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SHORT COMMUNICATION

The Rise of Riverine Flow-ecology and Environmental Flow Research

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Abstract Rivers worldwide are under increasing threat from hydrologic alteration. Managing for environmental flows (E-flows) is one way of dealing with this, but research remains heavily focused on development of methods for setting flows. We examined trends in riverine flow-ecology research (the link between the flow regime and biota of a river) from 1995 to 2012 internationally by assessing publication rate of all countries combined and identifying trends in research specifically on E-flows. USA dominated the research output in flow-ecology research, but Australian researchers were the most active on E-flows. We show that E-flow research has exponentially expanded since the mid 1990s, both in number and as a percentage of general river research. E-flow research productivity also increased weakly with the number of dams and per-capita gross domestic product (GDP) of countries, highlighting that this research is performed mostly in developed countries. We expect this trend will continue and suggest that E-flow research needs to be incorporated into policy in low-GDP countries to ensure healthy viable river ecosystems.

Keywords Dams · Environmental flow · Flow regime · Freshwater · Management · Rivers

1 Introduction

The natural flow regime is a critical component of the structure and function of aquatic ecosystems (Poff et al. 1997). Rather than simply allocating a minimum low flow, it has long been accepted that to maintain the ecological integrity of rivers, flow regimes need to incorporate natural variability (Poff et al. 1997; Bunn and Arthington 2002; Biggs et al. 2005), including aspects related to the magnitude, frequency, duration, timing and rate of change of flows (Poff and Ward 1989; Richter et al. 1996; Poff et al. 1997). Alteration of flow

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regimes is perceived as one of the major threats facing rivers and their connected floodplain wetlands (Bunn and Arthington 2002), potentially affecting biodiversity in many ways, including altering the physical habitat, life history and recruitment processes, lateral and longitudinal connectivity, and increasing the chance of exotic species invasion (Bunn and Arthington 2002). Nevertheless, these impacts of flow alteration can be highly variable depending on several factors such as the organism group and magnitude of alteration (Poff and Zimmerman 2010).

Research focusing on the link between river flow and ecology (flow-ecology) or management of river flows to minimize the impact of hydrologic alteration has flourished in the last two decades (Richter et al. 1996; Bunn and Arthington 2002; Tharme 2003; Poff et al. 2010). One such field is that of environmental flows (E-flows), which "describe the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems" (p. 1; The Brisbane Declaration 2007).

Recently, Davies et al. (2014) reviewed several aspects of Australian E-flow research in-depth, including, but not limited to, methods, modeling, tradeoffs, implementation and policy. While considerable progress has been made in recent years (Arthington et al. 2010; Pahl-Wostl et al. 2013), they highlighted that Australian E-flow research remains largely in the development phase, with few case studies documenting the effects of implemented environmental flows. Consequently, the primary objective of this paper is to examine the global trends in flow-ecology (the link between the flow regime and biota of a river) and E-flow research between 1995 and 2012, and identify key countries driving this research. The intention of this paper is not to provide a detailed look at differing approaches to E-flows but an overview of the current status and recent trends. We provide a snapshot of the current worldwide status of flow-ecology and E-flow research - crucial for the development of effective river management in the face of the ever-present threat of hydrologic alteration.

2 Methods

We extracted information on peer-reviewed publications from ISI Web of Science between 1995 and 2012 inclusive, focusing on the flow regime in combination with ecological aspects of rivers. We used a 'topic' search (title, abstract and keywords) and stopped our search in 2012 due to incomplete ISI indexing for 2013.

To provide a baseline of overall river research, we searched for all publications in river ecology, biology or hydrology during this period using the 'total river' search term outlined in Table 1. We used this search to assess outputs by country and year, using the 'filter by country' tool in Web of Science, followed by the analysis tool. Filtering by country yields all research performed by scientists with affiliations to that country. Thus, multi-authored publications may be assigned to several countries and in some instances the research focus of a publication may differ from the country in which the publication is assigned. However, this technique was more reliable than searching by country in the topic search, as focus country either may not have been included in the topic, or vice versa. We selected the top ten producing countries for comparison only.

We then searched for publications focusing on riverine ecology/biology using the 'river ecology' search term and for flow-related papers using the 'river flow' search (Table 1). Finally, we searched for research combining these two fields of river research using "AND" between hydrological and ecological terms (Table 1). We assessed the percentage that flow-ecology studies (i.e., the final search term) made up of the other more general searches: total river ecology and/or hydrology, river ecology, and river hydrology.

Table 1 Search terms and components used to extract publication data for flow-ecology and environmental flow research between 1995 and 2012 from ISI Web of Science

Category	Search terms/components
(a) Individual components	
River	(river* OR lotic OR stream OR streams OR creek OR creeks OR brook OR brooks)
Flow	("flow regime" OR "flow regulation" OR hydrolog*)
Ecology	(invertebrate* OR macroinvertebrate* OR fish OR alga* OR periphyt* OR macrophyt*)
E-flow	("environmental flow" OR "environmental flows" OR "environmental-flow" OR "environmental-flows" OR e-flow OR e-flows)
(b) Combined components	
Total river	River and (Flow OR Ecology)
Flow	River AND Flow
Ecology	River AND Ecology
Flow Ecology	River AND Flow AND Ecology
E-flow	River AND E-flow

Finally, we analysed E-flow research by using the 'E-flow' search term (Table 1). To assess whether E-flow publication productivity could be explained by population and dam data, we extracted per-capita GDP and population size (both from 2012) data for all countries resulting from the search on E-flows from the World Bank database (http://data.worldbank.org). Secondly, we extracted dam density for each member country from the International Commission on Large Dams (ICOLD) database (http://www.icold-cigb.net). We then regressed the number of E-flow publications against GDP, population density and number of registered dams using simple linear regression and correlated dam number, GDP and population size with Pearson's correlation in R (R Core Team 2013). Incomplete records for 2013 were also included in this final analysis.

3 Results and Discussion

3.1 Flow-Ecology Research

All forms of river research (ecology, hydrology/flow or both) increased in number over the 18-year period (Fig. 1a). Overall, the percent of flow-ecology research in relation to either river ecology or combined river ecology and flow research increased steadily (Fig. 1b). This trend held relatively true for the top 10 countries with the exception of France, where the percentage declined (Fig. 1d). As a percent of hydrological studies, however, it globally declined from 1995 to 2012. Nonetheless, this percentage was considerably higher than for ecological studies suggesting hydrological studies may consider biotic aspects of the riverine environment more regularly than ecological studies consider flow or hydrology.

The USA was the highest producer of all forms of flow and ecology research over the past 18 years (Fig. 1c), and most countries experienced a steady rise in flow-ecology research (Fig. 1c). One exception was China, with a rapid rise in research in the 2000s (Fig. 1c), which was expected given their rapid development during this time.

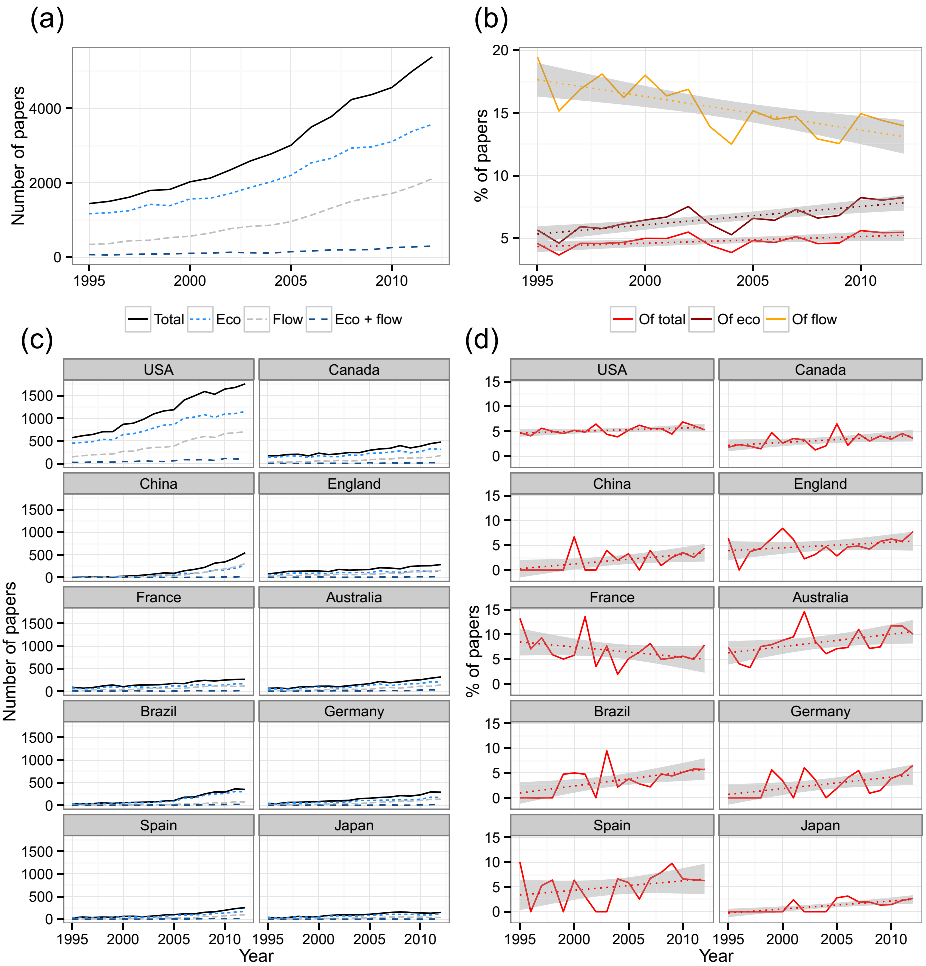

Fig. 1 Publishing trends of ISI papers during the period of 1995–2012 in flow-ecology research. Number of total river ecological and/or flow, individual ecological and flow, and combined flow-ecology papers for **a** all countries combined and **c** the top 10 countries individually. Percentage of papers focusing on combined flow-ecology research contributing to either ecological, flow, or total flow and ecological papers for **b** all countries combined and **d** top 10 countries individually, where we only included percent of total flow and ecological papers due to the low number of papers in some individual countries obscuring the pattern. *Dotted lines* in b and d represent linear trend lines with 95 % confidence interval (*grey area*). Of total: percent of total flow and ecological papers; of eco: percent of ecological papers; of flow: percent of flow papers

3.2 Environmental Flow Research

E-flow research has flourished since the mid 1990s with an exponential rise in the number of publications (Fig. 2b). It was around this time that several key papers appeared focusing on the natural flow regime and flow restoration (Richter et al. 1996; Poff et al. 1997; Richter et al. 1997). E-flow research comprises a diverse set of techniques, thus an important point to consider is that we only identified a fraction of all E-flow research using our search methods. We performed a simple and limited search on research associated with the term, or variants of

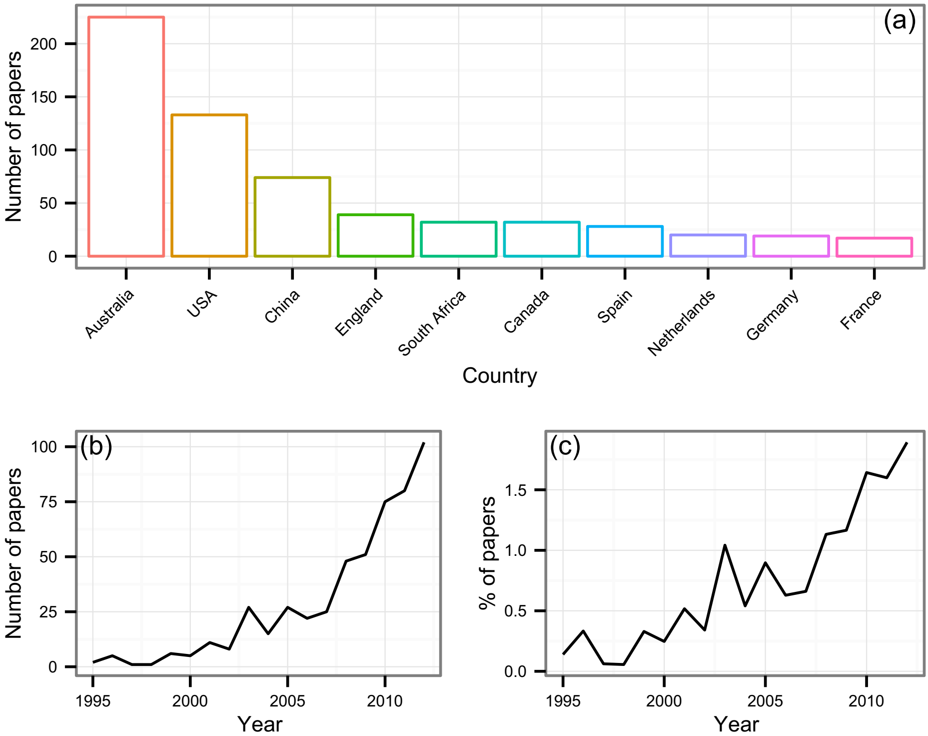

Fig. 2 Publishing trends for environmental flow ISI papers between 1995 and 2012 for the top 10 producing countries. **a** Number of papers per country, **b** aggregate number of papers of the top 10 countries published from 1995 to 2012, and **c** as a percentage of total river ecological and/or flow papers

the term, 'environmental flow', which first appeared in the mid 1990s, despite research dating back several decades (Tennant 1976; Tharme 2003).

In a more comprehensive review over 10 years ago, Tharme (2003) showed that the US originated and applied much of the techniques used in E-flow research, while other countries were increasingly advancing the field. Our approach, assessing publication frequency, and focusing on author location, differs from that of Tharme (2003), who assessed the number of techniques used by each country. Our results show Australia has dominated the E-flow research in terms of publication frequency, followed by the USA (Fig. 2a). E-flow research increased more strongly than the more general flow-ecology as a percentage of flow and/or ecology research in general (Fig. 2c). While our search methods did not differentiate author affiliation country from location of research, it is likely that the majority of research was conducted by authors in their country of affiliation. This trend likely reflects the fact that Australia's focus on E-flows is broad, with several high-profile examples such as the Murray-Darling Basin, and E-flows are embedded at the highest policy levels, with initiatives such as the National Water Commission (NWC).

One of the major issues facing the study of E-flows is the lack of research documenting practical application, despite the expanding literature on method development (Davies et al. 2014). Davies et al. (2014) found that of 156 papers published on E-flows in Australia between 1992 and 2012, 43 % focused on methods, modeling or techniques for E-flows, but only 18 % focused on some form of flow-ecology relationship. Several major challenges face the science of E-flows (King and Brown 2006), particularly transferring concepts, techniques, policies and individual case studies into the development of criteria at regional scales (Poff et al. 2003; Arthington et al. 2006). Of course, lack of peer-reviewed research does not necessarily reflect lack of real-world application. In fact, it is likely that much of the work in developing countries is finding its way into reports rather than peer-reviewed journals due to lower incentives to publish than in more developed countries. Recent developments have seen a rapid rise in the number of projects, with several case studies in progress such as the Sustainable Rivers Project in the US (e.g., Shafroth et al. 2010), and several other examples in developing countries such as China's Huai River (e.g., Zhang et al. 2012) and Yellow River Estuary (e.g., Sun et al. 2007).

Despite well-documented knowledge of the effects of dams (Ligon et al. 1995; Richter et al. 2010), dam development, both proposed and in action, is increasing at an unprecedented rate in many developing areas such as South America and China. The number of E-flow publications increased weakly with the number of registered dams of ICOLD member states (r^2=0.20, $F_{1,\ 33}$=8.30, p=0.007, y=12.03+0.01x) and with per-capita GDP (r^2=0.11, $F_{1,\ 37}$=4.75, p=0.036, y=4.84+0.0006x), but there was no relationship with population size (r^2=0.03, $F_{1,\ 37}$=1.29, p=0.26). GDP and number of dams were uncorrelated (r=0.03, p=0.89), but number of dams was positively correlated with population size (r=0.68, p <0.0001). Thus, despite the rapid rate of dam development (hydroelectric and water storage) in certain developing areas, a corresponding push for E-flow research has not necessarily followed, or is in a lag-phase following development. For instance, E-flow research has only recently expanded in China (first ISI paper in 2005), following rapid dam development in recent decades. What complicates matters more is the fact that, in many developing countries, the dam projects have cross-border effects, which may make setting E-flows even more challenging.

Understanding the natural flow regime is critical to the setting of realistic and achievable E-flows (Poff et al. 1997; Arthington et al. 2006). However, a clear understanding of the association between the natural flow regime and riverine biota is challenging, given the variable nature of linkages between flow and ecology (Poff and Zimmerman 2010). A major issue facing E-flows is, therefore, access to data, which is required to develop this flow-ecology understanding. First and foremost is the availability of hydrological data, which is dependent on flow gauging stations or the ability to extrapolate existing hydrological data between catchments or model catchment flows from nearby rainfall data (Poff et al. 2010 and references therein). Many methods have been proposed to develop river-specific E-flows in data-poor areas (Arthington et al. 2006). However, "rule-of-thumb" approaches, such as setting minimum flows or percentages of flows, are inappropriate and may lead to significant biodiversity losses downstream (Arthington et al. 2006). More recently, the ecological limits of hydrological alteration (ELOHA) framework uses a number of preexisting techniques to support comprehensive flow management of altered rivers (Poff et al. 2010). ELOHA identifies river types at regional scales using hydrologic and geomorphic river classifications, thereafter seeking to develop flow alteration-ecological response relationships for each river type.

4 Conclusions

Water managers are faced with major challenges to provide society with reliable water supplies for a variety of uses whilst maintaining ecological integrity of the waterways from which water is taken. Despite flow-ecology research being dominated by US studies, Australian authors are publishing the most specifically on E-flows. Our results suggest E-flow research and application is on the rise, particularly in developed countries with a long history of interest in the ecological processes supporting life in flowing waters, and the shared recognition that flow is an immensely important driver of such processes. Given the increased understanding of the importance of natural flows, E-flows will likely continue to rise as a dominant field in river ecology. However, the cost of maintaining E-flows (i.e., lost income through releasing water) may keep E-flows as somewhat of a luxury field of river management, despite the recent push in developing countries. With the projected alteration of rivers through both climate and water use (e.g., Laize et al. 2013), and to ensure limited riverine biodiversity loss, it is imperative to push the development of E-flows, particularly in developing countries experiencing rapid growth.

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