Science of the Total Environment 643 (2018) 850–867

Contents lists available at ScienceDirect

Science of the Total Environment

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

Review

# The cumulative impacts of small reservoirs on hydrology: A review

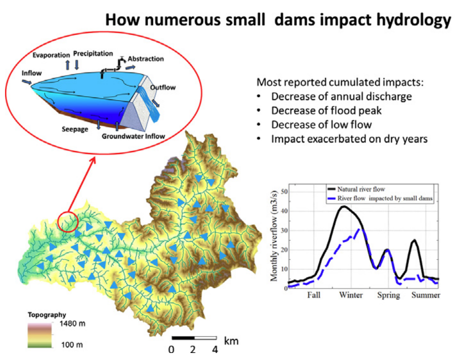
Florence Habets[a,*], Jérôme Molénat[b,*], Nadia Carluer[c], Olivier Douez[d], Delphine Leenhardt[e]

[a] CNRS/Sorbonne Université, UMR 7619 Metis, Paris, France
[b] UMR LISAH, Univ Montpellier, INRA, IRD, Montpellier SupAgro, Montpellier, France
[c] Irstea, UR RiverLy, centre de Lyon-Villeurbanne, Villeurbanne 69625, France
[d] BRGM, Bordeaux, France
[e] Toulouse Univ, INRA, INPT, INP EI PURPAN, AGIR, Castanet Tolosan, France

## HIGHLIGHTS

- The number of small dams is still increasing and is approaching 39 dams per square kilometre.
- Small dams lead to a decrease in annual stream discharge of 13% ± 8%.
- Cumulative impacts cannot be estimated using simple indicators.
- Cumulative impacts are difficult to estimate and are most often quantified from modelling.
- The lack of information on small reservoir characteristics is a real shortcoming for properly estimating their cumulative impacts.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 1 February 2018
Received in revised form 12 June 2018
Accepted 15 June 2018
Available online xxxx

Editor: Ashantha Goonetilleke

*Keywords:*
Small reservoirs
Cumulative impacts
Hydrology
Water resource management
Anthropization
Review

## ABSTRACT

The number of small reservoirs has increased due to their reduced cost, the availability of many favourable locations, and their easy access due to proximity. The cumulative impacts of such small reservoirs are not easy to estimate, even when solely considering hydrology, which is partially due to the difficulty in collecting data on the functioning of such reservoirs. However, there is evidence indicating that the cumulative impacts of such reservoirs are significant.

The aim of this article is to present a review of the studies that address the cumulative impacts of small reservoirs on hydrology, focusing on the methodology and on the way in which these impacts are assessed. Most of the studies addressing the hydrological cumulative impacts focused on the annual stream discharge, with decreases ranging from 0.2% to 36% with a mean value of 13.4% ± 8% over approximately 30 references. However, it is shown that similar densities of small reservoirs can lead to different impacts on stream discharge in different regions. This result is probably due to the hydro-climatic conditions and makes defining simple indicators to provide a first guess of the cumulative impacts difficult. The impacts also vary in time, with a more intense reduction in the river discharge during the dry years than during the wet years. This finding is certainly an important point to take into consideration in the context of climate change.

Two methods are mostly used to estimate cumulative impacts: i) exclusively data-based methods and ii) models. The assumptions, interests and shortcomings of these methods are presented. Scientific tracks are proposed to address the four main shortcomings, namely the estimation of the associated uncertainties, the lack of knowledge on reservoir characteristics and water abstraction and the accuracy of the impact indicators.



* Corresponding authors.
*E-mail addresses:* florence.habets@upmc.fr (F. Habets), jerome.molenat@inra.fr (J. Molénat).

https://doi.org/10.1016/j.scitotenv.2018.06.188

**Contents**



## 1. Introduction

Large reservoirs have strong impacts on hydrology at regional to global scales. Indeed, it was estimated that such large reservoirs have led to a approximately 2% (Biemans et al., 2011), to a sea level decrease of approximately 30 mm (Chao et al., 2008), and that they store a volume equivalent to approximately 10% of the natural annual soil storage capacity at the global scale (Zhou et al., 2016). However, these studies did not consider the impacts of smaller reservoirs on hydrology. Downing (2010) found that small ponds and lakes (smaller than 0.1 $km^2$) cover a larger area and are more numerous than large reservoirs and that approximately 10% of them are constructed reservoirs.

When considered individually, each reservoir may modify its local and remote environment. The cumulative impacts of many reservoirs in a catchment are the modifications induced by a set of reservoirs (or reservoir network) taken as a whole. The cumulative impacts are not necessarily the sum of individual modifications because reservoirs may be inter-dependent, such as cascading reservoirs along a stream course. Cumulative impacts are not the simple addition of individual impacts: they can develop via an additive or incremental process, a supra-additive process (where the cumulative effect is greater than the sum of the individual effects) or an infra-additive process (where the cumulative effect is less than the sum of the individual effects). The total impact is therefore equal to the sum of the impacts of the developments and to interaction effects. Indeed, addressing the cumulative impacts implies covering different spatial and temporal scales (Canter and Kamath, 1995) and having a reference state (McCold and Saulsbury, 1996). The cumulative impacts of small reservoirs on sediment transport, biochemistry, ecology and greenhouse gas emissions have been studied (Berg et al., 2016; Mbaka and Wanjiru Mwaniki, 2015; Downing, 2010; Poff and Zimmerman, 2010; St. Louis et al., 2000), as have the impacts of such reservoirs on hydrology (Nathan and Lowe, 2012; Fowler et al., 2015). The reported impacts are generally strong but present a large variation.

Estimating the cumulative impacts of systems of small reservoirs on a given basin has become an issue as their number increases (for instance, a 3% increase per year in the US; Berg et al., 2016). This trend may persist because these systems are often considered to be a technique to adapt to climate change (van der Zaag and Gupta, 2008). Indeed, small reservoirs are mainly used to store water during the wet season to support water use during the dry season, particularly for irrigation and livestock in rural areas (Wisser et al., 2010; Nathan and Lowe, 2012); to store water during storms to prevent flooding; or to store sediments in check dams to reduce erosion and muddy flood risks. Because the part of the global population that will experience water scarcity is projected to increase with climate change and because the intensity of storm events is also projected to simultaneously increase (Pachauri et al., 2014), there is increasing pressure to construct small reservoirs (van der Zaag and Gupta, 2008; Thomas et al., 2011).

However, an uncontrolled development of such small reservoirs may increase the water resource problem in both quantitative and qualitative ways. Thus, water managers are seeking some indicators that would help to determine optimal networks of small reservoirs in terms of storage capacities and in terms of locations and management. Consequently, in France, the Ministry of the Environment requested a joint scientific assessment to collect useful information/knowledge and tools to provide local stakeholders with such indicators and methods to assess the cumulative impacts of