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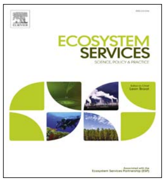

The flow regulation services of wetlands

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ABSTRACT

Wetlands potentially provide a range of ecological (or ecosystem) services including ground water recharge, nutrient retention, waste assimilation, shoreline stabilization, and carbon storage. One of the most cited and valuable services potentially provided by wetlands are their influence on flow regimes, especially flood attenuation and augmentation of low flows. Here we report the results of a meta-analysis of twenty-eight studies, including fifty-nine associated effect sizes, that have investigated the flow regulation services of wetlands. We found that, consistent with conventional wisdom, on average wetlands reduce the frequency and magnitude of floods and increase flood return period; augment low flows; and decrease runoff and streamflow. However, our results also indicate gross wetland characteristics have little predictive power with respect to the observed variation in the level of flow regulation services. This implies that in that in the absence of detailed site-specific information, estimates of flow regulation services provided by wetlands will generally have large uncertainty, as will any associated estimate of their economic value.

1. Introduction

Wetlands are considered to play an important role in hydrological functions and processes that underlie a range of potential ecosystem services. These services include enhancing groundwater recharge, nutrient and chemical retention and cycling, water purification and waste treatment, soil formation, and controlling erosion and sedimentation (Berlin and Handley, 2007; Brauman et al., 2007; Mitsch and Gosselink, 2007). But perhaps the most cited wetland services is their impact on flow regimes, specifically their potential to reduce flood peaks and increase flood return period, augment low flows, and reduce runoff and streamflow. Indeed, Mitsch et al. (1977) have argued that wetlands serve “as nature's age-old method of flood control” by virtue of their short- and long-term water storage capacity, both of which are expected to reduce downstream flood peaks.

There is evidence that floodplain wetlands reduce the frequency (Acreman et al., 2003 and Hillman, 1998) and magnitude (Ferrari et al., 1999 and Ogawa et al., 1986) of flood events and increase the time to peak of these events (Hardy et al., 2000 and Walton et al., 1996). Similar results have been obtained for headwater wetlands (e.g., Robertson et al., 1968 and Wu and Johnston, 2008). For example, draining wetlands in New Zealand was shown to increase the frequency of flood peaks substantially (Jackson, 1987). A study of wetlands in Illinois estimated that as the peakflow to average precipitation ratio decreased by (on average) 3.7%, floodflow volume to total precipitation ratio decreased by 1.4%, and low flow increased by 7.9% for an increase of one percent wetland area in a watershed (Demissie and Khan, 1993). Even beaver dams can substantially reduce discharge peaks downstream (Nyssen et al., 2011).

On the other hand, not only is there evidence that wetland drainage has little impact on flooding (e.g., Bengston and Padmanabhan, 1999 and Ehsanzadeh et al., 2012) but also some evidence that in some circumstances, wetlands may increase flood peaks (Acreman and Holden, 2013; Brauman et al., 2007; Bullock and Acreman, 2003 and Ogawa and Male, 1986). As flood regulation relies on available water storage, permanently saturated habitats with little or no storage capacity may generate or augment floods relative to semi-saturated or unsaturated habitats (Morris and Camino, 2011). Hence, it is unclear to what extent floods are attenuated or enhanced by wetlands of different types and sizes located in areas of different topographies (Cernohous, 1979 and Smakhtin and Batchelor, 2005). This dependence of water storage capacity on wetland type and topography makes it difficult to generalize the flow regulation services of wetlands (Acreman and Holden, 2013). Bullock and Acreman (2003), in their synthesis of the hydrological functions of wetlands, concluded that although there are many qualitative assessments of the impact on flow regulation, there are few quantitative assessments.

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The flow regulation services of wetlands are of considerable interest to economists (Barbier et al., 1997; Brander et al., 2006; Brander et al., 2013; Brouwer et al., 1999; Ghermandi et al., 2010; Gren et al., 1995; Mitsch and Gosselink, 2000 and Woodward and Wui, 2001) due primarily to the health and safety hazards posed by floods and an altered flow regime (Brouwer et al., 1999; Lehner et al., 2005 and Reed and Field, 1992) and their subsequent longer-term socioeconomic consequences (Ginexi et al., 2000). Despite the perceived value and importance to humans as being one of the most productive and economically valuable ecosystems in the world, wetlands have been destroyed or degraded through activities like drainage for agriculture and industry (Millennium Ecosystem Assessment, 2005; Zedler and Kercher, 2005).

The starting point for any assessment of wetlands with respect to flow regulation services (or indeed, any ecosystem service) is an estimate of the level of service currently provided. Moreover, if biophysical, economic or socio-cultural valuations are to be used in ecosystem services assessment and decisions about ecosystem management, we must be able to estimate (with some accuracy) how the level of service provisioning is likely to change under different management scenarios.

Here we use a meta-analytic approach to evaluate the current scientific evidence concerning the flow regulation services provided by wetlands. On the basis of a comprehensive review of the published scientific literature, we address two specific questions: (1) what is the level of flow regulation services provided by wetlands as measured by effect size (an index that measures the magnitude of a treatment)? and (2) to what extent can we predict the level of flow regulation service?

Several previous meta-analyses and reviews on the ecological functions and values of wetlands (Acreman and Holden, 2013; Brander et al., 2013; Bullock and Acreman, 2003; Meli et al., 2014) provide a solid basis for the present investigation. This analysis represents an improvement in knowledge from previous meta-analyses and reviews in several ways. The broad qualitative review of Bullock and Acreman (2003) has been updated and extended by adopting a formal meta-analytic approach which permits both a quantitative estimate (effect sizes) of wetland flow regulation services as well as an examination of candidate variables (moderators) that might explain variability among studies in the estimated impact of wetlands on flow regulation. Whereas several previous meta-analyses and reviews have investigated the socio-cultural and economic value of wetlands and their provisioning of ecosystem services (see Brander et al., 2006, 2013; Brouwer et al., 1999; Ghermandi et al., 2010; Woodward and Wui, 2001) or the effects of restoration activities on biodiversity (Meli et al., 2014) and inferred ecological services, here we focus directly on flow regulation services.

2. Methods

2.1. Literature search

Literature searches were conducted in ISI Web of Science from October 2011 to May 2014. Initial searches were conducted using a combined search string with two topic fields. The first field included keywords denoting common synonyms/inflections of flow regulation (“flood control”, “flood prevention”, “flood attenuation”, “flood regulat*”, “flood mitigation”, “flood protection”, AND “wetland*”). The second topic field specified different wetland types (“bog”, “dambo”, “ephemeral”, “fen”, “flooded grassland* and savanna*”, “floodplain* or flood-plain*”, “marsh”, “mire”, “peat*”, “pocosin*”, “pond”, “pothole*”, “paddy”, “riparian”, “swamp” and “vernal”) (step A, Appendix A, Fig. A1). Additional candidate studies were retrieved from Annex 1 of Bullock and Acreman (2003) and by reviewing the bibliographies of all articles retrieved in step A as well as those retrieved from Bullock and Acreman (2003). Any studies that appeared to be relevant to wetland flow regulation were also included in the initial pool of candidate studies (step B-Fig. A1). Results from the initial search suggested that the set of candidate search terms in field one did not capture the full set of flow regime attributes that have been investigated by researchers. Consequently, this field was expanded to include other flow regime attributes (step C-Fig. A1) (see Appendix B for a complete list of search terms).

2.2. Study selection criteria

Studies examining the influence of permanent wetlands as well as floodplain and ephemeral areas that may only hold water seasonally or temporarily (i.e., not throughout the entire hydrological year) were candidates for inclusion. Studies of non-natural wetlands (e.g., paddy fields) were also potential candidates so long as impoundment or engineered flood-control structures were not part of the system.

An independent set of studies (k) was identified based on the stringency of the applied selection criteria. In the most stringent sample, all studies retained for analysis: (i) report estimates of at least one hydrological measurement endpoint (attributes of the flow regime) or indicator (Table 1), and at least one wetland attribute (moderator) that might be expected to correlate with wetland flow (Table 2; for full description, see Appendix C) on a set of sampling units (e.g., experimental replicates, sites, etc.); (ii) provide sufficient statistical information (mean, standard deviation or some estimate of precision, correlation, sum of squares, sample size for the various groups, etc.) such that effect sizes (N) could be estimated; (iii) included a control treatment that permitted inference about the level of flow regulation service delivered by wetlands by, for example, contrasting the level of a specific endpoint before and after wetland drainage; and (iv) were published in a peer-reviewed scientific journal or in a government/institutional report. This sample of studies was then used in a full weighted meta-analysis and meta-regression. See Appendix A for a detailed description of the study selection procedure including identification, eligibility and screening.

We also conducted separate analyses for two other different sets of studies, based on relaxation of one or more of selection

Table 1
Flow regulation services, associated measurement endpoints, and examples of studies that use one or more of the listed endpoints.

Flow regulation service	Measurement endpoint (units)	Example Reference
Reduction in Flooding	Average or daily discharge, flow, flood frequency, streamflow, floodflow volume to precipitation ratio, mean annual flood (Cubic meters per second ($m^3\ s^{-1}$), cubic feet per second (ft^3/s^{-1}))	Wu and Johnston (2008)
	Average, maximum or instantaneous peak flow, flood peak, peak/maximum runoff, maximum flow, peak flow to precipitation ratio, peak flow ordinate, number of storm peaks above flow thresholds (Cubic meters per second ($m^3\ s^{-1}$), cubic feet per second (ft^3/s^{-1}), $l\ s^{-1}\ ha^{-1}$, $l\ s^{-1}\ km^{-2}$, m^3/h))	Jackson (1987)
	Time to peak, return period, peak lag, travel time, response time of flow or runoff (days, hours, years)	Acreman et al. (2003)
Increase in Low Flow	Low Flow (Cubic meters per second ($m^3\ s^{-1}$), cubic feet per second (ft^3/s^{-1}), measured at different thresholds: Q_{75}, Q_{95}, Q_{99}, Q_{355}…)	Drayton et al. (1980)
Reduction in Runoff	Average, surface or total runoff (mm, $l\ s^{-1}\ km^2$, $10^3\ m^3$)	Jung et al. (2011)