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Estimating minimum environmental flow requirements for well-mixed estuaries in Spain

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A B S T R A C T

Following the principles of the European Water Framework Directive, the current Spanish water management legislation requires the definition of the environmental flow regimes for all water bodies, including estuaries. The scientific community has tried to answer the question of how much freshwater an estuary needs since the mid-1970s, resulting in the development of several methodologies and approaches in different parts of the world. However the ability to reproduce most of these approaches is difficult due to the scarcity of required data and also to the differences between the studied estuaries. In this paper, we present a methodology to calculate environmental flow regimes in well-mixed estuaries based on the numerical modelling of salinity and which takes into account the seasonal climatic and hydrologic pattern of the catchment. The approach follows three sequential steps: 1) Definition of reference conditions based on the unaltered salinity patterns and zoning of the estuary, 2) definition of salinity thresholds and 3) calculation of the minimum flows required to satisfy these thresholds. The application of the methodology to five estuaries on the northern coast of Spain has highlighted the importance of considering the hydrological variability and the division of the estuary into homogeneous zones. Moreover, the studies carried out demonstrate the ineffectiveness of river specific methodologies when used to define environmental flow regimes in several estuaries and periods, and the need to apply specific methodologies. The methodology is based on the principles defined by other already tested approaches, but its greatest advantage lies in the ability to be applied to large scales, when physical and biological data is scarce.

1. Introduction

Freshwater inflow regimes, in terms of quantity and timing, are an essential element to maintain the processes and proper functioning of estuaries (Kimmerer, 2002b; McLusky and Elliott, 2004; Haslet, 2009). The mixing process between fresh and saltwater helps maintain circulation patterns, assists in the creation of a salinity gradient, in the supply and transport of sediments and nutrients or in the activation of several chemical processes (Longley, 1994; Powell et al., 2002).

Therefore, the modification of freshwater inflow regimes due to different water uses within the watershed may alter the original conditions of the estuary. This modification can affect many biological (Longley, 1994; Estevez, 2000; Doering et al., 2002; Kimmerer, 2002a), physicochemical (McLusky and Elliott, 2004; García et al., 2010) and physical (Jassby et al., 1995; Benda and Dunne, 1997; Chen et al., 2000; Peirson et al., 2002; Powell et al., 2002; Haslet, 2009) processes, which can then significantly impact the productivity of these ecosystems and compromise the goods and services they provide to human societies (Arthington et al., 2010; Atkins et al., 2011; Elliot and Whitfield, 2011). Given the increasing human demands of freshwater (Tharme, 2003; Naiman and Dudgeon, 2011) and the implications of freshwater in maintaining ecosystem processes and human services and benefits, the definition of an environmental flow regime (EFR) that covers the estuary requirements and not only the river's environmental demands (Acreman and Ferguson, 2010) remains a critical issue in water resource management.

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Although it is not a common issue, some regions and countries have recognized the problems associated with the modification of freshwater regimes flowing into the estuaries. For these cases, governments and water agencies have incorporated explicit policies into their legislations or into specific water resource management programs. The United States, for example, has been at the forefront in the development of specific policies, and some states, including Texas (Texas Water Act; Grubb, 1981), Florida (Florida Water Resources Act; Estevez, 2002; Mattson, 2002) and California (CALFED Bay-Delta program; Kimmerer, 2002b) have been addressing the requirements of freshwater inflow since the mid 1970s. The National Water Act in South Africa also recognizes basic human water requirements as well as the need to maintain the country's freshwater and estuarine ecosystems in a healthy condition (Adams et al., 2002), while in Australia the National River Health Program was created to fulfil the requirements of the Water Policy Agreement signed by the Council of Australian Governments (Peirson et al., 2002). In the European Union (EU), the Water Framework Directive (WFD) states a regional policy for community action in the field of water management. However, the role of environmental flows was not clearly stated neither for rivers nor for transitional waters and it has not been considered as a main quality element (Acreman and Ferguson, 2010). Consequently, few countries have explicitly included them in the legislation. Nevertheless, the Spanish Government, following the requirements established by the WFD, approved the Water Planning Decree (WPD; MARM, 2008) where the obligation to designate an EFR for all transitional water bodies in the country was set out. The WPD reported the general principles used to calculate these EFRs, but no specific procedure was established to undertake this task.

Since the mid 70s several methodologies have been used to estimate EFR in estuaries, although the number of publications covering this may result scarce (Mattson, 2002) if compared with the amount of methodologies regarding rivers (Annear et al., 2004; Sun and Yang, 2004). The typical approach for estuarine freshwater inflow management comprises first the quantification of the influence of streamflow over one or several ecologically relevant factors, such as the salinity gradient, sediment transport or nutrients loads (Longley, 1994; Alber, 2002). Then, the biological response driven by the dynamics of these factors is defined (Alber, 2002). Finally, based on the relationships between the flow condition and the biological response the freshwater inflows required to maintain targeted ecological processes are established. This approach would ensure a sound ecological condition in the estuaries while allowing certain degree of flexibility to regulate water resources in the upstream catchment. The definition of the biological responses to flow changes is recognized as a critical issue. There exist only a few approaches which are based on well-established patterns and interrelations between several physical processes and the overall ecosystem variability (e.g. Powell et al., 2002; Kimmerer, 2002b). These approaches were carried out thanks to the existence of data series regarding flow, estuary conditions and biological responses covering several decades and different ecological compartments (Powell et al., 2002; Montagna et al., 2002; Kimmerer, 2002b). However, in most of the works where no previous data were available, specifically designed studies have been developed to determine relationships for one or several species in each targeted estuary (Doering et al., 2002; Flannery et al., 2002; Sun et al., 2009; Palmer et al., 2011). For instance, several studies have focused on how specific organisms and processes, such as benthic invertebrates (Livingston et al., 2000; Buzan et al., 2009; Sun et al., 2009; Palmer et al., 2011), estuarine fish and nursery habitats (Flannery et al., 2002; Chícharo et al., 2006; Fernández-Delgado et al., 2007), submerged vegetation (Doering et al., 2002), primary production patterns (Flannery et al., 2002) or ensembles of biological metrics combined in a Health Index Score (Adams et al., 2002) respond to flow variability. In contrast, very few studies (Mattson, 2002) have defined streamflow withdrawals thresholds using existing knowledge of condition–response relationships developed in other estuaries. Moreover, Mattson (2002) stressed the need to monitor the selected habitats to then assess the initial criteria established.

Although the extrapolation of specific approaches to the Spanish estuaries seems to be a very difficult task, mainly due to the lack of proper data series, the analysis of all these methodologies has highlighted several common aspects. First of all, most of the flow-salinity-response relationships are based on the analysis of current and recent conditions, which usually reflect the changes of the upstream hydrological alterations. However the objective of establishing these relationships is to use them to recreate the reference conditions prior to water projects. The next aspect is the salinity, the indicator most frequently used to explain the relationships between freshwater flows and ecological conditions. Lastly the authors have noted that the most developed approaches are based on the application of complex numerical models, used to relate flow regimes, salinity patterns and ecosystem responses.

In this paper, we present an approach to calculating EFRs in well-mixed estuaries with scarce biological data and the results of its application in five estuaries located on the northern coast of Spain. The methodology satisfies the Spanish legislation requirements and main principles of the WFD for transitional waters bodies, is based on the knowledge and principles acquired in other approaches already tested, takes into account the natural climatic and hydrologic variability and is versatile enough to be applied at national and regional scales where it must deal with the lack of specific data and where estuaries with different shapes, sizes, ecological patterns, water uses and management policies are present (Galvan et al., 2010).

2. Methods

2.1. Study area

The methodology was applied to five estuaries located in Cantabria, on the northern coast of the Iberian Peninsula (NE Atlantic Region, Europe; Fig. 1). Two of them are large estuaries (Santoña and Santander), characterized by their intertidal flat extension, and three are small estuaries (Suances, Tina Menor and Mogro), characterized by a narrow main channel. All of them are mesotidal, shallow (maximum depth of 12 m) and well-mixed transitional waters (Galvan et al., 2010). Their surfaces range from 155 to 2346 ha (mean extension of 1006 ha). The estuaries are linked to short rivers, with high altitudinal gradients and dominated by surface runoff (García et al., 2008). These estuaries present typical spring-neap cycle tidal ranges varying between about 5.1 m (extreme spring) and 0.7 m (extreme neap).

As a consequence of the proximity to the ocean and a steep topography, the river catchments that feed the estuaries present a thermo-temperate Atlantic climate along the coast which gradually changes towards a mountain orotemperate climate in higher elevations (Rivas-Martínez et al., 2004). The mean annual precipitation is 1200–1450 mm with a wet period from October to April (840–1023 mm) and a dry period from June to September (368–432 mm). Moreover, maximum mean daily flows take place in April and minimum in September presenting mean values of 0.038 m^3 s^{-1} km^{-2} and 0.0075 m^3 s^{-1} km^{-2}, respectively (García et al., 2008).

Major water resource demands in the region are related to drinking water and industry supply, which increase in the summer when rivers suffer greater hydrologic stress.