**Appendix 1.** Descriptions of Case Studies Plotted in Figures 1-3

## Longitudinal Connectivity and Flow Dynamics

Figure 1 presents a diverse set of case studies in which longitudinal connectivity has been reduced by dams and diversions, and in one case (Torrens) increased by perennialization of flow. In these cases, flow variability was unchanged (Deschutes), increased (Butte, Condamine-Balanne), or decreased (Isar, Clear, Torrens). In three examples, longitudinal connectivity has been partly restored, by removing small dams (Clear, Butte) or restoring coarse sediment supply to the reach below the dam (Isar). Each case study is briefly described below.

*Deschutes River, Oregon*

The Deschutes River is a major tributary of the Columbia River, with a remarkably stable flow regime, dominated by springflow (O'Connor and Grant 2003). The Deschutes was impounded near Madras (about 160 km upstream of the Columbia River) in the late 1950s by the Pelton-Round Butte Hydroelectric Project, cutting off sediment supply to the lower river but leaving the flow regime nearly unaltered, an artifact of the relatively invariate pre-dam flow regime and operation of the hydroelectric project. Most significantly, the project blocked anadromous fish migration. While some adults successfully used the fish ladder to migrate upstream, juveniles were unable to migrate downstream because they could not find their way through the long, still-water reservoir reaches. It is an example in which longitudinal connectivity was reduced while flow variability was nearly unchanged.

*Butte Creek, California*

Butte Creek (380 $km^2$) is one of few remaining tributaries of the Sacramento River system still supporting healthy runs of spring-run Chinook salmon (*Oncorhychus tshawytscha*). Numerous small agricultural diversion dams built in the early $20^{th}$ century created partial barriers to upstream migration by adult salmon, reducing longitudinal connectivity. Irrigation diversions during the summer growing season reduce base flows, without affecting high flows, the net effect being increased flow variability. From 1993-1998, five dams ranging in height from 2m to 5 m were removed, and five other dams were retrofitted with fish ladders so they no longer impeded fish migration. The restoration program also included installation of fish screens and acquisition of land along the creek, at a total coast of approximately $35 million (Paul Ward, California Department of Fish and Game, personal communication 2006). Notably, these dams were removed (or retrofitted with ladders) in a way that still allowed the diversions to occur. Thus, the restoration restored longitudinal connectivity but did not reverse the diversion-induced change in flow variability, and did not conflict with water use established by agriculture. Fish counts in subsequent years showed substantially increased numbers of salmon in upstream reaches, increasing from a few hundred adults annually in most years prior to 1993, to over 7,000 in six of twelve years from 1994 to

2005, and making Butte Creek one of the most prolific spring-run salmon streams in the state (Friends of the River 1999, California Department of Fish and Game, unpublished manuscript 2005).

*Isar River, Germany*

Since its completion in 1924, the Reservoir Oberföhring near Munich has impounded the River Isar for hydroelectric power generation. The reservoir has thus trapped sediment supplied for upstream, creating a condition in the channel downstream often termed "sediment starvation" (Kondolf 1997). Gravel deposits in the reservoir delta had grown to such an extent that they caused backwater flooding upstream, prompting mechanical removal of about 100 000 $m^3$ of gravel from the reservoir in 1995-1996 (about one third of the reservoir deposit). The gravel was transported by trucks to the reach downstream of the dam, where flows have transported it downstream through a 30-km free-flowing reach, thereby partially restoring more dynamic channel processes and mitigating channel incision. This project thus (partly) restored longitudinal connectivity of sediment movement through the river system. Large floods in 1999 and 2002 left new deposits in the reservoir, creating the need for further sediment management (Walter Binder, Bayerisches Landesamt für Wasserwirtschaft, Munich, personal communication 2004). In parallel with the restoration of sediment supply, the channel through Munich, which had been channelized around 1900, was restored to a more complex geometry in 2000, thereby increasing lateral connectivity.

*Clear Creek, California*

Saeltzer Dam, a small agricultural diversion dam built in 1903, blocked upstream migration of most adult Chinook salmon but did not alter the flow regime (except during low flows). The much larger Whiskeytown Reservoir upstream (1963) reduced flow variability by impounding most floods and releasing smaller, steady base flows. In 2000, Saeltzer Dam was removed, allowing salmon passage to habitats up to Whiskeytown Dam (partially restoring longitudinal connectivity), but because Whiskeytown Dam remains in place, flow variability has not been restored (Tompkins and Kondolf 2003).

*Condamine-Balonne Rivers, Queensland, Australia*

In arid inland Australia, the floodplain of the Condamine-Balonne has been largely planted with irrigated cotton. Much of the river's flow is now diverted into large private storages on the floodplain with a total capacity of $1.5 \times 10^9$ $m^3$ (Kingsford 2000a). Pumping to fill these off-stream storages increases the intermittency of flow downstream while levee banks and reduced over-bank flow due to water extraction have restricted longitudinal and lateral connectivity in this river. There has been public outcry about the impacts of water extraction and loss of floodplain connectivity, constraining cotton developments on other arid Australian rivers (Kingsford et al. 1998), but thus far the flow regime has not been restored.

*Torrens River, South Australia*

The Torrens River was an intermittent stream when South Australia's capital city Adelaide was first established on its banks, but a weir in its lower reaches was soon constructed to ensure perennial presence of water in the city while upstream flows increased due to increased volume of wastewater and domestic use of water in gardens (Williams 1999). Streamflow variability has decreased, particularly in the lower reaches and it is unlikely that there would be much public support for removal of the weir and recovery of the intermittent and irregular flow regime. In this case, the streamflow variability has been reduced by the perennialization through urbanization. Longitudinal connectivity, once low due to natural fragmentation by intermittency, is now interrupted by a weir.

## Lateral Connectivity and Flow Dynamics

As plotted on Figure 2, lateral connectivity has been reduced by many mechanisms: blocking side channels (Pite), levees cutting off overbank flooding and deposition (Sacramento, Chorro, Paroo), cutting off meander bends (Kissimmee), channel incision (Tama), and reduced flood flows (Trinity, Sacramento, South Platte, Tama). The restorations have involved opening up side channels (Pite), setting back or breaching levees (Sacramento, Chorro), reactivating gravel bars (Tama), and releasing higher flows from the reservoir (Trinity). As a contrast, we also refer to an urban restoration project involving creating parks along the South Platte.

*Pite River, Sweden*

The Pite River in northern Sweden has been affected by several different human modifications. To efficiently float logs downstream, starting in the late 19th Century, the channel was progressively simplified, with wide reaches narrowed and side channels blocked off by stone piers, and many mid-channel bedrock knobs removed by blasting (Törnlund and Östlund 2002). The net result was to concentrate flow in a single channel and prevent overflow into side channels, reducing lateral connectivity (Fig. 2). Vertical connectivity was probably always limited because much of the channel is bedrock, but it too would have been reduced by eliminating overflow into the side channels. In 1930, small dams were constructed for hydroelectrical generation, reducing the longitudinal connectivity, but they were too small to regulate flows and thus did not measurably affect flow variability. In 1988, a larger dam was constructed, with reservoir capacity large enough to store high flows for later release, and which thereby reduced flow variability. Since 2001, the ongoing restoration efforts (Nilsson et al. in press) have involved removing some (but not all) stone piers to reconnect side channels, thereby partially restoring lateral connectivity, but without restoring the pre-dam flow regime.

*Trinity River, California.*

After construction of Trinity Dam in 1963, over 75% of runoff from the upper 1860 $km^2$ of the basin was exported to the Sacramento River. Pre-dam floods averaged over 525 $m^3s^{-1}$, post-dam only 73 $m^3s^{-1}$ (Wilcock et al. 1996). A steady minimum flow of less than 10 $m^3s^{-1}$ was released most of the time, with occasional uncontrolled spills. Because the active channel no longer experienced frequent flood scour, riparian vegetation (mostly *Alnus alba*) established along the 10 $m^3s^{-1}$ low-flow channel, and during occasional higher flows, sediment deposited in these trees, creating a growing berm that progressively confined flows within the low-flow channel, cutting off inundation of adjacent bottomlands and creating a "bowling alley" channel form that offered little refuge from high velocities during high flows (USFWS and Hoopa Valley Tribe 1999). To reverse this condition, berms were removed from several reaches of the river in pilot "feather-edging" projects to improve lateral connectivity and improve instream habitat complexity. In addition, flow regime was altered pursuant to a 2001 decision by the Department of Interior and the 1992 Central Valley Project Improvement Act, which required more flow be released into the Trinity River and thus less be exported to the Sacramento River. The resulting flow regime includes high flow releases that while much smaller than pre-dam floods, are expected to be sufficient to mobilize bed sediments and partially restore flow dynamics (USFWS and Hoopa Valley Tribe 1999). Concurrent with these actions, gravel has been added to the channel below the dams to partially restore coarse sediment supply. Thus, the Trinity River is an example of a river whose lateral connectivity and flow dynamics were both reduced, and both partially restored.

*Sacramento River, California*

Construction of Shasta Reservoir in 1945 reduced winter high flows and increased summer low flows (the latter to provide water for irrigation diversions from the river), thereby reducing flow variability, but the hydrologic changes were not nearly as great as those experienced on the Trinity. Along much of the Sacramento River floodplain, levees prevent overflow, thereby reducing lateral connectivity. A pilot levee setback project (approved and now in planning) near Hamilton City will involve moving an existing levee back 2-3 km from the channel, reconnecting part of the floodplain (which has been acquired for habitat restoration), thereby increasing lateral connectivity. However, releases from the dam will not be changed, and the area affected by the project is too small to increase flood storage; thus flow dynamics will not be affected.

*Kissimmee River, Florida.*

The Kissimmee River flows southward into Lake Okechobee, whose waters flow thence into the Everglades. In the 1960s, the US Army Corps cut a straight channel through the meander bends of the Kissimmee, piling dredging spoils along the new channel, eliminating flow through the cutoff bends, effectively draining former wetlands, and thereby reducing lateral connectivity (Fig. 2). By concentrating flows in the straight channel, downstream attenuation of peak flows was eliminated and the flow regime downstream became flashier. Restoration efforts begun in the 1990s have reconnected many cutoff meander bends, partially removed spoil piles and partially filled the artificial straight channel. Thus, lateral connectivity has been partially restored, and with flood attenuation, flow variability partly restored as well (Toth et al. 1995, Wohl 2004).

*South Platte River, Colorado.*

Dam-induced reductions in flood peaks eliminated frequent bed scour and reduced sediment supply such that the wide, dynamic braided channel converted to a narrow single-thread channel (Nadler and Schumm 1981, Eschner et al. 1983). The multiple former channels no longer received flow. Thus both flow dynamics and lateral connectivity were reduced (Fig. 2). Here we consider a restoration project in the Denver urban area, which involved extensive plantings, trail construction, and development of parks and other opportunities for urban residents to experience the river. This project restored neither lateral connectivity nor flow dynamics, so it would not result in a displacement on our bivariate plot, but appears simply as a point at the end of the trajectory of human-induced change. The restoration has been social in orientation, providing potentially valuable benefits for urban residents, but without restoring fluvial processes.

*Tama River, Japan*

The Tama River was dammed, which reduced peak flows and coarse sediment load, and experienced in-channel gravel mining. These actions resulted in channel incision, reduced overflow onto the floodplain and formerly active bars. In addition, gravel bars no longer scoured by floods were colonized by vegetation, such that both flow dynamics and lateral connectivity were reduced (Nakamura and Tockner 2004). Restoration actions have removed encroached vegetation and fine sediments, and mechanically recreated gravel bars with coarse sediment added to the channel such that the channel forms can be active under the current flow regime, thereby increasing lateral connectivity but not flow dynamics.

*Chorro Creek, California*

Morro Bay, an important habitat for birds, has been decreasing in volume, largely because of a ten-fold increase in sedimentation rates since the $19^{th}$ century (Philip Williams and Associates 1988). Sediment yields from the catchment of Chorro Creek (the bay's largest tributary, draining 112 $km^2$) have probably increased due to extensive land disturbance by European settlers in the $19^{th}$ century. But another factor leading to higher delivery of sediments to Morro Bay was the channelization of Chorro Creek and dyking of the floodplain reach known as Chorro Flats, which prevented Chorro Creek from shifting around on its floodplain and eliminated overbank deposition. In 1994, the levee was breached, allowing overbank sedimentation to occur in 1995 as levee splays. In 1997 a new pilot channel was created through the floodplain (roughly aligned with a historical channel position) and flow was routed through this new channel, restoring lateral connectivity between channel and 32 ha of floodplain. By 2001, over 150,000 $m^3$

of sediment had accumulated on the Chorro Flats floodplain, about 23% of the estimated sediment load during the period, thereby reducing sediment delivery to Morro Bay (Coastal San Luis Resource Conservation District, 2002).

*Paroo River, Australia*

The Paroo is an Australian arid-zone river with such low topographic relief on the floodplain that when a road was built across it, the slight raising of the surface acted as a low levee, isolating large parts of the floodplain from occasional small over-bank floods (Kingsford et al. 1998). As the Paroo floodplain is a 'boom-and-bust' ecosystem that relies heavily on floods to stimulate production (Boulton 1999), this isolation has had serious implications for its natural ecological cycles. Thus, while streamflow variability was not altered, lateral connectivity to the outer margins of the floodplain has been restricted.

## Vertical Connectivity and Flow Dynamics

Case studies shown in Figure 3 involve reduced vertical connectivity through channel simplification (McCoy), deposition of fine sediment over formerly permeable beds (Rhône, Creightons), drop in water table from pumping (San Pedro), and lining the bed with concrete (Los Angeles). Vertical connectivity artificially increased from water table rise, in turn caused by reduced evapotranspirative demand (Rocky). Examples of restoration involved restoring channel complexity (McCoy), excavating fine sediment (Rhône), and reducing groundwater pumping (San Pedro).

*McCoy Creek, Oregon*

In a floodplain meadow section, McCoy Creek (Northeast Oregon) was channelized into a straight channel to improve drainage in the meadow. Loss of horizontal and vertical channel complexity resulted in less interchange between surface and groundwater. Motivated by evidence that salmonid populations were limited by high summer temperatures, a pilot restoration project rerouted a 500-m reach of the creek from its artificial straight channel back into its original streambed. Before the restoration, remnants of the original streambed remained as swales in an agricultural field, and the lower part of the original streambed was still active, carrying a small amount of water supplied by a local tributary. Restoration actions included reshaping the cross sections of the swales, replanting shrubs to stabilize channel banks and restore shade, and blocking the upstream end of the channelized reach, diverting water along the original channel course. Within minutes after rerouting the stream, water temperature below the restored reach dropped by approximately 2 degrees C. Although a comprehensive monitoring plan was not in place to determine the cause, cooling in this unshaded reach was probably due to the reactivation of hyporheic flow pathways and circulation of water through the hyporheic zone.

*Rhône River, France*

The Brégnier-Cordon hydroelectric project (80 km downstream of Geneva) diverted most flow of the Rhône into a canal. Initially, this raised upstream water tables and waterlogged the floodplain, so in response drainage canals were constructed. The overall effect was to reduce seasonal variations in river stage and the alluvial water table, to prevent active channel migration, and to eliminate flushing flows from side channels while still allowing silt-laden overbank flows to deposit sediment in them. The Rosillon side channel was cut off from the main river by a sediment plug at its upstream end, and a layer of organic and nutrient-rich silt deposited over the length of the side channel sealed the surface flow from subsurface exchange (Henry et al. 1995). The restoration project involved mechanically removing the layer of fine sediment to increase the supply of nutrient-poor groundwater to the channel, and removing large woody debris from the channel to speed flood flows through the channel and thus discourage redeposition of sediment in the side channel. The sediment plug at the upstream end of the side channel was left in place to prevent entry of (nutrient-rich) river water at normal stage. By increasing the exchange of nutrient-poor groundwater (increasing vertical connectivity), the restoration was designed to reverse the rapid terrestrialization and eutrophication of the Rosillon channel, resetting the channel back to mesotrophic stage and thereby re-creating ecologically important floodplain habitats whose abundance has declined. Reducing hydraulic roughness and encouraging higher velocity flood waters through the side channel (increasing lateral connectivity) was intended to prevent deposition of fine sediment that would reduce vertical connectivity (Henry et al. 1995, 2002).

*Rocky River, New South Wales, Australia*

Once described as a narrow channel too deep for a horse to ford, Rocky River was subject to intense alluvial gold-mining in the mid-1800s and, with catchment clearance and soil erosion, the channel filled with sand and widened to its current state of 40-70 m broad with a braided stream of 2-8 m wide and up to 20 cm deep (Boulton et al. 2002). Paradoxically, the modified river now has vertical connectivity over a larger area than before with relatively little change to its flow regime although more of the water probably flows interstitially. The vertical connectivity is restricted by the fine sediments and downwelling surface water loses two-thirds of its oxygen content within 10 cm of entering the hyporheic zone (Boulton et al. 2002). Restoration, if feasible, would require control of erosion and sand input from the unstable banks, removal of the ‘sand slug’ within the channel, and probably result in reduced areas of vertical connectivity.

*San Pedro River, Arizona*

Heavy groundwater pumping in the alluvial aquifer for agricultural use and from the regional aquifer to support growth of the nearby community of Sierra Vista has significantly decreased annual runoff in the San Pedro River, with greatest declines occurring in summer months (USGS 1999). Pumping from the alluvial aquifer lowered the groundwater table to the extent that some sections of the river lose surface flow during the late summer, and flood volumes may be reduced due to greater transmission losses to the alluvium (Stromberg et al. 1996). By virtue of the reduced lwo flows, the net result has been an increase in streamflow variability and a shift from a well-connected surface-groundwater system to one with more limited vertical connectivity and greater dominance of groundwater recharge. Because the river's riparian corridor represents a biodiversity hotspot and one of the last remaining examples of an intact riparian community in the southwestern U.S., a large section of the river was designated as a National Conservation Area in 1988 in an effort to preserve and restore the ecosystem (McPhee and Yeh 2004). This designation mandated the cessation of several floodplain activities, including sand and gravel mining, floodplain agriculture, and groundwater pumping to enhance groundwater recharge and surface water flow. However, these measures have had limited success, as groundwater pumping outside the Conservation Area boundaries has created a regional cone of depression (Stromberg et al. 1996) that has restricted the re-establishment of vertical connectivity and flow variability in the river.

*Creightons and Mosquito Creeks, Australia*

In response to removal of deep-rooted native vegetation and replacement with shallow-rooted annual crops, there have been substantial increases in groundwater table elevations across much of southern Australia so that streams such as Mosquito Creek, South Australia, that were once intermittent, now have more permanent flow (Cooling and Richardson, 2000) and potentially enhanced vertical connectivity with its hyporheic zone. Catchment clearance has often accelerated the input of fine sediment into stream channels in other parts of Australia and one example of this is Creightons Creek, Victoria, where a creeping 'sand slug' is moving down the system, smothering riffles, filling pools, reducing vertical connectivity in parts of the stream even though there has been no change in flow regime (Davis and Finlayson 2000).

*Los Angeles River, California*

Following the devastating floods of 1938, the Los Angeles River and major tributaries were channelized to increase channel conveyance and prevent bank erosion. By the mid-1950s, about 600 km of channel had been encased in concrete, eliminating vertical connectivity over most of the river network. Ironically, two short reaches of river had concrete walls built but the beds were not covered because the groundwater seepage into the bed was so active it prevented installation of the concrete bed. Thus, these "soft-bottomed" reaches with positive seepage retain high vertical connectivity, largely because their connectivity was so strong originally. The channelization of the Los Angeles River also dramatically reduced its lateral connectivity by preventing overbank flows, channel migration, or any significant exchange between channel and floodplain.