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Large Rivers in the Anthropocene: Insights and tools for understanding climatic, land use, and reservoir influences

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Abstract Since the industrial revolution, human impacts on landscapes and river systems globally have intensified significantly. Humans nowadays artificially increase and decrease fluxes of water, sediment and nutrients on a scale far exceeding natural fluxes. Rivers integrate such changes occurring throughout their drainage basins, and thus can be considered as indicators of landscape processes and river basin "health" more broadly. This special issue brings together a set of papers that explore interactions of climate change and river processes, influences of land use changes, effects of reservoirs, as well as new approaches to sorting out the relative importance of these diverse influences on rivers and uncertainties in modeling future behavior. These papers contribute to a growing body of work demonstrating the fundamental differences between large rivers in the Anthropocene and rivers in prior time periods.

1. Introduction

With enhanced technology and increasing population, the scale of human activities is now recognized as overwhelming natural processes globally. The most widely recognized manifestation of this fundamental change in scale of effect is the change in climate resulting from greenhouse gases, a primary inspiration for coining the term the "Anthropocene" for the current era (since the industrial revolution) [*Crutzen and Stoermer*, 2000]. As summarized by *Kondolf and Podolak* [2013], an acceleration of impact can also be seen in land use change, with vast areas cleared for agriculture, mining, and other activities, changing runoff and erosion processes. From the second half of the 20th century through the present, the widespread construction of dams has altered water flows and trapped sediments and nutrients. Humans now artificially increase and decrease fluxes of water, sediment, and nutrients on a scale exceeding natural fluxes [*Syvitski et al.*, 2005], and mechanical excavation of mines and long-distance transport of materials by tankers, freighters, pipelines, trains, and trucks, are geomorphic agents that exceed rates of movement by "natural" processes [*Dalby*, 2007]. A striking example of large-scale landscape modification in the eastern US is the relatively recent practice of "mountaintop removal" coal mining, in which the tops of mountains are literally removed and dumped in intervening valleys, obliterating the preexisting topography, disrupting (and typically contaminating) surface runoff and groundwater flow [*Palmer et al.*, 2010].

While some preindustrial societies were able to effect landscape-scale changes, such as in the Mediterranean basin [*Conacher and Sala*, 1998] and China [*Liu et al.*, 2007], it was only since the industrial revolution that the intensity of transformation and rate of change in landscapes and river systems globally increased significantly. The transformation accelerated further after the second World War, not only with the exponential increase in population and pressure to expand into hitherto undisturbed landscapes, but also because of the spread of earth-moving machines, which allowed for greater landscape change by relatively few people. This intensification of land use change was reflected in increased sediment fluxes in rivers in the second half of the 20th century in China [*Walling and Fang*, 2003] and Brazil [*Martinez et al.*, 2009].

Until recently, studies documenting impacts of land use changes on river processes have been predominantly conducted in smaller river basins, wherein cause and effect can be more clearly sorted out. To date, most models to increase scientific understanding of landscape processes apply only a narrow range of space and time scales, and interactions across scales are a universal science issue [*NSF*, 2006;

Beck, 2009]. As we move to large river basins and space and time scales increase accordingly, new variables and interactions, emergent phenomena, can arise [*Murray et al*., 2009]. Moreover, human-landscape coupling and feedbacks between human-landscape systems, recently explored through scientific modeling [*Werner and McNamara*, 2007], become more complex at larger scales because of the multiplicity of factors operating at diverse spatial and temporal scales that come into play [*Kondolf and Podolak*, 2013].

The effects of climate change and land use alterations on large river basins are an increasingly studied topic. Rivers integrate changes occurring throughout their drainage basins, and thus can be considered as indicators of landscape processes and river basin "health" more broadly. It is especially timely now to assess trends in large rivers, not only as indicators of changes in the broader landscape, but also because of the inherent importance of large rivers to human society and ecosystems. This special issue brings together a set of papers that explore interactions of climate change and river processes, influences of land use changes, effects of reservoirs, as well as new approaches to sorting out the relative importance of these diverse influences on rivers and uncertainties in modeling future behavior.

2. Climate

The climate of most regions is made up of multiple influences, and the relative importance of these influences seasonally and year-to-year largely determines the regime of precipitation, runoff, and resulting erosion, sediment transport, and sediment delivery to oceans [*Milliman and Syvitski*, 1992]. The five Asian megarivers (Yangtze, Pearl, Mekong, Irrawaddy, and Ganges-Brahmaputra) are influenced by the Asian Monsoon Climate System (AMCS), and thus it follows that the strength of the AMCS will strongly influence erosion rates [*Colin et al*., 2010] and sediment transport [*Wang et al*., 2011]. However, upland erosion rates will not necessarily translate directly into sediment delivery to the western Pacific because of the potential to store sediment on floodplains or conversely for such stored sediment to taken out of storage by bank erosion. The Lower Mekong River is illustrative, lying at the intersection of three distinct components of the AMCS: the Indian Monsoon (IM), the East Asian Monsoon (EAM), and the Western North Pacific Monsoon (WNPM) [*Darby et al*., 2013]. Upstream of Vientiane, the IM dominates, while downstream WNPM and EAM dominate, with distinct signatures on the annual hydrograph of the Mekong [*Darby et al*., 2013]. In what is the first study of its kind, *Darby et al*. [2013], identified the relative importance of the distinct monsoonal systems and snowmelt from the Tibetan Plateau and their contribution to bank erosion, and found that a stronger influence from the Indian Ocean Dipole than from the El Nino Southern Oscillation. Understanding these climatically driven fluvial processes has practical importance in the current environment given the impacts of bank erosion on riparian residents, and assumes greater importance in predicting future river behavior under changed climate.

One of the most important implications of future climate change will be its impact on water supply quantity and reliability. However, predictions of climate change impacts on water supply are plagued with uncertainties stemming from multiple sources [*Kundzewicz et al*., 2008]. Most modeling efforts involve a "cascade" of different models going from a global climate model (CM) down to a regional hydrologic model (HM) to provide information for water management at useful scales [e.g., *Elshamy et al*., 2009; *Lopez et al*. 2009]. *Bosshard et al*. [2013] present an approach to separate uncertainties arising from the CM, the statisticial postprocessing (PP) scheme, and the HM. Applying the approach to the Alpine Rhine, they found that uncertainty associated with the CM dominated in summer and autumn, while uncertainties from the PP and HM were comparably important in winter and spring. Notably they determined that none of the uncertainty sources were negligible, and that some uncertainty arose from interactions among modeling chain components rather than components themselves.

A key component in all such model "cascades" from CMs is downscaling from global climate models (GCMs), whose results are generally useful only at scales greater than 200 km, to regional climate models (RCMs) that can provide information more useful to hydrologic models at a river basin scale. With initial and boundary conditions taken from a GCM, dynamic downscaling involves applying a higher-resolution regional climate model to produce more relevant precipitation patterns, taking topographic effects into account [e.g., *Giorgi*, 1990; *IPCC*, 2007]. However, RCMs tend to be biased, with diminished accuracy in representing convection rainfalls typical of tropical areas and summer months in temperate regions [*Chen et al*., 2013]. Various bias correction methods have been proposed, ranging from simple linear scaling (LS) approaches to sophisticated distribution mapping approaches. *Chen et al*. [2013] evaluated the performance of six bias correction methods for 10 river basins in Canada and the US, and found that bias correction acting on a monthly scale, such as LS, has only limited effect on daily scale simulations. The best-performing bias correction methods were quantile mapping based on an empirical distribution and quantile mapping based on a gamma distribution, and the RCMs generally did better simulating precipitation in river basins with snowfall and orographic effects [*Chen et al*., 2013].

In the western US, interannual variability in precipitation and available water is commonly addressed in water supply allocations using water year classifications, such that in years classified as "wet" there is more water to go around, and more water is available to junior water rights holders and for environmental releases. They provide a simple metric for rule-based decision making [*Dracup et al*., 1980]. These systems have proved to be workable compromises among competing interests, but the cutoffs (e.g., between "wet," "normal," and "dry" years) are typically based on historical flow records—which we know are no longer a valid basis for predicting the future [*Milly et al*., 2008]. Thus the problem: water allocation frameworks and environmental regulations now assume stationarity, and arguably need to be adapted to account for climate change [*Miller et al*., 1997]. *Null and Viers* [2013] illustrated the problem using the Sacramento-San Joaquin River system of California, and used downscaled, climate-forced streamflow estimates from the Variable Infiltration Capacity model, a large-scale physically based hydrologic model with multiple climate scenarios. They found that if the water year classifications are left unchanged while the climate becomes drier, more years will be classed as "dry" or "critically dry." The result would be disproportionate impact on environmental water needs, because environmental flows are reduced by about 36% between wet and dry years, while allocations for agriculture and municipal uses are relatively constant between year types [*Null and Viers*, 2013]. They also explored implications of alternatives, such as resetting the "normal" for future climate conditions.

3. Land Use

While human-induced climate change offers a compelling subject for analysis of impacts on precipitation and ET, changes in land use such as forest clearance for timber harvest and agricultural expansion are directly affecting other components of the hydrologic cycle such as interception, infiltration, and runoff, and increasing erosion rates. As argued by *Church et al*. [2009, p. 98], ". . .humans are modifying the terrestrial hydrological cycle and waterways in profound ways, indeed have been doing so for a long time. . . In comparison with the summary effects of these activities, the direct effects of climate change will remain relatively modest. Climate change will have important regional effects on the total water supply which will be critical where water supply is marginally adequate or already inadequate. However, the occurrence and quality of water and the condition of waterways are, in general, overwhelmingly dominated by human actions."

In large river basins with a long history of land use change and long gauging records, the question arises as to what degree these land use changes have altered runoff processes and ultimately the hydrograph. The headwaters of the Blue Nile in Ethiopia have undergone intensive land use transformation in recent decades [*Di Baldassarre et al*., 2011; *Gete and Hurni*, 2001], motivating *Gebrehiwot et al*. [2013] to document land-cover change and model hydrologic change in four tributary basins (ranging from 260 to 1800 km^2). They employed the Hydrologiska Byrans Vattenbalansavdelning (HBV) model, which simulates runoff using daily rainfall, temperature, and mean monthly potential evapotranspiration, and adjusted parameters based on results of Monte Carlo simulations, ultimately generating 50 "best parameter" sets [*Gebrehiwot et al*., 2013]. They found significant changes in model parameters over the past 45 years, but little change in actual runoff simulations, raising the possibility of compensation between parameters and questioning how well soil degradation and vegetation loss can be related to changes in hydrologic parameters at scales exceeding 100 km^2 [*Gebrehiwot et al*., 2013].

Sorting out the different influences of climate and land use change on the runoff of large rivers is complex challenge in light of the multiple variables and interactions among them, with some authors finding increases [e.g., *Labat et al*., 2004] and others not [*Dai et al*. 2009]. An ambitious look at long-term changes over a large area is presented by *Liu et al*. [2013], who applied the dynamic land ecosystem model (DLEM) to the entire area draining to the Gulf of Mexico, including not only the vast Mississippi River basin, but also the Rio Grande and all the smaller river systems emptying into the Gulf from Florida to the Yucatan. They modeled changes over the period 1901–2008, a period that saw a 42% increase in cropland and 250% increase in the area of impervious surface in the basin. They found that evapotranspiration (ET), runoff, and the ratio of runoff to precipitation decreased in the western parts of the drainage basin, but increased in the east. For example, deforestation in Mexico is contrasted with reforestation of large areas of Appalachia (and consequently increased ET). Climate change, specifically reduced precipitation in the last three decades, had the strongest influence on interannual variations in ET and runoff to the Gulf, but land use change exerted comparably large effects on the long-term trends in runoff. Thus, taking their study results in context with prior literature, the authors concluded that, "in certain places land use play[s] major roles in variations of water fluxes, while in other places natural factors may dominate" [*Liu et al*., 2013, p. 2002].

One of the most fundamental concerns motivating watershed-scale studies has long been the influence of land uses on water quality for water supply. Contamination of water supply by fecal coliform is a particularly important concern in regions dependent on riverine water supply, as is the case for Canada [*Ritter et al*., 2002]. Sources of fecal contamination can be both point sources (such as septic tanks or feedlots) and dispersed, diffuse, nonpoint sources (such as dog waste on public trails). *St Laurent and Mazumder* [2012] compared fecal coliform data from 42 riverine sites in British Columbia with land use in their drainage basins. Their results confirm and help to precise the widely accepted principle that such contamination is greater where drainage basins have more agricultural and urban land, with the highest fecal coliform levels associated with basins with more than 12.5% agricultural land and more than 1.6% urban [*St Laurent and Mazumder*, 2012].

At a larger scale across Canada, *Hurley and Mazumder* [2013] examined the spatial scales at which land use was most closely associated with drinking source water quality metrics. Results differed depending on the water quality parameter and season. Land use areas of greatest influence on turbidity can range from a 1 km subcatchment to the entire watershed depending on the season. Total organic carbon concentrations were only associated with land use characterized at the entire watershed scale, while fecal coliform concentrations were most influenced by land use at 5–10 km^2 scale.

4. Reservoirs

While the discourse on land use impacts increasing erosion rates and sediment loads is well established in the literature, most river systems around the world actually show decreasing sediment loads because of sediment trapping by dams. Of the approximately 15–20 billion tonnes per year (Bty^{-1}) of sediment delivered to the ocean under predisturbance conditions [*Walling*, 2006], human disturbance to catchments has increased erosion and sediment delivery by about 2.3 Bty^{-1}, but when trapping by reservoirs is accounted for, the net effect has been a reduction of about 1.4 Bty^{-1} [*Syvitski et al*., 2005].

Thus, the role of reservoirs in sequestering sediment and nutrients in river systems has drawn increasing attention in recent decades. While the reduction of sediment from existing and planned dams has been estimated with some precision on the individual river basin scale (e.g., G. M. Kondolf et al., 2013, Dams on the Mekong: Cumulative sediment starvation, submitted to *Water Resources Research*) and more broadly at the global scale [*Vorosmarty et al*., 2003], studies of sequestering in reservoirs of nutrients and other dissolved constituents are increasingly important, both for the role of nutrients in supporting aquatic and marine ecosystems and fisheries, and for the effects of some dissolved constituents on water quality.

The Yangtze River has most famously been impounded by the Three Gorges Dam, but less well known are over 100 dams being built, under construction, or planned upstream, with combined storage capacity exceeding that of Three Gorges by an order of magnitude. *Zhou et al*. [2013] analyzed data for concentrations of total phosphorous (TP) and particulate phosphorous (PP) to determine the effects of dams on phosphorous (P) load. They summarized sediment data and developed relationships between P and flow to develop a quantitative budget for P in the Yangtze River. They found that suspended sediment loads decreased in the Middle Yangtze River by 91% due to dams, TP decreased by 77%, and PP by 83% annually. *Zhou et al*. [2013] note that the reduction in sediment due to trapping by Three Gorges Dam has been greater than predicted, because the dam has not been able to pass the anticipated >35% of the inflowing sediment load. P is the limiting nutrient for bioactivity in the river, and it is more likely to be retained by reservoirs than nitrogen. The reduction in this critical nutrient implies a substantial reduction in primary productivity of the river and coastal region downstream is likely.

While not a globally large river in terms of discharge (average discharge approximately 640 m^3 s^{-1}), the Colorado River of the southwestern US is a critically important water source for seven states, whose populations grew nearly eightfold from 1920 to 2000 [*Gleick*, 2010]. The heavy reliance on the Colorado River waters is reflected in the extent of its regulation, with about 9×10^{10} m^3 storage capacities in its reservoirs, including the two largest reservoirs in the US, Powell and Mead. The suitability of Colorado River water for human consumption and aquatic ecosystems is influenced in large part by its load of dissolved organic carbon (DOC). *Miller* [2012] documented longitudinal patterns in DOC and chemical quality from the Colorado's headwaters in the Rocky Mountains to the United States-Mexico border from 1994 to 2011. With distance downstream, the river's hydrograph shifts from being snowmelt dominated to heavily regulated. *Miller* [2012] found that DOC concentrations increased in a downstream direction in the relatively unregulated upper basin, reflecting watershed inputs of water and DOC, but as the river encounters its massive storage reservoirs downstream, DOC concentrations decline, presumably because sequestration in reservoirs exceeds new inputs of DOC. At a reach scale, both Powell and Mead reservoirs appear to remove aromatic DOC while producing some autochthonous, less aromatic DOC.

Looking strictly at flow regimes and their alteration by reservoirs, *Moftakhari et al*. [2013] used a tidal exchange estimate (TDE) approach to backcalculate discharge from the Sacramento River system in California. The approach is based on the interaction between tides and river flow through quadratic bed friction, which diminishes and distorts the tidal wave as river discharge increases. *Moftakhari et al*. [2013] used a sequential 32 day harmonic analysis of tidal properties to calibrate tidal data at San Francisco with freshwater outflow from the Sacramento Delta from 1930 to 1990, then used this relation to estimate freshwater outflow for the period 1858 to 1929, for which reliable tidal data exist but not river discharge. Their analysis indicates that freshwater outflow from the Sacramento Delta is currently 30% less than prior to 1900 and the seasonal peak shifted, which is attributable to reservoir impoundment and diversions from the river system for agriculture and urban use.

5. Conclusion

While in the past, the effect of human alterations to landscapes and riverine processes was mostly obvious only a smaller scale, today even large rivers have been fundamentally changed. The papers in this special issue provide insights into climatic interactions with rivers (including implications of anthropically driven climate change), and influences of land use change and the effects of reservoir impoundment on flow and transport of sediment, nutrients, and other constituents. The papers present new methods of analysis, taking advantage of newly available technologies and data sets, and innovative ways to approach these issues. The evidence presented in these papers is consistent with a growing body of work indicating that large rivers in the Anthropocene are fundamentally different from rivers in prior epochs.

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