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The bright side of linking science and management in large river ecosystems: The Hudson River case study

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Abstract

Large river ecosystems (LRE) are important components of global cycles, influence large parts of the earth's surface, and provide many services in support of human civilization. However, understanding their condition, functioning, and trajectory of change is difficult in part due to their scale and diversity of forcing factors but also due to multiple and potentially conflicting human uses. Although these challenges are generally applicable and probably true to some degree for any large river ecosystem, there are also attributes of LRE that foster scientific understanding, can lead to knowledge-based management, and may catalyse their interaction. The absolute size of LRE means they will be complex, unique and the water quality, physical character, or habitat availability at any particular point may be the result of drivers acting further up the basin or legacies from previous times. On the bright side however, their absolute size also means there will be existing information on many important features, not least land cover and hydrology. Moreover, it is highly likely there will be a sizeable human population in the basin that derives some benefits from the river even if just in a narrow anthropocentric fashion and so there will be some motivation for understanding characteristics and potential change. Large size also suggests that the LRE will be viewed (perhaps with some basis in law) as a national or regional resource making it (at least nominally) worthy of study and management. I provide some examples of how science and management of the Hudson River in New York, USA, have benefitted from some of these perceived difficulties perhaps offering optimism for application in other systems.

KEYWORDS

benefits, conflicts, optimism, scale, stakeholders

1 | INTRODUCTION

The topic of this Special Issue is steps towards more effective linking of science and management in large rivers (LRs) in recognition of the success Keith Walker had in fostering such a link for the Murray-Darling system. There are clear difficulties in establishing and maintaining such a linkage, and I, along with others in this issue, describe those, but at the same time, there are aspects of LR systems that can be exploited to foster both good science, good management, and their productive interaction. I suspect other authors will agree that the linkage will never be perfect and perhaps not even satisfactory, but there is probably also consensus that even small steps are worthwhile.

Large river ecosystems (LRE) are generally agreed to be complex and difficult to study for a variety of good reasons, and layered on top of those is a diversity of often competing human uses and impingements that make management difficult. This paper will argue those two points of view are correct, there are also attributes of LRE that facilitate linkages between science and management. Whether the benefits described here outweigh, the difficulties will vary from case to case, but I will argue that for the Hudson River in New York, USA, there is good and effective interaction between the scientific community and those responsible for various aspects of management. Some of the approaches to overcoming the problems in LR science/management that have been applied to the Hudson may be transferable elsewhere, whereas others may be simply informative or cautionary.

LRE are in fact complex and difficult to study in part because their large spatial extent (generally a scale of hundreds to thousands of kilometres) means they will almost certainly span several physiographic regions, each of which will impose a “signature” on water quality and hydrology (Ashworth & Lewin, 2012). Moreover, there will be multiple types of land-cover, human-dominated, or more natural, which will also have strong effects on fundamental properties such as ionic strength of the water and flow responses to precipitation or snow-melt (Restrepo & Kjerfve, 2000). So, even in the absence of direct human impacts, characteristics of an LR will vary over space, and a given parcel of water will vary during transit as it mixes with and is influenced by local inputs, changes in channel morphology, and so forth. So attaining a simple understanding of why a river at some location has particular properties will require information from a large spatial extent and quite probably with different temporal lags or legacies. Just as contrast, in small streams, the properties observed at a point almost certainly carry a strong signal from local conditions whether these are conditions in the channel, the local riparian, or the nearby catchment. Temperature signals change rapidly with riparian condition (Moore, Spittlehouse, & Story, 2005); turnover lengths of important nutrients might be tens to hundreds of metres (Bernot & Dodds, 2005; Webster et al., 2003), so an observer at a point could probably understand water quality and biota based on relatively nearby attributes. An LR might carry sediments from great distances upstream, and the effect of local benthic processes will be much smaller relative to transport down the channel. So large systems are inherently harder to understand due to scale, and management efforts face the same challenge: The solution to a problem at a particular location may need to be applied some distance away.

Aside from external, catchment-derived influences on LRE, there is also tremendous potential for a given system to include multiple types of in-channel or riparian habitats that will vary dramatically in terms of suitability for particular organisms or in their capacity to support specific ecological processes (primary production, nitrogen removal, flood storage, and so forth). For LRs free of flow regulation, the floodplain will often be a major influence on the abundance, movement, and productivity of biota with consequences for nutrient transport and so forth (Junk, Piedade, Teresa, Schoengart, & Wittmann, 2012). Moreover, physical differences among hydrologically linked habitat types, sometimes magnified by the properties of biota, plant communities in particular, can strongly affect flow patterns or sediment and organic matter retention (Meitzen, Doyle, Thoms, & Burns, 2013; Steiger & Gurnell, 2003). LRs will naturally have differing abundances and extents of these habitats (Grabowski & Gurnell, 2016), and it is fair to say that most human modifications of LRs have acted to either reduce the connectivity of these habitats or remove them altogether.

Adding to the complexity in form and function of LR systems are the actions of humans. Again, simply because of scale, most LR basins will include significant human populations and their infrastructure. In fact, humans have been drawn to reside near LR throughout history for opportunities in commerce, food production, transportation, power generation, and so forth (Pennington, Bunbury, & Hovius, 2016; Yevjevich, 1992). Therefore, it is almost certainly safe to say that all LRs will have some signal of human activity whether it is altered flow regime, contaminants, or channel morphology adding to the complexity of system behaviour. Although current human activities can and do have large effects, there are many cases where past human activity has left a legacy of consequences that may be difficult to repair. The three major impacts are likely to be a legacy of contamination at various sites or in the sediments: alterations to channel morphology through dredging/levees/dams and existence of nuisance exotic species that arrived intentionally or otherwise (Strayer & Dudgeon, 2010). Addressing these problems raises a whole new set of complications such as decisions about how much damage to existing habitats is justified to mitigate contaminants in older, deeper sediments. Additionally, in many cases, the original responsible party (who may have a legal obligation to pay for remediation) might be unknown, unreachable, or no longer have the capacity to contribute to correcting the problem.

Multiple human uses of LRE for transport, power, waste disposal, and so forth obviously are important drivers of ecosystem attributes, but the fact that at least some of these demands will conflict with each other or conflict with some natural attribute or ecological process will make management challenging. Such interactions will be more complex in the face of climate change, altered human population, and possibly novel uses of the resources. Even in the abstract, if there were near-complete scientific understanding of the "costs/benefits" of a particular human use, there may still be conflicts among users that do not appear to have a rational basis for resolution. For instance, LRE are commonly used as a means to dispose of treated wastewater and industrial effluent (with widely varying regulations). If not done cautiously, this can lead to damage to natural resources and even back-contamination of humans who either consume water/fish from the system or simply live close enough to receive some exposure. Unless one is prepared to argue that zero risk to humans is the appropriate target (probably unachievable anyway), it is hard to set an acceptable value for risk, and there is an entire subdiscipline addressing risk analysis and at least quantifying the various options. Recognizing conflicting demands on LRs to support human uses alongside maintenance of system properties such as adequate flows is a prerequisite to any consensus-based approach to resolving such conflicts (Poff et al., 2016; Vörösmarty et al., 2010).

Accepting that the points above apply in varying degrees to most, if not all LRE, we are faced with understanding/managing an inherently complex system that is affected by both current and historical forces that are some combination of natural and anthropogenic influences on system behaviour. Moreover, the potential to manage any of the problems might face resistance from those who feel other issues are more pressing or who do not want to face the regulatory (possibly financial) burden of correcting a problem. Just to draw the contrast clearly, achieving scientific understanding and conducting management of LRE will be vastly more difficult than addressing a single water quality problem in a small water body that is completely owned by a single individual. Although the necessary action in this simple case may be expensive or somehow harmful to the individual, the justification and knowledge basis for action is probably clear without larger-scale consequences. In the case of LR management, almost any management action will be inherently more uncertain in terms of ultimate effectiveness and likely to have both proponents and opponents. Despite the apparent difficulties, good scientific understanding of LRE does exist and relatively civilized and effective management coordination can occur, and the rest of this paper will lay out ways this science/management link can be facilitated.

On the optimistic side, there are actually a variety of good reasons that LR systems will have a good scientific understanding of their attributes and strong motivation for thoughtful and effective management. One of the primary scientific justifications for studying LRs is that they are significant in global material cycles and budgets (Meybeck, 2003; Milliman & Meade, 1983), so simply the fact that they are big will attract some attention to understanding their function. Moreover, because each LR system will be somewhat unique, just because large catchments are not "replicated" around the globe, research effort will to some extent be distributed among systems. Although the information gathered on an LR system for purposes of understanding its role in global processes would not be the same as what is needed to guide management, there will still be facilitation due to these studies. The very basic system properties such as timing of flows, drivers of events (snowmelt vs. monsoon and so forth), and land-cover data will be useful to many management issues although unlikely to completely satisfy the needs for any particular issue. Studies may well leave valuable infrastructure in place such as gauging stations, sampling capability, remote sensing data, and trained staff that could form a starting point for acquisition of information necessary to address other issues. Again, to draw the contrast for clarity, almost any LR will have some degree of prior study and background knowledge, whereas for any particular small stream system, the chances are that there would not be any such supporting information. So large systems are inherently complex but at the same time will be research magnets at least partially enabling further, more focused study.

Another positive force that will help to counteract the difficulties in studying LRs and integrating science with their management is that, by virtue of their size, they will be considered public resources and to some degree the responsibility of the state. The willingness and capacity to assume this responsibility will vary widely among governments (Vörösmarty, Meybeck, & Pastore, 2015), but it is very unlikely that any LR system would be seen as under the jurisdiction of one or a few individuals. Perhaps the clearest case of "shared ownership" is the Water Framework Directive of the EU where a multinational body has taken responsibility and issues guidance for a large number of water resources distributed over a large area. In the United States, "navigable waters" are regulated by federal agencies, and although the lower size limit of affected waters is (almost constantly) under debate, there is no question that anything a reasonable person would consider a "large river" would be subject to federal regulation. These regulations are presumably to protect the resource into the future, and so there is some motivation (admittedly weak in many cases) to study, monitor, and manage these systems.

Lastly, most LRs will be used for some sort of commercial endeavour (power generation and transportation), and so these systems are seen as having some value. Almost any commercial use will trigger some kind of permit requirement, and information in the permit will be useful to some degree in addressing other questions. Something as basic as having good maps of channel conditions and geomorphology may derive from permits for a commercial enterprise and are useful in supporting other research and management issues.

2 | HUDSON RIVER AS CASE STUDY

I use the tidal freshwater Hudson River in New York as my case study because it does exhibit many of the difficulties and opportunities in linking science and management described above, whereas other LRE will have different mixes and different degrees of difficulty. My guess would be that no LR would have all the difficulties (or opportunities) that impede science, management, or their linkage but explicit exploration of what the mix might be for any particular case may help move towards the desired goals.

The Hudson River is located in eastern New York State (NYS), and its catchment includes portions of Massachusetts and New Jersey (Figure 1). It would not make a list of "large" rivers by almost any criterion (see Latrubesse, 2008) because its catchment area (34,000 km^2) and water discharge (mean annual Q ~ 400 m^3/s; Levinton & Waldman, 2006) are at best moderate even just by North American standards. Water quality on the Hudson is currently good with moderate levels of turbidity (mean Secchi depth 0.9 m [0.4 SD], suspended sediment ~20 mg DM/L [18] and inorganic nutrients [DIN 40 μM, SRP 1 μM]) and summertime chlorophyll generally less than 10 μg/L (Lampman, Caraco, & Cole, 1999). The lower reaches of the Hudson can be brackish during summer low flow with 5 psu salinities commonly observed 50 km north of RKM 0 (the Battery in New York City [NYC]). The tidal range in the Hudson River below the Federal Dam at Troy, New York (RKM ~ 250), varies from 1–3 m depending on location, lunar phase, and wind.

Habitats within the tidal freshwater Hudson River include ~2,900 ha of intertidal wetland, located primarily in the northern half of the reach. Many of these occur behind (and therefore are protected by) an embankment constructed for railroad tracks. So, in this case, it is likely that a management decision made over 100 years ago has actually promoted development of a valuable natural resource. Other channel modifications, largely to maintain a navigation channel, have resulted in filling or disconnecting littoral habitats (Collins & Miller, 2012) as has been so common in other LR of North America and elsewhere (Gray et al., 2011; Tockner, Pennetzdorfer, Reiner, Schiemer, & Ward, 1999). Submersed plants occupy ~5% of the river bottom and are recognized as valuable habitat for small fishes and invertebrates. There are ~300 species of fish known from the Hudson with approximately one third being exotic introductions. The Hudson is an important part of the North American flyway for waterfowl.

Despite its modest size, the Hudson River has great historical, artistic, and commercial significance to the United States (Dunwell, 2008) and includes one of the best-known cities in the world (NYC). The long history (by North American standards) of the Hudson as a site for industry, commerce, and transportation means that there is good historical knowledge of the system at least from a physical perspective, but it also means there is a long list of past insults extending from the well-known case of polychlorinated biphenyl contamination/remediation (Field, Kern, & Rosman, 2016) and alterations of channel and shoreline morphology (Collins & Miller, 2012). The Hudson is considered the birthplace of legal standing for environmental advocacy groups in U.S. law (Suszkowski & D'Elia, 2006), and there is a strong public interest in the condition of the river. There are many environmental advocacy groups focused on various aspects, so there is fairly strong sense of public ownership. The Hudson is also by any definition a well-studied system with two books on the state of various science topics (Levinton & Waldman, 2006; Limburg, Moran, & McDowell, 1986) and a recent Web of Science search on "Hudson River" in the Title yielded >500 records of scientific articles.

FIGURE 1 Map of the Hudson River watershed showing the head of tide above Albany, New York, and the mouth in New York City. [Colour figure can be viewed at wileyonlinelibrary.com]

The Hudson is heavily used for direct human activities including transportation, drinking water, recreation and sport fishing, and cooling water for power plants. Because of contamination and declining fish stocks, there is presently only a small commercial fishery for blue crabs, and the once-significant commercial harvests of shad and striped bass have been halted. The demand for use of the resource driven by several interest groups is balanced by the legal charge to federal and state agencies to manage the Hudson to attain "best use" as laid out in the Clean Water Act.

The Hudson has many of the attributes described above that make basic understanding of the system somewhat difficult. For instance, there are fairly distinct geomorphic and political differences along its relatively short (~250 km) length that prevent generality in understanding drivers and consequences for management action. Eutrophication with the potential for harmful algal blooms is recognized as a serious problem worldwide (Paerl et al., 2016; Rabalais et al., 2014), and the susceptibility of the Hudson to this problem varies greatly along its length. Nitrogen and phosphorous concentrations are moderate along the length of the Hudson due to a combination of wastewater and nonpoint sources (Swaney, Sherman, & Howarth, 1996), and combined with a fairly long residence time, particularly in the summer (Caraco et al., 1997), one might expect frequent problems related to excess phytoplankton. In actuality, blooms are uncommon throughout most of the tidal freshwater Hudson, particularly in the northern 200 km of its length. Two factors play into this: strong light limitation of phytoplankton due to a very shallow euphotic zone (on the order of 1 m) and a well-mixed water column (average 11 m), and second, an abundant population of filter-feeders (zebra mussels, *Dreissenia polymorpha*) in the northern reaches that are capable of clearing the water column every few days (Strayer, Pace, Caraco, Cole, & Findlay, 2008). This combination of factors (one natural—turbidity; one human-caused invasive filterer) prevents the widespread occurrence of what would otherwise be a serious problem. Further south in the river, transient stratification or wastewater supply directly to clearer seawater has and can lead to typical algal blooms with the usual consequences (Howarth, Swaney, Butler, & Marino, 2000).

Understanding of these differing susceptibilities is fairly solid and so can guide management to reach-appropriate levels of concern about effects of nutrient loadings. So, in this example, the changing nature of the system is a complexity that could have driven multiple management scenarios. It should be noted that better wastewater management will be required for other reasons; pathogen abatement but prevention of algal blooms would not be one of the main motivations.

Political and legislative boundaries also complicate any sort of whole-system management of the Hudson. As argued earlier, the scale of LRs will likely mean that they cross or actually form political boundaries, and so there may be multiple interested parties. The NYS Department of Environmental Conservation (NYSDEC) plays a significant role in regulation of the Hudson, yet they have a regional administrative structure that splits the Hudson ~40 km north of NYC. South of that line fisheries regulations and wetland protection are different than they are north of the line. Although there is some justification for a different set of rules, for instance, some marine fishes come part way up the Hudson in summer, there are also times when the change in rules seems capricious. Moreover, in the lower river (New York Harbor), the jurisdiction is split (down the middle of the river) between New York and New Jersey, and there are policy differences between the states (notably on oyster restoration) that lead to different management behaviours east versus west of the dividing line. To address these issues, there are oversight entities (usually advisory committees: New York–New Jersey Harbor Estuary Program; Hudson River Estuary Management Advisory Committee) charged with bringing some coordination and big-picture thinking to the issues (described below).

On the optimistic side of the issue, involvement by multiple political bodies may at times be helpful to forming and maintaining a strong science policy link. One of the clearest examples is regional fisheries management where it has been correctly recognized that stocks inhabiting a particular river may well depend on, and be affected by, habitats, harvest, or transit through waters in a different political region. Creation of interstate or international management bodies will help set a standard for monitoring and local management of a stock, and there may well be inducements, assistance, or penalties if an individual water body does not live up to their responsibility. So, in this case, being a large system harbouring a resource will lead to other interested parties watching, encouraging, or coercing adherence to some set of standards for behaviour. In the case of the Hudson, the Atlantic States Marine Fisheries Commission dictates that for several coast-wide stocks, there is a minimal set of monitoring data that must be collected and analysed on some schedule, thus maintaining some baseline knowledge of the state of the stock. Thus, the interstate or international nature of LRE may well lead to pressure to maintain some degree of monitoring/research to support a common goal.

Another advantage inherent in LRs is that there will almost always be opportunities for links to formal education in schools. Although the majority of water-based education in U.S. schools focuses on small streams for reasons of expediency, LRs can be used for “place-based” education (Haywood, Parrish, & Dolliver, 2016), which often seems to better engage both students and teachers. LRs will (almost certainly) have a large human population within their basin and are likely to be a familiar element of the local landscape. Having formal education about a significant regional or national resource is a good way to foster support within the resident population as well as get the attention (financial support) of relevant politicians. In the case of the Hudson, NYS schools are required to cover the historical events, and at a bare minimum, this gives students a sense of the river's importance. The NYSDEC education staff organizes a multisite synoptic sampling of the Hudson, and this typically involves thousands of students with their teachers collecting a common set of observations at ~80 locations. The training/preparation followed by analysis and interpretation gives all involved a sense of knowledge and ownership of the Hudson. Even smaller-scale student involvement in data collection or river restoration (such as riparian plantings) can build a constituency and generate support for maintaining, measuring, and managing the river of interest. Obviously, education about small streams can provide similar benefits, but they do not start with the pre-existing knowledge base or sense of regional/national importance embodied in a larger system.

From a very practical perspective, study and management of LRs also benefit from ready application of several existing data-gathering approaches suitable to the large spatial scale. Application of one of several remote sensing techniques may well provide a relatively fast and inexpensive way to acquire important baseline information about an LR system. Obviously, land-cover, human infrastructure, vegetation, and physiography are understood to be important variables, and for LR basins, there is a good chance that appropriate data layers derived from remote sensing already exist and might be freely available. Remote sensing of land-cover and so forth is well established, and now, high-frequency, automated monitoring of water quality is also becoming more accessible (Adu-Manu, Tapparello, Heinzelman, Katsriku, & Abdulai, 2017; Hou et al., 2017). On the Hudson, there is a network of ~12 real-time observation sites spread above the head of tide down to NYC allowing scientists, regulators, or other interested parties to watch the behaviour of the Hudson in near-real time. Although this network was primarily motivated by the need for observations of storm events, it has proven very popular and useful to educators, and we are presently getting real-time displays at public access points, so casual observers can see what is happening in the Hudson today. To once again draw the contrast with what are considered the more “amenable” small stream systems, any particular small stream is unlikely to garner the financial support or public interest in real-time conditions that will occur for most LRs. Similarly, although having many stakeholders with diverse interests can make management of LRs challenging, the benefit of such diversity is that it becomes more likely that there will be interest from one of the groups in some aspect of the available data for any interval.

2.1 | Bringing science management together

Recognizing the many potential impediments to well-integrated science and management of LRE, there have been quite a few mechanisms/approaches proposed to address the problem. One of the simplest and perhaps easiest is some kind of open forum on the current and future management problems, research priorities, and their potential overlap. Although these are often successful in attracting participants and may produce a credible and useful final report on gaps, questions, overlap in knowledge needs, they do not by themselves have the capacity to move science forward or make the connection between new knowledge and management questions. Often, some sort of advisory board or commission will be formed, and these have some mix of managers, resource users, and researchers along with a highly variable degree of authority to control management actions or provide support for gathering science (see http://www.state.nj.us/drbc/library/documents/compact.pdf for information on the Delaware Basin Commission or www.mdba.gov.au for the Murray-Darling Authority). Both of these have solid legal footing and considerable authority to make decisions binding on resource users and are intended to improve both science and management. Entities such as these will have highly variable political and financial support from the government that created them as well as variably effective communication and cooperation with stakeholders and the public. My 30 years experience has seen the effectiveness of a similar entity that serves as a nexus for information on the Hudson: the Hudson River Estuary Management Act, which created a program (the Hudson River Estuary Program [HREP]) within the NYSDEC to help manage the resources of the Hudson River and advise the department on actions/regulations. There are several attributes of this program that have worked well and may be worthy of consideration for other LRs. One of the first is that the staff of the program is mid-level, "career" state employees rather than the high-level elected officials or political appointees typical of many commissions. The staff tends to know the river system well along with all parts of the HREP. Although NYS support has fluctuated over the ~30-year span, the continuity in staffing and single-focus engagement of staff has created a strong program. Furthermore, the program has both "carrot" and "stick" opportunities. The program provides technical training and small grants to municipalities and other organizations and so helps them address general problems. At the same time, the program does advise NYSDEC, which has regulatory authority, and although the HREP has no capacity to issue regulations, it can provide advice to the department. The program also prepares periodic "Action Plans," so all involved can see what issues are being addressed and by what approaches (http://www.dec.ny.gov/lands/5104.html).

One of the most valuable attributes of the program is the advisory committee, which is composed of representatives for ~25 stakeholder groups who gather several times each year to bring forward, discuss, or learn about emerging issues on the Hudson River, impending changes in regulation and actions targeting ongoing needs. The group is very diverse (land stewards, educators, scientists, and municipal officials), and their ability to speak and listen in a serious yet nonbinding venue has been very successful in identifying emerging problems as well as describing multiple, sometimes conflicting, perspectives on the issues and their potential solutions. The crucial attributes of this advisory group would be difficult to codify or establish in a novel situation, but it is some balance between being able to speak freely in a nonbinding venue yet within a group of interested parties who might be able to take some action (for or against) any particular proposal or point of view. I would be prepared to argue that any LR (or other) system would benefit from having an information-sharing forum with a similar mix of potential for action (by funding, regulation, or education) and freedom to bring forward ideas in formation. The U.S. Environmental Protection Agency suggests stakeholder groups as part of their watershed planning process and specifically suggests consideration of those who are affected by the system, can implement, or even impede proposed actions (see https://www.epa.gov/sites/production/files/2015-10/documents/2008_04_18_nps_watershed_handbook_ch03.pdf).

LRE have and will continue to be important in human well-being, supporting many human uses, cultures, and significant in global-scale processes and biodiversity conservation. If there is general agreement that scientific knowledge and effective management of these systems are lagging, then any avenues to improvement should be pursued, and this paper suggests aspects of LRE that might support both study and management. Given the unique nature of any LRE, particularly when the human elements are added, it seems unlikely there will be complete transferability of an approach from one place to another. However, good descriptions of what has been applied and why it may have improved science, management, and their interaction should improve the resilience of the system itself and sustainable human uses.

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