3RD INTERNATIONAL CONFERENCE
Integrative sciences and sustainable development of rivers
4 > 8 JUNE 2018 Lyon - FRANCE

I.S. Rivers — Integrative Sciences — Recherches et Actions

WORKSHOP W1: 4th June 2018

Challenges in Managing Fluvial Systems in the Anthropocene: Innovations in Analysing Rivers Co-evolving with Human Activities

an academic-practitioner workshop

Convenors
Peter Downs and Hervé Piégay

PROGRAMME AND SPEAKER SUMMARIES

sponsored by Collegium de Lyon : COLLEGIUM DE LYON Université de Lyon

supported by Labex RFIEA+ :

PROGRAMME

Challenges in Managing Fluvial Systems in the Anthropocene: Innovations in Analysing Rivers Co-evolving with Human Activities

Human actions over the last 100-300 years have become an integral if not dominant influence on the hydrology, geomorphology, and ecological functioning of fluvial systems, with significant implications for developing approaches to river management that ensure river resilience and maximise their long-term ecosystem service provision. Analysing fluvial systems over such time-scales requires that human activities are considered along with natural factors during the diagnostic process, and that analyses are capable of locale-specific differentiation of cause and effect by integrating local- to catchment-scale drivers for change. This challenge requires novel analytical methods applicable at historical spatial and temporal scales: progress is being facilitated by advances in remotely-sensed and passively-monitored data, enhanced modelling capabilities, novel uses of historical data and sediment archives, etc. This knowledge exchange workshop will showcase innovative approaches for studying the co-evolutionary trajectory of river systems, with discussions focused on developing joint academic-practitioner viewpoints of the primary challenges facing sustainable approaches to river management in the Anthropocene.

09:30 – 09:40	Rationale for workshop	Peter Downs Plymouth
09:40 – 10:05	**Challenges in managing co-evolving fluvial systems: stability, thresholds, and the Anthropocene**	Anne Chin Colorado Denver
10:05 – 10:30	**Recognizing Spatial and Temporal Patterns of Anthropogenic Sediment: A Conceptual Review**	Allan James South Carolina
10:30 – 11:00	***Discussion – management challenges***	*Ian Fuller* *Massey*
11:15 – 11:40	**The River Culture concept – learn from the river**	Karl Wantzen UNESCO, Tours
11:40 – 12:05	**River, Power, and Justice in the Anthropocene**	Emeline Comby Bourgogne Franche-Comté
12:05 – 12:40	***Discussion – co-evolution & management***	*Matt Kondolf* *California Berkeley*
13:40 – 14:05	**Cumulative impact of human activity on the evolution of fluvial systems**	Peter Downs Plymouth
14:05 – 14:30	**Historical channel changes of Alpine Rivers: case studies from South Tyrol (Italy)**	Vittoria Scorpio Bozen-Bolzano
14:30 – 15:10	***Discussion: accommodating cumulative impact***	*Matthias Wantzen* *UNESCO, Tours*
15:25 – 15:50	**Insights from historical fish populations for future management**	Rob Lenders Radboud
15:50 – 16:15	**Multiple stressors and the response of riparian vegetation**	John Stella SUNY Syracuse
16:15 – 16:40	**Habitat measurement and responses to managed change**	Ian Fuller Massey
16:40 – 17:15	***Discussion: accommodating multiple stressors***	Joanna Zawiejjska Pedagogical Cracow
17:15 – 17:30	***Wrap-up: summary and implications of co-evolution for sustainable river management***	Peter Downs, Plymouth

SPEAKER SUMMARIES

Challenges in managing co-evolving fluvial systems: stability, thresholds, and the Anthropocene

Anne Chin

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Humans have changed river systems everywhere and in every way, leading to a need and desire to rehabilitate some of their lost functions and recoup ecosystem services. Research on human impacts on fluvial systems is traceable to the early work by Marsh in 1864 and to the seminal publication by Thomas in 1956, *Man's Role in Changing the Face of the Earth*. Numerous studies around the world since (e.g., James and Marcus 2006) have provided a basis for guiding management and restoration efforts (e.g., Downs and Gregory 2004). Yet, the introduction of the term and concept "Anthropocene" by Crutzen and Stoermer in 2000 has brought new recognition of the magnitude of the human influence on the functioning of Earth systems. In 2009, the Anthropocene Working Group began to analyze the case for formalizing "Anthropocene" as a new geologic epoch in the Geological Time Scale. Their proposal, in development for the International Commission of Stratigraphy, suggests that the "Anthropocene" is stratigraphically real, with an epoch/series rank based on a mid-20th century boundary (Zalasiewicz et al. 2017), coincident with accelerating human-induced trends in the Earth system (Steffen 2015). Ellis (2015) has also documented the increase in anthropogenic biomes or "anthromes," exceeding 75% of Earth's surface by the year 2000.

Managing rivers intertwined with human activity toward sustainable trajectories is urgent, entailing a sharpened recognition that erasing or reversing human impacts is sometimes not possible or feasible. Rather, understanding and predicting how human activities co-evolve from new reference conditions (or "new normals") into the future may be productive. In this regard, researchers and managers have opportunity to accelerate knowledge derived from traditional human-impact studies along three suggested challenge areas (NRC 2010). First, in reconstructing the *long-term legacy of human activity*, identifying possible thresholds or tipping points in the fluvial system remains a key challenge. Such recognition may allow practitioners to set realistic management targets beyond initial undisturbed conditions. Second, deciphering the *complex interactions* within co-evolving fluvial systems poses a continuing challenge. In particular, identifying the web of impacts and feedbacks among geomorphological, ecological, and human systems gives promise for more integrated and holistic management schemes (Chin et al. 2014). Third, if humans are integral in disturbed fluvial systems, then *coupling human and landscape dynamics* explicitly in understanding and predicting changing fluvial systems is essential for successful management into the future. In other words, understanding how landscape change may prompt human responses that may further elicit alterations in the biophysical fluvial system -- in positive or negative feedback cycles – remains an epochal challenge for development sustainable management strategies. Chin et al. (2016) illustrate an example of such coupling between human decisions and landscape change following the Waldo Canyon Fire of Colorado, USA. Agent-based modeling, a relatively new tool for geomorphologists, yet promising for tackling rivers in the

"Anthropocene," was capable of modeling changes in river morphology while incorporating human decisions.

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The Legacy of Land-Use Changes and Fluvial Response

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As the second paper in the workshop, this paper takes a broad view in hopes of stimulating dialogue and rapport for the rest of the day. Given that the theme of the workshop is management of anthropogenically altered fluvial systems and there is much interest in covering methods for the workshop, this presentation will take a two-fold approach to cover both concepts of anthropogeomorphic change and some methods that can be used to study them. There is no pretense that these two topics are inherently united, but they are complementary in that many of the examples in the case study pertain to the concepts. Concepts of anthropogenic changes to rivers could include several topics including hydrologic, ecologic, geochemical, or landscape changes. To narrow the first topic, the concepts to be covered focus on anthropogenic fluvial sediment; also known as "legacy sediment." The first topic draws heavily upon an invited paper to *Geomorphology* (James, 2018) that was released digitally as a page proof last week and is now available online in that preliminary form. The methods in the second part of the presentation focus on a geospatial data analysis to develop a sediment budget for hydraulic mining sediment (HMS) in a 55 km^2 mountain stream catchment in California. The second topic is drawn largely from another paper that is almost ready for submission (James *et al*., 2018).

River managers recognize the importance of human impacts on river systems, but a synthesis of conceptual models of anthropogenic changes is needed. This presentation examines ten conceptual models commonly associated with legacy sediment. Many of the concepts have been around much longer than the notion of legacy sediment and are not exclusive to that application, but they are essential elements to understanding the processes and history of anthropogenic sediment deposits and their likely impacts on river systems. The ten topics to be covered briefly are:

- Colluvial cascades
- Sediment delivery ratios
- Sediment waves
- Aggradation-degradation episodes and the channel evolution model
- Sediment residence times and storage potential
- Sediment budgets
- Connectivity
- Stream power
- Complexity, and
- Geohistorical, geoarchaeological, and chronostratigraphic perspectives

The case study demonstrates geospatial methods that can be used to reconstruct historical sediment budgets. The methods are based on high resolution (1x1 m) airborne LiDAR topographic data which can be used to map mine pits, fluvial terraces, and canyon side slopes. These, in turn, can be used to develop the pre-mining topography prior to 1853, the topography at the time of maximum stream aggradation ca. 1884, and the modern topography when the LiDAR data were acquired in 2014. Differencing DEMs for these three times produces sediment budgets for 1884 and 2014. Magnitudes and patterns of sediment storage and removal reveal processes at both the local and the regional scale. Approximately 23.5 x 10^6 m^3 of HMS was produced in the upper Steephollow catchment, mostly by two of the You Bet Mines. This represents an average denudation of 43.0 cm across the catchment. Approximately 7.15 x 10^6 m^3 (30%) was stored in 1884 representing a sediment delivery ratio of 70%. By 2014, half of the HMS was gone leaving 3.75 x 10^6 m^3 and the SDR had gone up to 84%. This clearly demonstrates the dynamic nature of SDRs. Most of the sediment present at both times was concentrated in a large tailings fan that remains 63 m thick. This fan is longitudinally and laterally disconnected from the channel, which was superposed onto a bedrock ridge and formed a gorge. Yet, the fan is being slowly eroded by gullies and mass wasting processes and continues to deliver HMS.

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The River Culture concept – learn from the river

Karl M. Wantzen

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Introductory remark: This abstract has been written in a provocative style on purpose, in order to initiate a vivid discussion.

I choose the title of my presentation because I would like to stress that 'co'-evolution is a mutual, interactive procedure. The workshop title says, *Rivers Co-evolving with Human Activities*, which implies that man is modifying the river and the river can only adapt to (rather than co-evolve with) that. This is, in my view, quite an anthropocentric perspective. Human beings are, by their genetic heritage, pleistocene-selected survival machines (Harari, 2011). We are perfect at reacting to immediate, fatal threats, but we are yet unable to antecipate the long term consequences of our activities, and to integrate this insight in our current decisions. Given the long temporal range of the consequences of our recent, high-tech activities, we are "doomed to survive ourselves to death". If any, there have been relatively few true adaptations of human activities to the river during the industrialization process, which is the cause for the current dilemma of the biodiversity, water, and other crises (see, e.g., Vorösmarty et al. 2010).

The River Culture Concept tries to overcome this dilemma by analyzing the selective shaping of biological and cultural adaptive traits as equivalent entities. *"Learning from the River"* means to apply natural or traditional strategies and to develop them further, integrating novel (bionic) technologies and by rediscussing values for political and for economical decision-taking. This strategy might be step to initiate a "*co*"-evolution between man and river that deserves the name.

The River Culture approach (Wantzen et al. 2016), has preliminarily been based on five tenets: (1) Reset values and priorities in riverscape management in favor of human wellbeing and a harmonious coexistence of man and riverscape; (2) Live in the rhythm of the waters, i.e. adapt management options in accordance with the hydrological dynamics rather than fighting against them; (3) Transform traditional use of rivers into modern cultural activities and management options; (4) 'Ecosystem bionics': by copying survival strategies of flood-pulse adapted organisms novel forms of human use can be developed; (5) Make the catchment (river basin) the geographical base unit for all kinds of political decisions in landscape management.

Here, I suggest to add a sixth tenet to this concept, which can be formulated using the provocative expression, "Think Haussmann!". Baron de Haussmann was the person who gave Paris its present shape, by delapidating parts of the city and establishing broad avenues, places, and a sewer system in the 19th century. His work has found admirers (reduction of water-borne diseases, aeration of the city) but it was disliked by others (construction of strategic routes for the counter-revolutionary troops of Napoleon III). Hausmann's work has shown that it is possible to deconstruct and transform parts of cities in order to adapt them to current needs. Here, I make a plea to "think Haussmann" for the re-establishment of socioecosystem functions of urban rivers and multi-usage floodplain zones, especially so in the case of sprawling cities in developping countries (cf. my other presentation on the conference). The need to tackle the problem is stressed by devastating floods (with an increasing number of lost lives), the unwillingness to pay by re-insurers for these damages, and the increasing need by humans to counteract "modern" healthcare problems such as respiratory diseases, psychological disorders, and allergies, which may be (partly) cured by the creation of man-river encounter sites in cities.

Further reading:

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River, Power, and Justice in the Anthropocene

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"*Welcome to the Anthropocene*". So began the United Nations Conference on Sustainable Development in 2012, twenty years after the Rio de Janeiro Earth Summit (Rio+20). Since (at less) a century, human actions have become an integral influence on the functioning of fluvial systems.

"*The rapid expansion of mankind in numbers and per capita exploitation of Earth's resources has continued apace. […] Dam building and river diversion have become commonplace. […] This will require appropriate human behaviour at all scales*" (Crutzen 2002). Water (and particularly dams and water diversions) seem emblematic of the river landscapes of the Anthropocene. To have water, nothing like taking it elsewhere. The water distribution in California provides a relevant example to understand a contemporary hydrosocial cycle (Linton and Budds 2014) in the Anthropocene. Water can be far from its watershed and can be close of money and powerful stakeholders. However, this approach causes dilemmas and even conflicts among the populations who can feel dispossessed of their resource (Swyngedouw 2015). This approach is often linked with capitalism development (Neyrat 2016). I will use the example of the Sacramento Delta (California) to show how the project of new tunnels generates strong tensions (Figure 1).

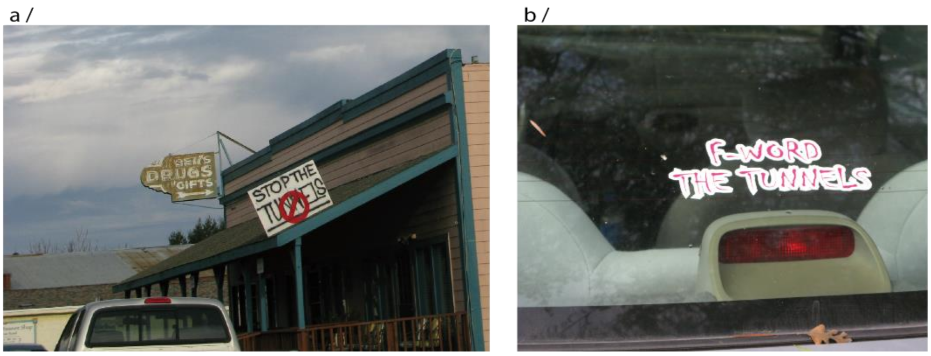

Figure 1. Mobilization against a new water diversion in California (Comby 2015)

Despite the fact that water injustices have been part of human history, water justice problems and policy have changed rapidly in the Anthropocene (Boelens, Perreault, and Vos 2018). I insist on Californian water rights and their consequences. Droughts are related to the availability of water, but they are also a mirror of how water is inequitably distributed among different stakeholders. Even though the Anthropocene refers to Anthropos (a generic human being), the Anthropocene underlines social inequalities and different responsibilities (Felli 2016).

The Anthropocene is a "political event" which enlightens topical issues such as water sharing arrangements and environmental justice (Bonneuil and Fressoz 2016).

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Cumulative impact of human activity on the evolution of fluvial systems

Peter W. Downs and Hervé Piégay

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Growing interest in the Anthropocene as a time period for research focuses attention on the relative roles of human activity and natural forces in shaping the earth's surface, with the relative balance of influences varying according to the system under study (Brown *et al*. 2017). It has even been proposed that the rate change of the Earth system is now so entirely dominated by human activity that natural functioning by astronomical forcing, geophysical forcing and the internal dynamics of the earth system are now relatively inconsequential (Gaffney and Steffan 2017). In river systems, human actions over the last 100-300 years have become an integral if not dominant influence on their hydrology, geomorphology, and ecological functioning, with the evolution of river channel morphology arising as a cumulative impact from the influence of numerous natural and human stressors operating at multiple spatial and temporal scales. However, the research requirement for data on impacts at multiple scales, and at sufficiently high spatial and temporal resolution to determine reach-level effect, largely prevented studies of such cumulative impact until recent improvements in digital technologies and data availability.

A meta-analysis of comprehensive cumulative impact studies begins to provide some global insights into these changes (Downs and Piégay *in prep*.). 'Medium-sized' (10^2-10^5 km^2) river systems over the last 125 years have been commonly been subject to changing land uses, instream aggregate mining, channelization and bank protection and the construction of dams, alongside changing flood and flow regimes. In response, river channels have narrowed, incised into their bed, reduced their lateral activity and frequently changed from multi-thread to single-thread channel patterns. If representative, these results suggest that river systems became significantly simplified, more static and more homogenous during the Twentieth century. Further, in many locations (see, for example, Downs *et al*. 2013) the focal period of the changes appears coincident with the proposed 'Great Acceleration' in human impact since *ca*.1950, (Steffan *et al*. 2007, Zalasiewicz *et al*. 2010) (Figure 1).

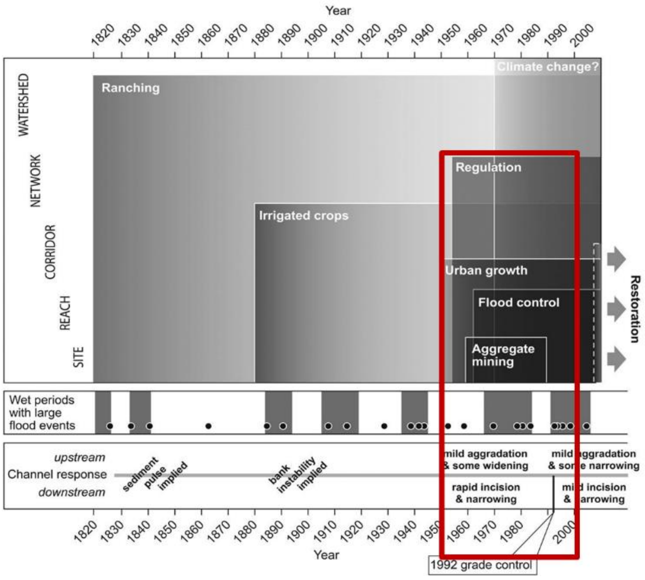

Figure 1. Temporal association of intense changes in the lower Santa Clara River, California, USA (lower panel) with human activities (upper panel) in the period of the 'Great Acceleration' (red box). Modified from Downs *et al*. 2013.

While informative, the analytical component of such studies is still overwhelmingly interpretative, with cause-and-effect reasoning based largely on temporal synchronicity and spatial proximity. In contrast, our conceptual understanding of adjustment processes is far more nuanced (Downs and Gregory 2004, Brierley and Fryirs 2016, Piégay 2016). We propose that Anthropocene-centred studies of cumulative impact should instead be underpinned by an analytical model of cause and effect, partly to test and enhance our predictive capabilities and allow scenario setting for the benefits of management, but also to learn about the relative sensitivities involved in different parts of the model and thus to prioritize future research endeavours. Such analyses should be inherently designed to detect reach-level changes over Anthropocene timescales, integrate co-existing and hierarchical human and natural pressures on fluvial systems, accommodate time-lagged effects and upstream-downstream connectivity, and be based on an explicit conceptual model that can be refined as our process understanding improves. Bayesian Belief Networks (BBNs) offer some potential in this regard (Borsuk *et al*. 2004) and have become an increasingly popular option for dealing with such highly complex, multi-scalar relationships in ecology and other environmental sciences. BBNs offer the flexibility of incorporating different variables at various scales within the catchment (thus accommodating geographical and historical differences in climate and human occupation), can be implemented even when there is some missing data, and can be rapidly optimised to improve data fit by modifying individual parts of the internal probability distributions. They are particularly well-suited to hierarchical cause and effect structuring because data uncertainties are inherently 'internalised' in the development of the model's structure, thus potentially mediating the overall error in a complex chain of relationships. Such approaches have potentially great utility in determining the primary causes of Anthropocene river system adjustment but are demanding both of data and conceptual clarity.

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Historical channel changes of Alpine Rivers: case studies from South Tyrol (Italy)

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Most European rivers have experienced considerable channel changes over the past centuries. Human disturbance has been assessed as a key driver of channel adjustments, as catchment scale (e.g. land use changes and torrent control works) and reach scale impacts (e.g. channelization, construction of dams, gravel mining) modify natural sediment and flow regimes. These factors work alongside natural control factors, especially climate change.

A quite large body of literature is available about channel changes in rivers draining the European Alps. This study investigates the historical channel changes experienced by the Adige River and 17 of its main tributaries (South Tyrol, Eastern Italian Alps). Changes in channel width, from 1850s to 1950s, were investigated by Marchese et al. (2017) for the 17 tributaries. Authors found a net tendency – despite large intra- and inter-catchment variability – for channel pattern simplification and narrowing mostly from 1850s to 1920s. The general tendency was attributed to climatic reasons (i.e. warmer and drier period following the peak of the LIA, with less flood events and reduced sediment supply from glaciers).

The Adige River, analyzed by Scorpio et al., (2018), represents a suitable case study to investigate the effect of channelization on channel morphology in Alpine fluvial systems. This river - as other in Europe (Zawiejska and Wyzga, 2010; Provansal et al., 2014) - was subject to massive channelization works by the Austrian Administration (under the Habsburg Empire) during the 19th century. Thanks to the availability of several large scale historical maps (Figure 1), it was possible to analyze channel planform characteristics before channelization, to reconstruct channel adjustments during and after channelization and to map the historical river corridor, in a valley segment 115 km long. Results show that the Adige River has considerably changed its morphology over the last centuries. Channel modifications were the result of the interaction of natural and anthropic factors, among which the human intervention prevailed.

Historical chronicles from Roman times and early Middle Age describe the course of the Adige as having several active channels and large wetland areas. The presence of anabrancing and braided pattern was probably high (Comiti, 2012). Starting from the Middle Age, land reclamation works were widely carried out. Immediately before the massive channelization (early 19th century) the Adige River presented a prevalence of single-thread channel planform. Multi-thread patterns developed only immediately downstream of the main confluences. Channel was rich in bars suggesting a relatively high supply from the catchment.

The most relevant changes are associated to the channelization, when the Adige underwent considerable channel adjustment, consisting of narrowing and straightening. Bars and islands suffered progressive reduction until the almost complete disappearance. Multi-thread and single-thread reaches evolved through different evolutionary trajectories, considering both the channel width and the bar/vegetation interaction. Afterwards, sediment supply to the Adige was reduced further during the late 1800s, due to construction of several retention check dams in its main tributaries, and more markedly around the early-mid 20th century for the construction of hydropower reservoirs. Presently, the Adige features a straight to sinuous pattern with an average width of 58-82 m.

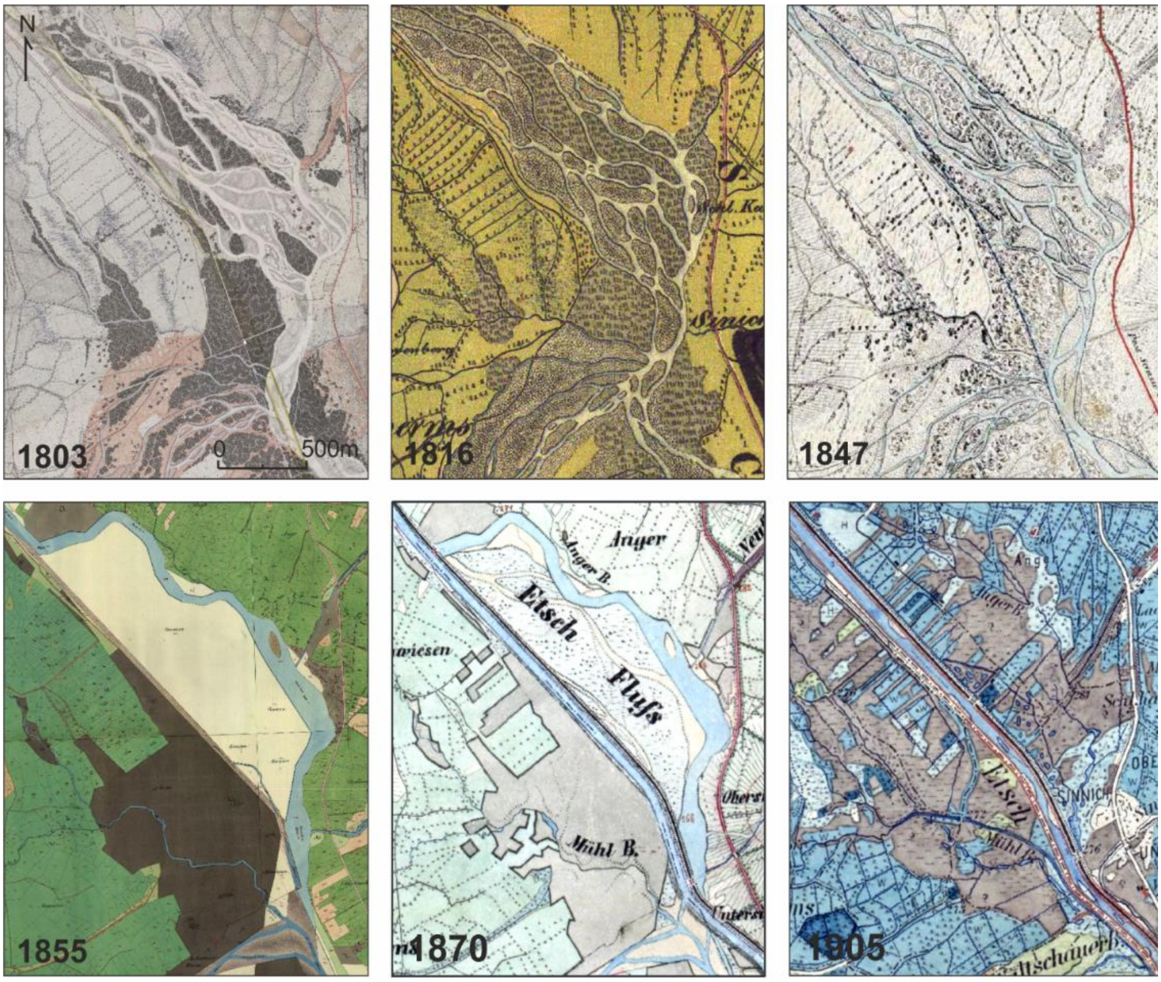

Figure 1. Examples of maps used in the multi-temporal analysis

Free-bar predictor was applied to help in the interpretation of the strong reduction of exposed sediments immediately after the channelization works. Predictor showed that the designed width of the channelized Adige controlled the occurrence of bars, being approximately 20m below the threshold for bars formation. Finally, the mapped historical river corridor, as well as the past channel morphologies offer a valid support to prioritize and identify the most correct rehabilitation interventions to be planned, with the aim to resume at least partly the capacity to establish more diverse channel patterns.

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Insights from historical fish populations for future management

H.J.R. (Rob) Lenders

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Riverine fish are still under great pressure despite various measures that have already been taken in our major rivers, such as reducing pollution, virtually stopping river fishing and redesigning our river systems (ecological rehabilitation). In the Rhine, these factors have definitively contributed in the past to the decline and extinction of typical riverine fish such as Atlantic salmon (*Salmo salar*), Atlantic sturgeon (*Acipenser oxyrinchus*), European sea sturgeon (*Acipenser sturio*), Houting (*Coregonus oxyrinchus*), Allis shad (*Alosa alosa*) and Twait shad (*Alosa fallax*). Recovery of populations of these species is currently poor or non-existent. The measures that have been taken are still bearing little fruit. With the disappearance of these species, various ecosystem services also became under pressure. This applies to cultural services (including sport fishing) and provisioning services (especially fish for consumption), but these are relatively insignificant compared to the impact on regulatory services, especially the transport of Marine Derived Nutrientens (MDN) to the upper reaches of river basins.

However, the underlying reasons for the decline and extinction of species are much more complex than they initially appear, especially when viewed from a historical perspective. This shows that, in many cases, the causes go back much further in time and that there are also relationships between the decline of different species. It also appears that the causes cannot be unambiguously attributed to a single factor.

This becomes clear, for example, when we analyse the history of Atlantic salmon on the basis of archaeological and historical sources. It appears that the introduction of agriculture in the Neolithic and the associated deforestation is a first factor that may have influenced the size of salmon stocks. This has led to much larger quantities of sediment ending up in the water, which had an effect on reproduction possibilities of salmon. A second major influence can be traced back to the Middle Ages. The huge numbers of water mills built in the capillaries of our river systems have made the salmon's breeding grounds virtually inaccessible and/or have affected them geomorphologically to such an extent that they should be considered functionally lost. With the decline of salmon reproducing in upstream regions, much smaller quantities of MDN were transported to the upper reaches of the river basins, which had a major impact on many large predators such as brown bears and sea eagles, also in Europe.

Despite restocking in the 19th century, salmon fishing yields continued to decline sharply (the real cause of decline had not been removed). These disappointing salmon yields have been a major reason for the shift in focus from salmon fishing to other species such as Allis shad and Twait shad. These species are much more sensitive to fishing pressure than salmon populations able to cope with severe population stress, which has led to the extinction of both shad species in the Rhine. One could speak of a human-induced ecological-trophic cascade.

Although historical analyses of fish population development provide insights into the causes of decline and extinction, trying to manage on population levels does not immediately offer solutions (as restocking often shows). This will require a more ecosystem-based approach with attention to relations between species. Nor is it the case that the analysis of one or a few species reveals the problems of all species. The sturgeon (in the Rhine originally actually two species, namely the Atlantic sturgeon (*Acipenser oxyrinchus*) and the European sea sturgeon (*Acipenser sturio*)) is a good example of this, of which the historical data can offer us useful insights.

Populations of sturgeon species have remained relatively stable in the Rhine catchment for a long time. Data from the Middle Ages until well into the 18th century show that there are considerable fluctuations, but that there is no clear negative trend. Such a negative trend, however, does occur in the course of the 19th and 20th centuries. Further analyses show that especially smaller and lighter specimens seem to disappear from the population, which indicates an increasing failure of reproduction. This appears to be the case 50 years after the implementation of profound river regulation measures in the main rivers. Here the cause does seem to lie in the main stream.

The main conclusions that can be drawn from these historical analyses are as follows:

- Longer periods of time, even thousands of years, should be taken into account for a proper historical analysis of the effects of human intervention.
- The decline of species is seldom due to a single factor; usually there are several factors at play at the same time and interspecies relations also play a role. For the species studied, however, an important key seems to lie in the possibilities of successful reproduction.
- Species- or population-based management will not lead, or will only lead with difficulty, to full ecological recovery. A better approach would be to consider the entire river basin from source to delta, especially including the capillaries of the water system.
- Even then, complete ecological recovery will be difficult because it is at odds with the preservation of our cultural heritage and the interests of other functions.

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Multiple stressors and the response of riparian vegetation

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Woody plants adapted to the dynamic environment of river corridors are foundation species in riparian ecosystems globally. Riparian forests and woodlands are adapted to natural disturbances such as floods, droughts, fire, and herbivory. Collectively, these multiple stressors have a profound influence on vegetation composition, structure and dynamics. Human pressures from land use, habitat degradation, water diversion, modified flood and fire regimes, invasive species and non-native pests, and climate change modify and interact with natural drivers to create combinations of stressors on riparian ecosystems (Figure 1). Multiple stressors can interact additively, synergistically, and/or antagonistically to influence plant survival, reproduction, growth and function, and ultimately the composition and structure of riparian communities. In this talk, I will examine the cumulative effects of multiple stressors on riparian communities in the context of ecological theory and economic production functions (Figure 2), with examples from water limited regions and outline challenges for management.

Key words: riparian forests, fluvial processes, multiple stressors, disturbance, ecosystem services, tradeoffs, production function

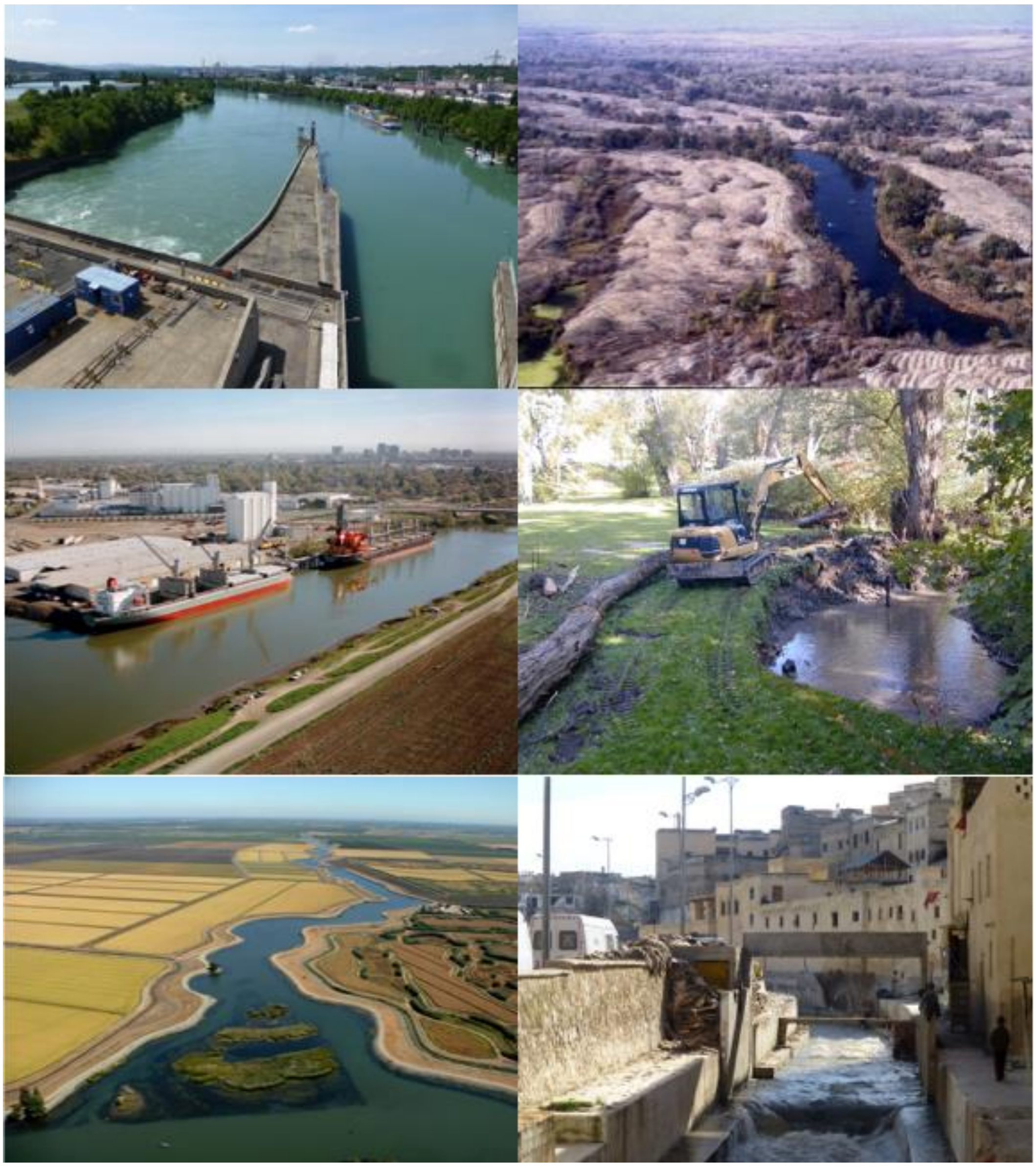

Figure 1. Human stressors in riparian ecosystems. Clockwise from upper right: gold mining tailings from floodplain dredging (Merced River, California, USA [Stillwater Sciences]); bank modifications on a suburban stream (Syracuse, NY, USA); urbanized stream and tanning effluent (Oued Issil, Marrakech, Morocco); floodplain agriculture and flood control levees (Sacramento-San Joaquin Delta, California, USA [CA Dept. of Water Resources]); river channelization for navigation and freight transport (Sacramento River, California, USA [CA Dept. of Water Resources]); hydropower dam and bypass navigation canal (Rhône River, France). All photos by the author except where noted.

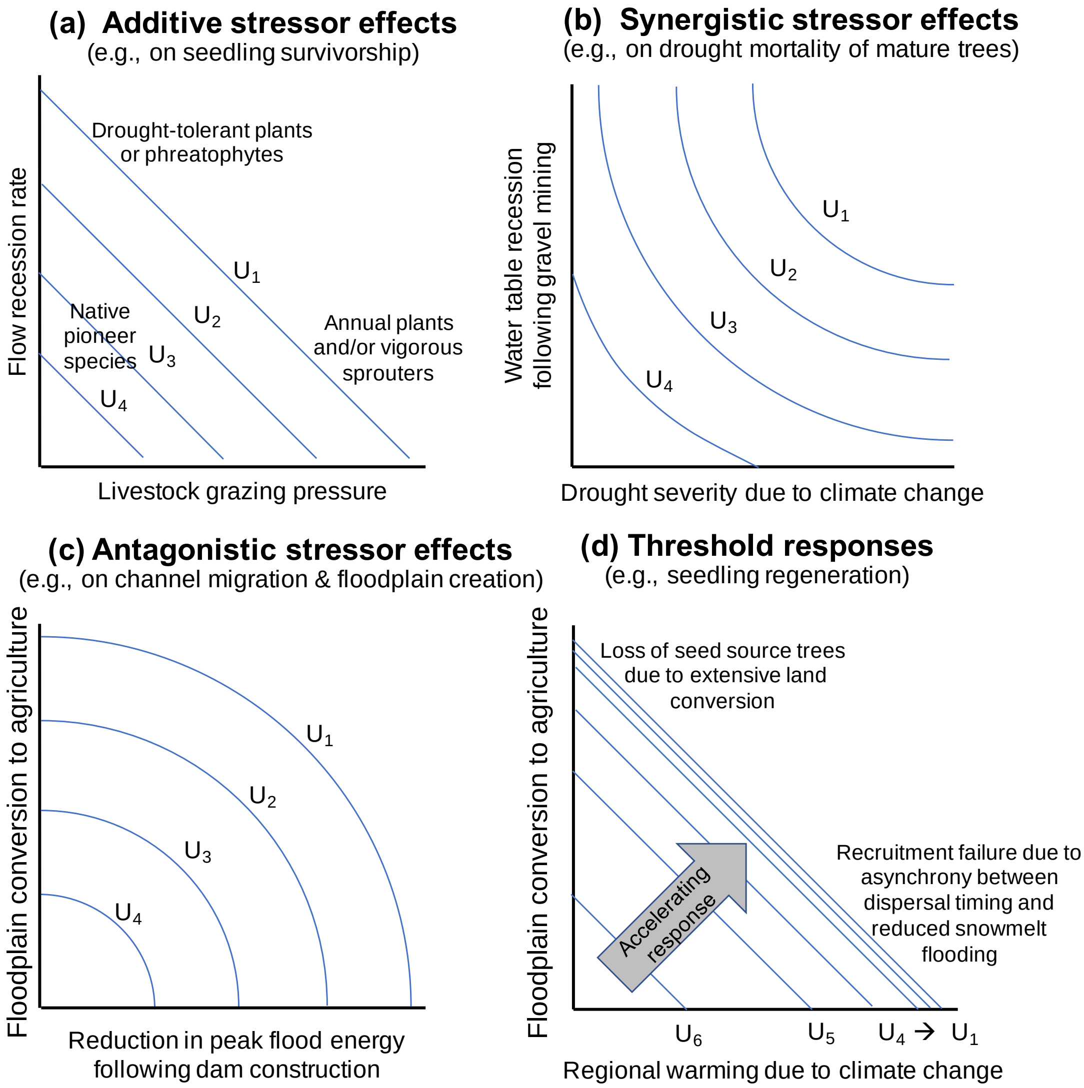

Figure 2. Classifying multiple stressor interactions. Each panel shows a hypothetical utility function for riparian ecosystem condition decreasing from U_4 (best condition) to U_1 (worst), as a function of tradeoffs and interactions between two stressors. Each line shows the levels of ecosystem function that can be achieved at different combinations of stressor influences. Additive stressors (panel a) are strictly proportional, in which their joint impact is equal to the sum of their individual effects, and no non-linear stressor interactions occur. Synergistic stressors (panel b) reinforce each other's effects such that the ecosystem condition degrades more rapidly under the joint influence of both stressors (i.e., a concave utility function). Antagonistic stressors (panel c) usually affect the same process so that their joint impact is less than the sum of their individual effects (i.e., a convex utility function). Threshold responses (panel d) occur when increasing stressor pressure beyond a certain range induces rapid degradation in the ecosystem. If these stressors are of sufficient intensity and duration, the composition and structure of the riparian community may change profoundly.

Habitat measurement and responses to managed change

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Rivers 'have' to be managed, often to the detriment of habitat quality and diversity. This scenario of habitat loss and disturbance creates a challenge for river management. Heavily modified rivers are out of equilibrium with prevailing catchment biophysical fluxes and as such are vulnerable to substantial change when design limits are exceeded. Furthermore, in this modified state river schemes are expensive to maintain, require repeated intervention, often involving hard-rock engineering, and the compromise in habitat quality and diversity degrades river health.

"*Knowledge of what a habitat should be like, in the absence of the effects of human activities, is fundamental to local stream habitat assessment*." (Davies *et al.* 2000). Essentially we need to understand 'how far gone' our rivers have become. How has managed change impacted river habitat? How can these impacts and changes be measured? How can any habitat loss be mitigated? These are questions to be addressed in this presentation by using examples from New Zealand.

The approach taken is a simple one. While not a criticism of preceding approaches to assessing river condition (e.g. Parsons *et al*. 2004; Rinaldi *et al*. 2013), in New Zealand there has been a desire to reduce the specialisation required to conduct habitat assessment, while retaining a fitness for purpose. Development of a simple metric means that such an index can be placed in the hands of non-specialist employees of Regional Councils, tasked with managing New Zealand's rivers on a regional basis. This also makes an index accessible to planners and policy-makers. The approach provides a rapid, cost-effective means of assessing broad scale morphologic character and geomorphic diversity, vis-à-vis habitat quality.

Quantification of habitat quality and change is here largely founded upon key geomorphic parameters that can be measured from aerial imagery (e.g. aerial photography and LiDAR). An index of habitat quality (HQI) is derived as a ratio of change in the parameter from pre- to post-engineering condition. A ratio of 1.0 indicates no change in the parameter, less than one indicates decline, while greater than one suggests improvement. Measured variables can be tailored to whatever is deemed most suitable to reflect the assemblage of geomorphic units or river type present and expected. Furthermore, exactly what is measured can be related to stream biota, along similar lines as Wheaton *et al*. (2010), but at a far broader scale than their work.

The Habitat Quality Index (HQI) can be deployed at a range of spatial and temporal scales. A multi-decadal scale permits assessment of habitat / geomorphic change in response to long-term management. In New Zealand it has been possible to compare genuinely equilibrium-form rivers prior to modification with post-engineered condition, to quantify response to managed change and extent of habitat loss. The HQI can also be used to assess direct impacts of discrete engineering works at an event scale. These works may be either traditional or enlightened, perpetuating loss, or providing mitigation, respectively. In this case, field-based assessments of habitat character can be deployed if required, e.g. measuring grain size and bed compaction. The HQI can be used as a tool to assess the success of mitigation efforts, in conjunction with river managers and planners. In addition the HQI can be used to identify targeted change in order to improve habitat quality and diversity, as well as river resilience (Fuller & Death, 2018).

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