Global and Planetary Change 122 (2014) 186–196

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Development of a new index to assess river regime impacts after dam construction

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ARTICLE INFO

Article history:
Received 25 January 2014
Received in revised form 20 August 2014
Accepted 22 August 2014
Available online 29 August 2014

Keywords:
impact assessment
hydropower and dams
river regulation
river regime
indicator of hydrologic alteration

ABSTRACT

Construction of dams affects river flow regimes and changes downstream ecosystems in many ways. The impacts of dams depend on local climate, dam purpose and operation policy. This study analysed the impacts of dam construction on river flow regimes and developed a new method to evaluate the effects on river flow. By using three main flow characteristics of river regime (magnitude, timing and intra-annual alteration), a new combined river impact (RI) index to assess construction impacts based on monthly flow data was developed. A preliminary evaluation of the method was made using the river Ebro as a case. A classification was developed where the impact was assessed using a scale from low to drastic. The method was further tested to quantify the effect of dams in 15 rivers located in different regions. The method showed good potential to classify different dam types of variable sizes constructed for different purposes. The RI index method also proved suitable for assessing the environmental impacts of dam construction and could be extended by adding other characteristics of flow regime to evaluate the effects of climate change or changes in land use on river flow regimes.

1. Introduction

Many large rivers have been dammed (Nilsson et al., 2005) and in total more than 47,000 large and 800,000 smaller dams have been built during the last 100 years (WCD, 2000; Rosenberg et al., 2000; Richter and Thomas, 2007). Depending on the size of the dam and the purpose, they have different impacts on downstream river flow regime by changing the variability, magnitude, timing and frequency of flow (Poff et al., 1997; Graf, 1999; Nilsson and Berggren, 2000; Rosenberg et al., 2000; Magilligan and Nislow, 2005; Molnar et al., 2008; Rolls et al., 2013). These changes in river flow regime can lead to alteration in the diversity of fauna and flora (Chen and He, 2000; Nilsson and Berggren, 2000; Stave et al., 2005; Finger et al., 2006; Gordon and Meentemeyer, 2006; Beauchamp et al., 2007; New and Xie, 2008; Mallik and Richardson, 2009; Tealdi et al., 2011; Li et al., 2012) and effects on river ecosystem goods and services (Brismar, 2002; McCartney, 2009). Dam construction and water allocation for new purposes can also affect recipient lakes and riverine wetlands.

Dams can be constructed for several purposes, such as i) water supply for potable water consumption or irrigation, ii) hydropower or iii) flood control (Sternberg, 2006; Richter and Thomas, 2007). Diversion dams are single-purpose (only irrigation) and divert part of the river flow to meet irrigation demands. Run-of-the-river (ROR) dams are single-purpose (only hydropower generation) with low capacity, and typically have only minor effects on river regime (Richter and Thomas, 2007). Storage dams store water and distribute it when needed, and are generally multi-purpose. Storage dams can have a significant effect on river regime depending on their capacity and operating policy (Richter and Thomas, 2007).

Several metrics and indicators have been proposed to assess the river regime alterations after dam construction (Poff and Ward, 1989; Poff and Allan, 1995; Richter et al., 1996; Olden and Poff, 2003; Magilligan and Nislow, 2005; Poff et al., 2007; Döll and Schmied, 2012; Torabi Haghighi and Kløve, 2013). The indicator of hydrological alteration (IHA; Richter et al., 1996) is widely used to assess river regime alteration, especially the impacts of dam construction. It has been used to assess flow alteration in e.g. the Roanoke river in North Carolina (Richter et al., 1996), the La Nga in Vietnam (Babel et al., 2012), the Tana in Kenya (Maingi and Marsh, 2002), the Huaihe and Yellow in China (Hu et al., 2008; Yang et al., 2008; Yang et al., 2012) and the Karkheh in Iran (Madadi, 2011). However, the IHA method is time-consuming and requires daily flow data, which are not easily accessible in all regions.

To address the lack of daily flow data, we developed a new general method to evaluate changes in river regimes based on monthly data. We then investigated the capacity of this method to simulate the effect of dams in different river construction scenarios using dam inflow and outflow data instead of data from the pre- and post-impact periods. To do this, we quantified three impact functions, for changes in flow magnitude, intra-annual regime and timing, based on monthly data. By defining an integrated impact function, we then classified dams with different flow regime impacts. In order to show the methodology in a wider context, the Ebro river in Spain was used as a first case study.

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http://dx.doi.org/10.1016/j.gloplacha.2014.08.019

Monthly flow data from the pre- and post-impact periods of constructed dams in 15 rivers with good global coverage were then used to study a wider range of cases.

2. Materials and methods

The method developed for studying the effects of dams on river flow considers the impacts on flow magnitude, timing and variability. The rivers analysed here using the method, the Ebro river in Spain and the 15 other rivers located in different continents, have all undergone major construction work for development of irrigation (IR), hydropower (HPP), water supply (WS) and/or flood control (FC).

2.1. Case study rivers

The Ebro river was chosen as an example because it has been severely changed by dams and good sets of data are available from before and after dam construction. The Ebro discharges into the Mediterranean Sea at Tortosa, and is one of the most important rivers in Spain, with a catchment area of 85,530 km^2 (Fig. 1). A total of 187 dams have been built in the Ebro and its tributaries, and approx. 57% of mean annual flow (MAF) has been dammed (Batalla et al., 2004). The main purposes of dam construction are irrigation, hydropower generation and flood control with 520 hm^3 capacity (1 $hm^3 = 10^6$ m^3). Most dams were constructed between 1950 and 1975, including three large reservoirs (Ebro and Mequinenza on the main river and Canelles on the Noguera Ribagorcan river) that have more than 500 hm^3 storage (Table 1).

The 15 rivers chosen to test the method are located in different climates (USA, Iraq, Iran, Nigeria, Finland, China, Japan, Egypt, Australia and Ghana) and have different types of dams (Fig. 2). The data were collected from river gauging stations close to the dam outlets. These rivers are modified in different ways, and in some cases there is only one large dam in the catchment (e.g. Kor river), whereas in other cases there are many dams (e.g. Kemijoki river). The main criterion for site inclusion was the availability of suitable monthly flow records for the river from before and after impact. The period before dam construction was selected to include the pristine conditions and the period after to assess the effects of the construction.

The river flow data were divided into two categories, pre-impact and post-impact flows (Fig. 3). In most cases the pre-impact flows represent the natural flow regime before the dams were constructed and the post-impact flows represent the time after dam construction (e.g. Volta, Karkheh and Nile rivers; see Table 1). However, in some cases dam inflow was used as the pre-impact hydrograph and dam outflow as the post-impact hydrograph (e.g. Niger, Zayanderoud and Kasegawa rivers; see Table 1). For two rivers, the Tigris at Mosul (Fig. 3f) and the Kor at Doroudzan (Fig. 3m), both data series were available. In the diagrams, Tigris1 (Fig. 3f) and Kor1 (Fig. 3m) represent the pre-construction period, while Kor2 and Tigris2 show the inflow of dams in same period as outflow, as described in Table 1. In two cases (the Volga river in Russia and the Kemijoki in Finland), there was a time lapse between the pre-impact and post-impact periods, during which several dams were constructed in addition to that mentioned in Table 1. For these two rivers, the post-impact period is the result of several construction events

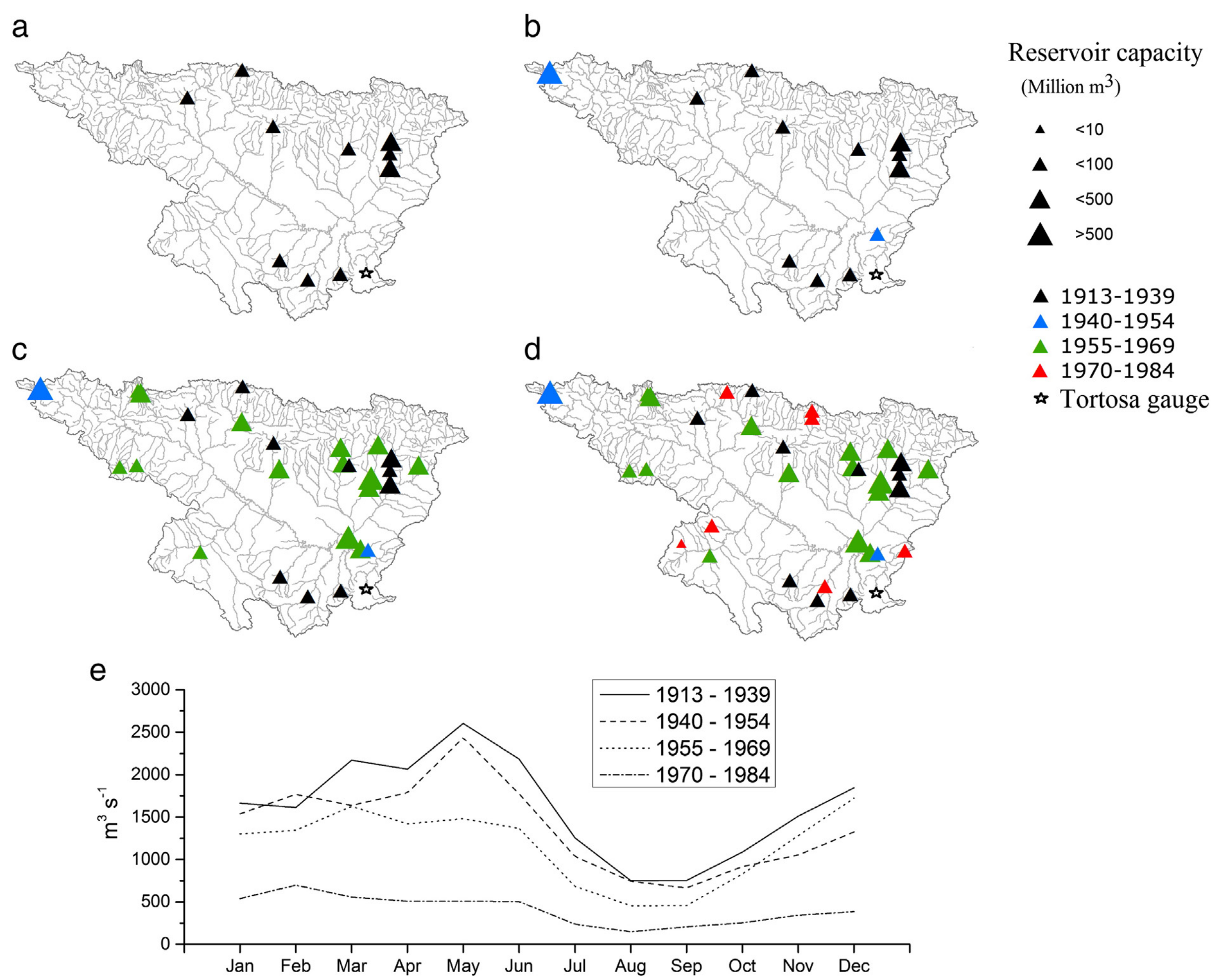

Fig. 1. Ebro river regulation process. Major constructed dam locations in the Ebro river a) up to 1939, b) up to 1954, c) up to 1969 and d) up to 1984; and e) hydrograph for the Ebro at Tortosa in different periods. Dams location maps based on dam location recorded in http://www.fao.org/nr/water/aquastat/main/index.stm.