noteworthy because they sought to establish broader understanding of the effects of dams by analyzing more than a single site. Magilligan and Nislow (2001) evaluated the effects of dams of a variety of sizes on flows in the Connecticut River watershed. Their investigation of several structures showed that peak flows declined 32% in regulated rivers, with the effect of

decreasing with longer flow durations. Magilligan et al. (2003) assessed hydrologic changes at 21 dams of various sizes scattered across the nation, and found that on average the 2-year flow decreased 60% after dam installation. Further investigations are forthcoming (Magilligan and Nislow, 2005).

The literature pertaining to geomorphic changes downstream from dams has usually assessed three general subjects: sediment-related effects, effects on specific types of fluvial features, and planform changes. Many of the early investigations focused on the scour downstream from dams that caused armouring of the channel and degradation of its profile (Turner, 1971; Chadwick, 1978). General studies, site specific investigations, and research based on models all came to the same conclusion: channels downstream from dams degrade through erosion related to the trapping of sediment in the reservoir behind the dam (Taylor, 1978). Water released from the dam is relatively free of sediment and capable of downcutting, leaving the remaining bed material to consist of coarse sizes (aentûrk, 1994). The earliest wide-ranging evaluation of the downstream sediment effects of dams was that of Williams and Wolman (1984). They showed that such effects extended for up to hundreds of km downstream from the 21 large American structures that they investigated.

A second early thread of research concerned the downstream effects of dams on individual types of features along the downstream channel, beginning with the work of Dolan et al. (1974) on beaches in the Grand Canyon, a line of work in that locale that continues to the present (Powell, 2002). Beaches generally eroded, but were not rebuilt during high flows as had commonly occurred under pre-dam conditions. Downstream rapids in canyon rivers controlled by dams have also attracted attention (Graf, 1980; Dolan and Howard, 1981; Kieffer, 1987). These common features of canyon and mountain rivers responded to the reduced flood peaks imposed by upstream dams. Rapids became more stable and accumulated increasing amounts of debris, because the smaller post-dam floods could not develop sufficient force to move their deposits.

A third thread of research has sought understanding of the planform changes in rivers with hydrology altered by dams. Williams' (1978) pioneering investigations on the Platte River system of Nebraska were recently expanded by Simons and Associates (2000) and Murphy and Randle (2004). Subsequent investigations have included evaluations of the changing channel of the Rio Grande in New Mexico downstream from Cochiti Dam (Dewey et al., 1979; Lagasse, 1994) and downstream from Elephant Butte Dam (Everitt, 1993). Most of the research related to planform changes has shown that the controlled flows
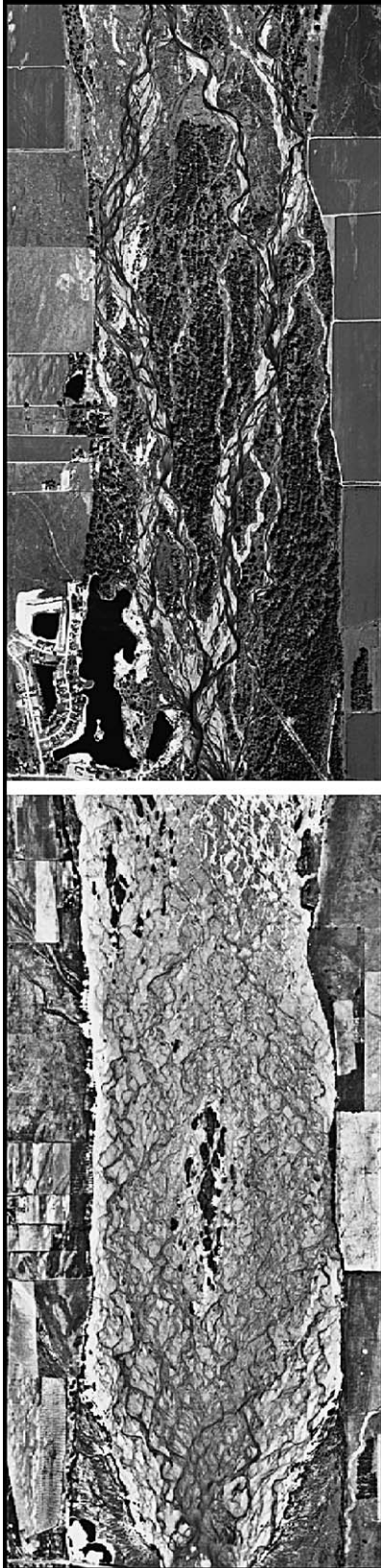
Fig. 5. Kingsley Dam built in 1941 and capable of storing 2.3 km³ (1,900,000 ac ft). The Platte River influences downstream conditions as shown in two views of the same 5.8 km (4 mi) channel reach of the river near Kearney, Nebraska, one made before the dam and the other 57 years after the installation of the dam. Left image: 1938 aerial photograph showing an extensive braided channel with a few small dark patches of wooded islands. Right image: 1998 infra-red aerial photograph showing substantial reduction in active channel width and expanded woodland cover. Source: U.S. Geological Survey.

from dams eliminate large floods, so that many areas of the previously active surfaces become stabilized and channels shrink. The loss of large annual floods also results in reduced rates of lateral migration (Shields et al., 2000). Often, extensive riparian forests colonize the inactive surfaces (Fig. 5).

The existing body of knowledge about the downstream effects of dams does not provide a national-scale picture of the effects of very large dams on large rivers, because it does not provide an understanding of the continent-wide magnitude of adjustments in many hydrologic variables. Existing reports also do not provide generalizations about adjustments in the geomorphology that are the critical underpinning of the riparian ecosystems. Presently, the most useful summary of hydro-geomorphic changes related to dams is that of Collier et al. (1996), which is an excellent introduction to the present work.

3. Methods

3.1. Basic research construct

This paper seeks to supplement existing knowledge by undertaking a standardized analysis of data from a representative sample of 36 of the largest dams in the United States to quantify the hydrologic and geomorphic changes they impose on downstream reaches of the rivers. In such a broadly-based study it is impossible to assess all aspects of the hydrologic and geomorphic changes, but it is possible to identify (1) a restricted set of hydrologic parameters and estimate the responses to the controls of dams, and (2) measure ecologically meaningful characteristics of the geomorphology that respond to hydrologic adjustments. By this approach, it may be possible to enhance the basic conceptual construct in Fig. 3 to make it more specific. Although habitat characteristics, such as diversity and stability, are beyond the present work, the hydrologic and geomorphic connections for these ecosystem parameters are obvious from the work of others (Howard and Mitchell, 1985; Malanson, 1993; Anderson et al., 1996; Bennett and Simon, 2004).

3.2. Sampling approach

One approach to assessing the effects of large dams might be to analyze hydrologic changes with historical streamflow records and assess geomorphic changes through historical aerial photography. The difficulty with this approach is that downstream from a dam changes in hydrology and geomorphology result from at least two

primary variables in addition to the influences of the structure: land use changes in the contributing basin and hydro-climatic change. Sorting out the entanglements of these two indirect influences and the direct dam-related controls is a fluvial Gordian knot. An alternative approach

is to select two representative reaches for each dam, one upstream from the structure and the other downstream, with each reach possessing similar geomorphic, geologic, and ecological characteristics. One reach is the unregulated control case, while the other is the regulated experimental

Table 1
Identification, storage capacity, and annual yield data for the 36 very large dams in the present study

Map Ref.	Dam	Reservoir	River	State	Capactiy		Annual yield	
					(km³)	(ac ft)	(km³)	(ac ft)
Eastern								
8	Douglas	Douglas	French Broad	TN	1.803	1,461,000	6.070	4,918,631
19	Kinzua	Kinzua	Allegheny	PA	1.604	1,300,000	3.333	2,700,903
17	John H. Kerr	Kerr	Roanoke	VA	3.394	2,750,300	6.738	5,460,376
12	Fontana	Fontana	Tennessee	NC	1.781	1,443,000	3.163	2,563,495
5	Center Hill	Center Hill	Caney Fork	TN	2.582	2,092,000	3.400	2,755,643
23	Norris	Norris	Clinch	TN	3.149	2,552,000	3.591	2,910,101
15	Hartwell	Hartwell	Savannah	GA	3.508	2,842,700	3.992	3,235,242
29	Sardis	Sardis	Tallahatchie	MS	3.722	3,016,000	2.193	1,776,760
4	Buford	Sidney Lanier	Chattahoochee	GA	3.152	2,554,000	1.813	1,469,508
Great Plains								
18	Keystone	Keystone	Arkansas	OK	2.144	1,737,600	6.248	5,063,425
24	Oologah	Oologah	Verdigris	OK	1.874	1,519,000	3.730	3,022,996
9	Eufaula	Eufaula	Canadian	OK	4.687	3,798,000	4.954	4,014,397
32	Tenkiller Ferry	Tenkiller	Illinois	OK	1.518	1,230,000	1.304	1,056,702
34	Tuttle Creek	Tuttle Creek	Big Blue	KS	2.785	2,257,000	1.923	1,558,194
7	Denison	Texoma	Red	TX	6.555	5,312,300	4.182	3,388,889
35	Whitney	Whitney	Brazos	TX	2.592	2,100,400	1.410	1,142,854
33	Tiber	Elwell	Marias	MT	1.758	1,424,500	0.755	611,730
36	Wright Patman	Marion	Sulphur	TX	7.072	5,730,800	2.145	1,738,027
28	Sam Rayburn	Sam Rayburn	Angelina	TX	7.819	6,336,200	1.337	1,083,779
31	Sanford	Meredith	Canadian	TX	3.004	2,434,200	0.261	211,905
Ozark and Ouachita								
2	Beaver	Beaver	White	AR	2.409	1,952,000	1.356	1,098,982
14	Grears Ferry	Grears Ferry	Little Red	AR	3.509	2,844,000	1.407	1,140,031
22	Norfork	Norfork	North Fork	AR	2.447	1,983,000	0.930	753,722
3	Blakely Mtn	Ouachita	Ouachita	AK	4.641	3,760,700	1.309	1,061,046
Pacific Northwest								
1	Albeni Falls	Albeni Falls	Pend Oreille	ID	1.425	1,155,000	22.448	18,191,552
13	Grand Coulee	F.D. Roosevelt	Columbia	WA	11.800	9,562,000	97.531	79,036,847
26	Palisades	Palisades	SF Snake	ID	1.750	1,417,800	5.886	4,770,218
Interior Western								
16	Hungry Horse	Hungry Horse	SF Flathead	MT	4.428	3,588,000	3.231	2,618,161
21	Navajo	Navajo	San Juan	NM	2.451	1,986,600	1.049	850,335
10	Flaming Gorge	Flaming Gorge	Green	UT	4.675	3,788,700	1.904	1,543,136
25	Owyhee	Owyhee	Owyhee	OR	1.481	1,200,000	0.376	304,935
6	Coolidge	San Carlos	Gila	AZ	1.324	1,073,000	0.291	235,796
California								
11	Folsom	Folsom	American	CA	1.382	1,120,000	3.305	2,678,330
27	Pine Flat	Pine Flat	Kings	CA	1.234	1,000,000	2.076	1,682,738
30	Shasta	Shasta	Sacramento	CA	5.615	4,550,000	8.167	6,618,651
20	Monticello	Berryessa	Putah	CA	2.347	1,902,100	0.388	314,803

Map references refer to Fig. 6A for locations. Sources: dam, reservoir, and capacity data from U.S. Army Corps of Engineers (1996); yield data from U.S. Geological Survey.

case, with the only major difference between the two reaches being the presence or absence of the influence of the dam (see VanLooy and Martin, 2005, for other influences eliminated by this approach). In a few cases, a reach on a nearby similar river might also serve as an unregulated control. This paired approach with comparisons between control and experimental conditions has been common in hydrology and geomorphology for small streams and watersheds (e.g., Lusby et al., 1971; Branson et al., 1981), and more recently for investigating the effects of vegetation along channels (Hession et al., 2003).

The dams and river reaches in this study met the following five selection criteria. First, the dams are very large, with reservoirs exceeding 1.2 km^3 (10^6 ac ft) of storage and 30 years old or greater, so that they are capable of exerting substantial influence on downstream
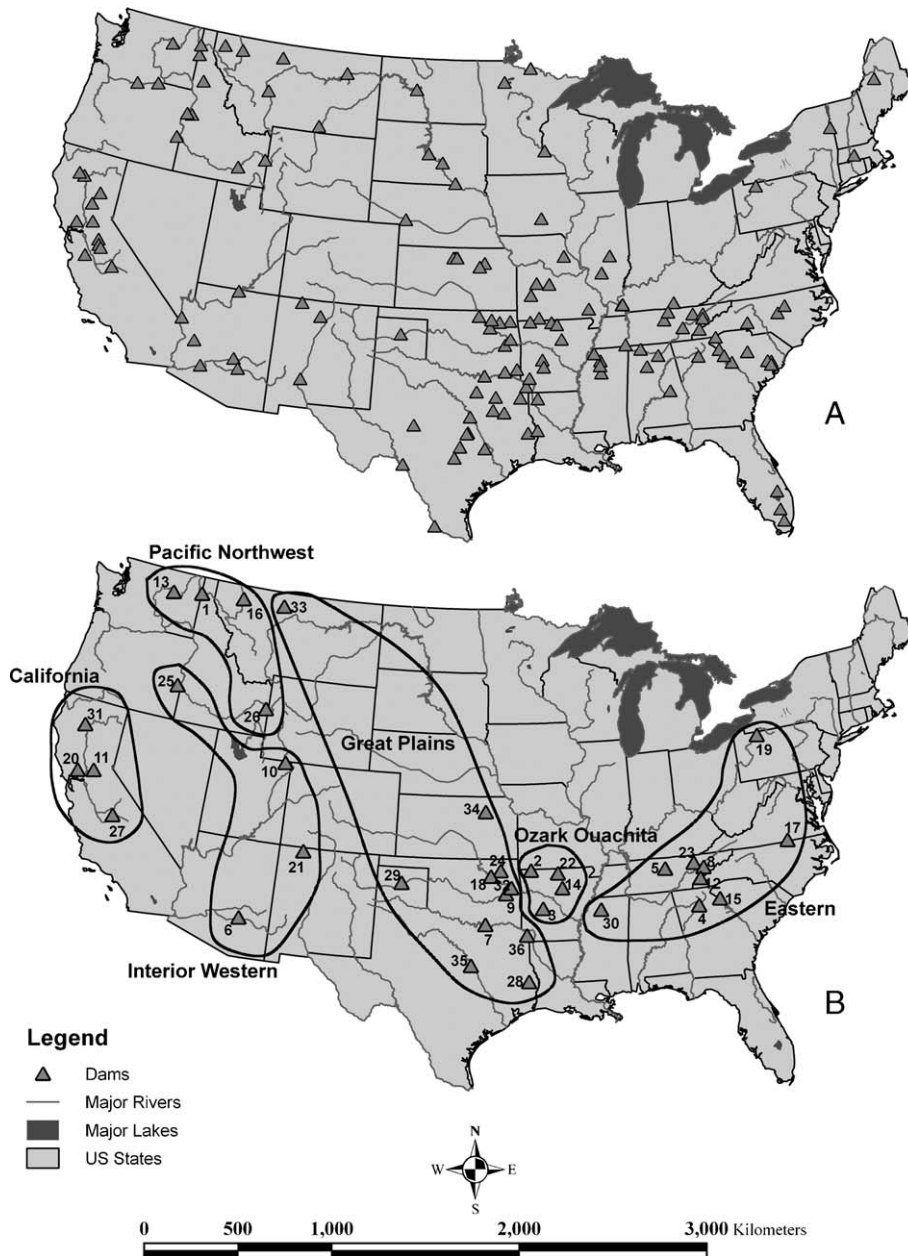

Fig. 6. The distribution of all very large American dams with storage capacity of 1.2 km^3 (10^2 ac ft) shown in map A is broadly similar to the distribution of dams in the present analysis shown in map B. Numbers and regions on map B correspond to map reference numbers in column 1, Table 1. Sources: A, modified from Graf (2005) by T.M. Plewa; B, T.M. Plewa and author.

hydrology and have had enough time to affect changes. Geomorphic responses to the installation of dams may require decades to become apparent, as indicated by a detailed investigation of the effects of dams on the Trinity River, Texas (Wellmeyer et al., 2005). Second, the dams do not have other very large structures nearby upstream that might greatly control the flow in the unregulated control reach. Third, unregulated control and regulated experimental reaches include a U.S. Geological Survey stream gage or a gage is within 5 km of the reach without intervening major tributaries. Fourth, unregulated and regulated reaches have similar, geology, biogeography, and geomorphology (valley configurations). Fifth, for geomorphic mapping purposes both reaches for each dam appear on high quality, same-date aerial photography made at least 30 years after installation of the dam. Thirty-six dams, with a total of 72 associated unregulated and regulated reaches, met these criteria, representing all the regions of the country with very large dams (Table 1; Fig. 6).

3.3. Methods for hydrologic analysis of reaches

With this data set, analysis proceeded through three tasks: hydrologic analysis, geomorphic analysis, and correlation analysis among hydrologic and geomorphic variables. Comparison of the hydrologic properties of flows in the regulated experimental reaches with those in the unregulated control reaches required a standardized assessment of both records for each of the 72 river reaches (one unregulated and one regulated reach for each of 36 dams). The 72 reaches had gage records that ranged from 13 to 56 years in length, with an average of 35 years, and yielded 868,000 daily flow values. Analysis was for daily flows only on those days when records were available from both reaches. Individual runs of the versions 5 and 7 of the software package "Indicators of Hydrologic Adjustment" (IHA) for each reach provided descriptive statistics for more than 30 characteristics of the flows, but a shorter list of 17 (which includes 3 parameters not calculated by the program, but determined separately) provided a suitable evaluation of hydrology related to geomorphology (Table 2).

The IHA program created for The Nature Conservancy and Smythe (2001), accepts daily flow records as input and produces summary statistics as output. The IHA program originated in research into river ecology and restoration of flows influenced by dams (Poff et al., 1997). Previous uses of IHA include assessments of the effects of individual dams on the downstream rivers (e.g., Richter et al., 1996), or for several dams in a particular watershed. The IHA program is fundamentally different from the traditional statistical hydrologic approach that fits data to frequency curves, and then assesses the curves, the coefficients, and predicted values for interpretation. Instead, the IHA approach provides descriptive statistics of daily flows before and after installation of the dam for a single record of flow divided into pre- and post-dam periods. Alternatively, as used in the present work, it provides statistical summaries for a single time period in a single record. The IHA method extracts statistical summaries of the daily flow record that have interpretations with direct and obvious ecosystem implications (Richter, 1999), and this paper adds geomorphic interpretations (Table 2). In the present application, values for the 17 parameters from the unregulated control reach and the regulated experimental reach for each dam are for the same time period, so that the identified changes in flow are likely to be only the result of the dam. Regional and national aggregations of the statistics provide a general picture of the changes brought about by installation and operation of the structures.

3.4. Methods for geomorphic analysis

The geomorphic analysis in this project provided an assessment of the differences in fluvial geomorphology between regulated and unregulated river reaches that paralleled the changes in hydrology revealed by the hydrologic analysis. The 72 unregulated control reaches and regulated experimental reaches ranged from 5 to 10 km long, and had an average length of 8 km; the total length of river assessed in this project was 576 km. Recent (1990s or later) scanned and registered aerial photographs of both reaches for each dam provided the basis for comparison of regulated and unregulated geomorphology. The underlying assumption in this approach is that prior to the installation of the dam, both reaches had similar geomorphology, an assumption borne out by review of historical images for six pairs of representative reaches. Because of the large number of reaches, it was not possible to conduct a complete historical analysis, a price of investigating a large number of dams.

The present study uses a series of terms and associated concepts to standardize the analysis and discussion of results. Graf (2001) provides the philosophical background for the terms. Specific definitions are as follows.

Reaches are lengths of channel up to a few km long that have similar physical (hydraulic and geomorphic), biological, and chemical characteristics throughout the individual lengths. Examples of individual reaches include a length of a steep mountain stream with a series of pools and rapids, or a length of an alluvial channel with similar meander patterns or braiding throughout.

Table 2
Potential hydrologic changes as a result of dams and dam operations, along with the geomorphic and ecologic effects

Hydrologic parameters	Geomorphic implications	Ecologic implications
Instantaneous maximum flow	Amount of available space for river forms, sediment, and processes; flood plain size	Amount and types of patches for aquatic and riparian organisms
1-day maximum flow	Overall channel morphology, number and size of functional surfaces	Hydration in riparian habitats for terrestrial animals
30-day maximum flow	Dominant particle size of bed materials, flood-plain changes	Long-term dehydration in riparian habitats for terrestrial animals, duration of stressful high temperatures, low oxygen
Date of maximum flow	Interactions between erosive flows and stabilizing vegetation	Habitat cues for reproduction and survival behaviors in aquatic and riparian organisms.
Maximum/mean flow	Spatial range of processes, frequency and sizes of functional surfaces	Size, variety, and distribution of habitat patches for aquatic and riparian organisms
Mean daily flow	Size of ordinarily active low flow channel, channel pattern, geomorphic complexity	Amount of habitat space, patch size, amount of water available for organisms, amount of food and cover, access by predators to nesting sites, soil moisture availability for riparian plants, food and cover, availability of habitats
Instantaneous minimum flow	Limit on sediment transportation, channel maintenance	Limits for aquatic organisms
1-day minimum flow	Sediment storage and mobility	Balance among competitive stress-tolerant organisms
30-day minimum flow	Particle sizes distributions of bed material	Stability of channel habitats for fishes
Date of minimum flow	Interaction between vegetation and deposition processes	Habitat cues for reproduction and survival behaviors in aquatic and riparian organisms
Date of minimum flow	Interaction between flows and riparian vegetation that invades active channel areas	Access to nesting habitats, isolation from predators during nesting, habitat cues for survival and reproduction
Range of daily flows	Spatial extent of active area of functional surfaces	Habitat patch size
Number of reversals	Overall annual stability of channels and banks	Frequency of changes in marginal aquatic and riparian habitats
Mean up-ramp rate	Likelihood of erosion of banks, bars, islands	Entrapment of terrestrial organisms on islands and flood plains, inundation stress on plants and low-mobility stream-side organism
Mean down-ramp rate	Likelihood of erosion of banks, bars, islands	Entrapment of aquatic organisms in abandoned pools and channels, drought stress on plants and low mobility stream-edge organisms
Number of high flow pulses	Frequency of mobility of channel bed and bank materials, frequency of changes in functional surfaces	Access for water birds to feeding and nesting sites
Mean duration of high flow pulses	Magnitude of erosion on banks and in channels, bedload transport, channel sediment texture,	Utility of aquatic habitats for organisms, especially for reproduction
Number of low flow pulses	Length of time for stability of channels and banks, frequency of depositional regimes in channels	Frequency and magnitude of soil moisture change or anaerobic stress for plants, availability of flood-plain habitats for aquatic organisms
Mean duration of low flow pulses	Magnitude of deposition processes in channel	Nutrient and organic matter exchanges between river and flood plain, soil mineral availability

Source: modified from Richter et al. (1996) with additions for geomorphology by the author.

Segments are lengths of channels tens of km long made up of combinations of reaches; segments are separated from each other by major boundaries that impose significant changes in river processes or forms. Common examples of segment boundaries include dams, major tributaries, geologic structures, or major changes in geologic substrate.

Functional surfaces of a river reach are geomorphic components of the aquatic and riparian landscape; they are defined by topography and surface materials that are less variable throughout the internal area than across the boundaries with neighboring surfaces; and they are active in the fluvial processes of the present regime of the river (the last ten years of record). Functional surfaces are polygons that include low flow channels high flow channels, low bars, high bars, islands, active flood plains, and some engineered surfaces. These functional surfaces are "functional" in the sense that they have inputs, storage, and outputs of water, sediment, and nutrients. Inactive flood plains are not functional but are included in the analysis. See Table 3 for definitions.

Standard active area of a reach is the total surface area of all the functional surfaces within a single river reach, standardized by (1) the upstream drainage area at

the beginning of the reach, and (2) the length of the reach. Computationally, standard active area of a river reach equals the sum of the areas of all the functional surfaces associated with the reach (m^2) divided by the total drainage area upstream from the reach (km^2) and the length of the reach (km). The result is the active area per square km of contributing basin area per km of channel.

Geomorphic complexity of a reach is the total number of functional surfaces associated with the reach per unit length of the reach. Computationally, geomorphic complexity of a river reach equals the number of functional surfaces divided by the length of the reach, resulting in metric that is the number of different polygons per km of channel.

These geomorphic measures have direct implications for connecting hydro-geomorphic processes with vegetation and habitat patches. Polygons that are individual functional surfaces correspond to individual patches (Forman and Godron, 1986). Geomorphic complexity underlies ecological complexity, so that a reach exhibiting a high degree of geomorphic complexity is likely to have many varied patches, and offer many different habitats (Fig. 7).

In this study, the measurement of sample reaches with assemblages of functional surfaces depended on aerial photography. All the images were U.S. Geological Survey photography from 1991 to 1998. For each pair of control and experimental reaches associated with a dam, the photography date is the same. The image for each reach,

imported into an ArcInfo geographic information system (GIS), provided the basis for mapping the functional surfaces. Howard and Mitchell (1985, p. 113–123) provided the specific diagnostics for the image interpretation, and field visits to the river reaches supplied additional information to aid in deciphering the images and mapping boundaries of individual functional surfaces. Digitized polygons, drafted on screen as a layer over the base aerial image, provided mapped definition of 7 types of functional surfaces plus inactive flood plains (Table 3). Internal operations within the GIS permitted the measurement of the frequency and total areas of each functional surface type for each reach, as well as the summed area for each reach, data that provided input to calculating standard active area and geomorpic complexity (Fig. 8).

3.5. Methods for statistical tests

Two simple types of statistical analyses illuminate the hdyrologic and geomorphic differences between unregulated control reaches and regulated experimental reaches: non-parametric tests of the differences of means and correlation analysis between the hydrologic and geomorphic variables. A difference of means test, using means and standard deviations, reveals whether or not the observed differences between unregulated control and regulated experimental reaches are statistically significant. A test of the ordinary least squares correlations between active channel area and complexity on one hand with frequency

Table 3
Functional surfaces mapped for river reaches

Functional surface	Definition	Ecological significance
Low flow channel	Channel along the thalweg, occupied by mean annual low flow	Aquatic habitat with longest annual inundation
High flow channel	Channel occupied by high flows that are not contained by the low flow channel	Occasional aquatic habitat, substantial flood potential with fast flowing water
Low bar	Sediment accumulation attached the margin of the low flow channel, materials mobilized regularly	Location for unstable communities, frequent instability, often the site of pioneer or invasive vegetation
High bar	Sediment accumulation attached to the margin of the high flow channel or valley side, materials mobilized infrequently	Location for moderately stable communities, often for pioneer species
Island	Sediment accumulation with surface above mean annual low flow level, not attached to channel margins	Usually similar to low bar surfaces, but in some higher configurations may have communities similar to flood plain
Active flood plain	Nearly level surface next to the low flow channel, separated from the channel by banks, inundated regularly	Stable community adjusted to frequent inundation, complex patches of vegetation
Inactive flood plain	Nearly level surface next to the low flow channel, separated from the channel by banks, rarely inundated	Stable community not adjusted to frequent inundation, less complex patches of vegetation than active flood plain
Engineered surface	Surface constructed, built up, or excavated by human activities	Often bare, or with planted communities

Specific frequencies vary from region to region. Source: author.
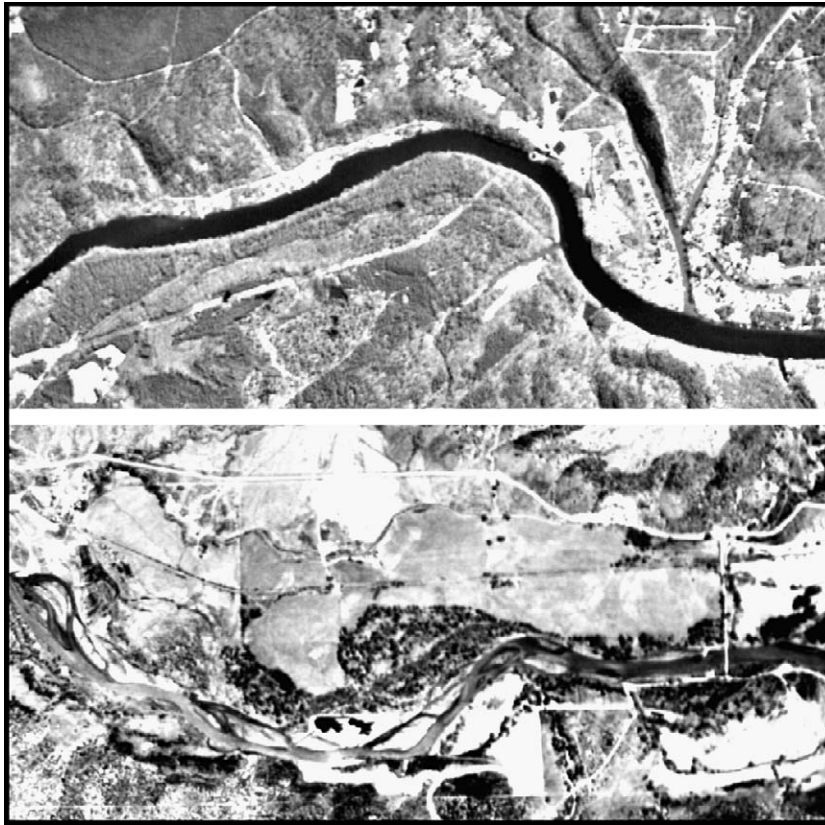Frequency definitions are for the present regime of the river, flows during the period of record.

Fig. 7. American rivers evidence a range of geomorphic complexity. Upper image: 1994 aerial photograph of the relatively simple, restricted channel of the Ouachita River downstream from Blakley Mountain Dam in central Arkansas. Lower image: 1991 aerial photograph of the more complex channel and associated functional surfaces of the San Juan River upstream from Navajo Dam in northwestern New Mexico. Source: U.S. Geological Survey.

and total area of the individual functional surface types on the other hand reveals which particular functional surfaces contribute most to variability of active area and complexity. A test of the correlations between the geomorphic variables of active area and geomorphic complexity with various hydrologic parameters indicates which hydrologic characteristics altered by dams contribute most to the variance of the ecologically important parameters.

3.6. Methods for regional hydrologic analysis

Regional analysis of basic hydrologic conditions provides keys to understanding the regional variation of the effects of dams through the assessment of three metrics: maximum/minimum annual flow ratio, reservoir capacity/annual watershed yield ratio, and the reduction in annual maximum flows caused by dams. The ratio between maximum and mean daily flows for each year of record is a convenient statistic encapsulating the basic hydrologic character of the rivers. High max/mean ratios indicate rivers that have large floods with respect to the

average flows, and they create complex geomorphology as a result of highly variable discharges. These rivers have riparian landscapes and changes that are event driven. Low max/mean ratios characterize rivers with little variability in flow, simpler configurations, and change that is gradational.

Considerable regional variation occurs in the ability of dams to store the annual inflows in reservoirs, and, thus in their ability to control downstream outflows. A useful measure of the potential of a dam to control downstream hydrology is its capacity/yield ratio, the ratio between its storage capacity and the annual water yield of the upstream basin. This statistic is an essential comparison between the hydrologic magnitude of the river and the hydrologic magnitude of the dam. If the capacity/yield ratio is greater than one, the reservoir for the dam can store flow for more than a year. Depending on operating rules, such a large amount of storage has the potential to substantially reduce annual maximum flows. On the other hand, dams with low capacity/yield ratios store only a minor fraction of the annual inflow to the reservoirs, and

Fig. 8. Mapping of functional surfaces is by on-screen digitizing of an aerial photograph, exemplified by two images of a reach of the Canadian River upstream from Eufala Dam in eastern Oklahoma. The upper image, a 1995 aerial photograph, serves as the basis for a functional surface map showing in the lower image. Sources: aerial photograph from U.S. Geological Survey, mapping by author.

they, therefore, exert less control over downstream flows. In some cases, operators of such structures adopt run-of-river rules whereby the amount of water released from the dam is roughly equal to the amount flowing into the reservoir. In these cases, the dam exerts relatively little hydrologic control over downstream hydrology. The reservoir still acts as an effective sediment trap, however, so that it still affects downstream geomorphology.

Because of basic hydrologic variation, dams are likely to have different effects from one region to another. The greatest potential effects are on those rivers where dam operations can substantially reduce annual maximum discharges, and, thus, depress the max/mean ratio. Downstream reaches with geomorphology and ecology tuned to high ratios in pre-dam periods would experience large adjustments in post-dam periods.

Those dams with reservoir capacity that is high in comparison with the annual water yield would be likely to have the greatest effect. The combination of river hydrology and dam characteristics determines the ability of dams to reduce maximum flows. Additionally, those dams that suppress the maximum annual flow to the greatest degree are likely to have the greatest downstream geomorphic and ecologic effects by reducing standard active areas and geomorphic complexity.

4. Results

4.1. Hydrologic results

This study produced results of four types, with outcomes related to hydrology, geomorphology, correlations

between hydrology and geomorphology, and regional aspects of the analysis. Hydrologic results show that on a national basis, dams have statistically significant effects on several characteristics of stream flow (Table 4). The most important significant effects are related to annual maximum or peak flows. For the 36 very large dams in the data set, the structures reduced instantaneous maximum flows 67% based on comparisons between stream gage records for unregulated control reaches and those for regulated experimental reaches. The reduction was 71% for 1-day maxima, but only 25% for 30-day maxima, a result that demonstrates the decreasing effects of regulation for peak flows of longer durations as shown for the Connecticut River Basin by Magilligan and Nislow (2005) using different methods. The reduced daily range of flow magnitudes by 64% is mostly a reflection of the depressed values of peak flows. These reductions show that very large dams accomplish the intended objectives of providing flood suppression, at least for short-term events. The reductions also show why riparian ecosystems, dependent on floods, are likely to experience large-scale changes because of dams and dam operations throughout the nation, and why a reduced range in floods is likely to have multiple effects on ecosystem processes as outlined by Doyle et al. (2005).

Dams affect two other components of the stream flow to a statistically significant degree: minimum discharges and flow changes. Regulated reaches have 30-day minimum flows that are 52% higher than unregulated reaches, largely the product of conveying water from reservoir storage to downstream users during summer months which keeps flows in regulated reaches from declining to more natural lows. Regulated reaches, therefore, are less likely to support extensive ecosystem components requiring a dry period in summer. Operations of the dams also significantly influence the way in which the magnitude of flowchanges in regulated reaches. The number of reversals is 34% greater in regulated reaches than in unregulated ones, a product of dam releases designed to meet water supply, power, recreation, wildlife, and navigation needs. Regulated daily flows are, therefore, more complex in temporal trends and reversals than the unregulated ones. The up-ramp rates for regulated flows are 60% less than unregulated rates on a national basis, probably reflecting the damping of flashy increases in undammed rivers. The daily discharge data used in this project do not reflect the hourly changes introduced by typical hydroelectric power operations.

The dates of maximum and minimum flows are different in regulated reaches than in unregulated reaches for many dams, a factor that may have more ecologic than geomorphic significance. For example, many avian species have evolved to take advantage of the exposure of the surfaces of low bars and flood plains for nesting purposes, migration stopovers, or forage. Therefore, if dam operations alter the date of the of the

Table 4
Mean values for basic hydrologic parameters for regulated and unregulated river reaches near the 36 very large dams in Table 1

Parameter	Unregulated river		Regulated river		Difference
	$m^3 \ s^{-1} \ km^{-2} \ mi^{-2}$	$ft^3 \ s^{-1}$	$m^3 \ s^{-1} \ km^{-2}$	$ft^3 \ s^{-1} \ mi^{-2}$	
Instantaneous maximum	0.1802	16.49	0.0590	5.40	−67%*
1-day maximum	0.1634	14.95	0.0471	4.31	−71%*
30-day maximum	0.0388	3.55	0.0292	2.67	−25%*
Max/mean	14.29		5.74		−60%*
Date of maximum	May 16		May 16		None
Daily mean flow	0.0122	1.12	0.0108	0.99	−12%
Instantaneous minimum	0.0016	0.15	0.0011	0.10	−33%*
1-day minimum	0.0016	0.15	0.0019	0.17	−13%
30-day minimum	0.0023	0.21	0.0035	0.32	+0.52*
Min/mean	0.14		0.10		−29%*
Date of minimum	Aug. 31		Sept. 11		+12 days
Range of daily flows	0.1618	14.80	0.0579	5.30	−64%*
Number of reversals	104.43 per year		140.29 per year		+34%*
Up-ramp rate	0.0066	0.60	0.0026	0.24	−60%*
Down-ramp rate	0.0028	−0.26	0.0023	−0.21	−19%
Number of high pulses	5.74 per year		5.75 per year		+<1%
Duration of high pulses	8.35 days		14.28 days		+71%*
Number of low pulses	8.06 per year		17.16 per year		+13%
Duration of low pulses	12.76 days		11.27 days		−12%

Table 2 defines the parameters. Values expressed as unit discharge, discharge volume ($m^3 \ s^{-1}$ or $ft^3 \ s^{-1}$) divided by drainage area (km^2 or mi^2). Asterisks indicate differences that are significant at the 0.05 level of confidence. Source: calculated by author from U.S. Geological Survey data.

Table 5
Comparison of functional surface frequency and area between control and experimental reaches, showing the difference with respect to the control reaches

Functional surface	Parameter	Control reaches	Experimental reaches	Difference (%)
Low flow channel	Frequency	0.12	0.12	0
	Area	0.740	0.976	+32*
High flow channel	Frequency	0.41	0.10	−77*
	Area	0.128	0.063	−50*
Low bar	Frequency	0.64	0.20	−68*
	Area	0.225	0.108	−52*
High bar	Frequency	0.09	0.04	−52*
	Area	0.056	0.060	+7
Island	Frequency	0.26	0.21	−20
	Area	0.238	0.059	−75*
Active flood plain	Frequency	0.60	0.34	−43*
	Area	2.230	0.490	−79*
Inactive flood plain	Frequency	0.09	0.31	+236*
	Area	0.625	2.890	+363*
Engineered surface	Frequency	0.03	0.05	+51*
	Area	0.013	0.031	+145%*

Frequency and area standardized by channel length, with areas measured in km^2 Differences calculated with 5 significant digits from original data. Asterisks indicate differences that are significant at the 0.05 level of confidence. Source: mapped and calculated by author.

transition from high to low flows, downstream effects on bird populations are almost sure to follow. Several dams in this study shift the mean dates of high or low flows by as much as 6 months. The substantial changes do not appear in the results summary of Table 4, however, because some of the regulated dates among the 36 cases are before the unregulated date, while other cases are after. The mean values of the Julian day for the maximum or minimum flows for regulated and unregulated are similar, giving the false impression that dams in the aggregate do not impose substantial changes. The absolute differences between regulated and unregulated dates for maximum or minimum flow provide a clearer picture of the effects of dams. As a national average, the very large dams in this study adjusted the date of the maximum flow 39 days (usually earlier in the year) and the date of the minimum flow 58 days (usually later in the year).

4.2. Geomorphic results

Geomorphic results address individual types of functional surfaces and the more general measures of active area and complexity. Results related to functional surfaces show that the hydrologic differences in peak flows and low flows of unregulated and regulated reaches produce very different fluvial geomorphologies (Table 5). Regulated reaches have 32% larger low flow

channels, reflecting the elevated low flows. High flow channels in regulated reaches are 77% fewer in number and are 50% smaller than in unregulated reaches where higher maximum annual flows more easily maintain such channels. Low channel-side bars are 68% less frequent and 52% smaller in regulated reaches than in unregulated ones, because in regulated channels the range between maximum and minimum flows is much less. The result is a more restricted vertical range for the formation of bars. Reservoirs are efficient sediment traps, so material for bar formation in regulated reaches is scarce. High bars are 52% less frequent in regulated reaches because of the lack of high flows necessary for formation and maintenance. Although the frequency of occurrence of islands is not statistically different between regulated and unregulated reaches (overall the number of islands in the study reaches is small), those in regulated reaches are 75% smaller than islands in unregulated reaches, reflecting the sediment starvation of reaches downstream from dams.

From the perspective of riparian ecology, the most important downstream effects of hydrology altered by very large dams are related to flood plains. Regulated reaches have 43% fewer active flood plain surfaces than in regulated reaches, and the average standard active

Table 6
Comparison between regulated and unregulated river reaches in terms of mean values for standard active area and complexity, showing the difference with respect to control reaches

Parameter	Regional group	Control reaches	Experimental reaches	Difference %
Standard active area (m^2 km^2 km^{-1})	Eastern	73.22	53.29	−27
	Ozarks	161.50	28.70	−82*
	Great Plains	107.71	9.81	−91*
	Pacific NW	7.67	4.39	−43*
	Interior Western	34.00	11.81	−65*
	California	113.81	41.00	−64*
	All regions	87.41	24.28	−72*
Geomorphic complexity (number of surfaces km^{-1})	Eastern	2.33	1.02	−56*
	Ozarks	1.91	1.16	−39*
	Great Plains	2.27	1.96	−14
	Pacific NW	1.01	0.85	−16
	Interior Western	4.80	2.32	−52*
	California	2.42	1.24	−49*
	All Regions	2.32	1.47	−37*

Asterisks indicate statistically significant differences at the 0.05 confidence level. Source: mapped and calculated by author.

area is 79% less than in unregulated reaches. Evidently the regulated reaches once had larger active flood plains, because now they have more than twice as many inactive flood plains with 3.5 times larger area than in unregulated reaches (Fig. 2). These effects from very large dams are likely to constrain ecosystems that have evolved to flourish on active flood plains.

Results related to standard active area and complexity show that both of these measures have important ecological implications and are substantially less in regulated reaches than in unregulated ones (Table 6). On a national basis, active area is 72% less than in unregulated reaches, and complexity is 37% less. These results mean that regulated rivers have active, functional surfaces hydrologically connected to the channel that are much less extensive than along undammed rivers. The results pertaining to individual functional surfaces indicate that this reduction in active area is largely related to reductions in the sizes of active flood plains (Table 5). The remaining active surfaces along regulated rivers are also simplified landscapes, because fewer functional surfaces occur than along regulated rivers. These outcomes imply that regulated rivers are shrunken, simplified versions of former unregulated rivers.

4.3. Correlation results

Correlation results illustrate the connections among hydrologic changes created by dams, frequency and area of functional surfaces by type, and the two ecologically most important geomorphic variables: standard active area and complexity. These correlations, produced from a correlation matrix containing all hydrologic data (17 variables) and functional surface data (18 variables) from all 72 river reaches, show that at the 0.05 confidence level only a few statistically important connections occur between controlling and responding variables (Table 7). The size of the standard active area is primarily a function of the frequency of high flow channels and the size of the active flood plain. As high flow channels become limited in number and the active flood plain decreases in size across the sampled reaches, active area declines, a set of adjustments accentuated by dams. The hydrologic variables related to standard active area to a statistically significant degree are predominantly those related to peak discharges: the daily maximum, 1-day duration maximum, and 30-day duration maximum. Occasional high flows of a variety of durations obviously maintain a large active area. Ramping rates are also significantly correlated with the size of the standard active area, but this is probably not a direct connection. Rather, the positive correlation with up-ramp rates is connected to

Table 7
Correlations (significant at 0.05 confidence level) of active area and complexity with functional surfaces and hydrologic controls altered by dams

Summary parameter (dependent variable)	Functional surface (independent variable)	Corr. coef.	Hydrologic parameter (independent variable)	Corr. coef.
Standard active area	Frequency of high flow channels	+0.68	Maximum daily discharge	+0.34
	Area of active flood plain	+0.54	1-day maximum discharge	+0.56
			30-day maximum discharge	+0.42
			Up-Ramp Rate	+0.67
			Down-Ramp Rate	−0.52
Complexity	Area of low flow channel	−0.43	Mean daily discharge	+0.27
	Frequency of high flow channels	+0.53	1-day maximum discharge	+0.52
	Frequency of low bars	+0.60	30-day maximum discharge	+0.40
	Frequency of active flood plains	+0.31	Up-ramp rate	+0.47
			Down-ramp rate	−0.39

Source: author.

flashy, high annual maximum flows, and the negative correlation with down-ramp rates is connected to the long duration peak flows, hydrologic conditions associated with unregulated rivers.

The correlation analysis for complexity shows that among the functional surfaces, the frequency of low bars, high flow channels, and active flood plains are the parameters associated most closely with complexity. As the numbers of these features increase, the fluvial landscape becomes increasing complex, but the reaches downstream from dams have the lowest frequencies for these surfaces and corresponding lowest complexity. The area of the low flow channel is negatively correlated with complexity to a statistically significant degree, so that smaller low flow channels are associated with the most complex cases, which are invariably unregulated reaches. In these unregulated cases, minimum flows are lower than in regulated cases, and peak flows occupy high flow channels or broad active flood plains. In regulated cases, elevated minimum flows and reduced variability downstream from dams maintain low flow channels that are larger than they would be without the influence of dams. Unmeasured controls, such as valley configuration and regional climatic differences, are likely to produce much of the unexplained variance in

Table 8
Regional analysis of mean capacity/ratios, peak/mean flow ratios, and reductions in peak flows by dams

Region	Max/mean annual flow (ratio)	Capacity/ yield (ratio)	Reduction in maximum annual discharge (%)
Eastern	14.38	0.87	−58
Great Plains	21.35	2.75	−65
Ozark and Ouachita	25.36	2.61	−56
Pacific Northwest	3.58	0.46	−19
Interior Western	11.17	3.22	−67
California	15.81	1.94	−58
All regions	16.10	1.92	−58

Source: calculated by author with data from U.S. Army Corps of Engineers and U.S. Geological Survey data.

the correlation analysis. Although the 36 cases in this analysis are large from the perspective of available data about rivers and dams, the number of cases is low from a statistical perspective, because of the wide range of conditions across the country and a corresponding low number of cases in each region.

4.4. Regional hydrology results

Regional mean values for the max/min annual flow ratio, reservoir capacity/basin yield ratio, and the reduction in maximum annual discharge by dams shows considerable variation from one region to another (Table 8). The combinations of these three regional hydrologic descriptors for each region provide a backdrop for interpreting the downstream changes related to dams. For example, dams in the Great Plains region with high values for max/mean ratio, capacity/yield ratio, and average reduction in maximum annual flow by dams provides a geographically specific context for the geomorphic effects of the structures. A different context emerges for the Pacific Northwest, for example, where the max/mean ratio, the capacity/yield ratio, and the reduction in annual maximum flow is also very low. Other regions have mixtures of high, average, and low values for these metrics. The substantial variability from one region to another in standard active area and geomorphic complexity reviewed in Table 6 seems expectable in light of this geographic variability of the basic regional hydrology.

5. Discussion

The results of this investigation into the downstream hydrologic and geomorphic effects of dams lead to three additional issues that require further attention. First, what are the reasons for the regional hydrologic variability of large rivers affected by dams; second, what are the drivers of the regional variability in geomorphological effects of dams; and third, what are the habitat implications of the differences between unregulated and regulated reaches? See Benke and Cushing (2005) for regional descriptions of the hydro-geomorphology and associated aquatic and riparian biological systems, and Abell et al. (2000) for aquatic ecosystem descriptions. Thornbury (1965), Hunt (1974), and Orme (2002) provide information on regional geomorphology and sediments.

5.1. Regional hydrologic variation

All dams are not created equal, nor are the rivers they partially control. Regional variation in the max/mean ratios for the 36 unregulated control river reaches in this study show that substantial differences exist from one part of the nation to another in this fundamental characteristic of river response (Table 8, column 1). Huge variability in flow is the defining characteristic of Great Plains streams and those in the Ozark Plateau/Ouachita area, while Pacific Northwest rivers have remarkable consistency of flow. Eastern, California, and Interior Western rivers are intermediate on the scale for max/mean flow ratios.

Eastern and Pacific Northwest dams have the lowest capacity/yield ratios, so it is reasonable to expect that the downstream hydrologic and geomorphic impacts are less than for similar dams in other regions (Table 8, column 3). Eastern and Pacific Northwest rivers also have the smallest difference between unregulated and regulated reaches in terms of standard active area (Table 6, column 5). This arrangement comes about because the rivers in these two regions of the country are in areas of copious runoff, and dams do not store more than a fraction of the total annual runoff at the major dam sites. As a result, despite considerable storage capacity, dams exert only limited hydrologic control for downstream flows which maintain at least some of the pre-dam characteristics. This limited control explains why the annual maximum discharge in Pacific Northwest rivers is only 19% smaller in regulated streams than in unregulated ones. For Eastern streams the decrease in annual maximum flows is greater, but the reservoir capacities still average less than the mean annual flow, so these dams have moderate effects.

The general regional geomorphic settings for streams in the two regions also account for limited adjustments, because the sediment loads of the Northwest and Eastern rivers are less than for the streams in the arid and semi-arid parts of the continent. The rivers' flows can partially maintain pre-dam conditions, and as a result, the regulated and unregulated reaches of Eastern streams exhibit only moderate differences in geomorphology.

At the opposite extreme are examples from the Great Plains, Ozark/Ouachita, and Interior Western regions, where dams have the highest capacity/yield ratios (Table 8). The unregulated rivers in the mid-continent regions have exceptionally large ranges of annual flows, with the peak annual flow equal to more than 20 times the annual mean flow. Dams in all three regions store more than 2.5 times the mean annual discharge, so they exert substantial influence on downstream flows with a capability to greatly alter pre-dam hydrology. These structures also produce the greatest reductions in the maximum annual discharge. The three mid-continent regions exhibit, therefore, the most drastic reduction in standard active area for regulated streams (a difference between regulated and unregulated streams of −91% for Great Plains rivers). Great Plains rivers that are regulated appear to maintain much of the complexity, however, because the complexity is only 14% less than unregulated rivers. This combination of reduced standard active area, but with substantial complexity, reflects annual flows that are much smaller in regulated rivers, but they continue to fluctuate within a smaller hydrologic range. The Plains stream also operate in broad alluvial valleys with relatively high sediment loads, so that they are able to construct and maintain a variable (though spatially restricted) suite of functional surfaces.

Despite the substantial regional variability in max/mean ratios and capacity/yield ratios, planning, engineering, and operation of dams have produced a remarkably consistent reduction in annual maximum flows from a variety of regions (Table 8, Column 4). Every region but one has an average reduction in the annual maximum discharge of 56–67%. The only divergence from the national average is in the Pacific Northwest, with its consistent river flows and run-of-river dams for hydroelectric power production. In its broadest interpretation, the widespread downstream effects of dams are expectable outcomes of a one-half to two-thirds general reduction of maximum annual flows throughout the nation.

5.2. Regional variation in geomorphic effects

The results in Tables 5 and 6 show that although dams have a profound effects on downstream geomorphology, the effects are geographically variable. The fluvial geomorphology of the Great Plains and Ozark–Ouachita rivers show the greatest difference where regulated rivers have 82 to 91% less standard active area than similar unregulated reaches (Table 6). This difference might be expected in light of the high maximum/mean annual flood flows of unregulated streams, and the large storage capacity of the dams controlling regulated reaches. In these two regions, dams have the ability to greatly modify a previously extreme hydrologic regime, and to convert it to a regime with much lower annual peak discharges (Table 8). These hydrologic changes then alter geomorphology downstream from the structures by drastic shrinkage, not only of the channel (as previously documented by Williams, 1978, for example), but shrinkage of the entire assemblage of functional surfaces associated with the channel.

The Eastern and Pacific Northwest regions have the lowest standard active area differences, with regulated reaches having 27 and 43% less standard active areas than similar unregulated reaches respectively. The relatively small difference is traceable to two primary reasons: first, Eastern examples in the data set are mostly from the geomorphic provinces related to the Appalachian Mountains (mountains, plateaus, valleys and ridges, or Piedmont) and the Pacific Northwest examples are also in bed-rock confined valleys. The unregulated streams in these two general regions have relatively little sediment available for storage and sculpting into extensive functional surfaces. When dams regulate the flow of such rivers, they do not have extensive original active areas and so shrinkage is less than in other regions with large sediment supplies and large standard active areas. Second, the average capacity/yield ratio for Eastern and Pacific Northwest dams is less than 1.0, indicating that the dams in these regions cannot exert as much regulatory control over downstream hydrology as is possible for dams in mid-continent regions with capacity/yield ratios of more than 2.5.

Regional variation in the reduction of geomorphic complexity shows how pre-existing geomorphic conditions, water discharge, and sediment supply respond on various regional stages. The greatest complexity effects are in Eastern, Interior Western, and California regions where the regulated reaches have geomorphic complexities that are reduced to values that are about 50% less than in similar unregulated reaches. The unregulated reaches in the data set from these three regions have much more frequent occurrence of low and high bars and islands. When these features disappear under the erosion of clear-water discharges from dams, and when sediment is unavailable for their replacement due to reservoir storage, the regulated reach is much simpler with few remaining functional surfaces. Unregulated Pacific Northwest streams have relatively low complexity, so that the imposition of dams has little effect on the complexity of regulated reaches. Great Plains rivers similarly lack complexity in comparison with some other regions because although the braided channels appear to be intricate, they consist mostly of connected low flow channels (a single functional surface) and islands.

Table 9
Representative examples of previous investigations on large rivers that show downstream hydrologic, geomorphic, and habitat effects attributed by authors to dams

River	Region	Example affected species	Observed changes attributed to dams
Hudson River, New York	Eastern	America shad, Atlantic sturgeon	Altered conditions in many reaches downstream from dams; loss of active surfaces, bars and islands mapped by a method similar to the method used in this paper "showing loss of complexity and shallow water habitats", resulting in the loss of commercial fisheries (Jackson et al., 2005, p. 42).
Everglades, Florida	Eastern	Several wading bird and fish species	Originally sustained by broad sheet flows that essentially constituted a river (albeit 50 km wide and less than 1 m deep) controlled by low dams and control gates; Micro-topographic and vegetation heterogeneity of ridge and slough topography analogous to complexity of rivers in this study. Variable flows are disappearing, and the heterogeneity, derived from natural flow fluctuations now substantially decreased by controls, contribute directly to loss of productivity and diversity (Loftus and Kushlan, 1987; Trexler et al., 2002).
Platte River, Nebraska	Great Plains	Whooping crane, piping plover, least tern, and pallid sturgeon	Loss of habitat diversity for whooping crane, coincidental with drastic shrinkage of channel and simplification of the river's geomorphology due to the influence of dams (Murphy et al., 2005); once-active channel areas became inactive riparian forest (National Research Council, 2005; Johnson, 1997); restoration includes restoring complexity with variable flows (NRC, 2005, p. 140–143).
Lower Missouri River, Missouri, Kansas, Nebraska, and Iowa	Great Plains	Plains minnows, riparian forests	Comparative mapping reveals dam-induced changes in lower 1300 km of the river, 1879–1972, including 8% reduction in channel length, 50% reduction in channel water surface (low flow channel), 98% reduction in island area, 89% reduction in number of islands; resulting in declines in populations of archetypical Missouri river fishes and birds (Funk and Robinson, 1974).
Upper Missouri River, Nebraska, South Dakota, North Dakota, and Montana	Great Plains	Pallid sturgeon, riparian forests	Changes related to dams deactivated floodplains and altered channels, leading to lose of biodiversity for vegetation and habitat for fish spawning; channel has been "greatly simplified" (NRC, 2002, p. 68). The endangered pallid sturgeon that uses "flooplain, backwaters, chutes, sloughs, islands sand bars, and main channel" is highly endangered because dams have reduced or eliminated these complexities. It is difficult for pallid sturgeon to reproduce and thrive in the Missouri (Ruelle and Henry, 1994). On abandoned or deactivated floodplains, forests are "likely to be considerably lower in tree and bird diversity"(Riley and Johnson, 1982).
Gila River, New Mexico and Arizona	Interior West	Southwestern willow flycatcher	Flycatchers depend on riparian forests near still or slow moving water (Sogge and Marshall, 2000); decline of bird has been coincidental with habitat loss which in turn has been coincidental with installation of large dams (Graf, 2002) Spatial distribution of the WIFL habitat reflects the fluvial geomorphology of the SW that has undergone significant changes because of dams (U.S. Fish and Wildlife Service, 2000).
Yakima River, Washington	Pacific Northwest	Floodplain vegetation communities	Two reservoirs storing about 1/3 of the annual basin runoff in part of the watershed release scouring floods on five year intervals sustaining existing "complex floodplain habitat, especially at the lower ends of major floodplains" (Snyder and Stanford, 2001); elsewhere in the watershed, flow regulation resulted in the loss of 60% of floodplains and compromised ecological integrity of vegetation communities (Eitemiller et al., 2002 or Snyder et al., 2003).
Willamette River, Oregon	Pacific Northwest	Pacific salmon, riparian forests	For native fishes, "loss of floodplain forest and channel complexity in the Willamette River limits the current functions and structure of the ecosystem and demonstrates a trend of continued decline and impairment" (Stanford et al., 2005, p. 622); stream habitat for salmon is improved by adding debris and "increasing channel complexity" (NRC, 1996, p. 176), and "simplified channel structure and reduced habitat heterogeneity have generally reduced the productivity of river basins for salmon" (NRC, 1996, p. 201).

Sources: indicated in column 3.

5.3. Ecological implications

Finally, what are the ecological implications of the 72% reduction in standard active area and 37% reduction in geomorphic complexity in American regulated rivers associated with 36 of the largest dams? The biological components of riparian ecosystems are intimately related to the hydrologic and geomorphic support systems, and any changes in those systems are likely to ripple through the vegetation assemblages and habitats essential for wildlife. Through these connections and contributions to patchiness of aquatic and riparian ecosystems rivers
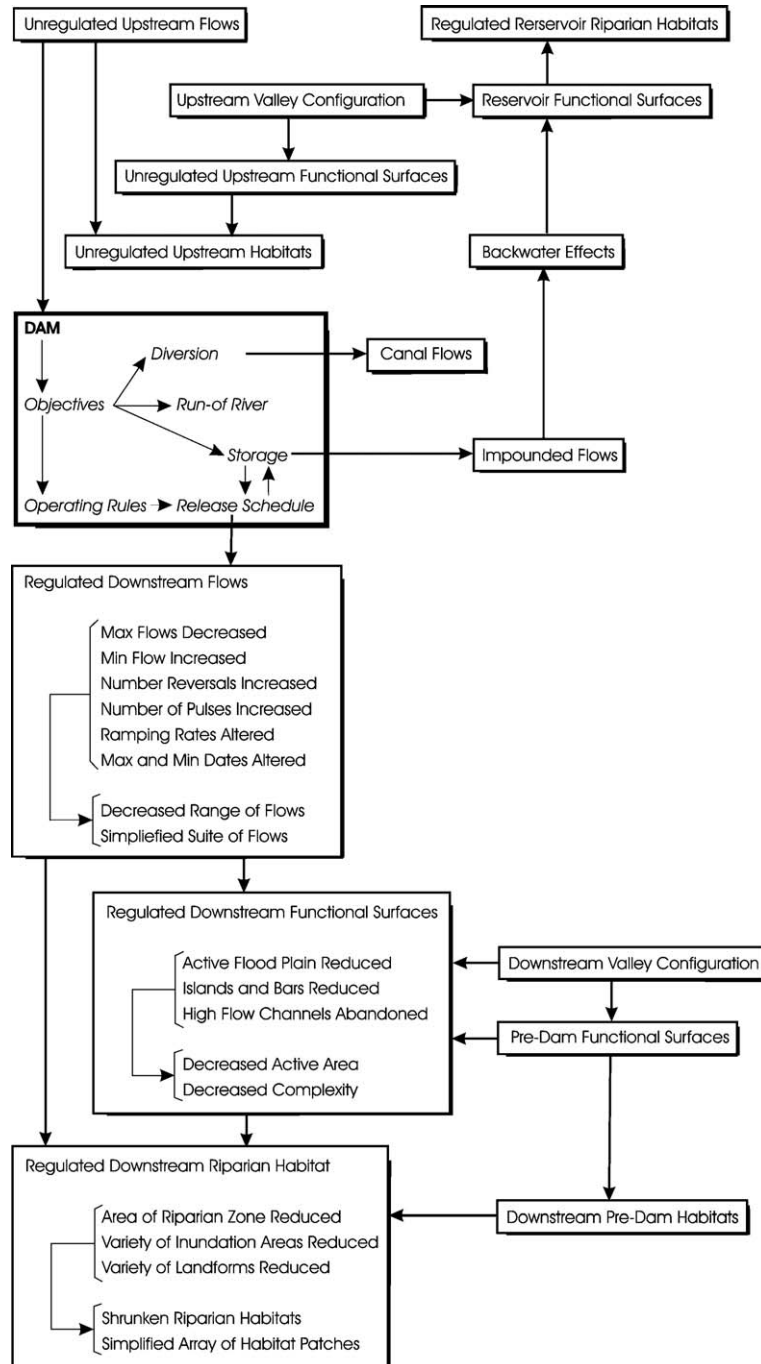
Fig. 9. A specific construct (an expansion of Fig. 2) of the conclusions of this investigation showing the connections among hydrology, geomorphology, and habitats associated with a very large dam on a large American river.

contribute to the maintenance of the biodiversity (National Research Council, 1992, p. 177, 181). The precipitous decline in populations of many riparian obligate bird species and native fishes are outcomes directly related to the changes in regulated river reaches outlined in this paper.

Previous research into the downstream effects of dams on threatened and endangered species from all parts of the United States demonstrate the connections among physical and biological components of rivers that affect wildlife habitat. Table 9 provides representative examples from an extensive body of literature supporting the conclusions of the present research and the construct in Fig. 9. Despite the wide range of geographic regions represented by the rivers in Table 9, they are similar to each other in that dams have altered hydrology, and in so doing have reduced the active area and complexities of channels, accompanied by habitat losses and declines in the populations of threatened or endangered species.

These representative examples show that the broadly defined, collective results from the present research have appeared in previous specific studies of individual cases. The studies show that investigators have used the concepts of standard active area and geomorphic complexity to describe and explain changes, though they may not have used the specific quantitative formulations for the these concepts used in the present paper. The previous specific studies make clear connec-

tions between the downstream physical changes associated with dams and the responses of the biological parts of ecosystems, particularly habitats for threatened and endangered species.

6. Conclusions

Very large dams on American rivers have large, statistically significant effects on downstream hydrology and geomorphology, summarized in the specific construct in Fig. 9. These hydrologic and geomorphic effects translate themselves into far-reaching adjustments to riparian ecosystems, and are likely to be part of the explanation for the decline of some threatened or endangered riparian wildlife, particularly riparian obligate avian species. River reaches regulated by dams have significantly smaller hydrologically active areas and significantly less complex assemblages of functional surfaces upon which the biotic system depends than in similar unregulated river reaches (Fig. 10). This restricted fluvial landscape with reduced complexity leads to shrunken and simplified ecosystems that offer reduced habitat for aquatic and riparian wildlife. The challenge for the generations of river researchers and managers who have followed Leopold (1956) is to reverse, even to a minor degree, the changes he foresaw. Stream restoration for large American rivers must take into account the likely effects of very large dams, and use the operating rules for these dams as a means of restoring at

Fig. 10. A reach of the Rio Chama about 1.6 km (1 mi) downstream from Abiquiu Dam shows the simplification of a once braided channel and a shrinkage of the active functional surface to a narrow single thread. The dam, built in 1963, stores 1.7 km^3 (1,369,000 ac ft), suppresses annual maximum flows, and sustains a low flow for water conveyance shown here. Source: 2002 image by author.

least some active areas and geomorphic complexity to the shrunken systems downstream.

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