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Experimental floods: A new era for Spanish and Mediterranean rivers?

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ABSTRACT

The provision of human-designed floods in regulated rivers is still an incipient worldwide practice. However, these floods have already been shown to have relevant effects on the ecogeomorphic integrity of rivers altered by flow regulation. In Spain, experimental floods were legally established in 2008 and were stipulated in two subsequent Basin Management Plans as compulsory practice for improving the functioning of strategic river reaches. Since that time, a number of flooding events have been carried out in rivers of Mediterranean condition. This paper reviews the main consequences of experimental flood releases in three Spanish river sites downstream of major hydraulic infrastructures. In each case, the ecologic and geomorphic effects of the releases are analysed in parallel with their causes and consequences, thereby providing a detailed understanding of the dynamics of each scenario. The Spanish examples and the lessons learned from them are contrasted with examples of experimental floods from other countries (U.S.A., Switzerland, Australia). Lastly, recommendations are proposed to improve the implementation of future experimental floods in Spain and other Mediterranean countries.

1. Introduction

Human alteration of water-dependent ecosystems is a global concern, particularly with regard to its implications for the degradation of aquatic and riparian ecology and reductions in the range of environmental services provided by rivers and wetlands (Falkenmark, 2004; Vörösmarty et al., 2010). Modification of the natural patterns and processes inherent in aquatic ecosystems has led to core changes in many ecosystem components—especially those related to the natural occurrence of flow regimes. River regulation has been the primary driver of modified natural flow features (Nilsson et al., 2005). Dam construction and other human-made structures in rivers have also altered thermal and sedimentary regimes and energy and material flows, and consequently, the extent and distribution of available habitat for many river species (Ward and Stanford, 1995).

Restoration of altered flow patterns has been a major water management issue during the last decades. Many attempts to identify and discharge the flow events most relevant to the protection of a rivers critical ecological processes have been made (Fernández et al., 2012). To that end, numerous methods and methodologies for the determination of environmental flows were designed between the 1970s and the present (Tharme, 2003; Acreman and Dunbar, 2004; Magdaleno, 2009). However, almost none of those procedures have proven effective for the conservation or restoration of a rivers values and functions. The high degree of complexity and variability inherent to river systems hinders the selection of universally-valid mechanisms to protect river flows. Despite recent advances in the legal and technical definitions of requirements for environmental flows in various countries, flow restoration remains an underdeveloped aspect of river restoration (Davies et al., 2014).

Many authors have suggested that one of the main limitations to the successful implementation of environmental flows is a lack of adequate flood regimes in regulated rivers (e.g., Acreman and Ferguson, 2010; Richter, 2010). The effects of flooding on different types of rivers are relatively well known. Floods are recognised as a major driving force for the spatial and temporal functioning of river ecosystems and are indispensable for ecosystem rejuvenation (Junk and Wantzen, 2004; Marks et al., 2014), even in tropical (Junk, 1999) or braided glacial systems (Malard et al., 2006).

Different works (even from the late 1970s) have provided conceptual recommendations for the design and release of floods from dams (normally named *flushing flows*) (Reiser et al., 1987; Kondolf and Wilcock, 1996). For instance, the Montana Method proposed periodic discharges of 200% of the mean annual flow (Tennant, 1976); Wesche et al. (1977) and O'Brien (1984) offered recommendations upon field measurement of bankfull discharge; Beschta and Jackson (1979) proposed discharging the 5th percentile on the flow duration curve or an estimated 0.16 cms/km^2; and Hoppe (1975) suggested a 48-h flushing flow at the 17% exceedance probability of the flow duration curve; their main objective being the improvement of river habitat along the regulated reaches as a result of the expected amelioration of riverbed substrate after release. However, the majority of these

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methods are office-based procedures that lack some of the essential features which allow large-scale experiments to be really effective, such as previous ecohydrological modelling and repeated monitoring (Konrad et al., 2011).

Experimental flood methods founded on more solid scientific evidence have been developed from the late 1990s. In the scientific and technical literature, such events have been variously termed controlled floods or experimental/artificial/managed floods, or more rarely planned/scour/regulated/spate floods (Gillespie et al., 2015). In this paper, the term “experimental flood” is adopted to refer to events of this kind because the term is commonly used in recent specialised literature (Olden et al., 2014).

During the last two decades, pioneering initiatives for the discharge of experimental floods have been carried out in some basins, commonly through participative processes between water managers, water uses, and scientists. One of the first examples of managed flooding took place between 1993 and 1995 in the middle Rio Grande in New Mexico (U.S.A.), with various ecological and morphological targets but largely focused on the regeneration of riparian ecosystems downstream of the Cochiti Dam (Molles et al., 1998). Between 2006 and 2007, two experimental floods were released in the Bill Williams River, Arizona (U.S.A.), from the Alamo Dam, following a flow requirements workshop and close collaboration between river scientists and resource managers (Shafroth et al., 2010). Also in Arizona, Cross et al. (2011) monitored a controlled flood experiment in the Colorado River, released in 2008 from the Glen Canyon Dam. Two other experimental floods were studied in the Colorado River in 1996 and 2004 (Patten et al., 2001; Schmidt et al., 2001).

Outside the U.S., one of the most important and best-monitored experimental flood programmes took place in the River Spöl (Switzerland), downstream of the Livigno Dam on the Swiss-Italian border (Mürle et al., 2003). In that river, 15 experimental floods were released from 2000 to 2006 as part of an agreement between conservation authorities, the Hydroelectric Power Company managing the dam, and the Cantonal and Federal governments. In Australia, Coleman and Williams (2016) analysed intra-annual experimental floods released from Jindabyne Dam to mobilise fine sediment in the regulated Snowy River.

In Spain, water legislative initiatives recently named experimental floods as a compulsory component of environmental flow regimes in strategic water bodies. The national Instructions for Hydrologic Planning (2008) developed a mandate for releasing managed floods in heavily regulated rivers, with the aims of ‘(i.) controlling the presence and abundance of river species; (ii.) maintaining the physico-chemical conditions of water and sediments; (iii.) improving the status and availability of river habitats by means of the geomorphic dynamics; and (iv.) favouring flow processes that control the connections among rivers, associated aquifers, transitional waters, and the sea.’

In the referred Instructions, managed floods are required to be calculated approximately as bankfull flows, in order to balance high geomorphic relevance with a limited impact on consolidated land uses in the river margins. The definition of the flood hydrographs must incorporate the magnitude of the peak discharge; the frequency, duration, and seasonality of the event; and the rates of change in the rising and recession limbs. All of these features would mimic the characteristics of natural floods in the pre-regulated condition.

Experimental floods were calculated in strategic river reaches for conservation and management purposes, and were published in the River Basin Management Plans (RBMP) as part of the environmental flow regulations. Because most regulated river reaches in Spain are located in the dryland Mediterranean areas, bankfull floods are commonly defined as inter-annual floods, with recurrences ranging between 1.5 and 3 years. Since the publication of the RBMPs (2013–2015), a limited number of experimental floods have been carried out. Despite this small number of events, analysis and understanding of these floods may help to guide flow management in heavily regulated rivers in the coming years, and to optimise new experimental floods planned for the following decade, both in Spain and abroad.

To help clarify and improve experimental flood releases, this paper presents a comparative analysis of three different scenarios developed in Spain during the last decade. The specific objectives addressed by this work are

- To outline the rationale, design, and functioning of different experimental floods recently released in Northern Spain.
- To discuss the main benefits and challenges that occurred during, and after their applications, with a special focus on ecological and geomorphological effects.
- To develop a set of recommendations for the future design and implementation of experimental floods in regulated rivers in Spain and other Mediterranean countries.

2. Materials and methods

2.1. Study area

The comparative analysis was based on three case studies in Spain: the Pisuerga River downstream of Requejada Dam, the Cardener River downstream of Llosa del Cavall Dam, and the Lower Ebro River downstream of Mequinenza-Ribarroja-Flix Dam complex (Fig. 1). The three study sites are situated in the northern one-third of Spain, but are characterised by Mediterranean conditions in terms of climatic and flow patterns. The analysis takes into consideration differences in the surveyed reaches downstream of the reservoirs, including lengths and monitoring methods. The case studies were selected on the basis of their representativeness (of the Spanish river types and the functioning of regulated rivers in the country), regional importance, and distinguishing features.

2.1.1. Pisuerga river

The Pisuerga River is located in the Duero Basin. Downstream of the Requejada reservoir, the river runs through the “Fuentes Carrionas y Fuente Cobre-Montaña Palentina” natural park. This protected area in Northern Spain has been designated as a large (about 80,000 ha) Natura2000 Site of Community Importance (SCI) and a Special Protection Area for Birds (ES4140011). The water body downstream of the Requejada Dam is considered to be heavily modified, according to the Duero Basin Plan (CHDuero, 2014). The Requejada Dam was constructed in 1940, has a storage capacity of 64.73 hm^3, and is used for domestic and irrigation supply and the production of hydroelectricity. According to Morán-Tejeda et al. (2012), the input river regime to the reservoir exhibits a snow-related peak in the early spring and a secondary peak in winter. The output flow regime is intensively modified, especially because of seasonal irrigation uses.

The study river reach (17.86 km) is located between the Requejada Dam and the tail of the next major downstream reservoir, Aguilar. Most monitoring analyses were conducted along a 400 m long sub-reach, 1.6 km distant from the Requejada Dam (Cebrián et al., 2015).

2.1.2. Cardener river

The Cardener River is a tributary to the Llobregat River, which debouches in the Mediterranean Sea near Barcelona. The release of experimental flooding took place in the Cardener River from the Llosa del Cavall Dam, a hydraulic facility located in the eastern Pyrenees area, also in Northern Spain. The dam was constructed in 1997 and its storage capacity is 80 hm^3, while the median water volume which annually enters the reservoir is 76 hm^3. Stored water is mostly used for domestic supply and is managed by the Catalan Water Agency. The study river reach has a length of 7 km, measured from the dam toe. The Cardener basin is mostly covered by forests, and as in other basins of the southern flank of the Pyrenees, historical flow series show decreas-