Hydrobiologia (2013) 719:451–482
DOI 10.1007/s10750-012-1289-4

 Review Paper

Water management in mediterranean river basins: a comparison of management frameworks, physical impacts, and ecological responses

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Received: 15 January 2012 / Accepted: 19 August 2012 / Published online: 11 September 2012

Abstract Rivers in mediterranean climates have been extensively modified by water management infrastructure and practices, yet patterns of development and consequent effects on freshwater ecosystems have not been compared across multiple regions. To evaluate the influence of water management on mediterranean-climate rivers, we compare the historic progression of management policies, institutions, and ecosystem impacts in the Sacramento River (California, USA), Ebro River (Spain), and Biobío River (Chile) basins. There are broad similarities in patterns of ecosystem alterations related to the extensive development of dams and water management infrastructure in the three study basins. Flow regimes have been altered by the reduction of winter peak flows and increased summer baseflows. There are also common patterns of disturbance from sediment transport alteration, water quality degradation, and declines in freshwater biodiversity. Current approaches are inadequate for addressing the formidable water management challenges in California, Spain, and Chile, yet the dramatic evolution of water policies and institutions over the past 150 years suggests that further adaptation is possible. Advances toward integrated and sustainable water management models are likely to occur through incremental change, driven by growing awareness of climate change effects and public demands for water-use efficiency and improved environmental quality.

Keywords Integrated water resources management · Water policy · River ecosystems · California · Chile · Spain

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

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Introduction

Rivers play a critical role in the management of water in Mediterranean-climate regions (med-regions) of the world. In contrast to humid regions where year-round rainfall serves to irrigate crops and replenish reservoirs, highly variable precipitation patterns, an extended dry season, and scarcity of natural lakes make rivers a primary source of water in med-regions. The seasonality of precipitation patterns and asynchronous timing of when water is available and when it is most needed have provided a strong catalyst for building dams to manage the timing and magnitude of water supply (Gasith & Resh, 1999; Kondolf & Batalla, 2005). The regulation of mediterranean rivers (med-rivers) has also been fueled by efforts to control seasonal floods (Singer, 2007). Finally, the high topographic relief of many med-river basins has made them desirable locations for water storage and hydropower development (Conacher & Sala, 1998). As a consequence, rivers in med-regions have been heavily impounded and tend to be more affected by dams and conveyance infrastructure than rivers in humid climates (Thoms & Sheldon, 2000; Kondolf & Batalla, 2005).

The development of water resources has been critical in supporting increased agricultural productivity, economic development, and growth of population centers in med-regions. However, the benefits of water projects have come with substantial costs to the environment. Impoundments, dam operations, and other water infrastructure interfere with fundamental hydrological processes that control riverine habitat structure, maintain natural patterns of longitudinal and lateral connectivity, trigger behaviorial responses in native organisms, and influence water quality conditions (Prat & Ward, 1994; Bunn & Arthington, 2002; Pringle, 2003). Hydrologic infrastructure in med-river basins is also correlated with the establishment of alien species, which can alter ecosystem processes and adversely affect native biota (Elvira & Almodóvar, 2001; Clavero et al., 2004; Light & Marchetti, 2007). Although modifications to river flows are globally pervasive (Dynesius & Nilsson, 1994; Vörösmarty & Sahagian, 2000; Nilsson et al., 2005), water management has had a particularly strong impact on med-river ecosystems because of the intensity and scale of alterations (Grantham et al., 2010). As a consequence, med-regions are among those reported to have the most rapid losses of freshwater biodiversity in the world (Moyle & Leidy, 1992). In California, for example, water management is the primary factor responsible for declines in fish biodiversity, where 83% of native freshwater fish taxa are extinct or at risk of becoming so (Moyle et al., 2011). A similar trend in fish biodiversity loss has been reported for rivers in the Iberian Peninsula, which is strongly associated with water management pressures (Aparicio et al., 2000; Benejam et al., 2010a; Clavero et al., 2010, 2004).

In response to loss of biodiversity and important ecosystem services, new water management approaches have been proposed to improve protections of rivers and achieve a better balance between freshwater resource utilization and ecosystem maintenance (e.g., King et al., 2003). In many countries, water management frameworks have followed a similar evolution, beginning with water supply oriented management for agricultural production and progressing toward new forms of management that regulate multiple water uses, address water quality issues, and apply measures to control water demands. In some cases, these evolving approaches to water management have been augmented by broader protections of ecosystem processes and services, for example, by requiring the maintenance of healthy biological assemblages (e.g., the European Water Framework Directive; European Communities, 2000). To meet the growing number and diversity of management objectives, it is increasingly recognized that strategies should center on the principle of sustainable water use, which is management of water that provides for the the economy, the ecosystem, and equity among water users, including the needs of future generations (Richter et al., 2003). Nevertheless, progress toward sustainable water management has been limited in most countries (Gleick et al., 2011). This is particularly true for mediterranean and other water-scarce regions, where intense competition for water tends to produce strong political and social resistance to upsetting the status quo, thereby limiting opportunities for reform (Araus, 2004).

The environmental impacts and challenges of water management are not unique to med-regions. Many river ecosystems of the world are facing tremendous pressures from water resources development (Vörösmarty et al., 2010). However, the study of water management in med-rivers is useful because they have been subject to perhaps the highest levels of water infrastructure development in the world (Prat & Ward, 1994; Kondolf & Batalla, 2005). Furthermore, the impacts of dams and other water management practices on med-river ecosystems are relatively well studied. Finally, because med-regions are defined by growing population densities, land-use pressures, and intense competition for water (Araus, 2004; Underwood et al., 2009), investigations of the relationship between water management and med-rivers may offer insight into addressing similar challenges in other water-scarce regions of the world.

In this review article, we evaluate the scale and pattern of water resources development in three distinct med-regions through a comparative approach, focusing on the Sacramento River basin in California (USA), the Ebro River basin in Spain, and the Biobío River basin in Chile. The selected river basins occur at least partially within the mediterranean-bioclimatic zone, defined by Olson et al. (2001), and each has played a critical role in shaping water management frameworks and economic development in their respective regions. We restricted the analysis to Sacramento, Ebro, and Biobío Rivers because med-river basins of comparable size (>25,000 km^2) are not present in the med-regions of South Africa and Australia. We hypothesize that common climatic and biogeographic characteristics of the three med-climate river basins have led to similar patterns of water resources development and resulting impacts to freshwater ecosystems. However, the distinct historical, cultural, and political settings of California, Spain, and Chile are expected to give rise to differences in prevailing water management policies and practices, and to diverse manifestations of ecosystem alteration. The overall objective of this study is to compare the influence that water management has had on med-river ecosystems and to evaluate progress toward, and obstacles to, environmentally sustainable water management in these distinct regional contexts.

To characterize water management within the Sacramento (California), Ebro (Spain), and Biobío (Chile) River basins, we first compare relevant biogeographic, demographic, and land- and water-use data. We then provide a brief account of the evolution of water management since the mid-nineteenth century, identifying major policy developments, infrastructure projects, and social-political conflicts that have influenced water management and its environmental impacts within each region. We use this information to construct a timeline, identifying distinct periods of water management approaches (modified from Hanak et al., 2011). These include the Local Organization Era, the Hydraulic Era, and the Integration Era. The Local Organization Era is characterized by water management projects and activities undertaken by individuals, corporations, and local governments with little federal or state intervention. It also includes the first laws adopted to regulate water use and facilitate the systematic development of water resources. The Hydraulic Era is defined by large regional and interregional water management projects, driven by growth in agricultural and urban water demands. The period involves construction of large-scale engineering projects supported by state and federal agencies, and is guided by a vision of complete control of rivers for water supply, hydropower, and flood-protection purposes, with little or no regard for environmental impacts. The Integration Era is characterized by the incorporation of multi-use management goals and environmental considerations, and includes landmark state and federal initiatives that recognize public benefits of water quality protection and of "non-consumptive" water uses including recreation, aesthetic values, and aquatic species conservation.

Next, we evaluate the specific effects of water management on med-river ecosystems through a review of the scientific literature. We report comparable statistics on known physical and ecological impacts of water management infrastructure on rivers in each of the study basins. The analysis is focused on the hydrologic alterations of water management, impacts to geomorphic processes, changes in water quality conditions, and alterations to ecosystem structure. Finally, we offer a summary and comparison of key water management challenges in each of the study regions.

Geography and water-use patterns in three mediterranean river basins

The Sacramento and Ebro are the largest rivers in California and Spain, respectively, and the Biobío is the second largest river in Chile. The Sacramento River extends 640 km from the Oregon border south to its confluence with the San Joaquin River at the Sacramento–San Joaquin Delta, which drains west through San Francisco Bay to the Pacific Ocean (Fig. 1). The basin has a relatively low average population (41 inhabitants/km^2), most of which occurs in the Sacramento metropolitan region. The Sacramento River basin is one of the most important regions for agricultural production in California, supporting approximately 8,700 km^2 of irrigated agriculture (12.3% of basin area; Table 1).

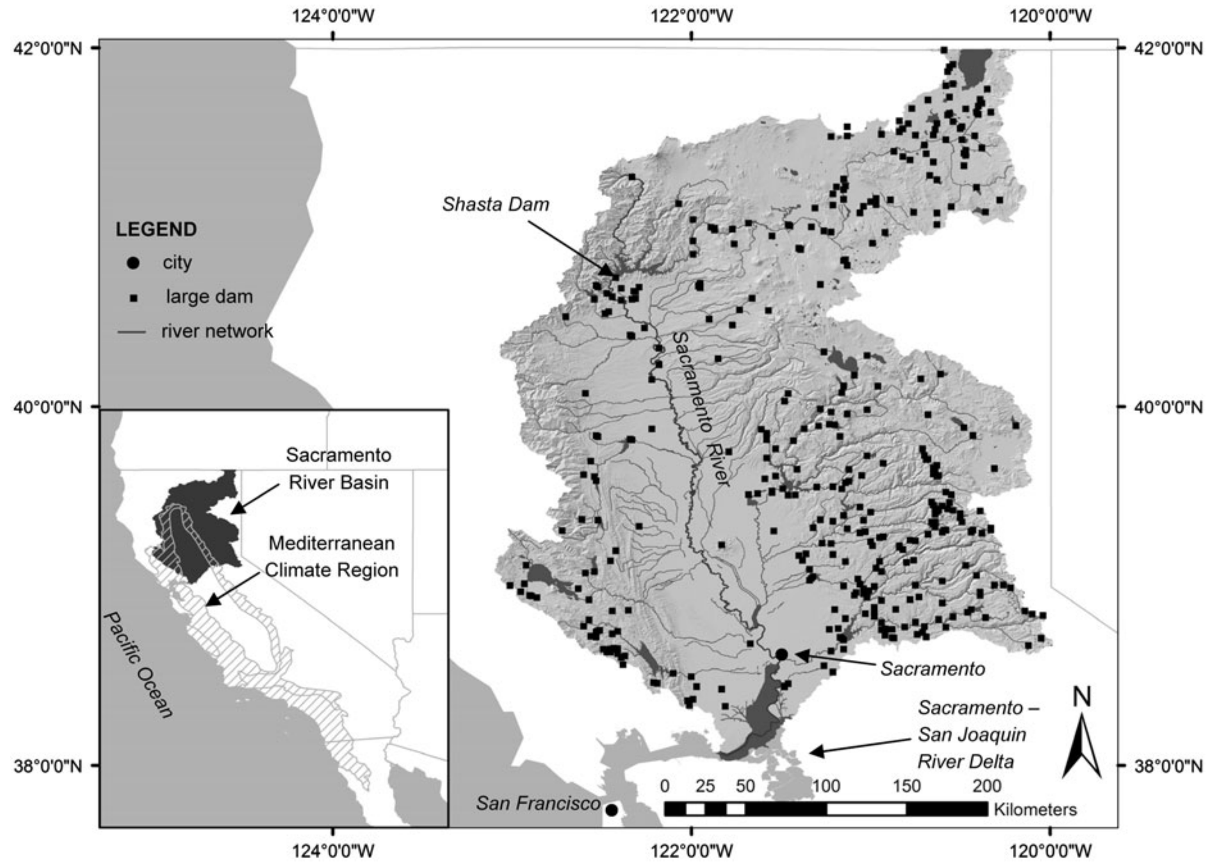

Fig. 1 The Sacramento River basin, California, USA

The Ebro flows 930 km from the west to southeast into the Mediterranean Sea at Deltebre, located approximately 160 km south of Barcelona (Fig. 2). Similar to the Sacramento River, agriculture is the dominant land use in the Ebro River basin, which includes approximately 8,000 km^2 of irrigated lands (10.0% of basin area) (Confederación Hidrográfica del Ebro (CHE), 2011). The valley and delta zones of the Ebro River are intensively cultivated, while urban and industrial land uses are largely concentrated in the cities of Zaragoza and Pamplona (Fig. 3).

The Biobío River, with a 24,260 km^2 basin area, flows 380 km from the Andes in a northwestern direction to the Pacific Ocean at the city of Concepción (Fig. 3). In comparison to the Sacramento and Ebro River basins, the Biobío has a low population and limited irrigated agricultural (less than 3% of basin area; Table 1). However, the Biobío River basin is heavily influenced by forest plantations, consisting primarily of non-native pine (*Pinus radiata*) and blue gum (*Eucalyptus globulus*), which occupy approximately 5,000 km^2 or $\sim$19% of the basin (Dirección General de Aguas, 2004).

All three river basins show strong seasonality in precipitation and discharge patterns, characteristics of med-rivers (Gasith & Resh, 1999). While coastal and low-elevation med-rivers are characterized by rainfall-runoff hydrology with flows that closely track winter precipitation events, the hydrographs of these large river basins are influenced by both rainfall and snowmelt components, yielding a mediterranean-montane flow regime. Mean annual runoff is 20.9, 14.2, and 30.3 km^3 for the Sacramento River, Ebro River, and Biobío River, respectively.

Water-use patterns

The Sacramento River carries approximately one-third of California's total surface water and provides most of the water used by the state's urban and agricultural

Table 1 Geographic characteristics of the Sacramento, Ebro, and Biobío River basins

	Sacramento	Ebro	Biobío
Basin size (km^2)	70,567	85,534	24,264
River mainstem length (km)	640	930	380
Mean annual precipitation (mm)	930	650	1,330
Population (millions)	2.9	3.2	0.9
Population density (inhabitants/km^2)	41	37	29
Land use (km^2)			
Urban	1,287 (1.8%)[a]	853 (1.0%)	101 (0.4%)
Irrigated agriculture	8,680 (12.3%)	8,534 (10.0%)	705 (2.9%)
Dryland agriculture	1,611 (2.3%)	29,081 (34.0%)	NA
Rangeland	1,394 (2.0%)	NA[b]	NA
Grassland	3,383 (4.8%)	15,600 (18.2%)	1,629 (6.7%)
Forest and shrub	51,868 (73.5%)	28,000 (32.7%)	7,383 (30.4%)
Wetland and aquatic	1,740 (2.5%)	800 (0.9%)	NA
Other	604 (0.9%)	2,666 (3.1%)	14,446 (59.5%)[c]

[a] Total area and percentage of land cover in basin

[b] Information not available (NA)

[c] "Other" land-use includes 4,626 km^2 of forest plantations and 500 km^2 of barren land cover

sectors (Mount, 1995). To meet state-wide water demands, the basin has been transformed by a vast and complex network of water storage and conveyance systems. There are over 400 dams in the basin with a total storage capacity of 20.7 km^3 (Department of Water Resources, 2010), representing nearly 100% of the Sacramento River's mean annual outflow (Table 2). Flows through the Sacramento River and its tributaries are highly regulated to meet multi-use objectives, including water supply, flood control, hydropower production, recreational flows, and ecological water allocations. Agricultural irrigation accounts for annual water withdrawals of 8.1 km^3, representing 90% of the net water use in the basin (Department of Water Resources, 2009a). Many of the dams in the Sacramento basin have associated hydropower production facilities. One of the most important water management responsibilities in the basin is the delivery of water to the southern Sacramento–San Joaquin Delta (Fig. 1), where large pumps lift water into conveyance channels that flow south to irrigators and municipal water users. In 2005, approximately 9.5 km^3 of water was exported from the Delta to southern California (Department of Water Resources, 2009b).

The Ebro River has had a strong influence on human settlement patterns in the Iberian Peninsula and has been vital to the political and economic development of Spain. The Ebro River is a primary source of water for irrigation, domestic water supply, industry, and transportation. Nearly 90% of water use in the basin is for irrigation (Table 2), which is managed through an extensive network of dams and irrigation channels. There are 289 dams on the Ebro River and its tributaries, which collectively impound 8.0 km^3 or over 50% of the mean annual basin runoff (Ministerio de Medio Ambiente, 2011). In addition, there are 340 hydroelectric facilities in the Ebro River basin that have concessions to use over 12,000 m^3/s (38 km^3/year) of water (Romaní et al., 2011). Annual water demand for domestic uses is 0.8 km^3, while approximately 3.1 km^3 of water are allocated for environmental and water quality protection purposes (CHE, 2011).

The Biobío River is one of the most heavily used water bodies in Chile and supports a wide range of activities including irrigation, industrial uses, hydropower generation, recreation, and provision of drinking water (Valdovinos & Parra, 2006). Water use in the Biobío River basin has increased dramatically since the 1980s, and has involved construction of several new hydropower plants and major irrigation diversion projects, expansion of industrial forestry, and development of new water supply infrastructure for a population of approximately 900,000 people.

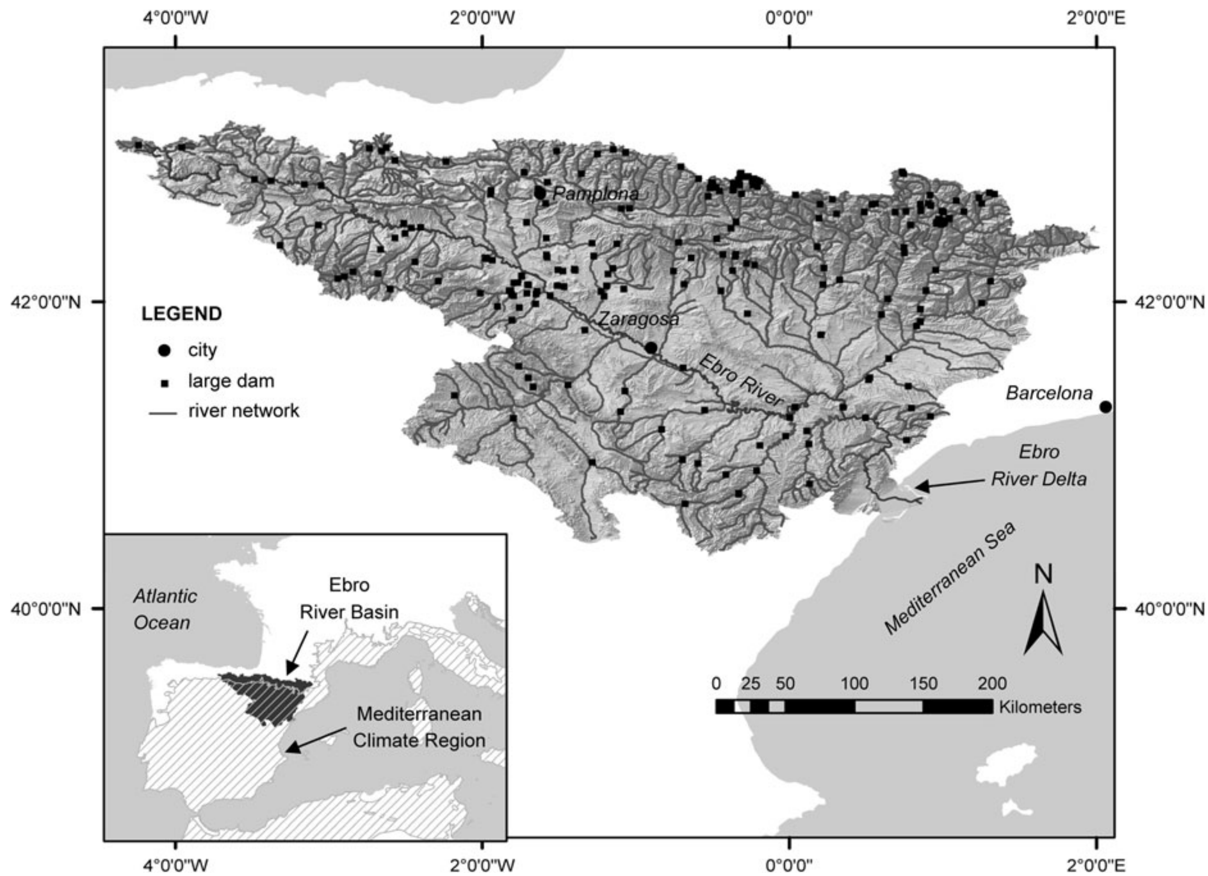

Fig. 2 The Ebro River basin, Spain

The river network has also been fragmented by the construction of over 200 dams (Dirección General de Aguas, 2010a). The Biobío River basin supplies over 50% of the hydropower capacity of Chile, making it by far the most important contributor to the nation's electrical grid (Goodwin et al., 2006). The Biobío River basin is also affected by water withdrawals, including 2.2 km^3 per year for agriculture and forest plantations (Table 2). Forest plantation products are used in pulp and paper mills along the Biobío River, which account for over 80% of total pulp production in Chile (Karrasch et al., 2006).

Evolution of water resources management

Water management in California

The development of water infrastructure and management approaches in California has not followed a central plan or long-term vision, but reflects the dynamic changes in the state's demographics, land-use patterns, and water demands over the past 150 years (Hanak et al., 2011). The intensive use and development of water resources in the Sacramento River basin began with the Gold Rush of the mid-nineteenth century. Dam construction on major tributaries to the Sacramento River soon followed, which provided water to gold mining operations in the foothills and expanding agricultural areas on the valley floor (California State Lands Commission, 1993). These early water management projects in California were largely undertaken by individuals, corporations, and local municipalities, with limited coordination and little federal or state intervention (Hanak et al., 2011). However, economic and population growth in California in the early twentieth century brought about a transformation in water demands and management with the creation of irrigation districts, construction of hydroelectric

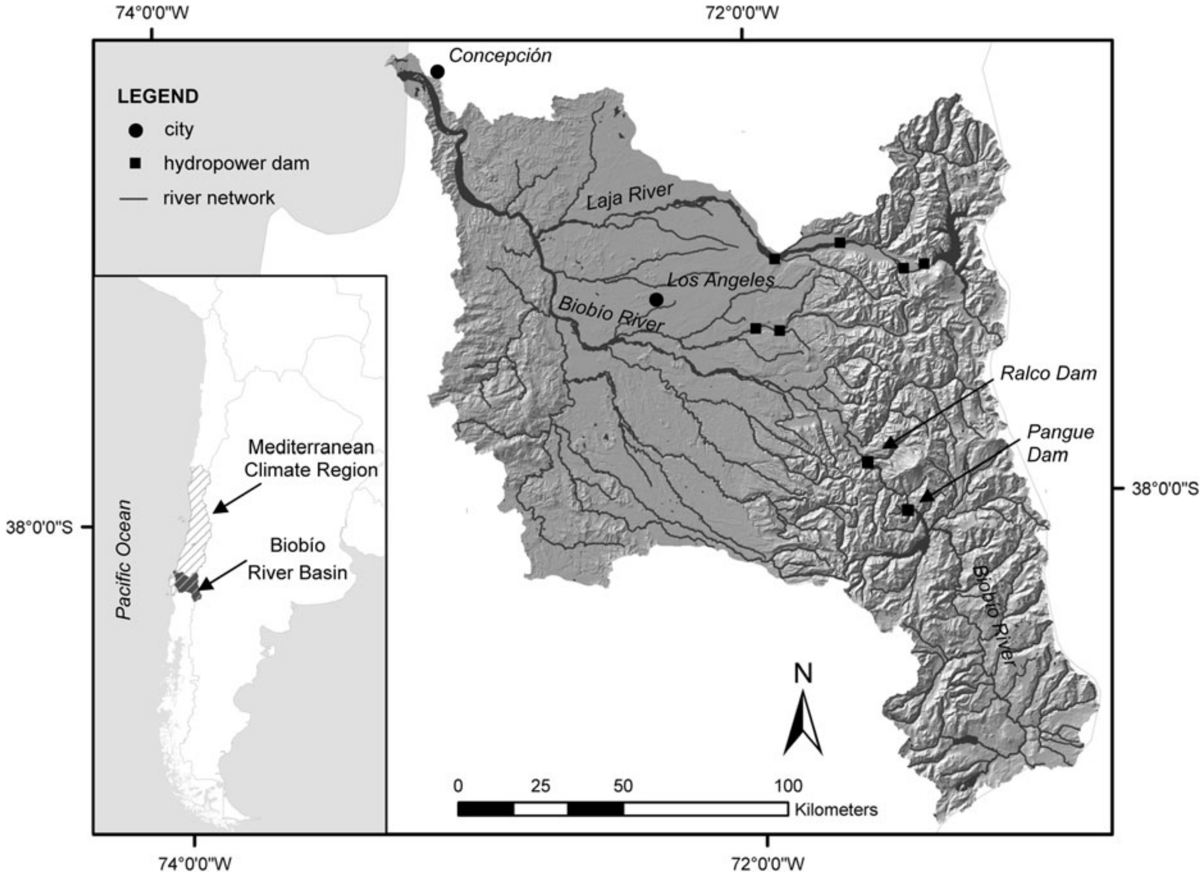

Fig. 3 The Biobío River basin, Chile

plants, and development of large municipal water supply projects.

The Federal Reclamation Act of 1902 authorized the construction of dams and irrigation projects throughout the West and created a new federal agency, the Reclamation Service (later the Bureau of Reclamation), to administer the program. Reclamation projects were initiated throughout California, and rapidly accelerated expansion of agriculture in the Sacramento–San Joaquin Valley. During the same period, hydraulic gold mining activities generated enormous quantities of sediment debris, filling river channels, and causing flood problems downstream (Gilbert, 1917; Isenberg, 2005). Continued agricultural expansion and the initiation of hydraulic mining, coupled with growing recognition of the environmental and economic impacts of mining activities, encouraged more centralized systems of control that could address regional flooding and water-allocation issues.

At the turn of the twentieth century, economic prosperity, urban population growth, and expansion of agriculture led policy makers and water managers to embrace increasingly large-scale water projects, which marked the transition in California water management from the Era of Local Organization to the Hydraulic Era (Fig. 4). The overall goal of water management during this period was to overcome two fundamental realities of California's geography and climate: (1) that most of the state's precipitation fell in the northern and mountain regions, far from the most productive agricultural lands in the Central Valley and urban population centers on the coast, especially the Southern coast; and (2) that water supplies were highly variable, characterized by seasonal and interannual droughts as well as severe episodic flooding. In the early 1900s, both San Francisco and Los Angeles developed plans to build massive storage and delivery systems to transport water from the Sierra Nevada to the coast in order to ensure that water scarcity would

Table 2 Water availability and demands in the Sacramento, Ebro, and Biobío River basins

	Sacramento	Ebro	Biobío
Mean annual precipitation (mm)	930	650	1,330
Mean annual discharge (km^3)	20.9	14.2	30.3
Mean daily discharge (m^3/s)	664	450	960
Number of dams in basin	406[a]	289[d]	242[f]
Total reservoir capacity (km^3)	20.7[a]	8.0[d]	>1.4 [h]
Storage capacity/annual runoff	0.99	0.56	>0.05
Annual water withdrawals (km^3)			
Agricultural gross	10.3[b]	6.3[e]	2.2[g]
Agricultural net	7.4[b]	4.4	0.9[g]
Domestic gross	1.0[b]	0.8[e]	0.5[g]
Domestic net	0.7[b]	0.2	0.4[g]
Percent agriculture of net total	91.0%	90.0%	70.3%
Percent domestic of net total	9.0%	10.0%	29.7%
Annual hydropower water use			
Water demand (km^3)	NA	38.0[e]	41.8[h]
Potential (MW)	>1,330[c]	3,831[e]	>1,200[h]
Annual environmental water allocations (km^3)	8.8[b]	3.1[e]	0.8[i]

[a] *Source*: Department of Water Resources (2010)

[b] Average values from 1998 to 2005 Department of Water Resources (2009b)

[c] Bureau of Reclamation (BoR)-operated power plants in Sacramento River basin (Bureau of Reclamation, 2011b)

[d] *Source*: Ministerio de Medio Ambiente (2011)

[e] *Source*: Confederación Hidrográfica del Ebro (CHE) (2011)

[f] *Source*: Dirección General de Aguas (2010a)

[g] *Source*: Dirección General de Aguas (2004)

[h] Storage capacities, hydropower water demand and energy potential indicated for Ralco and Pangue dams only (García et al., 2011)

[i] Environmental flow requirement for Ralco dam only (Goodwin et al., 2006)

not limit future growth. At the same time, state and federal governments increased support for agricultural reclamation projects, subsidizing construction of dams and inter-regional water conveyance systems. The federal government also became more involved in flood management, providing financial and technical support for construction and operation of dams and other flood-control infrastructure (Hanak et al., 2011).

Between 1910 and 1970, California was transformed by construction of dams and water infrastructure. The Central Valley Project (CVP) was the most ambitious attempt to harness the state's rivers and secure water supplies for agricultural water users. Construction of the CVP was completed by 1948 with its principal function to store and transport water from the Trinity and Sacramento Rivers in northern California to agricultural water users in the Sacramento–San Joaquin Valley. The CVP is operated by the federal Bureau of Reclamation (BoR) and includes 20 storage and diversion dams, 41 pumping plants, and over 1,000 km of canals, tunnels, and related conveyance facilities (Bureau of Reclamation, 2011a). A second major water infrastructure plan for a State Water Project (SWP) was initiated in the 1960s, which mirrored many elements of the federal CVP, including the construction of dams on major tributaries to the Sacramento River and conveyance of water to southern California. The Department of Water Resources was also created at this time, which consolidated state water planning and development responsibilities (Hanak et al., 2011).

The development of water management infrastructure on the Sacramento River to secure water supplies and control floods has played a critical role in fostering

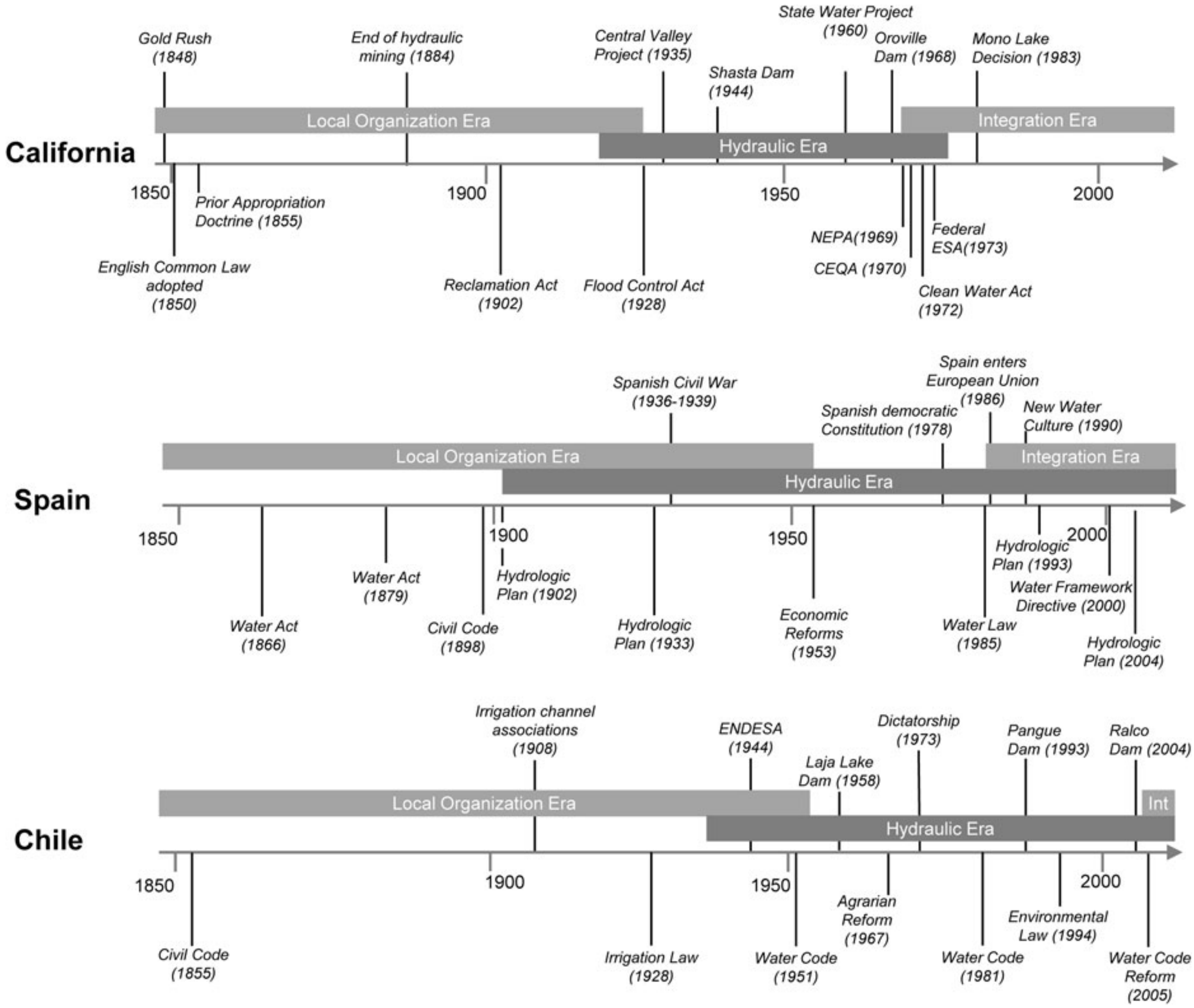

Fig. 4 Generalized *time line* depicting important historical events and policy developments since the mid-nineteenth century that have affected mediterranean-climate river basins of California, Spain, and Chile

the state's economic growth to this day. At the same time, the massive scale and broad extent of development projects have fundamentally altered the physical, hydrologic, and ecological character of the Sacramento River and nearly all of the state's major rivers and streams. By the 1960s, a growing awareness of the negative effects of California's water management system on the environment was linked with a larger, national movement to improve environmental protections of public resources. During the late 1960s and 1970s, the U. S. Congress passed several landmark environmental statutes, including the National Environmental Policy Act, the Clean Water Act, the Wild and Scenic Rivers Act, and the federal Endangered Species Act, with similar laws enacted at the state level. These laws ushered in a new period of water management in which consumptive water users (e.g., irrigation districts, dam operators, and municipalities) were required to consider and mitigate the environmental effects of their actions. New water projects received greater public scrutiny and were often not approved, while some existing projects were curtailed to offset environmental impacts.

Since the 1980s, several steps have been made to improve the management of California's large water projects to protect water quality in rivers and reduce impacts to endangered fish populations. Environmental protection criteria have been integrated with decision-making about water supply management, flood protection, and hydropower facility operations. For example, the State Water Resources Control Board has established strict water quality standards for the Sacramento–San Joaquin Delta, which has curtailed water exports from the CVP and SWP. The listing of salmon and other native fish species under the federal Endangered Species Act has also had a major effect on water management operations, including increased flow releases from dams for fish habitat and further restrictions on water exports from the Delta (Department of Water Resources, 2009b; Hanak et al., 2011). Environmental protections have come at the expense of agricultural and municipal water users and stimulated significant social and political conflict. Entrenched political interests, scientific uncertainty surrounding the causes of fish population declines, and economic recession have all contributed to a contentious atmosphere among federal and state agencies, water users, and environmental interest groups.

Water management in Spain

The evolution of water management policies and practices in Spain tracks historical forces that have driven the country's social and economic transformation over the past 100 years. For most of the nineteenth century, water management was focused on agricultural and municipal water supply. These priorities were reflected in the Water Acts of 1866/1879 and Civil Code of 1889, which promoted the development and use of available water resources on private and municipal property. The end of the nineteenth century was marked by the first cooperative effort to develop centralized water projects to promote agricultural land expansion. A grand vision for revitalizing the economy through investment in major water infrastructure was presented in the National Plan of Hydraulic Works in 1902, and again in 1933. However, these ambitious efforts to centralize water management were ultimately unsuccessful, primarily resulting from the lack of financial investment, social resistance to agricultural reforms, and beginning of the Spanish Civil War in 1936 (Costejà et al., 2002).

While the ideology of the Hydraulic Era had been in place since the turn of the century, major water infrastructure development was delayed in Spain until the period of government rule under Franco's dictatorship (Fig. 4). Economic reforms in the early 1950s brought about new opportunities for foreign trade and stimulated unprecedented economic growth. Changes in social and economic structure were accompanied by the diversification and growth of water demands, and by heightened risks of regional water scarcity. The state responded by adopting strong supply oriented policies, focused on infrastructure development. At the same time, the construction of large hydraulic works and centralization of management control affirmed the nationalistic vision of the authoritarian regime (Tàbara & Ilhan, 2008). Over 400 dams were built in Spain during the Franco era, leaving the country with one of the highest densities of dams in the world (World Commission on Dams, 2000).

The end of the Franco dictatorship and democratization of the political system in 1978 stimulated major changes in government policies that promoted decentralization and transferred authority to Spain's regional governments. The transition to democracy also accelerated the reorganization of economic sectors in which water played an important role, including agriculture, industry, energy, and municipal water supply and sanitation services. The diversification and increase in water demands led to heterogeneous patterns of over-use and regional water scarcity. The transformation of Spain's rivers by dams and irrigation projects had expanded the irrigated area of land by up to 4 million ha (Torrecilla & Martínez-Gil, 2005). Accompanying this, a transition to more intensive production methods greatly increased the application of fertilizers and pesticides. Industrial activity fueled by hydropower poured pollutants into rivers and contaminated groundwater sources, while untreated sewage from a growing urban population was often discharged directly into rivers.

These dynamic environmental, political, and economic factors revealed weaknesses in Spanish water policy, leading to major reforms under the Spanish Water Act of 1985 and initiating an Integration Era of water management in Spain (Fig. 4). The new law formalized the nationalization of water, affirming that all water resources are public goods are held in trust by the state to manage in accordance with the public interest. The water law also included three important provisions pertaining to environmental protections: (1) a requirement to assess effects of the water infrastructure and allocation decisions on the environment and on public water resources; (2) the need to consider minimum volumes of flow required to maintain ecological functions or sanitary water quality conditions; and (3) the establishment of a system for authorizing and controlling the discharge of pollutants to public waters (Loras, 1999).

Despite the major changes in water management under the 1985 Water Law, the construction of hydraulic works remained the dominant paradigm for addressing water scarcity and promoting economic growth. The Spanish National Hydrologic Plan (NHP) of 1993 proposed massive investments in water infrastructure, a dominant feature being a grand scheme of inter-basin transfers from the Ebro River to agricultural and population centers along the Mediterranean coast, which would have had severe environmental impacts (Ibañez & Prat, 2003). However, growing social resistance to the NHP stalled its approval and launched a debate on water management among a broad range of participants, including scientists, NGOs, regional and municipal governments, and state agencies. The outcome of these discussions was an alternative vision of Spain's water management framework described as the "New Water Culture" (NWC) (Tàbara & Ilhan, 2008). The NWC advocated a holistic view that recognized ecological and public trust values of water, in addition to utilitarian values protected under the traditional Hydraulic Era of management (Torrecilla & Martínez-Gil, 2005; Prat & Estevan, 2006). The government eventually approved National Hydrologic Plans in 2001 and 2004 that authorized the construction of approximately 100 new dams. However, the 2004 law repealed the Ebro River inter-basin transfers in response to concerns over potential environmental impacts and flawed assessment of the economic costs and potential alternatives to the project (Albiac et al., 2003; Garrido & Llamas, 2010).

While internal forces shaped the debate on the National Hydrologic Plan, a broader shift in the dominant water management paradigm was facilitated by Spain's integration with the European Union (EU). The most important piece of EU legislation to influence water management in Spain has been the Water Framework Directive (2000/60/EC, hereafter WFD). The WFD directly challenges Hydraulic Era principles by incorporating aquatic ecosystem protections, transparency and social participation, and economic cost recovery at the core of its management vision (Kaika, 2003). The WFD establishes long-term environmental objectives and series of benchmarks to facilitate progress toward sustainability in the planning and management of water resources. The ultimate objective of the WFD is to improve the quality of water within each EU Member State by identifying and controlling all activities that negatively affect the condition of surface and groundwater, thereby securing future water supply and protecting the heritage values of EU waters. The WFD also requires that administrative districts be established to coordinate water uses and activities that affect water-body conditions (determined by water quality parameters and ecological indicators). As a consequence, the WFD supports the integration of a wide range of historically independent economic sectors (e.g., industry, agriculture, forestry) and government functions (e.g., land-use planning, nature conservation, water rights administration), including regional and international trans-boundary collaborations (Kaika, 2003).

The WFD was transposed into Spanish legislation in 2003 and incorporated into the existing national water policy and planning framework by 2007. Current national water policy affirms the primary objectives of the WFD relating to the good condition of water, the aquatic ecosystem and sustainable use of water. However, national water policy also identifies traditional goals of Spanish hydrologic planning related to water security and the need to meet regional water demands through the expansion of water supply infrastructure. Thus, implementation of the WFD has not led to a complete rejection of Hydraulic Era principles. Perhaps the most significant effect of the WFD on water management in Spain has been the improved integration of planning and management within and between river basins. The establishment of nationally consistent monitoring and reporting programs, articulation of clear management goals, and enhanced institutional capacity for basin scale management represent significant progress toward the ultimate goal of sustainable water management. Nevertheless, substantial challenges to WFD implementation remain, particularly in Spain where problems of chronic pollution, overexploitation, and natural water scarcity prevent the fulfilment of environmental objectives (Munné & Prat, 2006; Grindlay et al., 2011).

Water management in Chile

Through the nineteenth century, water management in Chile was focused on agricultural irrigation and small domestic water supply projects. The management framework guiding water resource use was formalized under the Civil Code of 1855, which recognized water as a public resource to be managed by the State. The government authorized the private use of public water resources through licenses, which could be modified and canceled without compensation to the owner. With the expansion of irrigated agriculture throughout the nineteenth century, additional water rights laws were passed to facilitate the coordination of water rights by irrigation associations (Basualto et al., 2009). Until the mid-twentieth century, most water projects were carried out by small organizations of agricultural irrigators, with limited involvement of the state. However, to stimulate recovery from the Great Depression, the national government substantially increased investments in local industry in the 1940s, marking the transition from the Local Organization to Hydraulic Era of water management in Chile (Fig. 4). Hydropower development was targeted as a key element for facilitating economic growth and, from the 1940s on, hydropower became the core of Chile's national electricity system. In 1944, the Chilean government established ENDESA, the state-owned national utility company responsible for carrying out the long-term mission of national electrification (Bauer, 2009). The plan was focused on developing hydropower plants and a major transmission grid that would transfer electricity from the Biobío River and other rivers in southern Chile to population centers in the middle of the country. To better coordinate the growing and increasingly diverse demands on water resources from urban, agricultural, and industrial sectors, Chile adopted a comprehensive water code in 1951, which established a balanced system of private water rights and public regulation.

The rise of the socialist government in the 1960s led to a series of economic and social reforms aimed at centralizing public control over natural resources. In 1967, the Agrarian Reform Law authorized government expropriation and redistribution of landholdings and expanded government authority over water management. The Agrarian Reform Law replaced the 1951 Water Code and declared the nation's water to be public property, effectively nullifying existing private water rights (Bauer, 2004). The central water agency, the "Dirección General de Aguas" (DGA), was formally established in 1969 and given broad authority to redistribute water rights as part of the Agrarian Reform Law. The objectives of the Agrarian Law were centered on improving the productivity of agricultural land and expanding the sphere of land ownership, putting an end to large private estates. To support these aims, the state made major investments in hydraulic infrastructure to improve access to irrigation water (Basualto et al., 2009).

In 1973, the Chilean armed services, who were opposed to land reform efforts and troubled by deteriorating economic conditions, overthrew the socialist government. The military government under Pinochet brought an abrupt end to government expropriation of property and adopted radical free-market policies to foster economic growth. From 1973 to 1990, the government enacted economic reforms to encourage export-driven growth, primarily based on natural resource use such as mining, agriculture, forestry, and fisheries. Water and environmental goods were recognized as economic commodities and rights to use and profit from these and other natural resources were largely privatized. Chile's free-market approach to water management was formalized in the 1981 Water Code, which strengthened private property rights and sanctioned a market-based system for the allocation and management of water rights (Bauer, 1998). The underlying philosophy of the Water Code of 1981 was to establish a water rights system that allowed for markets to promote trading and maximize the efficient use of water (Basualto et al., 2009). Although the DGA was retained under the 1981 Water Code, its function was curtailed and management authority effectively transferred to private individuals and corporate water rights owners (Bauer, 2004).

Despite the political and economic turbulence in Chile from the 1960 to 1990s, the national electric utility greatly expanded its hydropower capacity. Much of the development was focused on the Biobío River basin (e.g., El Toro and Antuco Dams). In order to promote further hydropower development in Chile, the 1981 Water Code established non-consumptive water rights that could be granted even when available supplies were fully allocated. The military government also restructured the electricity sector, culminating in the privatization of ENDESA and other public utilities by the late 1980s. Water supply and sanitation services were also privatized during this period, which is considered a success by some because of the high rates of potable water and sewage services now available in Chile (Hearne & Donoso, 2005).

Environmental concerns related to water management in Chile was not part of the political dialog until the 1990s. The 1981 Water Code was principally designed to facilitate the management of water among irrigators based on free-market principles, but did not effectively address non-agricultural water uses, including environmental water needs (Bauer, 2004). Chile's first environmental law, "Ley de Bases del Medio Ambiente", was enacted in 1994. This law was partially in response to public concerns over water pollution problems, but much of the pressure to pass environmental legislation was external. For example, Chile's goal of strengthening international trade relations required that it establish basic standards for environmental protection (Bauer, 2004). The 1994 law provided a general framework for guiding government actions concerning the environment, established a centralized environmental commission, and was primarily focused on environmental impact assessment procedures. Nevertheless, the environmental law had little effect on water rights and water resources management (Bauer, 2004).

Reforms to the Water Code were passed in 2005 to address social equity issues and environmental concerns. The reforms largely reaffirm Chile's commitment to free-market principles for guiding water management, but corrected perceived weaknesses of the 1981 Water Code (Basualto et al., 2009). To prevent water hoarding and improve water efficiencies, the 2005 reforms established fees for unused water rights and required that applicants specify the intended use of water. Provisions of the reform also included requirements that the DGA consider environmental consequences of water use, an expansion of Presidential authority to override private water rights in order to protect the public interest, and enhanced public participation requirements. These changes have been viewed by some as significant progress toward integrated water resources management (Williams & Carriger, 2006). However, others remain critical of Chile's water management system and believe fundamental changes are needed to coordinate and balance the allocation of water resources among multiple users, including the environment (Brown & Peña, 2003; Bauer, 2004; Basualto et al., 2009).

While modifications to the Water Code expanded the scope of environmental protections, reforms also removed obstacles from obtaining water rights for hydropower use, thus encouraging further hydropower development. Chile continues to pursue plans for the major expansion of hydropower capacity, primarily in the Biobío and river basins in southern Chile. In 2004, the Ralco hydropower dam was completed on the upper Biobío River and is currently the largest power plant in the country (Fig. 3). Several other major hydropower projects funded by national and international conglomerates have been proposed and are currently in the planning phase. Proposed dams in the Patagonia region have triggered international controversies over the environment and indigenous rights (Bauer, 2009; Nelson, 2011). These campaigns failed to block the Ralco dam, but have led to a shift in the national dialog discouraging the *carte blanche* approval of hydropower projects. There is evidence of growing opposition to the market-based principles and privileges of private interests under the Water Code (Bauer, 2009). However, the dominant management paradigm in Chile continues to support Hydraulic Era principles and progress toward integrated forms of water management remains slow (Fig. 4).

Water management effects on mediterranean river ecosystems

Water management effects on hydrologic regimes

The development of large dams and conveyance water projects in the Sacramento, Ebro, and Biobío River basins have substantially altered natural flow regimes. Examples of hydrologic alterations include changes in flow variability at multiple temporal scales, shifts in the timing and magnitude of floods, and disruption to dry season flows. The general effect of large dam development has been to reduce the magnitude and frequency of high flow events in the winter and spring, and to increase summer and fall base flows (Table 3). For example, it is estimated that the magnitude of flood flows in the Sacramento basin has declined between 30 and 90% relative to pre-dammed conditions, while summer baseflows have generally increased (Kondolf & Batalla, 2005). This "flattening" of the hydrograph has been observed in the mainstem and all major tributaries to the Sacramento River (Singer, 2007; Brown & Bauer, 2010). Such modifications reflect management objectives of water storage and flood protection in the winter rainy season and water deliveries for agriculture during the dry irrigation season.

In the Ebro River basin, dams have also reduced seasonal flow variability, and for some river reaches, contributed to a complete inversion of natural seasonal flow patterns, with higher dry season flows and lower wet season flows (Batalla et al., 2004; Magdaleno & Fernández, 2011). Moreover, the magnitude of floods has been significantly reduced, particularly for moderate floods (Batalla et al., 2004; Batalla & Vericat, 2009). Similar patterns of alteration have been caused by the major hydropower dams on the Biobío River basin, resulting in reduced flood magnitudes and increased summer flows (Goodwin et al., 2006; García et al., 2011).

Despite the changes in the magnitude of seasonal flows, the annual mean discharge of the Sacramento River has not changed appreciably (Brown & Bauer, 2010). In contrast, mean annual flow of the lower Ebro River has declined by 29% in the last century, largely attributed to increases in water use in the river basin (Ibañez et al., 1996). There is no evidence that annual flow of the Biobío River has declined after dam construction, although land-use change and increasing irrigation water withdrawals during the dry season for forest plantations have the potential to reduce river flows (Valdovinos & Parra, 2006; García et al., 2011).

Flow regimes downstream of hydropower dams in all three river basins have also been modified by hydropeaking operations (Table 3). For example, hydropower dams in the Biobío River basin cause strong daily fluctuations in flows associated with hydropeaking, which has led to a shift in flow regime variability from monthly to daily scales (García et al., 2011). There is also evidence that hydropower dams on the lower Ebro River have increased diurnal fluctuations in flows (Prats et al., 2009), although these dynamics have not been fully characterized in previous hydrological analyses of the Ebro River basin (e.g., Ibañez et al., 1996; Batalla et al., 2004; Batalla & Vericat, 2009; Batalla & Vericat, 2011a; Magdaleno & Fernández, 2011). The effects of hydropeaking on the Sacramento River basin have generally been mitigated by construction of small, flow-regulation dams downstream of hydropower facilities. However, other major tributaries to the Sacramento, such as the American River, are strongly affected by short-term pulse-flow releases for hydropower and recreational purposes (Young et al., 2011).

Although the hydrologic effects of urban water uses have not been well documented in the Sacramento, Ebro, and Biobío River basins (perhaps because urban water use is low compared to agricultural and industrial water demands), studies from other med-rivers indicate that urban settlements are an important driver of flow regime alteration (Prat & Ward, 1994). In many cases, small tributaries and streams are diverted from upstream sources to meet water supplies, reducing flows downstream of diversions and accelerating stream drying in the summer. At the same time, domestic irrigation runoff and sewage discharges may contribute a significant proportion of the stream flow downstream of urban settlements (Canobbio et al., 2009). In areas where many settlements occur along a stream, water-use patterns lead to highly modified spatial variation in hydrologic conditions in which contiguous reaches may alternate between completely dry (below diversions) and artificially high flows (below wastewater treatment plants).

The pronounced effects of urban water use and wastewater discharges on stream flows have been documented in many arid and semi-arid regions of the world, particularly during low-flow and drought periods (Brooks et al., 2006; Martí et al., 2010). Thus, it is likely that that small streams and rivers located near urban settlements in the Sacramento, Ebro, and Biobío River basins are affected by effluent discharges and other hydrologic alterations associated with urban development (e.g., Debels et al., 2005; Walsh et al., 2005).

Ecological responses to hydrologic regime alteration

Dams and flow regulation have been identified as a dominant driver of freshwater ecosystem degradation and loss of aquatic diversity (Dynesius & Nilsson, 1994; Dudgeon et al., 2006). They have resulted in changes in the structure and function of river ecosystems from hydrologic alterations, and these have been documented in all of the study basins. In California and Spain, dams have been identified as the most important factor causing declines of freshwater fish populations (Clavero et al., 2004; Moyle et al., 2011). Although the ecological consequences of flow regime alterations and other major human disturbances in the Biobío River basin have not yet been fully documented, there is evidence that prevailing water use

Table 3 Documented ecosystem responses to water management in the Sacramento, Ebro, and Biobío River basins

	Sacramento	Ebro	Biobío
Hydrologic alterations			
Longitudinal hydrologic connectivity	–[a]	–	–
Lateral (floodplain) connectivity	–	–	?
Seasonal flow variability	–	–	–
High flood frequency	–	–	–
Flood magnitude	–	–	–
Dry season baseflows	+	+	+
Diurnal flow pulse variability	0/+[b]	?	+
Annual discharge	0	–	0
Flow effects of diversions	–	–	–
Flow effects of wastewater discharges	?	+	?
Geomorphic alterations			
Sediment transport load	–	–	?
Channel incision	+	+	?
Channel migration/movement	–	–	?
Floodplain inundation area	–	?	?
River delta subsidence	+	+	?
Water quality alterations			
Water temperatures below dams	–/+[c]	–/+[c]	?
Nutrients	+/0[d]	–/+[d]	+
Pesticides	+/0[d]	+	0
Fecal coliform	0	0	+
Pharmaceuticals	?	+	?
Heavy metals	+	+	0
Chlorinated organic compounds	0	+	+
Saline intrusion	–	+	?
Seasonal salinity variability in river delta	–	–	?
Ecological effects			
Anadromous fish species	–	–	?
Native fish populations	–	–	–
Native fish biodiversity	–	–	–
Introduced fish species	+	+	+
Macrophyte biomass	0	+	?
Bioaccumulation of toxic compounds	+	+	+

[a] Symbols refer to an increase (+), decrease (–), no reported change (0), or unknown change (?) in response to water management activities

[b] Hydropeaking flow fluctuations have a strong effect on some tributaries to the Sacramento but do not influence the mainstem river

[c] Seasonal inversion of temperatures below dams with hypolimnetic flow releases, such that winter temperatures are higher and summer temperatures are lower compared to unimpaired conditions

[d] Effects are seasonal and associated with low-flow period. In the Ebro, phosphorus levels have decreased, while nitrogen has increased in reaches affected by agricultural land-use

practices have altered ecosystem processes and threaten the persistence of native biota, including several endemic fish species (Habit et al., 2006).

The construction of large dams disrupts the natural hydrologic connectivity of habitat within the river network, which has particularly impacted anadromous fishes and other migratory species. For example, the construction of impassable dams in the Sacramento River basin is has reduced the availability of habitat historically used by salmon and steelhead by over 50% (Yoshiyama et al., 2001; Lindley et al., 2006) and has substantially curtailed the distribution of green sturgeon (Mora et al., 2009). In the Ebro River, large dams have also restricted the distribution of eels, lampreys, and sturgeon compared to their historic range (García de Jalón et al., 1992).

The reduction in flow variability tends to reduce habitat complexity and structural features preferred by fish and other aquatic organisms (Thoms, 2006). For example, the reduction in the magnitude and frequency of flood flows in the Sacramento River has dramatically decreased the period of inundation of seasonal floodplains and off-channel habitats. Floodplains are critical for the reproduction of many native species and have been identified as an important limiting factor to salmon and other native fishes in the Sacramento River basin (Sommer et al., 2001, 2002; Opperman et al., 2010). Flow regulation and agricultural land use in alluvial valleys of the Ebro River have also reduced the complexity of floodplain habitats utilized by macroinvertebrates and other aquatic species (Gallardo et al., 2008). In addition, the stabilization of flows in the middle Ebro has facilitated the expansion of riparian vegetation to the historically active channel of the river, resulting in the loss of channel complexity and instream habitat structure (Magdaleno & Fernández, 2011).

Despite the fact that large hydropower dams tend to increase flow variability, hydropeaking causes flow fluctuations at daily or sub-daily timescales that do not occur under natural conditions and tend to negatively affect aquatic biota. For example, aseasonal pulse-flows on a tributary to the Sacramento River have been shown to cause the downstream displacement of fishes (Jeffres et al., 2006) and to limit recruitment of riverine amphibians (Kupferberg et al., 2012). Summer flow fluctuations below a hydropower generation facility on a tributary to the Ebro River reduced the abundance and diversity of the benthic macroinvertebrates (García de Jalón et al., 1988). On the Biobío River, García et al. (2011) found that strong fluctuations in daily flows associated with hydropeaking operations created greater spatial–temporal variability in aquatic habitat than under natural conditions and likely disrupted invertebrate drift patterns, fish feeding and spawning behavior, and other biotic interactions. Despite the general negative effects of hydropower peaking flows on freshwater biota, other studies from Sacramento River tributaries have indicated that some native fishes species are resilient to pulse flows, presumably the result of adaptations to the high flow variability that naturally occurs in med-rivers (Klimley et al., 2005; Cocherell et al., 2010).

Water diversion is another cause of hydrologic alterations in med-rivers and an important driver of ecological degradation. Direct surface water diversions modify instream habitat by reducing flows and hydrologic connectivity (McKay & King, 2006; Dewson et al., 2007). Diversions can also accelerate stream drying, leading to the stranding and desiccation of aquatic organisms. In the Sacramento River, large water diversion pumps have altered the natural flow patterns of the river delta, affecting migratory fish behavior and causing the direct mortality of native fishes through entrainment. Over 400 water diversions have been identified along the Sacramento River mainstem and over 2,000 have been counted in the river delta (Herren & Kawasaki, 2001). Most of the water diversions in the basin are unscreened and are likely to be a contributing factor to native fish species declines (Herren & Kawasaki, 2001; Moyle, 2002). No information is available on the ecological effects of water diversions in the Ebro and Biobío River basins.

A general effect of flow regime alteration is the loss of biotic diversity and homogenization of fish assemblages (Moyle & Mount, 2007; Poff et al., 2007). This is a result not only of the direct effects of habitat modification, but also of indirect effects associated with alien species introductions (Light & Marchetti, 2007). For example, dams are strongly associated with the non-native species assemblages in rivers of the Iberian Peninsula (including the Ebro) and both factors are linked to patterns of native species imperilment (Clavero et al., 2004). On Putah Creek, a tributary to the Sacramento River, flow alterations below a dam were shown to promote the expansion of non-native species range to the detriment of native fish assemblages (Marchetti & Moyle, 2001). When a more natural flow regime was restored in Putah Creek, the range of downstream habitat dominated by native fish assemblages expanded, while the distribution of non-native species contracted (Kiernan et al., 2012). There is also empirical evidence that native fish assemblages in the Sacramento River basin are favored over non-natives in wet years, when higher spring flows and cooler temperatures provide more appropriate spawning conditions for native fishes species (e.g., Marchetti & Moyle, 2001; Brown & Ford, 2002). The reduction of spring flows in most years probably limits the availability of spawning habitat for native fishes in the Sacramento relative to historical conditions (Brown & Bauer, 2010). Fish introductions have already contributed to major changes in fish faunal assemblages in California, Spain, Chile, and other med-regions (Marr et al., 2010). Thus, non-native species are likely to be a persistent factor influencing ecological responses to water management in med-rivers, including the Sacramento, Ebro, and Biobío.

Water management effects on geomorphic processes

Water management in the Sacramento, Ebro, and Biobío River basins has severely impacted sediment transport and other geomorphic processes (Table 3). Alterations to natural sediment regimes of the Sacramento River have occurred since the beginning of the 19th century caused by hydraulic mining activities, which increased average annual sediment loads of 0.8 million m^3 up to peak yields of 7.3 million m^3 (Gilbert, 1917). However, sediment loads have progressively declined throughout the twentieth century as a result of dam construction, flood-control infrastructure, bank protection, and gravel mining (Wright & Schoellhamer, 2004). Dams interrupt sediment transport by capturing bedload sediment and inducing deposition of the suspended load in the low-velocity waters of reservoirs. It is estimated that since the construction of major dams in the Sacramento–San Joaquin basin, annual bedload transport has fallen by an average of 45%, with total bedload of particles greater than 8 mm decreasing by 42% (Minear, 2010). Ibañez et al. (1996) estimated that sediment transport in the Ebro River Basin was reduced from approximately 1.0×10^7 metric tons per year (Mt/year) to $0.1–0.2 \times 10^6$ Mt/year after the construction of dams on the lower Ebro, representing a reduction of more than 99%. However, the river partially retains its sediment transport capacity by entraining material from the riverbed and lateral deposits, resulting in incision of the river channel (Vericat & Batalla, 2005). In comparison to the Sacramento and Ebro Rivers, the effects of water management activities on sediment transport processes in the Biobío River basin are less well known. The Biobío is estimated to yield between 9.7 and 15.8 million tons of bedload sediment and 6 million tons of suspended sediment per year (Valdovinos & Parra, 2006). Cisternas (1993) characterized sediments along the main segments of the Biobío, reporting that the upper portion of the river was dominated by boulders and that the lower portion by medium-sized sand. The absence of fine sediments indicates that the river transports significant volumes of suspended sediment to the coastal zone, which is likely to have important consequences for the ecosystem of the lower Biobío River and estuary (Bertrán et al., 2001).

A general consequence of reduced sediment inputs to reaches below dams is channel incision and coarsening of bed sediments during high flow events. This so-called hungry water effect (i.e., in which flows retain their energy to move sediment but have lost their sediment supply, resulting in erosion of channel bed and banks) has been observed on tributaries to the Sacramento River and other rivers throughout the world affected by major dams (Kondolf, 1997). Extensive bank protection by levees and revetment structures have also reduce sediment supplies to the river channel by preventing lateral erosion (Michalková et al., 2011). The effects of reduced sediment load by dams are intensified by the mining of aggregate from the river channel. For example, most of the materials used to construct dams in the Sacramento River basin were mined directly from downstream reaches of river dams and it is estimated that 1.5 million m^3 of aggregate continue to be mined annually in the basin (Buer et al., 1989). Gravel mining is also a major contributor to sediment deficits in the Ebro River. It is estimated that total extraction of gravels from the Ebro and Catalan coastal ranges reached 1×10^6 m^3, a quantity exceeding the annual bedload yield of all rivers in the two regions (Batalla & Vericat, 2011b).

Floodplains in both the Sacramento and Ebro River basins have been substantially altered by agricultural activities and flood-control management. The conversion of floodplains for agricultural production typically results in the stabilization of river channels behind embankments, limiting natural channel migration and floodplain inundation periods (Mount, 1995). In the past 100 years, the alluvial valley of the Sacramento River has been mostly converted to agricultural land uses, resulting in the loss of nearly all (98%) of its original riparian forests since 1850 (Katibah, 1984). A complex network of levees and bypass channels has been constructed in the Sacramento River Valley to protect agricultural crops, residential development, and infrastructure from flooding. Although there is less flood-protection infrastructure on the Ebro River, the regulation of flows and armoring of channel banks has stabilized long reaches of the river channel (Magdaleno & Fernández, 2011). At the same time, increases in summer base flows have facilitated the establishment of riparian vegetation in the river channel, further stabilizing the channel and limiting active channel meandering (Magdaleno & Fernández, 2011). Studies quantifying the extent of floodplain modifications in the Biobío River basin have not yet been conducted, although the expansion of residential development in recent decades has likely produced similar floodplain impacts as observed in the Sacramento and Ebro River systems.

Ecological responses to geomorphic alterations

Disruption to sediment transport from dams and water projects have contributed to the degradation of river ecosystems. In the Sacramento River basin, the construction of dams has not only blocked access to historic salmonid habitats upstream, but has also degraded the quality of spawning habitats downstream as a result of the loss of sediment inputs (Kondolf, 1997). The combined effects of spawning habitat loss and degradation has been identified as a primary factor contributing to salmon population declines in the Sacramento River (Good et al., 2005). Gravel mining has intensified sediment deficits below dams and required large-scale gravel replenishment projects to restore salmonid spawning habitats in the Sacramento River basin (Kondolf & Matthews, 1991; Pasternack et al., 2004). The disruption of sediment transport in the Ebro River from dams has also had major ecological effects, particularly in the delta. The Ebro River Delta is considered one of the most important ecological areas of Spain for migratory shorebirds and supports diverse assemblages of fishes, macroinvertebrates, and other aquatic biota. The reduction in sediment delivery by an estimated 99% of its original yield has resulted in the subsidence and loss of delta wetlands. It is estimated that 45% of the current Ebro Delta will be under the sea by 2100 if management actions to increase sediment loads are not taken (Rovira & Ibañez, 2007).

The stabilization of the large river reaches in the Sacramento River Valley by levees has reduced habitat complexity and negatively impacted a wide range of freshwater biota, including riparian tree species (Katibah, 1984; Buer et al., 1989), birds such as bank swallows (Moffatt et al., 2005), and pond turtles (Spinks et al., 2003). Bank stabilization and reduction of channel meandering has also reduced habitat complexity in the Ebro River and its riparian ecosystem (Gonzalez et al., 2010; Magdaleno & Fernández, 2011). In recognition of the importance of floodplain habitats to native fishes, the restoration of floodplains through levee setbacks and environmental flow releases has become a central component of native fish species recovery efforts in the Sacramento River Valley and its delta (Feyrer et al., 2006; Opperman et al., 2010). Strategies for floodplain restoration are also being considered on the Ebro River. In comparison to the Sacramento and Ebro basins, the geomorphology of the Biobío River (and the potential effects of geomorphic alterations on the ecosystem) has received little attention. However, increasing water and land-use pressures in the basin indicate the potential for significant alterations to sediment transport and floodplain processes.

Water management effects on water quality

Water management activities have a broad range of effects on water quality in the study basins (Table 3). For example, changes in flow regimes from dams and water diversions strongly affect downstream temperatures and the dilution capacity of rivers. Agricultural irrigation runoff is an important source of pollution to rivers, as is wastewater and runoff from urban settlements. Finally, industrial activities that rely on rivers to produce electricity and goods are major sources of pollution and water quality degradation.

The creation of artificial reservoirs and the release of stored water from dams significantly alters natural spatial and temporal thermal profiles of rivers. For example, water released from the Shasta Dam to the Sacramento River tends to be 5–10°C colder than pre-dam temperatures in the summer, while from September–November water temperatures of flow releases are slightly higher than pre-dam conditions (Yates et al., 2008). Studies on the thermal effects of dams on the Ebro River have revealed similar downstream patterns: higher temperatures in the winter; lower temperatures in the summer; reduced daily and annual thermal amplitude; and displaced annual maximum and minimum water temperatures (Prats et al., 2010, 2011). Thermal regimes in the lower Ebro River are also affected by a nuclear power plant, where discharged water used to cool the reactor increases river temperatures by approximately 3°C (Prats et al., 2011). Water use activities do not appear to have significantly altered natural temperature regimes in the Biobío River basin (Link et al., 2008), although the expansion of forest plantations is likely to reduce the availability of water and increase the risk of forest fires, both of which could increase river temperatures.

The regulation of flows in the Sacramento has had profound effects on seasonal salinity patterns in the

Sacramento–San Joaquin Delta. Flows into the Delta are managed to prevent intrusion of saltwater from San Francisco Bay and maintain low levels of salinity in water exported to southern California. As a consequence, much of the seasonal and interannual variability in the estuarine system has been lost (Lund et al., 2007). The regulation of flows in the Ebro River has also affected the seasonal dynamics of its delta and estuary. In contrast to the Sacramento River Delta, water management on the Ebro has increased the salinity of the lower river. The reduction in floods and stabilization of dry season flows has caused intrusion of a persistent marine salt wedge up to 25 km into the lower Ebro River that is less dynamic than under historic conditions (Ibañez et al., 1996; Sierra et al., 2004).

Agricultural, urban, and industrial water uses have all contributed to the degradation of water quality in the Sacramento, Ebro, and Biobío River basins. Based on the findings of a National Water Quality Assessment Program in the 1990s, the Sacramento River and its tributaries are of sufficient quality to support most beneficial water uses, including drinking, irrigation, recreation, and protection of aquatic life (Domagalski et al., 2000). Mercury and other heavy metals from historic mining activities are the most significant water quality issues in the basin (Alpers et al., 2000; Domagalski, 2001). In comparison to the Sacramento, the Ebro River has more severe water quality problems. The upper section of the river is characterized by high inputs of heavy metals and organic compounds from mining, industry and urban sources (Terrado et al., 2011). The middle course of the river is affected by the accumulation of nutrients and salts, primarily derived from agricultural sources, but which are also present in high natural levels in the soils and underlying geology (Terrado et al., 2011). The lower Ebro River is affected by both organic and heavy metal contamination associated with industrial activities. Over the past 25 years, there has been a trend of decreasing phosphate concentration, decreasing DOC, and increasing oxygen content, which has been attributed to the construction of water treatment plants and improvements in sewage treatment processes (Torrecilla et al., 2005; Ibañez et al., 2008; Oscoz et al., 2008). At the same time, there has been an overall increase in nitrate concentration associated with changes in agricultural land-use (Lassaletta et al., 2009). Currently, agricultural runoff is considered the dominant source of pollution in the Ebro River basin, contributing high-levels of nutrients and pesticides (Claver et al., 2006; Hildebrandt et al., 2008; Kock et al., 2010; Terrado et al., 2011). However, accumulated historical contamination from industrial sources remains a persistent pollution source (Cid et al., 2010; Navarro-Ortega et al., 2010; Carrasco et al., 2011).

Similar to the Ebro, the Biobío River basin is characterized by chronic water quality problems. The primary contributor to water quality degradation is the pulp production industry. The Biobío region produces over 1.4 million tons of cellulose per year in pulp mills and paper plants (Goodwin et al., 2006), and is responsible for nearly all of the paper production in Chile (Parra et al., 2009). Effluents from the plants are discharged directly into the middle and lower zones of the Biobío River, and these contain high levels of toxins derived from wood and chemicals used during pulping and bleaching processes (Karrasch et al., 2006). Wastewater discharges are another important contributor to water quality degradation in the Biobío River and its tributaries. The middle and lower regions of the river receive wastewater effluents from sewage treatment plants of the city of Los Angeles, Santa Juana, and the Concepción–Talcahuano–Chiguayante area. While the construction of several new treatment plants in the late 1990s has reduced the discharge of untreated sewage to the Biobío River, wastewater effluents continue to affect water quality with high levels of fecal coliforms, nutrients, and hydrocarbons. Levels of heavy metals and pesticides detected in the Biobío River are low and within the limits of minimum water quality standards (Dirección General de Aguas, 2004). The combined effects of industrial and wastewater effluents have created a pattern of decreasing water quality from the upper to the lower regions of the river (Parra et al., 2004). Nutrient levels in the upper Biobío are low, but the concentrations of ammonia, nitrate, nitrite, and phosphorus significantly increase in the downstream direction. Concentrations of toxic compounds from industrial operations follow a similar increasing spatial trend from upstream to downstream (Habit et al., 2006).

The natural seasonality of flow regimes in the river basins has a strong influence on water quality dynamics. During the low-flow season, runoff from agricultural areas and mining operations has caused localized, short-term deterioration of water quality conditions in Sacramento River (Domagalski et al., 2000). In the Ebro River, low-flow periods are associated with spikes in concentrations of nitrate and DOC, reductions in dissolved oxygen, and eutrophication (Torrecilla et al., 2005; Romaní et al., 2011). In the delta region of the lower Ebro River, concentrations of herbicides are also directly correlated with field applications and patterns of river discharge (Romaní et al., 2011). The degradation of water quality in the Biobío is most pronounced during the low-flow season and is compounded by flow regime alterations from dam operations and water withdrawals (Goodwin et al., 2006).

Ecological responses to water quality degradation

The degradation of water quality conditions has affected freshwater ecosystems in all of the study basins. The primary water quality issues are temperatures, nutrients, industrial contaminants, and heavy metals. Because of blocked access to historic spawning grounds on the upper Sacramento River, the reach immediately downstream of Shasta Dam has become the only suitable area for spawning of winter-run Chinook salmon, and releases from the dam are actively managed to maintain required cold-water temperatures (Slater, 1963). Regulation of downstream temperatures is critical for protection of this species. However, regulation of releases has been shown to alter other ecological attributes, including increases in particulate organic matter and zooplankton biomass, which may influence the aquatic food web (Lieberman et al., 2001). Cold-water releases below dams in the Ebro River system have also been shown to cause a local reduction in macroinvertebrate community richness, growth rates and productivity (García de Jalón et al., 1988).

Water quality conditions in the Ebro and Biobío Rivers are severely impaired by pollution from agricultural, industrial, and urban sources. The effects of water quality contamination on the Ebro River ecosystem have been studied across a wide range of trophic levels. Studies have documented bioaccumulation of heavy metals, pesticides, and other toxic compounds in water fowl (Manosa et al., 2001), fish (van Beusekom et al., 2006; Benejam et al., 2010b; Carrasco et al., 2011), mussels (Alcaraz et al., 2011), macroinvertebrates (Cid et al., 2010), and macrophytes (Manosa et al., 2001). Although there has been evidence of biological water quality improvement in the Ebro River since the adoption of the Water Framework Directive (Oscoz et al., 2008; Ibañez et al., 2012), pollution remains a major threat to aquatic life in the system. Nutrient levels in the lower Ebro River have begun to decline, probably due to improved water treatment and other factors (Torrecilla et al., 2005). The decrease in phosphorus levels has limited phytoplankton production and increased water clarity. As a consequence, there has been a proliferation of submerged macrophytes in the river bed, creating problems for recreational navigation and producing a high abundance of black flies that are a nuisance pest for people working on the river and adjacent agricultural fields (Ibañez et al., 2012).

In the Biobío, Habit et al. (2006) found that the deterioration of water quality in the middle and lower reaches of the river produced a pattern of decreasing fish abundance and diversity from upstream to downstream, opposite of what is typically observed. Ecological studies on reaches of the Biobío River that are affected by pulp and paper mill effluents have demonstrated shifts in planktonic community structure (Karrasch et al., 2006), found evidence of endocrine disruption and reproductive alterations in fishes (Orrego et al., 2006; Orrego et al., 2009; Chiang et al., 2011), and detected high concentrations of persistent organochlorine residues in fish and water birds (Focardi et al., 1996). Although water quality conditions are less degraded in the Sacramento than the Ebro and Biobío, persistent levels of heavy metals from historic mining in the basin have been shown to bioaccumulate in the aquatic food web (Domagalski, 2001), potentially affecting the fitness of biota and presenting human health risks. Finally, there is evidence that degradation of water quality has promoted the dominance of alien species, further impacting native biota. On the Biobío, for example, pollution-tolerant introduced fish (e.g., *Gambusia holbrooki* and *Cyprinus carpio*) have increased in abundance and expanded their range in degraded reaches of the river. These species have been shown to have negative impacts on native species in other river systems and are likely to further threaten native fish species in the Biobío River already impacted by habitat alteration (Habit et al., 2006).

Key water management challenges in California, Spain, and Chile

California, Spain, and Chile face formidable water management challenges that are both physical and institutional in nature. All three med-regions are defined by the spatial segregation of where water is most abundant and where demands are greatest, requiring large-scale infrastructure and broad institutional powers to effectively convey and allocate water over large geographic ranges. Furthermore, high seasonal and inter-annual precipitation variability presents fundamental challenges for securing reliable water sources for both human and ecosystem needs. Population growth will unquestionably increase competition among water users and place additional pressures on river ecosystems already showing signs of deterioration. Furthermore, management conflicts related to regional disparities in water availability are likely to intensify in the future due to climatic change. Robust and effective water governance systems are needed, but existing management frameworks, their guiding principles, and institutional capacities may be insufficient to address these challenges.

Population growth

Populations are expected to increase in all of the study regions over the next 50 years. California is projected to experience the greatest population growth, from approximately 39 million (in 2010) to as many 60 million by 2050 (Hanak et al., 2011). The population of Spain is expected increase by approximately 5 million and in Chile by 3 million by 2050 (United Nations, 2012). In all regions, most of the population growth is expected to occur in urban areas, expanding urban land use and increasing domestic water demands. In Spain, regions with growing populations and agricultural production are already contributing to local water scarcity crises. For example, Iglesias et al. (2007) estimated that seasonal tourism in Spain has increased water demands on the dry, Mediterranean coast by 30 million m^3, while in the Segura River basin, accelerated agricultural land expansion and urban development have aggravated water shortage issues (Grindlay et al., 2011). In California, the urban sector's share of human water use has increased, although conservation efforts appear to have reduced per capita water use in urban areas (Hanak et al., 2011). However, much of California's water infrastructure is nearing the end of its intended lifespan and showing signs of deterioration (Department of Water Resources, 2009b), suggesting that even moderate increases in urban water demands may be difficult to accommodate. Substantial public investment is needed to repair or replace dams, canals, and flood-control levees at a time when the California is struggling to meet its annual operating budget. While the population density in southern Chile is expected to remain low in the near future, growth in Santiago and other urban centers will increase national energy demands, which are likely to be met through increased hydropower development in the Biobío and other rivers in Patagonia (Bauer, 2009).

Environmental degradation

Despite the growing recognition of environmental values in the management of rivers in California, Spain, and Chile, trends of ecological degradation and biodiversity loss continue. The intensive and widespread construction of dams has fundamentally altered hydrologic and geomorphic processes upon which freshwater ecosystem depend. Significant improvements in controlling point-source pollutants in California have not been followed by effective management of non-point pollution sources from agricultural and urban areas. Water quality degradation continues to threaten river ecosystems in Spain and Chile. The initial environmental assessment required by the WFD in Spain indicated that freshwater ecosystem conditions were much worse than expected (Ministerio de Medio Ambiente, 2007b). Enforcement of current regulations remains lax, and the Ministerio de Medio Ambiente (2007b) expects that most river basins will see most water quality parameters worsen, or at best stabilize, by 2015. Thus, contamination of surface water and groundwater in Spain remains a major threat to urban drinking water supplies and aquatic ecosystems. In Chile, new regulations were enacted in 2002 to address persistent pollution problems in rivers and groundwater bodies. However, implementation has been slow and water quality standards have only been approved for two basins in southern Chile that are largely unimpaired (Basualto et al., 2009). Water quality standards remain weak or non-existent in the central med-region of Chile that has higher industrial and agricultural pressures than other areas. Although environmental assessment requirements have been incorporated in the permitting process for water rights and major water infrastructure projects in Chile, environmental and indigenous rights groups have been critical of the findings and scope of analysis of environmental impact studies (Bauer, 2009; Goodwin et al., 2006). Chile's ambitious plans for economic growth and increased energy capacity will undoubtedly increase pressures on the environment, suggesting that further degradation of freshwater ecosystems will occur.

Climate change

Climate change is expected to compound existing water supply and ecosystem management challenges by altering the distribution and availability of water resources. Flow regimes of the major rivers in each region, including the Sacramento, Ebro, and Biobío, are expected to change with the reduction of seasonal snowpack in the mountains. In California, climate forecasts predict a reduction in snowpack in the Sierra Nevada by 80% by the end of the century (Maurer et al., 2007) and an increase in precipitation variability (Barnett et al., 2008). Seasonal peak flows are likely to increase in intensity and occur earlier in the winter. Similarly, climate projections for Spain predict runoff regimes that are more variable and prone to extremes (Ministerio de Medio Ambiente, 2007a). As a consequence, the intensity of flooding and the risk of flood damage are expected to increase. Furthermore, if reservoirs are managed to retain lower storage volumes in order to increase flood risk security, less water may be available for agriculture and other needs, thus compounding water scarcity problems (Garrido & Llamas, 2010). Higher temperatures and decreased snowpack are also expected to have major impacts on the agricultural and hydropower sectors in Chile (Bauer, 2009). Overall, climate change is expected to make it increasingly difficult to meet future water demands (Purkey et al., 2008) and ecological management goals (Yates et al., 2008).

Governance challenges

Water governance reforms are likely needed to support more integrated and environmentally sustainable forms of water management. California's water laws have proven to be flexible in accommodating changing public uses and values for water, including environmental benefits (Hanak et al., 2011). Sustainable resource use and integrated management have also been identified as guiding management principles for the state's Water Plan, the primary framework for developing California's long-term water management strategy (Department of Water Resources, 2009b). Nevertheless, California's approach to addressing water supply, water quality, flood control, and environmental management challenges remains fragmented and highly decentralized among local, state, and federal entities (Hanak et al., 2011). Increased integration of management authority is required to coordinate inter-related issues such as water quantity and quality, flood-control management and land-use planning, and groundwater and surface water use. In some cases, the capacity to implement management reforms is limited due to conflicting legal jurisdictions. Notably, revisions to California Water Law are needed to coordinate the regulation of groundwater with the administration of surface water rights. Some promising steps have been taken to develop a broader vision of governance based on co-equal goals of ecosystem restoration and water supply management (e.g., Delta Vision Blue Ribbon Task Force, 2008) and the state legislature enacted a package of reforms in 2009 that begins to address many of California's persistent water management problems (Department of Water Resources, 2009b). However, an $11 billion bond measure to fund the reforms has not yet been passed and the ultimate outcome of the political process remains uncertain. Thus, the institutional capacity to implement and enforce new forms of integrated water management in California remains limited.

As in California, addressing chronic problems of water scarcity and water quality deterioration in Spain will require large public investments and an increased level of management coordination. The integration of land-use planning and hydrological planning is particularly needed to stabilize water demands and reverse patterns of ecosystem degradation (Grindlay et al., 2011). Required measures for sanitation, purification, river restoration, and the recovery of groundwater resources in Spain will cost billions of euros. The WFD establishes a clear framework for integrated water management based on principles of environmental sustainability. However, adequate funding mechanisms are required to accomplish the ambitious environmental objectives of the WFD. Finally, enhanced public participation and transparency in decision-making are viewed as critical to overcoming the adversarial positions of water users and to supporting efforts to better integrate water management in Spain (Garrido & Llamas, 2010).

There is growing recognition that water management in Chile under the existing Water Code does not provide an adequate framework to perform essential functions, including coordination of different water uses and sustainable allocation of water resources. In fact, there is no mention of environmental sustainability as a goal or guiding principle to water management in the Water Code (Dirección General de Aguas, 2010b). The Chilean management framework gives precedence to individual water rights and relies on economic principles for allocating water to highest value uses (Williams & Carriger, 2006). Furthermore, the state water agency, DGA, has primarily been restricted to a technocratic role, with limited regulatory authority to plan and coordinate uses across water sectors (Brown & Peña, 2003; Basualto et al., 2009), particularly between consumptive (e.g., agriculture) and non-consumptive (e.g., hydropower) water users (Bauer, 2009). The emphasis of Chile's Water Code on market principles has also created problems for water management. The original 1981 Water Code fostered speculation because it granted water rights for free to applicants and led to consolidation of rights among a relatively small number of private owners. Changes in the 2005 water code addressed speculation in part by requiring evidence of water use and charging annual fees, but monopolization remains a problem (Basualto et al., 2009). The Water Code provides little protection of freshwater ecosystems. Although the 2005 reforms did recognize water rights for environmental benefits, water allocations to support ecological functions have been limited and may not affect existing water rights holders (Dirección General de Aguas, 2010b). Furthermore, environmental uses are not economically valued in water rights transactions, so impacts to the environment are generally treated as externalities. Thus, there is need to incorporate environmental costs and benefits in Chile's market-based approach to water management if sustainable outcomes are to be achieved (Basualto et al., 2009).

Conclusions

Despite their unique geographic and historical contexts, there are broad similarities in the patterns of water resource development and consequent alterations to freshwater ecosystems in the Sacramento, Ebro, and Biobío River basins. In particular, the intensive development of large dams and conveyance infrastructure for water supply, flood protection, and hydropower generation has led to common forms of hydrologic alteration, including river network fragmentation, a reduction in seasonal flow variability, decreased flood magnitudes, and increased summer base flows. Similar modifications to physical process are also present, such as the reduction of sediment transport below large dams in both the Sacramento and Ebro River basin. The loss and degradation of floodplain habitats from reduced flood flows and channel embankments are also well documented in the alluvial valleys and deltas of the Sacramento and Ebro Rivers. Finally, all three river basins are characterized by strikingly similar patterns of ecological alterations, particularly with respect to the loss of native fish assemblages and the concurrent increase in abundance and distribution of non-native fishes.

There is general support for the hypothesis that the common climatic and biogeographic characteristics of med-river basins lead to similar forms of ecosystem impacts from water management. In all three regions, intensive water infrastructure development has been driven by climatic and geographic constraints related to the asymmetric distribution of water (and hydropower potential) in relation to urban and agricultural needs. The construction of large dams and conveyance projects in the Sacramento and Ebro River basins has been motivated primarily by demands to provide reliable year-round supplies for agricultural and urban water uses, both within and outside of the basin. In contrast, the Biobío River basin has relatively low consumptive water demands relative to annual supplies, but the development of a country-wide power grid based on hydropower has made the Biobío (and other rivers in southern Chile) a critical energy source for industry and urban populations in central Chile. In all three regions, large dams have been the primary means employed to overcome the high seasonality and spatial gradients in water availability and demands. As a consequence, there are strong similarities in the patterns of flow regime change, sediment transport alteration, and ecosystem disturbance.

However, there are notable differences in the documented effects of water management in the three basins. For example, the Sacramento River Basin has much higher levels of dam development than the Ebro and Biobío Basins. Reservoirs in the Sacramento River have a total storage capacity equivalent to the annual runoff of the basin, while the capacity of reservoirs in the Ebro and Biobío Basins is approximately 56% and >5% of annual runoff, respectively. Thus, the degree and extent of flow alteration is probably much higher in the Sacramento River and its tributaries than the other study basins. In contrast, the deterioration of water quality from pollution is a much more significant problem in the Ebro and Biobío Rivers than the Sacramento River. This may be in part the result of the more intensive industrial uses in the Ebro and Biobío, but probably also reflects the longer history of water quality protections in the United States that have controlled pollution from urban and industrial sources, thus allowing for the recovery of water quality conditions. There is some evidence that water quality conditions in the Ebro River basin have improved in the past 20 years as a result of stronger environmental regulations and a growing number of wastewater treatment plants (Oscoz et al., 2008; Ibañez et al., 2012). However, many sections of the Ebro and its delta are still strongly affected by pollution from industrial, urban, and agricultural activities which impair water quality and the aquatic ecosystem. The deterioration of water quality in the lower Biobío River from pulp mills and urban wastewater discharges remains a dominant threat to the health of the river ecosystem (Habit et al., 2006).

The lack of data from the Biobío River makes it difficult to fully compare the effects of water management with the Sacramento and Ebro Rivers. For example, the fact that the development of dams in the Biobío River basin are focused on hydropower production, while dams on the mainstem Sacramento and Ebro are principally managed for agricultural water supplies, suggests that there may be important differences in patterns of hydrologic alterations and associated ecological responses. There is evidence that flow regulation and water withdrawals in the Biobío River Basin have impacted native fish assemblages (García et al., 2011), as has been documented for the Ebro and Sacramento River. However, data gaps indicate that med-rivers of Chile (including the Biobío) warrant greater attention. Given the growing pressures on Chile's med-river ecosystems from hydropower development and forest plantations, further study is urgently needed to document the effects of water management on hydrologic and geomorphic processes, and its influence on ecosystem structure and function.

The observed effects of water management in the study basins are not necessarily representative of all med-river systems. For example, the study basins support relative low population densities and none of the major metropolitan areas of the broader med-region are represented, such as Los Angeles (California), Barcelona (Spain), and Santiago (Chile). These med-region metropolitan centers have had enormous impacts on the physical and biotic structure of rivers that are distinct from those in the Sacramento, Ebro, and Biobío basins. For example, the Los Angeles River and its tributaries have been encased in over 800 km of concrete channels, which have completely destroyed natural habitat functions. In Barcelona, the two large rivers located within the metropolitan area have been highly modified by water supply projects, industrial activities, and urban wastewater treatment plants (Prat & Ward, 1994; Prat & Estevan, 2007). The flow of one river is regulated by upstream dams and is held nearly constant until it reaches a large water treatment plant, where most of the river water is diverted (Prat et al., 1984). The other river is unregulated but has flows augmented by discharges from inter-basin transfers and approximately 70 wastewater treatment plants (Prat & Rieradevall, 2006). Water quality is poor and much of the native fauna (particularly fishes) have disappeared (Prat & Munné, 2000; Munné et al., 2012). In Barcelona, as well as other highly urbanized med-regions, the severity of ecosystem degradation means the potential for restoring native species assemblages in these rivers is limited (Brooks et al., 2006). Thus, some of the water management challenges in urbanized regions are distinct from those of the large river basins described in this study.

Changes in water management are urgently needed to reverse trends that threaten both river ecosystems and the long-term availability of freshwater for human uses in med-regions such as California, Spain, and Chile. Mediterranean biomes of the world are experiencing rapid land use change from the growth of urban areas and conversion to agriculture (Underwood et al., 2009), which are major threats to both terrestrial and aquatic ecosystems. In the Sacramento River basin, population growth, urban expansion, and intensive agricultural practices continue to put pressure on freshwater ecosystems and native species already in decline, while the risks of floods and water scarcity increase (Mount, 1995; Hanak et al., 2011). The Ebro River basin faces similar challenges, with growing populations on the arid coast, increased agricultural water demands, and widespread indicators of water quality and ecological deterioration. Chile's growing economy and plans for additional hydroelectric development in the southern region is likely to increase pressures on the Biobío River basin, already highly impacted by the expansion of forest plantations and intensive industrial activities. Furthermore, the ability to meet the increasing intensity and diversity of water demands in all three med-regions is threatened by climate change, which is expected to decrease natural supplies provided by annual snowmelt and increase the variation in annual and seasonal precipitation patterns.

Prevailing approaches to water management are not adequate for addressing the formidable challenges in California, Spain, and Chile that are associated with population growth, environmental degradation, and climate change. Improvements in water governance are needed to meet the water needs of society and the environment in a sustainable manner. Nevertheless, the dramatic evolution of water management over the past 150 years in each region suggests that further adaption is possible. In all regions, freshwater ecosystems are now recognized as a legitimate user of water, and there has been an incremental transition to more integrated forms of management and an increasing recognition of the value of water as a public good. Of the three med-regions addressed in this study, Spain has arguably made most progress toward management integration through its adoption of the WFD and its focus on sustainable, ecosystem-based management. At the same time, Spain has not completely emerged from the Hydraulic Era and remains committed to building new dams and infrastructure to address water management challenges. California's water policy, which accommodates changing public values of water, appears to provide a strong foundation for pursuing sustainable water management. However, institutional fragmentation and the lack of effective funding mechanisms have hindered progress toward a more integrated water management approach in California (Hanak et al., 2011). Fragmentation of management authority by geography, jurisdiction, and mission has created similar problems in Spain (Grindlay et al., 2011) and Chile (Brown & Peña, 2003; Basualto et al., 2009).

Chile has perhaps made the least progress toward an integrated system of water management. Although the importance of sustainability has been recognized in national development planning (Williams & Carriger, 2006), principles of sustainable water use have not been incorporated in Chile's water governance system. Chile's progress in developing water markets has facilitated the transfer of water rights to uses with high monetary values, thus promoting economic efficiency, but has failed to account for the needs and values of the environment (Basualto et al., 2009). A growing environmental movement in Chile indicates that changing public opinion may lead to stronger protections of aquatic ecosystems (Bauer, 2004). Nevertheless, environmental laws remain weak and provisions of environmental water allocations are not adequate for the long-term maintenance of freshwater ecosystems. As the review of Biobío River basin illustrates (Table 3), there are significant data gaps regarding the scale and severity of ecosystem impacts from water management. Additional research on the Biobío and other med-rivers in Chile is needed to document ecosystem impacts and could be helpful in promoting water policy reform.

Current approaches to water management in California, Spain, and Chile do not reflect a grand vision but have evolved over the past century in response to dynamic shifts in social and economic conditions. While there has been substantial adaptation over time to meet increasingly diverse water demands and management challenges, many of the existing laws, policies, and infrastructure reflect outdated paradigms that hinder progress toward more sustainable forms of water management. While a broad range of technological and legal solutions exist to support the further integration and improved efficiency of water management, ideology is perhaps the biggest obstacle to reform. In all of the study regions, debates over water management reform are tightly linked to fundamental ideological and political divisions over the appropriate roles of government and private enterprise, tradeoffs between short-term economic growth and long-term sustainability, and competing paradigms of utilitarianism and environmental stewardship. These fundamentally conflicting views make the possibility of comprehensive reform to prevailing management frameworks unlikely in the near term. However, advances toward integrated and sustainable water management models may continue through incremental change, driven by growing awareness of climate change effects and public demands for water-use efficiency, improved water quality, and stronger environmental protections.

Acknowledgments We thank V. Resh and N. Bonada for inviting us to contribute to this special issue. A. Merenlender and P. Moyle and two anonymous reviewers provided valuable feedback on earlier versions of this manuscript. T.G. was supported by a U.S. Scholar Fulbright Grant.

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