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 Review paper

Restoring mediterranean-climate rivers

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Abstract Mediterranean-climate rivers (med-rivers) have highly variable flow regimes, with large, periodic floods shaping the (often-braided) channels, which is different from stable humid-climate rivers, whose form may be dominated by the 1.5-year flood. There is a fundamental challenge in attempting to "restore" such variable, ever-changing, dynamic river systems, and the most effective restoration strategy is to set aside a channel migration zone within which the river can flood, erode, deposit, and migrate, without conflicting with human uses. An apparent cultural preference for stable channels has resulted in attempts to build idealized meandering channels, but these are likely to wash out during large, episodic floods typical of med-rivers. Med-rivers are more extensively dammed than their humid-climate counterparts, so downstream reaches are commonly deprived of high flows, which carry sediments, modify channel morphology, and maintain habitat complexity. Restoration of the entire pre-dam hydrograph without losing the benefits of the dam is impossible, but restoration of specific components of the natural hydrograph (to which native species are adapted) can restore some ecosystem components (such as native fish species) in med-rivers.

Keywords Episodic channels · Mediterranean climate · Variable flow regime · River restoration · Channel migration zone

Introduction

Mediterranean-climate rivers (med-rivers) behave notoriously badly from a human perspective. Driven by highly seasonal precipitation, flows range from raging flood to a summer trickle. These seasonal changes in temperament on the Carmel River, California were described by Steinbeck (1945, p. 77) as follows, "In the winter it becomes a torrent, a mean little fierce river," contrasted with the summer, when "it is a place for children to wade in and for fishermen to wander in". The channels of med-rivers reflect the influence of infrequent, large floods, which periodically rearrange the channel and scour vegetation. In subsequent quiet years, riparian vegetation recolonizes and channels develop complex forms. The native biota of these rivers is adapted to these cyclical changes (Gasith & Resh, 1999; Lytle & Poff, 2004).

Guest editors: N. Bonada & V. H. Resh / Streams in Mediterranean climate regions: lessons learned from the last decade

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Given that they are naturally highly variable, ever-changing, and dynamic river systems, what do we mean by "restoring" med-rivers? There is a fundamental challenge in attempting to restore such a moving, undefined target, especially when apparently deep-seated cultural preferences for stable flows and stable channels are taken into account. In this paper, we review some of the principal human alterations to med-rivers and consider potential restoration approaches to address these impacts and restore their biota.

Fig. 1 Hydrographs showing gradients from fully mediterranean (rainfall-runoff dominated) to fully montane (snowmelt influenced) in the Sacramento-San Joaquin River system of California, with **A** rainfall-dominated hydrograph for Orestimba Creek at Newman (elevation 66 m), which drains the Coast Ranges on the west side of the San Joaquin Valley; and **B** hydrographs for the Merced River at Pohono Bridge (1,177 m elevation), with a snowmelt hydrograph, and at Snelling (99 m elevation), which shows the addition of rainfall-runoff components (from lower elevation tributaries) overlain upon the snowmelt hydrograph. **C** Map shows gauge locations and their relation to topography, reflecting the greater snowmelt component for the high-elevation gauge and orographic effects more generally. Data from US Geological Survey website

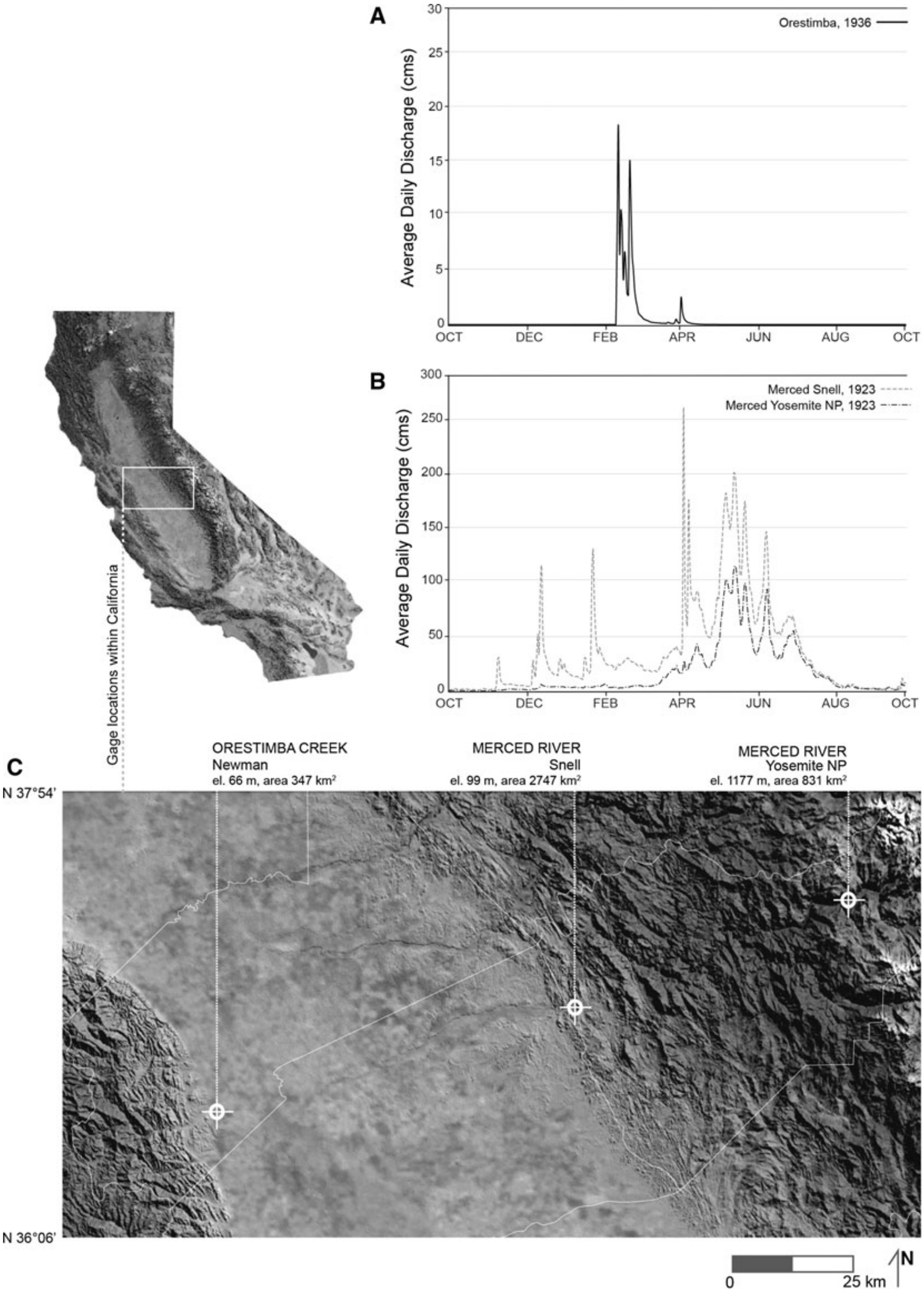
Flow variability and its gradients

The seasonal difference between low and high flow is invariably greater in med-rivers than in their humid-climate counterparts (Wainwright & Thornes, 2004). In California's med-rivers, for example, maximum natural monthly discharge is often 20–200 times greater than minimum monthly flows, while in the eastern United States (with its humid Atlantic climate) the ratio is generally less than 10 times. Although mediterranean-climate regions (med-regions) are considered dry climates, they often receive as much precipitation as humid regions. For example, Healdsburg on the Russian River in Sonoma County, California, has more annual rainfall (1,094 mm, 1960–2010) than Lafayette in Tippecanoe County, Indiana (941 mm, 1960–2010). However, Indiana receives enough rainfall year round to farm without irrigation, while Sonoma County experiences a dry summer and relies on rivers, reservoirs and groundwater to support irrigated agriculture (Deitch, 2006). Moreover, inter-annual variation is much greater as well: the coefficient of variation for Healdsburg is 33.5 % compared to only 14.1 % for Lafayette.

The high variability in seasonal discharge in med-rivers is directly related to precipitation patterns. In med-regions, nearly all annual precipitation falls within the winter and spring months, followed by a predictable drought period extending from summer through the fall (Gasith & Resh, 1999). In the dry season, many streams naturally dry up completely or contract to isolated pools, while in the winter, flows spill their banks, inundating floodplains, scouring beds, and modifying channels. Med-rivers are not only seasonal, but also are characterized by high year-to-year variation. Prolonged droughts are common as are extreme wet years. The El Niño Southern Oscillation (ENSO) is an important driver of multi-year climatic cycles in med-regions, and has been linked to severe drought and extreme flood events for med-rivers in Australia (Bond et al., 2008), California (Schonher & Nicholson, 1989; Cayan et al., 1999), and Chile (Waylen & Caviedes, 1990).

Flow regimes among med-rivers also show substantial variation over spatial gradients. The strong seasonality of med-climate precipitation patterns is moderated in rivers whose drainage basins include sufficiently high mountains to develop snowpack. Snowmelt runoff occurs with warming temperatures in late spring and summer, and thus is substantially delayed from precipitation events in the winter. In the Ebro River basin of Spain, tributaries from the Pyrenees to the north have a significant snowmelt component, while tributaries draining the lower elevation mountains in the southern part of the basin are entirely rainfall-runoff driven (Batalla et al., 2004). A similar contrast is evident in the Sacramento-San Joaquin River basin in California, where tributaries draining the Sierra Nevada (in the eastern part of the basin) have important snowmelt hydrograph components while tributaries draining the lower elevation Coast Ranges (in the western part of the basin) are entirely rainfall-runoff fed (Fig. 1). Even within fully rainfall-dominated med-regions of coastal California, there are pronounced latitudinal gradients, such as Sonoma County north of San Francisco, which receives 1,000 mm of annual precipitation on average, contrasted with Santa Barbara County in the south with less than 500 mm of mean annual precipitation.

Med-climate stream ecosystems are physically, chemically, and biologically shaped by the sequence of prolonged drought followed by a concentrated


A
Orestimba, 1936
Average Daily Discharge (cms)
0
5
10
15
20
25
30
OCT
DEC
FEB
APR
JUN
AUG
OCT
B
Merced Snell, 1923
Merced Yosemite NP, 1923
Average Daily Discharge (cms)
0
50
100
150
200
250
300
Gage locations within California
C
ORESTIMBA CREEK
Newman
el. 66 m, area 347 km²
MERCED RIVER
Snell
el. 99 m, area 2747 km²
MERCED RIVER
Yosemite NP
el. 1177 m, area 831 km²
N 37°54'
N 36°06'
0
25 km
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period of rainfall (Gasith & Resh, 1999; Bêche & Resh, 2007). Native species are, by definition, adapted to the high seasonal variability of med-rivers and have evolved traits that provide resistance to drought and the ability to recover from flood disturbance (Bonada et al., 2007). Med-regions are also hotspots for biodiversity (Myers et al., 2000), presumably owing to the high spatial and temporal heterogeneity of environmental conditions (Munné & Prat, 2004; Bonada et al., 2007) and the influence of glaciation events in promoting speciation (Ribera & Vogler, 2004). While the challenge of surviving the drought and flood cycle keeps out competitors, the low-flow period is stressful even to natives and is probably a limiting factor for many aquatic species (Grantham et al., 2012). Native freshwater species are highly susceptible to impacts from water management and other anthropogenic disturbances (Clavero et al., 2010; Grantham et al., 2010), particularly during the drought period, when even modest diversions or pumping of alluvial aquifers can dry out a channel (Bond et al., 2008; Deitch et al., 2009a). Such problems are especially manifest in dry years, with their naturally lower base flows and increased human demands for water.

The dammed

Med-climate landscapes are generally well-suited for agriculture by virtue of their warm, sunny summers. However, water availability is distinctly out-of-phase with human demands. Rainfall-runoff dominated rivers run high in the winter, when water needs for agriculture and domestic purposes are low, but can dry out in the summer, when water is needed most. Thus, agriculture in med-regions is highly dependent on water storage and irrigation projects, and can use five to ten times more water to irrigate crops than agricultural regions of more humid-Atlantic climates (Kenny et al., 2009). Social and governmental institutions have commonly built reservoirs to store water to compensate for seasonal and inter-annual variability in water supplies, and it is clear that med-rivers tend to be more heavily regulated by reservoirs than their humid-climate counterparts (Kondolf & Batalla, 2005; Grantham et al., 2010).

The effects of reservoir impoundment are well illustrated in California and Spain, med-regions that were extensively dammed in the twentieth century. The impounded runoff ratio (IR) is a good indicator of the degree to which reservoirs can affect flow; it is calculated as the total reservoir storage capacity divided by the mean annual inflow. For the Sacramento-San Joaquin River basin in California, overall IR values are 0.8 and 1.2, respectively, with IRs for individual tributary reservoirs ranging from 0.5 to 4.6 (Fig. 2A). As a consequence, frequent high flows (Q2 and Q10) have been reduced by 60% overall below the dams (Kondolf & Batalla, 2005). In the Ebro River basin of Spain, the overall IR is lower (0.6) and varies by tributary subregion (Fig. 2B), and the Q2 and Q10 have been reduced only about 30% overall (Batalla et al., 2004). These large IR values can be contrasted with typically much-lower values in humid-climate rivers, for example, 0.05 to 0.18 in the Elbe, Rhine, and Wesser Rivers, Germany.

As a consequence of the reduction or elimination of frequent scouring flows, vegetation can establish in the active channel, a phenomenon termed "vegetation encroachment". The consequent loss of open sand/gravel habitats can be a problem for species that depend on such features. Along the semi-arid Platte River, Nebraksa, USA, encroachment of woody riparian vegetation has resulted in loss of habitat for the whooping crane (*Grus americana*), which depended upon long sight distances to see potential predators over mostly unvegetated braided channel bars. Habitat "restoration" has been undertaken by mechanical removal of vegetation, because sufficiently high flows to scour vegetation cannot be released from upstream dams (NRC, 2005).

Reaches downstream of dams are deprived of their sediment load that is now trapped behind the dam. This creates a condition known as "hungry water", because flows have the energy to move sediment but have lost their sediment supply, so they tend to erode their bed and banks, causing channel incision and stripping away of bars and other features contributing to habitat complexity. Exceptions are rivers whose flow regimes have been so reduced by reservoirs that they can no longer carry the sediment supplied by tributaries, and aggradation can result. The effects of hungry water on channel geomorphology and ecology tend to be greatest in rivers with high pre-dam sediment loads, where sediment cut off creates the greatest change. Because their unit sediment loads tend to be higher than in humid-climate rivers with

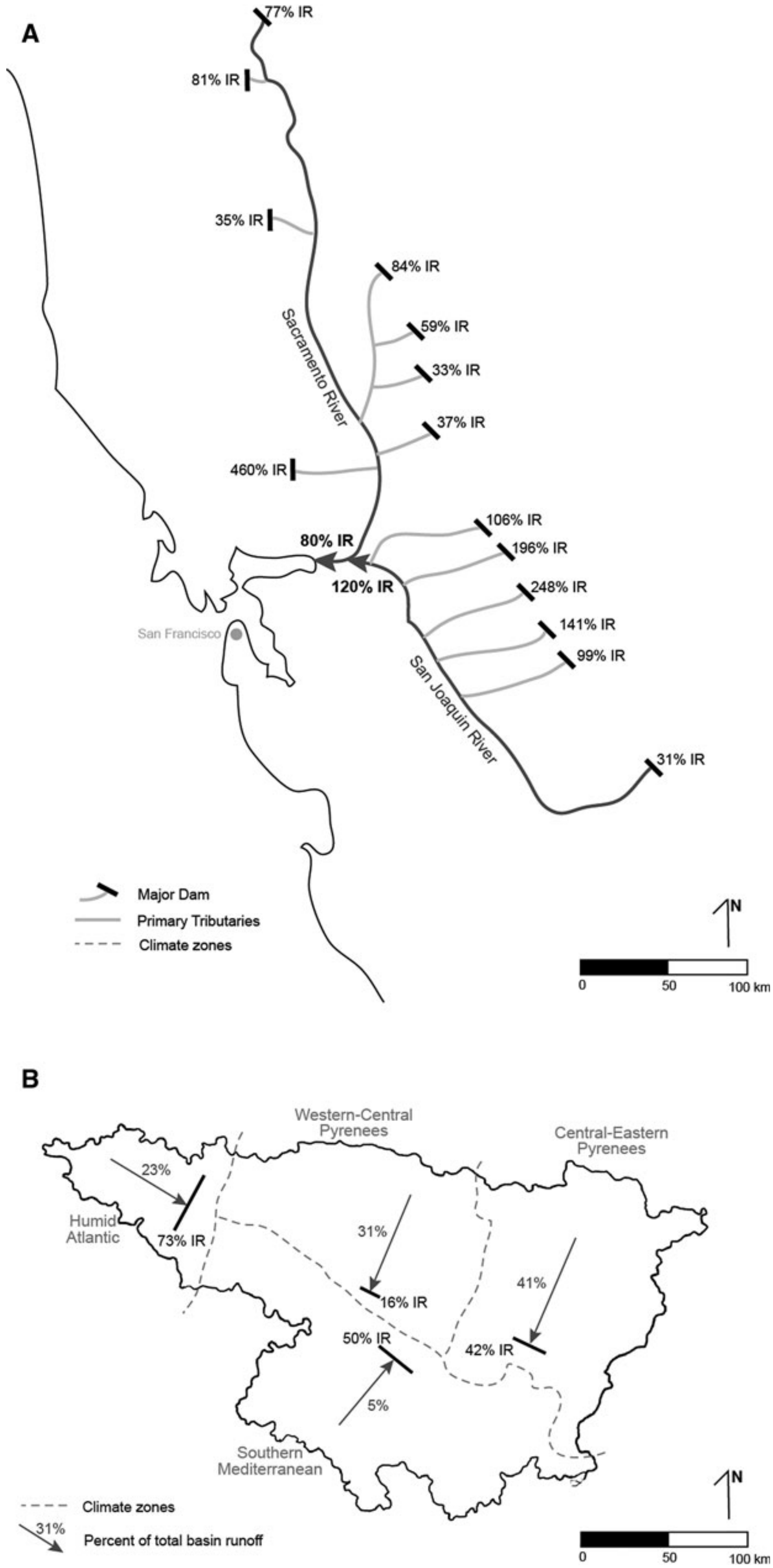

Fig. 2 **A** Degree of impoundment by reservoirs in the Sacramento-San Joaquin River of California. Values of impounded runoff ratio (IR) for major foothills dams, adapted from Kondolf & Batalla (2005). **B** Degree of impoundment by reservoirs in the Ebro River basin of northestern Spain, adapted from Batalla et al. (2004)

well-vegetated catchments (Wainwright & Thornes, 2004), the effects of hungry water tend to be greater in med-rivers.

Within the reservoirs themselves, rivers have undergone widespread conversion of lotic to lentic ecosystems, eliminating habitat for natives and favoring exotic species (Clavero et al., 2004). Downstream of dams, the post-dam, "flat-lined" hydrology also favors exotic fish species over native (Baltz & Moyle, 1993; Moyle & Mount, 2007). Native fish species tolerate natural flood and drought disturbance better than non-native species, but when flow dynamics are moderated by regulation, non-natives can become competitively dominant. Furthermore, native species are often adapted to require specific flows to complete their life history (Lytle & Poff, 2004). For example, many native California fishes spawn on river floodplains that are temporarily inundated in the early spring. The recruitment and growth of juveniles decrease dramatically when flow releases from dams are not sufficient to inundate floodplain habitats (Opperman et al., 2010). Thus, flow regulation can negatively affect native species both by altering habitat dynamics and by facilitating the establishment of competitively dominant, non-native species. Not surprisingly, dams have been identified has a key factor contributing to declines in native fish populations in med-regions of the world, including California (Moyle et al., 2011) and the Iberian peninsula (Clavero et al., 2004).

Episodic channels as distinct from "bankfull" channels

The channels of med-rivers can be considered to be episodic in that they are predominantly shaped by large, infrequent floods. This is in contrast to the pattern often observed in humid-climate and snowmelt streams, where the channel dimensions correspond to more frequent "bankfull" flows, often taken to be the Q1.5, which is the flood that occurs (as an annual maximum) two years out of three (Leopold et al., 1964). For these channels, the Q1.5 was also found to be the "effective discharge", the flow that moves the most sediment over time (Wolman & Miller, 1960). These are the classical 1960s-era concepts in fluvial geomorphology, which were developed based on observations in humid Atlantic-climate landscapes such as Brandywine Creek, Pennsylvania (Wolman, 1955) and Watts Branch, Maryland (Leopold, 1973), and snowmelt-dominated rivers, such as the Yampa in Colorado and Utah (Andrews, 1980). The notion that the active channel is shaped by the 1.5-year flow is an easily comprehended idea, and one that has clearly fixed itself in the mindset of natural scientists in allied fields and among restoration practitioners (NRC, 1992). However, in climates with more variable hydrology, such as med- and semi-arid climates, less frequent floods have a greater role in shaping the channel (Wolman & Gerson, 1978).

The underlying concept of effective discharge was established by Wolman & Miller (1960), who argued that geomorphic work could be estimated as the product of magnitude and frequency. That is to say, we know a big flood can erode, move, and deposit more sediment than a moderate flood, but the moderate floods occur more frequently. So which moves the most sediment (i.e., has the greatest influence on channel form) over time? They illustrated the concept with a colorful analogy:

> Perhaps the state of knowledge as well as the geomorphic effects of small and moderate versus extreme events may be best illustrated by the following analogy. A dwarf, a man, and a huge giant are having a wood-cutting contest. Because of metabolic peculiarities, individual chopping rates are roughly inverse to their size. The dwarf works steadily and is rarely seen to rest. However, his progress is slow, for even little trees take a long time, and there are many big ones which he cannot dent with his axe. The man is a strong fellow and a hard worker, but he takes a day off now and then. His vigorous and persistent labors are highly effective, but there are some trees that defy his best efforts. The giant is tremendously strong, but he spends most of his time sleeping. Whenever he is on the job, his actions are frequently capricious. Sometimes he throws away his axe and dashes wildly in the woods, where he breaks the trees or pulls them up by the roots. On the rare occasions when he encounters a tree too big for him, he ominously mentions his family of brothers – all bigger, stronger, and sleepier. (Wolman & Miller, 1960, p. 73)

The examples developed in the early 1960s literature were dominated by humid-climate and snowmelt streams, which tended to support the idea that frequent small floods, i.e., the Q1.5, would accomplish the most geomorphic work over time. Using the wood-cutting analogy, it would be the man who chops the most wood in total. But as noted by Wolman & Miller (1960, p. 60), "The evidence also suggests that the more variable the regimen of flow of the stream, the larger the percentage of total sediment load which is likely to be carried by infrequent flows." Thus, it is the large, infrequent flood—the "giant"—that will accomplish the most geomorphic work in episodic channels. For example, on the Santa Clara River, California, of the roughly 57.6 million tons of sediment load measured at Montalvo from 1968–1975, 55% was moved in only 2 days during the 1969 flood (Williams, 1979). Moreover, of the total sediment load moved over 72 years from 1928–2000, 25% was transported in just 4 days (Warrick, 2002). In such an episodic channel, the effective discharge is not the Q1.5, but rather the largest flood on record, which is consistent with Wolman & Gerson (1978) (Peter Downs, University of Plymouth, personal communication).

While smaller features adjacent to a perennial baseflow channel (termed the *lit mineur* in French) can be shaped by these frequent high flows, the overall form of the active channel (the *lit majeur*, Bravard & Petit, 1997) in med-rivers is shaped by larger floods. Despite Wolman & Gerson's (1978) admonition that in drier climates, it is the larger, less frequent floods that shape the channel, and despite research demonstrating that bankfull channels very frequently did not correspond to Q1.5 (Williams, 1978), the notion that river channels are shaped by the 1.5-year flood became widely accepted, and has been a common basis for stream restoration designs, even in med-rivers (NRC, 1992).

The ecological implications of episodic channel processes are profound. Unlike the bottomland of a stable, humid-climate river, where a clearly defined channel is flanked by stable stands of mature riparian vegetation, the channel substrate in an episodic med-river is "renewed or rejuvenated abruptly, at intervals shorter than that typically needed for a mature woodland to develop" so that the banks and islands are dominated by early successional-stage vegetation (Hecht, 1994). These channels are typically disturbed at intervals of one to several decades, when they experience sudden influxes of sediment (as from landslides and debris flows) during floods, and especially after wildfires. The valley floor may be reworked beyond the limits of the current riparian vegetation, with erosion commonly eating into the depositional aprons at the toe of slopes. For months or years after such a sediment influx, pools can be filled and riffles buried, but in subsequent years, flows scour out the deposits, and pools reemerge or reform within the rearranged channel (Hecht, 1994).

From a flood-risk management perspective, episodic channels present challenges, because floods are so infrequent that inhabitants may not have experienced a flood and do not understand the risks of living in a flood zone. In many cases, developers, elected officials, and government agency staff responsible for land-use decisions may not even recognize dry washes as active river channels (Stein et al., 2011).

Restoration implications of variable hydrology and episodic channel processes

Give the river room

Given that dynamic fluvial processes create the complex habitats needed by native species, it follows that the most effective restoration strategy in med-rivers is to set aside a zone within which the river can flood, erode, deposit, and shift course without conflicting with human uses. So as long as its flow regime (including the alluvial water table) is relatively intact, the river can be relied on to fashion habitats suitable for native species, as the river has done for millennia. An exception is when invasive exotic plant species are present, which may require aggressive vegetation management to prevent their establishment and expansion within the river channel. As a general rule, however, the best restoration approach is to prevent degradation in the first place, which may be achieved by setting aside a generous river corridor within which a dynamic channel can build the complex forms that yield diverse, complex habitats, and avoid the conflicts between fluvial process and human occupation of floodplains and river banks. This approach, variously termed the *channel migration zone* (Washington state, US), *erodible corridor* or *espace de liberté* (France), or *territorio fluvial* (Spain), arguably represents the most nuanced and sophisticated approach to river restoration because it allows natural fluvial processes to do the restoration work. Moreover, it permits the natural variability of flow and sediment load from year-to-year to be expressed in dynamic channel changes and consequent evolution of habitats, to which native species are adapted (Kondolf, 2011). The limits of such zones have commonly been set based on mapping of past channel locations and modeling probable future channel movements (Piégay et al., 2005). This approach can be viewed as not really restoration but might be better thought of as preservation of what is already working, and is especially well-suited to the dynamic med-river, given the virtual impossibility of establishing a sustainable constructed channel in such a naturally dynamic environment.

The French *espace de liberté* approach works only where river has sufficient stream power and sediment load to recover its channel, and where urban encroachment has not excessively restricted the channel (Kondolf, 2011). However, this approach is typically not applicable in reaches through dense urban areas, where the channel is already highly constricted, or below dams, where the flood flows have been largely eliminated and coarse sediment supply cut off, or in deeply incised channels that are caught in a cycle of incision by virtue of concentrating higher and higher flows within a narrow channel width. Agricultural and urban development commonly encroach upon formerly wide river corridors. Where berms or levees prevent inundation of the floodplain and hardened banks prevent bank erosion and channel migration, such features can in many cases be removed to restore the natural range of river channel movement, as exemplified by the Kleblach-Lind reach of the River Drau in Austria (Habersack & Piégay, 2008).

In Spain, the *territorio fluvial* approach (Ollero, 2007) was identified as a key strategy for restoring rivers and the national Decree Law 9/2008 (adopted 11 January, 2008) has greatly expanded the river public-domain (i.e., the channel and riparian zone). Instead of being limited to the area covered by the average annual peak flow (unregulated), the river zone is delineated on geomorphic and ecological criteria, using historical references derived from aerial photographs (Ollero et al., 2009; Gonzalez del Tánago et al., 2012). The fluvial territory approach has been implemented in at least ten rivers in Spain (Ollero & Ibisate, 2012). In California, the best examples of this approach are from the Sacramento River basin: near the Lower American River Parkway within the city of Sacramento, and the Sacramento River Conservation Area along a 160-km reach of the river designated based on historical and predicted future channel migration (Greco et al., 2007).

Restore flow and sediment dynamics

In addition to the space needed for dynamic channel migration, true restoration of episodic med-climate river systems requires variable flow and sediment loads. However, because med-rivers are more extensively dammed and more heavily regulated than humid-climate rivers, it is rarely possible to restore pre-dam hydrographs below dams without conflicting with the dam's purpose of regulating flow, and the inevitable sediment trapping yields widespread sediment starvation downstream of dams. Nonetheless, in some cases, it may be possible to restore components of the hydrograph to create conditions for native biota and achieve other ecosystem objectives. To mitigate for the lack of frequent natural floods, artificial high flows capable of mobilizing the bed and transporting sediment (typically sand and finer particles) downstream may be used as a management tool. Termed "flushing flows" or "channel maintenance flows", these are commonly specified based on tractive-force calculations of flows required to mobilize the bed, or on the assumption that the Q2 is likely sufficient to achieve bed mobility (Kondolf & Wilcock, 1996).

The Trinity River, a major tributary of the Klamath River in Northern California, offers an example of how restoration flows have been incorporated in dam operations. The river historically supported healthy runs of anadromous salmon, but fish populations declined precipitously following construction of Trinity Dam in the early 1960s. The dam cut off access to upstream spawning grounds, diverted most flow to the Sacramento River (with reductions to flows in the Trinity averaging 90% in the first years), and resulted in extensive habitat loss as sand from tributaries accumulated in the channel gravels, without periodic high flows to remove it. Restoration efforts began in the 1970s, with a significant federal commitment in recent decades. Water diversions from the basin have been reduced, and a restoration flow regime adopted, with different flows specified for five classes of year from very dry to wet (USFWS & Hoopa Tribe, 1999). Minimum flows are now specified to facilitate downstream migration of juvenile salmonids and periodic high flows are made to mobilize the river bed in all but dry years. Gravels are added to the channel below the dam to compensate for the lack of coarse sediment supply (Krause, 2011).

A lower elevation, more med-climate example is Putah Creek, a tributary of the Sacramento River, also dammed in the 1960s. Its reservoir impounds 4.5 times the mean annual flow (visible as the western-most labeled value of IR 460% in Fig. 2A), so it effectively eliminates frequent high flows, while artificially elevating summer baseflows between the reservoir and a downstream diversion dam, from which most of the flow is diverted into a canal for agricultural and urban use. The severe alteration of the natural hydrograph resulted in declines of native fish and invasion by exotic fish species (Moyle et al., 1998). Following a legal battle, the dam operator now releases additional water to improve conditions for fish, although the basic function of the dam is unchanged, and most flow is still diverted from the stream. Nevertheless, the restoration of key elements of the natural flow regime, including spring flow releases for native fish spawning, has facilitated the expansion of native-dominated fish assemblages and contraction of the distribution of non-native fish throughout the creek (Kiernan et al., 2012). The recovery of native fishes under the new management plan demonstrates that the restoration of med-river ecosystems does not necessarily require removing dams or restoring the full natural flow regime, which is infeasible in most circumstances. Rather, the findings indicate that when key elements of the hydrograph are preserved (e.g., flow events to which native species are adapted), desirable ecological benefits can be maintained (e.g., native biodiversity) despite significant human water use pressures.

In general, however, the restoration of natural flow regimes to restore med-rivers remains a major challenge because of conflicting human water demands. In Spain, for example, national assessments conducted for the National Strategy for River Restoration identified flow withdrawal as the principal human impact on rivers nationwide. A review of 60 restoration projects in Spain undertaken as part of the European FORECASTER research project (http://www.forecaster.deltares.nl) found that flow regulation was the main stressor in 18% of the projects reviewed, yet only 2% of the projects included measures for environmental flows, reflecting the high "social and political resistance to restricting water allocation…to irrigation," because of the high profits of irrigated agriculture (Gonzalez del Tánago et al., 2012).

Salmon in mediterranean California

Restoration efforts along the west coast of North America are dominated by efforts to restore habitat for anadromous salmonids, especially runs of Pacific salmon (*Oncorhynchus* spp.) and steelhead trout (*O. mykiss*) that are now listed under the Endangered Species Act (Bernhardt et al., 2005). The threat of extinction is especially serious in the southern end of the Pacific salmonid distribution, in California, where habitat alteration and flow diversions have been extensive, and where water temperatures often marginal at best. The listing of these salmon runs has created profound conflicts between efforts to preserve the species and the human uses of rivers and surrounding landscapes. River restoration investments in California have been largely directed at improving habitat for these species, and many projects are undertaken to mitigate for the effects of new development (Kondolf et al., 2007).

In most rivers, habitat has been degraded by multiple human alterations, but restoration projects tend to address only some of the stressors, which are those that can be changed most easily, and which entail the least financial cost, or encounter the least political resistance. Thus, the trajectories of restoration rarely parallel the trajectories of degradation (Kondolf et al., 2006). This has certainly been the case in restoration efforts for salmon in California, which have been dominated by attempts to physically improve habitat, either without restoring natural flow regimes, or ignoring the highly variable nature of flows in some streams. An example of this is evident from a restoration effort on Selby Creek, a tributary to the Napa River in California (drainage area 2.4 km^2). A 2008 project involved installation of multiple structures, including 102 boulder wing deflectors, 11 boulder weirs across the channel bed, 18 "boulder streambank protection sites", and 3 "boulder armor sites" (Bioengineering Institute, 2009). The boulder deflectors extended from the banks into the channel, intended to create scour pools (Fig. 3). The project affected 2.5 km of the stream channel and involved

Fig. 3 Habitat restoration project on Selby Creek, Napa Valley, California. Over 100 boulder structures were installed in the channel of Selby Creek with the intention of inducing bed scour and creating pools for fish. However, this alluvial fan reach naturally dries up each summer, so the fish could not benefit from the intended habitat during the season when it was needed (photo courtesy of Laurel Marcus, California Land Stewardship Institute, 2008)

9,700 ha of grading. Unfortunately, this alluvial fan reach dries up each summer from rapid infiltration of flow into its coarse sediment, so the structures do not create the intended habitat in the summer season, when deep pools are most needed by the fish.

Volumes have been published about salmon restoration in California rivers and streams. Rather than repeat these statements, we offer a perspective that has not been widely acknowledged: Anadromous salmonids in California can be viewed as non-mediterranean species that evolved in the cold waters of the north Pacific, but that they took advantage of periods of colder climate during the Pleistocene, and established themselves in med-climate California. Thus, salmon can be viewed as cold water organisms that have managed to persist in what is not a fundamentally favorable climate through remarkable adaptation to local hydrologic and climate conditions (Healey & Prince, 1995; Beechie et al., 2006) and through phenotypic plasticity (Thorpe, 1989; Williams, 2006). Most med-rivers have very low native fish diversity (Almaça, 1995), so the occurrence of native anadromous salmonids in the rivers of California creates a unique overlapping of med-climate hydrology and channel dynamics with anadromous salmonid life histories. The degree of human alteration to the riverine habitats of California has been extensive and severe, yet most of the runs have managed to persist by evolving "…extraordinary life history diversity to persist in the face of stressful conditions that often approach physiological limits" (Katz et al., 2012, p. 1).

There are three principal runs of Chinook salmon (*O. tshawytscha*) in California rivers, named after the seasons in which they typically migrated upstream as adults: spring, fall, and winter. Prior to overharvesting and habitat loss that accompanied the nineteenth century influx of European settlers to California, the spring run was by far the largest, with between 2 and 3 million adults migrating upstream through the Golden Gate of San Francisco Bay annually, to spawn mostly in higher elevation tributaries of the Sacramento-San Joaquin Rivers (Moyle, 2002). The life history of these fish was well-adapted to the seasonal hydrology of the river system. During spring snowmelt, abundant cold water flowed from upper reaches of the basin to the ocean, providing longitudinally connected paths for salmon migration to a myriad of natal spawning streams. The adults would hold over the hot summer months in pools with consistently cold water temperatures, most often maintained by groundwater sources, but also by snowmelt. As air temperatures dropped in the early fall and the threat of high water temperatures passed, the adults would spawn. The extensive construction of dams has blocked access to nearly all these natal spring-run salmon streams in the system (Fig. 2) (Kondolf & Batalla, 2005; Lindley et al., 2006), leaving remnant populations only in smaller tributaries that were spared dam construction in the twentieth century, such as Mill, Deer, and Butte Creeks.

By contrast, the winter run formerly spawned in upper reaches of the Sacramento River system. These reaches are now completely cut off by Shasta Dam, but ironically the run persists by spawning in the artificially cold waters released by Shasta Dam, in waters directly downstream of the dam. The principal run that persists today is the fall run, whose adults wait to ascend the lowland rivers until late October or early November, after water temperatures have dropped, spawning in gravel beds in valley or foothills reaches of the rivers. Unlike the winter and spring runs, much of the historical fall-run habitat remains accessible, but it has been degraded by sediment starvation and loss of gravel substrate, channel simplification, flow alteration, and degraded water quality. Moreover, the fall run is now largely supported by hatcheries, whose progeny have essentially overwhelmed wild fish (Williams, 2006).

Alterations to salmon habitat in the Coast Ranges of California take a different form. Here, water management is generally more dispersed, with multiple small diversions and dams operated by private landowners and local water districts (Deitch et al., 2006). Cumulatively, these can be significant in their impact, especially in times of base flow, where there is naturally very little water available to maintain flowing water or even perennial pools (Grantham et al., 2010). Continued flow alterations, loss of habitat, and deleterious effects of hatcheries threaten anadromous salmonids of California with extinction (Katz et al., 2012), and invocation of the Endangered Species Act on behalf of these threatened fish has created persistent conflicts over water and land management.

Imposing humid-climate form on mediterranean-climate channels

Attempts to restore med-rivers often betray cultural preferences for single-thread, meandering rivers with stable hydrology, more likely encountered in humid Atlantic environments such as northern Europe or the eastern seaboard of the US. There is considerable evidence of a cultural preference for Atlantic-climate river forms, notably stable, sinuously meandering, single-thread channels (Kondolf, 2006), and for "medium" water levels, that is, steady flows that are small enough to stay within the channel, but large enough that they do not expose large areas of the channel bed (Brown et al., 1991; Whittaker et al., 2005; Litton et al., 1974). It is notable that stable channels and moderate water levels rarely occur naturally in med-rivers. However, these attributes have consistently been the objective of prior attempts to restore these rivers.

Much of what is funded as restoration in rivers of North America can be seen as attempts to transform dynamic systems, viewed as ugly or messy (Nassauer, 1995), into less dynamic, tidy, stable systems (Kondolf, 2006). These efforts may have been based on outdated notions of stability as beneficial to ecosystems, and were certainly influenced by the concept of Q1.5 as the effective discharge. These projects have experienced a high failure rate across the continent, and certainly so in the med-rivers of California, where such projects have commonly failed by washing out in modest floods (Kondolf, 2006) (see Cuneo Creek case study below). However, even if they remained stable, the ecological benefits claimed from such channels, artificially stabilized into an ideal form imported from other landscapes, would be questionable at best. In contrast in Europe, river restoration became widespread more recently, and at least outside of dense cities, has been based more toward restoring ecosystem dynamics (Habersack & Piégay, 2008).

Transformation of urban rivers

Urban rivers have historically been contaminated by effluent, dredged, and straightened for navigation and flood conveyance, and their banks occupied by industry and navigation. Small rivers have been channelized and lined with concrete to increase flood conveyance, or buried in underground culverts so the valuable space they occupied could be converted to other uses such as streets, industry, or as in the case of the torrent Paillon in Nice, France, a convention center. Burial or conversion to concrete channels results in permanent loss of riverine habitat, as illustrated by the well-studied case of the Los Angeles River, where the mainstem and tributaries are encased in 800 km of concrete channels (Gumprecht, 2001). In some cases, buried streams have been exhumed and restored as free-flowing waters, a practice referred to as "daylighting" (Riley, 1998). However, many buried streams, such as *la Rambla* (a local term for torrential stream, derived from the Arabic) (Permanyer, 2008), which flows under the famous Barcelona street of the same name, are unlikely ever to be daylighted, as the benefits of having an open seasonal stream could not compete with the current economic value of the urban space.

When considering the restoration potential of urban rivers, it is important to recognize the changes in hydrology, such as increased peak flows, loss of natural base flows, and introduction of artificial base flows, e.g., return flow from over-irrigation of landscape plants and leaks from water and sewer pipes. This new base flow is often termed "urban slobber", and can make formerly seasonal streams, perennial (commonly observed in California) (Tyagi et al., 2008). Consequently, given fundamental alterations in urban catchments and stream corridors, how much ecological restoration can realistically be achieved? When the potential for restoring ecological functions is limited, the social benefits of providing open space and parkland, connecting children with streams, and providing public educational opportunities, may be the greatest benefits of such projects (Riley, 1998).

In the developed world, larger rivers typically have improved water quality thanks to wastewater treatment plants constructed in the last quarter of the twentieth century and, more recently, the deindustrialization of waterfronts and shift of navigation activities to centralized container ports have opened riverfronts to public access (Kibel, 2007). Thus, we see increased opportunities for restoration of urban rivers and development of river banks for trails, parks, cafés, and other human uses. Many of these urban restoration projects on med-climate rivers have involved attempts to transform the naturally seasonal river into a river with more stable water levels, more resembling the northern European ideal, as illustrated by the Guadalupe and Fervença River case studies described below.

Case studies

Cuneo Creek, California, USA

An illustration of the popular attempts to 'restore' an episodic channel to a stable meandering condition is Cuneo Creek, in the Coast Ranges of northern California. Cuneo Creek drains a rural landscape of Douglas fir (*Pseudotsuga menziesii*), with a highly seasonal mediterranean-climate flow regime. Its 10.8 km^2 catchment was almost completely logged in the 1950s and early 1960s, which triggered slope instability and resulted in high sediment yields to the stream channel (Hansen, 2003). Reflecting this high sediment supply and episodic flow regime, the channel is braided, with multiple threads shifting over an active channel bed of gravel and sand 150 m wide and with a slope of $\sim$0.03. Cuneo Creek flows into Bull Creek, and deposition of sediment in Bull Creek downstream caused channel instability that threatened a grove of old-growth redwoods (*Sequoia sempervirens*). In an effort to reduce sediment yield, a consultant proposed that Cuneo Creek be reconstructed as a 10-m wide channel with 43 symmetrical meander bends (Fig. 4A, B), on the theory that building this idealized "C3" channel form would stabilize the stream (Rosgen, 1991). About half of the proposed length of channel was reconstructed as proposed (Fig. 4C) (Burnson, 1992), but the new channel was damaged in the high flows of 1995 (Fig. 4D), and subsequently obliterated in 1997.

Recognizing the need to address the underlying cause of the problem, the land owner, California State Parks, (CSP) has since focused on reducing upslope sediment sources through removal of, or improvements to, abandoned logging roads and service roads. With over 50% of the roads treated, CSP is now phasing into upslope and riparian silvicultural treatments to improve forest trajectories toward late seral conditions. Detailed observations confirm that region-wide erosion rates have now declined significantly compared to mid-twentieth century rates, but still remain high in the Cuneo Creek catchment, so CSP does not intend any further in-channel projects, but is focusing instead on addressing causes of the disturbance and high sediment yields (Kondolf, 2006).

Guadalupe River, California, USA

The Guadalupe River (drainage area 440 km^2) flows 19 miles through the center of San Jose, California, discharging into San Francisco Bay. Despite its med-climate seasonal flow regime and the urbanization of much of its catchment, the Guadalupe supports a run of anadromous steelhead trout (*O. mykiss*). Persistent flooding problems initially led to calls for a river improvement project in the early 1960s, but the city of

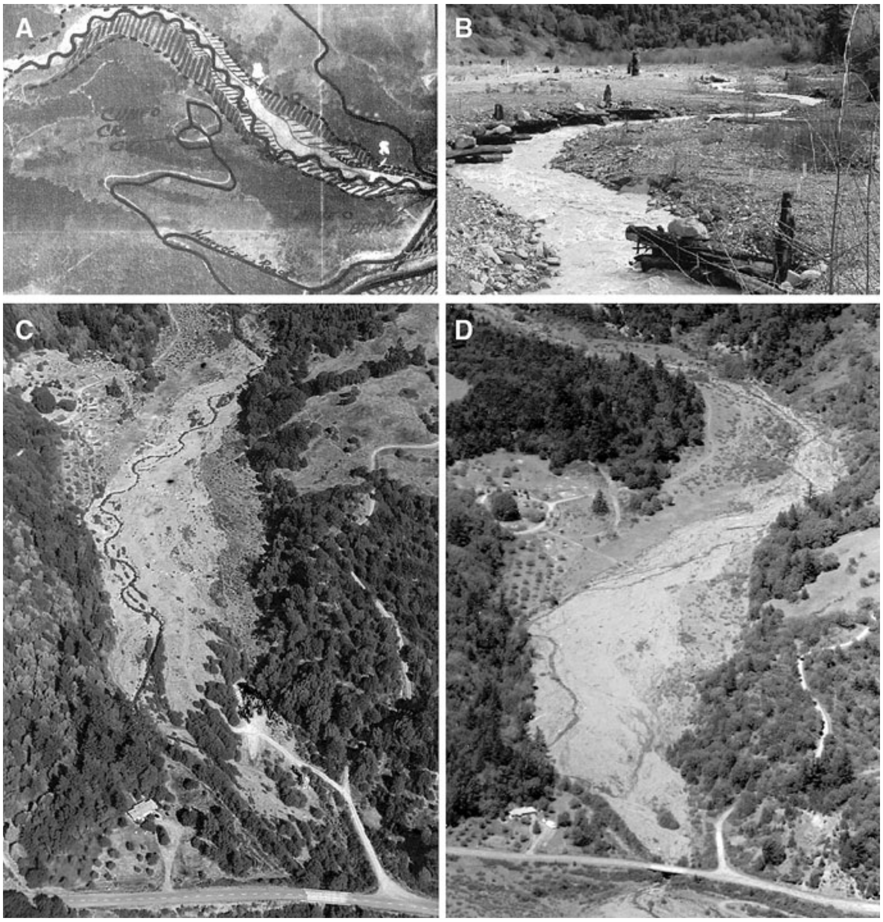

Fig. 4 **A** Plan for meandering C3 channel in Cuneo Creek (Rosgen, 1991) (photo(s) courtesy of California State Parks). **B** Cuneo Creek after restoration to C3-type channel (photo(s) courtesy of California State Parks). **C** Oblique aerial view of Cuneo Creek showing project reach, after construction, and **D** after 1995 high flow. (photo(s) courtesy of California State Parks)

San Jose soon adopted a vision for the river based on an example from the San Antonio River, in San Antonio, located in a humid-climate region of Texas.

The San Antonio River is a spring-fed river with naturally high summer base flows. In 1941, a 1,200-m long meander bend was developed into a commercial and public promenade, protected from flooding by a bypass channel. The water level in the river bend is maintained at a fairly constant level with a water gate at the upstream end and a weir at the downstream end. This constant flow level provides a water depth to accommodate riverboats that provide tours, a taxi ride, or dinner cruises, and allows restaurants to seat diners outdoors on patios that are within 1 m of the water surface, with little seasonal fluctuation.

After a visit by the San Jose mayor and city council members to San Antonio, the city sought to transform the Guadalupe into a similar river in the proposed "Park of the Guadalupe" in 1965 (Nicholson, 2002). In addition to dealing with flooding from expanding urbanization of the basin, the city saw the park as providing esthetic, economic, and recreational benefits. During the planning process, the city of San Jose used photographs of San Antonio Riverwalk to illustrate how the Guadalupe Park could become, "a substantial water element in the way of elongated lakes, waterfalls, and fountains… with the water for summer enjoyment" (City of San Jose, 1965).

The Guadalupe River, however, with its seasonal flow regime and low flows in the summer, did not live up to the ideal envisioned for The Park of the Guadalupe. Boat cruises and a consistent water level would require additional water and water infrastructure. The city secured a water right from the San Joaquin River at a subsidized price of \$0.02/m^3 for scenic and recreational purposes (Nicholson, 2002). The city hired a landscape architecture firm, which created images of boats, fishing areas, sailing for children, and swans swimming in the transformed Guadalupe River (City of San Jose, 1969). However, creating this placid water feature would have required a series of dams, which would have blocked migration of the steelhead trout, among other environmental impacts. With passage of the National Environmental Policy Act in 1969, the environmental impacts, along with economic constraints, made this idealized vision unachievable. Instead, a citizen’s task force converted a downtown street into a pedestrian street, which they renamed San Antonio Street (Nicholson, 2002).

In 1985, the planning and landscape architecture firm EDAW updated the architect’s plan, proposing impoundments to form large artificial lakes for boating, fishing, and swimming, with summer water levels supplemented with well water. However, the biological impacts of this plan were seen as greater than those of an Army Corps of Engineers (USACE) proposal, which included a concrete channel for part of the river. Finally, a second landscape architecture firm developed a new plan to impound “Confluence Lake”, which posed a threat of trapping salmon and steelhead who ventured into the lake during floods (Fig. 5) (City of San Jose, 1989). As a result of these and other impacts (land use, relocation, cultural resource, and noise), the project was not approved and the city abandoned the idea of copying the San Antonio Riverwalk.

In 1991, 30 years after the initial river planning effort, Congress authorized funding for another park design by the second landscape architectural firm that included both flood control and recreational features of a river walk without the impounded lakes (Nicholson, 2002). Mitigation was required for a broad range of environmental impacts, including fish passage, fish resting areas, replacement of spawning gravels, and thermal impacts. The project plan stipulated that if mitigation measures were insufficient for meeting fish requirements, supplemental water drawn from the San Joaquin Delta in central California would be used to increase flow and improve fish passage (US Army Corps of Engineers (USACE), 2001), which would result in impacts to the source rivers. Ironically, in the course of creating a trail along the creek, long reaches of bank were artificially stabilized, and areas of the riparian corridor were given over to “wave berms”, which are naturalistic mounds of earth covered in lawn that were meant to suggest water movement, but which provided no habitat value for native species.

The 30-year complex planning for the Guadalupe River Park illustrates how an ideal river with an esthetic imported from a humid-climate setting, and the desire for recreational instream uses, conflicted

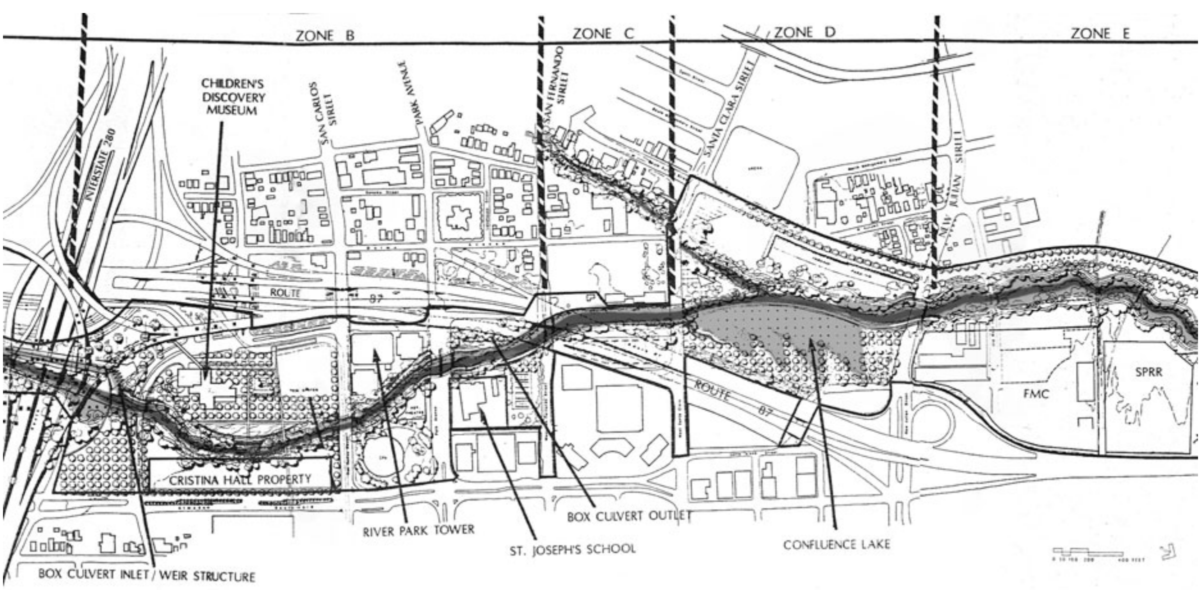

Fig. 5 An illustration of Confluence Lake in the 1988 Guadalupe River Park Master Plan Design Refinement (City of San Jose, 1989, p. 10)

with environmental considerations, notably passage for an important species of fish. It was not possible to transplant the San Antonio Riverwalk from Texas to med-climate California without unacceptable environmental impacts. The idea of creating water bodies with consistent flow levels in a med-climate river is a theme repeated in recent urban river projects in Portugal.

River Fervença, Bragança, Portugal

The Lisbon World Exhibition project (the 'EXPO') turned an abandoned industrial waterfront along the estuary of the Tagus River into an appealing leisure, cultural, and residential location, reestablishing the city's relationship with the river (Partidário & Correia, 2004). The EXPO area is now one of the most popular residential areas of the city. Inspired by the tremendous success of the EXPO, the Polis Programme was launched in 2000 to improve social and environmental conditions in Portuguese cities. Polis included projects in 28 cities, of which 17 involved interventions to the river and riverbanks (Saraiva et al., 2008). The river designs included dams and weirs to create lakes, thereby creating permanent water bodies with consistent water levels, more typical of humid-climate rivers than the med-climate setting of the cities. In some cases, such as the Montego River in Coimbra, damming the river eliminated the opportunity for traditional summer wading during low flows, but created opportunities for boating and swimming recreation. Unfortunately, some of these lakes have been plagued with algal blooms, creating an undesirable esthetic and impacting their recreational value.

One of the most striking examples was the Polis project in Bragança, which involved impounding the River Fervença with several weirs, creating a broad pool about 30 m wide in front of a hillside park featuring a concrete plaza and fountain near the artificial lake (Fig. 6). By contrast, downstream the river flows through pools and drops in a channel about 1.2-m wide during summer low flows. Even though the river is wide and deep in the impounded section, swimming is now rare, perhaps because algae in the standing water may deter human use of waters, which is consistent with observations elsewhere (Smith et al., 1995).

Conclusions

With their variable flow regimes and episodic channels, med-rivers are often inconvenient for humans, but support a diverse assemblage of native species. Changes to their fundamental characteristics through incidental or deliberate actions has severely degraded river ecosystems and facilitated the establishment of exotic species. Even in California, with its unique overlap of anadromous salmon and a med-climate,

Fig. 6 The mirror-water effect created by damming the River Fervença in Bragança, Portugal (photo by K. Podolak, 2009)

natural flow regimes and complex channels provide the best conditions for native fish and other native fauna and flora. Perhaps the greatest challenge to restoring med-rivers is overcoming the underlying cultural preference for stable, meandering channels and constant flows. Many restoration projects have been attempts to transform messy med-climate channels into idealized trout streams or San Antonio style urban water features. These projects are unlikely to be sustainable, and even if maintained, cannot be considered ecological restoration.

There is a fundamental challenge to 'restore' channels whose overriding characteristics include seasonal drought, high sediment loads, and a dominant influence of infrequent large floods, the "capricious giants" that shape the landscape. By allowing natural processes to operate within bounded corridors, pulling infrastructure back from river channels, and removing barriers to flooding and channel migration, the most sustainable approaches to restoration of med-rivers may be logically achieved. Furthermore, below dams that have 'flat-lined' river hydrographs, flow regimes can be modified to increase flow variability and meet important life history needs for fish, without eliminating benefits of the dams.

As global change causes climatic gradients to shift, there is likely to be increased episodicity in channels as seasonal and annual variability of truly med-climates increases. For example, in coastal California, we will see northern Californian streams behave more like those of southern California, and in the Mediterranean Basin, we will see med-type hydrology extending farther north into regions with montane or Atlantic-climate influences. These changes have implications for water and land management: more extreme droughts will increase stress on water supplies, while more extreme floods will make past delineations of floodplains outdated and inadequate in many areas. These scenarios provide another argument for establishing wide corridors for river migration and flooding.

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References

Almaça, C., 1995. Freshwater fish and their conservation in Portugal. Biological Conservation 72: 125–127.

Andrews, E. D., 1980. Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming. Journal of Hydrology 46: 311–330.

Baltz, D. M. & P. B. Moyle, 1993. Invasion resistance to introduced species by a native assemblage of California stream fishes. Ecological Applications 3: 246–255.

Batalla, R. J., C. M. Gomez & G. M. Kondolf, 2004. River impoundment and changes in flow regime, Ebro River basin, northeastern Spain. Journal of Hydrology 290: 117–136.

Bêche, L. A. & V. H. Resh, 2007. Short-term climatic trends affect the temporal variability of macroinvertebrates in California "Mediterranean" streams. Freshwater Biology 52: 2317–2339.

Beechie, T., E. Buhle, M. Ruckelshaus, A. Fullerton & L. Holsinger, 2006. Hydrologic regime and the conservation of salmon life history diversity. Biological Conservation 130: 560–572.

Bernhardt, E. S., M. A. Palmer, J. D. Allan, G. Alexander, K. Barnes, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follsted-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G. M. Kondolf, P. S. Lake, R. Lave, J. L. Meyer, T. K. O'Donnell, L. Pagano, B. Powell & E. Sudduth, 2005. Synthesizing U.S. river restoration efforts. Science 308: 636–637.

Bioengineering Institute, 2009. Final Project Report, Selby Creek Stream Restoration and Riparian Revegetation Project.

Bonada, N., S. Dolédec & B. Statzner, 2007. Taxonomic and biological trait differences of stream macroinvertebrate communities between mediterranean and temperate regions: implications for future climatic scenarios. Global Change Biology 13: 1658–1671.

Bond, N. R., P. S. Lake & A. H. Arthington, 2008. The impacts of drought on freshwater ecosystems: an Australian perspective. Hydrobiologia 600: 3–16.

Bravard, J. P. & F. Petit, 1997. Les Cours d'Eau. Armand Colin, Paris.

Brown, T. C., J. G. Taylor & B. Shelby, 1991. Assessing the direct effects of streamflow on recreation: a literature review. Water Resources Bulletin 27: 979–989.

Burnson, D., 1992. Lower Cuneo Channel Dimensions Report of Findings. California Department of Parks and Recreation, Sacramento, CA.

Cayan, D. R., K. T. Redmond & L. G. Riddle, 1999. ENSO and hydrologic extremes in the Western United States. Journal of Climate 12: 2881–2893.

City of San Jose, 1965. Park of the Guadalupe Plan. California, San Jose.

City of San Jose, 1969. Guadalupe River Park and Central District Master Plan. Lawrence Halprin and Associates, San Jose, CA.

City of San Jose, 1989. Final Environmental Impact Report: Guadalupe River Park. Resolution No. 89-16. Department of City Planning, San Jose, CA.

Clavero, M., F. Blanco-Garrido & J. Prenda, 2004. Fish fauna in Iberian Mediterranean river basins: biodiversity, introduced species and damming impacts. Aquatic Conservation 14: 575–585.

Clavero, M., V. Hermoso, N. Levin & S. Kark, 2010. Geographical linkages between threats and imperilment in freshwater fish in the Mediterranean Basin. Diversity and Distributions 16: 744–754.

Deitch, M. J., 2006. Scientific and institutional complexities of managing surface water for beneficial human and ecosystem uses under a seasonally variable flow regime in Mediterranean-climate Northern California. Dissertation, Department of Environmental Planning, University of California, Berkeley.

Deitch, M. J., G. M. Kondolf & A. M. Merenlender, 2009a. Hydrologic impacts of small-scale instream diversions for frost and heat protection in the California wine country. River Research and Applications 25: 118–134.

Deitch, M. J., G. M. Kondolf & A. M. Merenlender, 2009b. Surface water balance to evaluate the hydrological impacts of small instream diversions and application to the Russian River basin, California, USA. Aquatic Conservation 19: 274–284.

Gasith, A. & V. H. Resh, 1999. Streams in Mediterranean climate regions: abiotic influences and biotic responses to predictable seasonal events. Annual Review of Ecology and Systematics 30: 51–81.

Gonzalez del Tánago, M., D. García de Jalón & M. Román, 2012. River restoration in Spain: theoretical and practical approach in the context of the European Water Framework Directive. Environmental Management 50: 123–139.

Grantham, T. E., A. M. Merenlender & V. H. Resh, 2010. Climatic influences and anthropogenic stressors: an integrated framework for streamflow management in Mediterranean-climate California, U.S.A. Freshwater Biology 55: 188–204.

Grantham, T. E., D. A. Newburn, M. McCarthy & A. M. Merenlender, 2012. The role of stream flow and land use in limiting over-summer survival of juvenile steelhead trout in California streams. Transactions of the American Fisheries Society 141: 585–598.

Greco, S. E., A. K. Fremier & E. W. Larsen, 2007. A tool for tracking floodplain age land surface patterns on a large meandering river with applications for ecological planning and restoration design. Landscape and Urban Planning 81: 354–373.

Gumprecht, B., 2001. The Los Angeles River: Its Life, Death, and Possible Rebirth. The Johns Hopkins University Press, Baltimore.

Habersack, H. & H. Piégay, 2008. River restoration in the Alps and their surroundings: past experience and future challenges. In Habersack, H., H. Piégay & M. Rinaldi (eds), Gravel Bed Rivers VI: From Process Understanding to River Restoration. Elsevier, Amsterdam: 703–737.

Hansen, A. 2003, Post-project appraisal of a channel reconstruction on Cuneo Creek, California [available on internet at http://repositories.cdlib.org/wrca/restoration/].

Healey, M. C. & A. Prince, 1995. Scales of variation in life history tactics of Pacific salmon and the conservation of phenotype and genotype. In Nielsen, J. L. & D. A. Powers (eds), Evolution and the Aquatic Ecosystem: Defining Unique Units in Population Conservation. American Fisheries Society, Bethesda, Maryland: 176–184.

Hecht, B., 1994. South of the spotted owl: restoration strategies for episodic channels and riparian corridors in Central California. In Kent, D. M. & J. J. Zentner (eds), Western Wetlands, Selected Proceedings of the 1993 Conference of the Society of Wetland Scientists. University of California, Davis, California: 104–117.

Katz, J., P. Moyle, R. Quiñones, J. Israel & S. Purdy, 2012. Impending extinction of salmon, steelhead, and trout (Salmonidae) in California. Environmental Biology of Fishes 1–18. doi:10.1007/s10641-012-9974-8.

Kenny, J. F., N. L. Barber, S. S. Hutson, K. S. Linsey, J. K. Lovelace & M. A. Maupin, 2009. Estimated Use of Water in the United States in 2005. US Geological Survey Circular 1344, Reston, VA.

Kibel, P. S., 2007. Rivertown: Rethinking Urban Rivers. MIT Press, Cambridge, MA.

Kiernan, J. D., P. B. Moyle & P. K. Crain, 2012. Restoring native fish assemblages to a regulated California stream using the natural flow regime concept. Ecological Applications 22: 1472–1482.

Kondolf, G. M., 2006. River restoration and meanders. Ecology and Society 11:42 [available on internet at http://www.ecologyandsociety.org/vol11/iss2/art42/].

Kondolf, G. M., 2011. Setting goals in river restoration: when and where can the river 'heal itself'? In Simon, A., S. J. Bennett, J. M. Castro (eds), Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools. Geophysical Monograph Series, Vol. 194. American Geophysical Union, Washington, DC: 29–43.

Kondolf, G. M. & R. J. Batalla, 2005. Hydrological effects of dams and water diversions on rivers of Mediterranean-climate regions: examples from California. In Garcia, C. & R. J. Batalla (eds), Catchment Dynamics and River Processes: Mediterranean and Other Climate Regions. Elsevier, London: 197–211.

Kondolf, G. M. & P. R. Wilcock, 1996. The flushing flow problem: defining and evaluating objectives. Water Resources Research 32: 2589–2599.

Kondolf, G. M., A. Boulton, S. O'Daniel, G. Poole, F. Rahel, E. Stanley, E. Wohl, A. Bang, J. Carlstrom, C. Cristoni, H. Huber, S. Koljonen, P. Louhi & K. Nakamura, 2006. Process-based ecological river restoration: visualising three-dimensional connectivity and dynamic vectors to recover lost linkages. Ecology and Society 11 [available on internet at http://www.ecologyandsociety.org/vol11/iss2/art5/].

Kondolf, G. M., S. Anderson, R. Lave, L. Pagano, A. Merenlender & E. Bernhardt, 2007. Two decades of river restoration in California: what can we learn? Restoration Ecology 15: 516–523.

Krause, A., 2011. Mechanical Extraction and Augmentation of Coarse and Fine Sediment on the Trinity River, California, 1950–2011. Technical Report: TR-TRRP-2011-3. Trinity River Restoration Program, Weaverville, CA.

Leopold, L. B., 1973. River channel change with time: an example address as Retiring President of The Geological Society of America, Minneapolis, Minnesota, November 1972. Geological Society of America Bulletin 84: 1845–1860.

Leopold, L. B., M. G. Wolman & J. P. Miller, 1964. Fluvial Processes in Geomorphology. WH Freeman, San Francisco.

Lindley, S. T., R. S. Schick, A. Agrawal, M. Goslin, T. E. Pearson, E. More, J. J. Anderson, B. May, S. Greene, C. Hanson, A. Low, D. McEwan, R. B. MacFarlane, C. Swanson & J. G. Williams, 2006. Historical population structure of Central Valley steelhead and its alteration by dams. San Francisco Estuary & Watershed Science 4: 1–19.

Litton, R. B., R. J. Tetlow, J. Sorensen & R. A. Beatty, 1974. Water and Landscape: An Aesthetic Overview of the Role of Water in the Landscape. Department of Landscape Architecture, University of California. Water Information Center Inc., New York.

Lytle, D. A. & N. L. Poff, 2004. Adaptation to natural flow regimes. Trends in Ecology & Evolution 19: 94–100.

Moyle, P. B., 2002. Inland Fishes of California. University of California Press, Berkeley.

Moyle, P. B., M. P. Marchetti, J. Baldrige & T. L. Taylor, 1998. Fish health and diversity: justifying flows for a California stream. Fisheries 23(7): 6–15.

Moyle, P. B. & J. F. Mount, 2007. Homogenous rivers, homogenous faunas. Proceedings of the National Academy of Sciences 104: 5711–5712.

Moyle, P. B., J. V. E. Katz & R. M. Quiñones, 2011. Rapid decline of California's native inland fishes: a status assessment. Biological Conservation 144(10): 2414–2423.

Munné, A. & N. Prat, 2004. Defining river types in a Mediterranean area: a methodology for the implementation of the EU Water Framework Directive. Environmental Management 34: 711–729.

Myers, N., R. A. Mittermeier, C. G. Mittermeier, G. A. B. da Fonseca & J. Kent, 2000. Biodiversity hotspots for conservation priorities. Nature 403: 853–858.

Nassauer, J. I., 1995. Messy ecosystems, orderly frames. Landscape Journal 14: 161–170.

NRC (National Research Council), 1992. Restoration of Aquatic Ecosystems. National Academy Press, Washington, DC.

NRC (National Research Council), 2005. Endangered and Threatened Species of the Platte River. National Academy Press, Washington, DC.

Nicholson, S., 2002. Water resource development and the evolution of decision-making processes in the post-modern era: claims making in the urban environment. Master of City Planning Thesis. University of California, Berkeley.

Ollero, A., 2007. Territorio fluvial. Diagnóstico y propuesta para la gestión ambiental y de riesgos en el Ebro y los cursos bajos de sus afluentes. Bakeaz & Fundación Nueva Cultura del Agua, Bilbao, Spain.

Ollero, A. & A. Ibisate, 2012. Space for the river: a flood management tool. In Wong, T. S. W. (ed.), Flood Risk and Flood Management. Nova Science, Hauppauge, NY: 199–218.

Ollero, A., A. Ibisate & J. Elso, 2009. El territorio fluvial y sus dificultades de aplicación. Geographicalia 56: 37–62.

Opperman, J. J., R. Luster, B. A. McKenney, M. Roberts & A. W. Meadows, 2010. Ecologically functional floodplains: connectivity, flow regime, and scale. Journal of the American Water Resources Association 46: 211–226.

Partidário, M. R. & F. N. Correia, 2004. Polis—the Portuguese programme on urban environment: a contribution to the discussion on European Urban Policy. European Planning Studies 12(3): 409–423.

Permanyer, L., 2008. Eixample: 150 anys d'història. Viena Edicions i Ajuntament de Barcelona, Barcelona.

Piégay, H., S. E. Darby, E. Mosselman & N. Surian, 2005. The erodible corridor concept: applicability and limitations for river management. River Research and Applications 21: 773–789.

Ribera, I. & A. P. Vogler, 2004. Speciation of Iberian diving beetles in Pleistocene refugia (Coleoptera, Dytiscidae). Molecular Ecology 13: 179–193.

Riley, A. L., 1998. Restoring Streams in Cities. Island Press, Covelo, CA.

Rosgen, D. L., 1991. Bull Creek Watershed Restoration Plan. Wildland Hydrology, Pagosa Springs, CO.

Saraiva, M. G., I. L. Ramos, L. Vaz, F. Bernardo & B. Condessa, 2008. Towards Sustainability in Rehabilitating Urban River Landscapes. In Proceedings of the 4th ECRR Conference on River Restoration, Crossing Ecology with Social Concerns. Venice, Italy: 929-938.

Schonher, T. & S. E. Nicholson, 1989. The relationship between California rainfall and ENSO events. Journal of Climate 2: 1258–1269.

Smith, D. G., G. F. Croker & K. McFarlane, 1995. Human perception of water appearance. 1. Clarity and colour for bathing and aesthetics. New Zealand Journal of Marine and Freshwater Research 29: 29–43.

Stein, E. D., K. Vyverberg, G. M. Kondolf & K. Janes, 2011. Episodic stream channels: imperatives for assessment and environmental planning in California. In Proceedings of a Special Technical Workshop, Southern California Coastal Water Research Project Report No. 0645. California State Water Board, Sacramento, CA: 1–87.

Steinbeck, J., 1945. Cannery Row. The Viking Press, New York.

Thorpe, J. E., 1989. Developmental variation within salmon populations. Journal of Fish Biology 35(Suppl A): 295–303.

Tyagi, A., B. Chongtoua, D. Medina, A. Patwardhan & C. Slater, 2008. Management of Dry Weather Flows in Semi-Arid Climates Using Low Impact Development Technology. In ASCE Conference Proceedings. American Society of Civil Engineers, New York.

US Army Corps of Engineers (USACE) 2001. Final Integrated General Re-Evaluation Report/Environmental Impact Statement, Report Supplement Environmental Impact Statement for the proposed modifications to the Guadalupe River Project, Downtown San Jose, California, Santa Clara, CA.

USFWS & Hoopa Tribe (US Fish and Wildlife Service and Hoopa Valley Tribe), 1999. Trinity River Flow Evaluation Final Report. USFWS, Arcata, CA.

Wainwright, J. & J. B. Thornes, 2004. Environmental Issues in the Mediterranean. Routledge, London.

Warrick, J. A., 2002. Short-term (1997–2000) and long-term (1928–2000) observations of river water and sediment discharge to the Santa Barbara channel, California. Dissertation, University of California, Santa Barbara.

Waylen, P. R. & C. N. Caviedes, 1990. Annual and seasonal fluctuations of precipitation and streamflow in the Aconcagua River basin, Chile. Journal of Hydrology 120: 79–102.

Whittaker, D., B. Shelby & J. Gangemi, 2005. Flows and Recreation: A Guide to Studies for River Professionals. Hydropower Reform Coalition and National Park Service Hydropower Reform Coalition, Washington, DC.

Williams, G. P., 1978. Bank-full discharge of rivers. Water Resources Research 14(6): 1141–1154.

Williams, J. G., 2006. Central Valley Salmon: a perspective on Chinook and Steelhead in the Central Valley of California. San Francisco Estuary and Watershed Science 4(3): 1–398 [available on internet at http://escholarship.org/uc/item/21v9x1t7].

Williams, R. P., 1979. Sediment Discharge in the Santa Clara River Basin, Ventura and Los Angeles Counties, California. US Geological Survey Water Resources Investigations Report 79-78, Menlo Park, CA.

Wolman, M. G., 1955. The Natural Channel of Brandywine Creek, Pennsylvania. US Geological Survey Professional Paper 271. US Government Printing Office, Washington, DC.

Wolman, M. G. & J. P. Miller, 1960. Magnitude and frequency of forces in geomorphic processes. The Journal of Geology 68(1): 54–74.

Wolman, M. G. & R. Gerson, 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Processes 3: 189–208.