River Confluences, Tributaries and the Fluvial Network

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Preface

When the book proposal that led to this publication was reviewed, we were flattered, but mainly daunted, by the suggestion from a particularly generous referee that we should write this book ourselves. While grateful for the referee's support of the project, we persevered with our original intention of compiling an edited volume. The resulting collection of chapters draws on the research of an international group of scholars and practitioners who work in universities, government agencies, private consultancies and research establishments. Their expertise is in academic and applied geomorphology, hydrology, sedimentology, ecology and engineering. Their methods include numerical modelling, laboratory experimentation and detailed field investigations. Looking at the chapters that they have produced, it is clear to us that we were right to favour the great variety and depth of their expertise and experience over our own, inevitably inferior, knowledge of their areas of specialization. We are therefore grateful to our authors for embracing our project, for sharing their understanding and for helping us to, in a sense, avoid having to write this book ourselves.

And it is a book that needed to be written (in one way or another). River confluences are ubiquitous and critical nodes in river networks, and the branching pattern of tributaries and sub-networks is one of the most characteristic features of river systems on Earth and elsewhere. We find it somewhat remarkable, then, that this will be the first book to focus attention explicitly on confluence dynamics, tributary impacts and the links between processes at these scales and river network functions. We believe that understanding confluence processes and interactions between the tributary and main stem are keystones for scaling-up our understanding of river processes to the drainage network scale: without an understanding of the nodes in the network and the interactions between connected links, the development of basin-scale models and tools is restricted. We subscribe to the view that such network-scale understanding is central to the successful integration of Earth, environmental and biological sciences within riverine landscapes and thence the sustainable management of our riverscapes. We therefore hope that this book will be a helpful stepping-stone for the pursuit of an integrated, cross-scale river science.

To date, work in this area has been communicated almost exclusively via academic journals in geomorphology, ecology, geology and engineering. By bringing together the expertise represented here in one place, our aim is to provide a single benchmark reference that defines the current state of understanding as well as the leading edge of contemporary research. Each chapter is built around two central pillars: a critical review of work in the author's area of expertise and unpublished research that highlights the cutting edge of research in that area. In this way, the book is at once intended to fulfil the needs of students (of whatever age and standing) who require sound, thoughtful reviews of particular topics and also those who are actively involved in conducting and applying research on confluences, tributaries and networks. We therefore hope that the book will be useful both as a standard reference and as a source of new research questions and hypotheses.

To close, some thanks. First to the authors of these chapters for their time and effort: we are grateful and hope that the exercise has been rewarding. Each chapter was fully reviewed and we must thank the large number of colleagues who acted as independent referees; their input was consistently constructive and has substantially improved the quality of the end product. Natasha Todd-Burley's editorial assistance was invaluable during the final stages of production. Finally, the book has been a number of years in the making and we therefore want to thank family and friends for their continued support. In particular, SPR would like to thank Georgina for her support and encouragement throughout this process and dedicate his contribution to his brother Mike, who beat him to a publication with tributary associations. BLR thanks Kathy, Jamie and Steven for helping him to keep life in proper perspective at all times. AGR thanks his co-editors for their enthusiasm for this project, his research team for their constant support and Catherine for being there.

Stephen Rice, Bruce Rhoads, André Roy
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1

Introduction: river confluences, tributaries and the fluvial network

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Introduction

That river systems are networks consisting of links and nodes is one of their most obvious characteristics. Despite the ubiquity of confluences and tributary networks, the first century of modern fluvial geomorphology paid little consistent attention to river junctions and the interactions between tributaries and the main stem (Kennedy, 1984). Important exceptions include classic contributions from Playfair (1802), Lyell (1830) and Sternberg (1875), works on tributary–main-stem interactions (e.g. Krumbein, 1942; Miller, 1958), considerations of junction hydraulics and mixing (e.g. Taylor, 1944; Mackay, 1970) and the seminal works on river network structure (e.g. Horton, 1945; Shreve, 1967). However, the 1980s marked the beginning of a period in which confluence, tributary and network studies developed rapidly. Key contributions were concerned with: confluence morphology, hydraulics and sedimentology (Mosley, 1976; Best, 1986, 1988; Roy *et al.*, 1988), tributary-induced changes in channel form (Richards, 1980; Roy

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and Woldenberg, 1986; Rhoads, 1987) and bed sediments (Church and Kellerhals, 1978; Knighton, 1980), the ecological role of tributaries along unregulated (Bruns *et al.*, 1984) and regulated rivers (Petts, 1984; Petts and Greenwood, 1985), tributaries as repositories of paleoflood information (Kochel and Baker, 1982) and tributary network structure (Abrahams and Campbell, 1976; Flint, 1980; Abrahams and Updegraph, 1987).

Figure 1.1 indicates the rapid increase in the volume of published work on tributaries and confluences in the period since 1980 and illustrates how the initial impetus of the 1980s was consolidated in the 1990s. Ecological interest has lagged behind geomorphology and hydraulics, but it is clear that ecological interest is now growing at the fastest rate. This body of work has demonstrated that river confluences are critical nodes in river systems where tributary fluxes of water and sediment can elicit adjustments in the geomorphology, hydraulics, sedimentology and ecology of the recipient channel. At

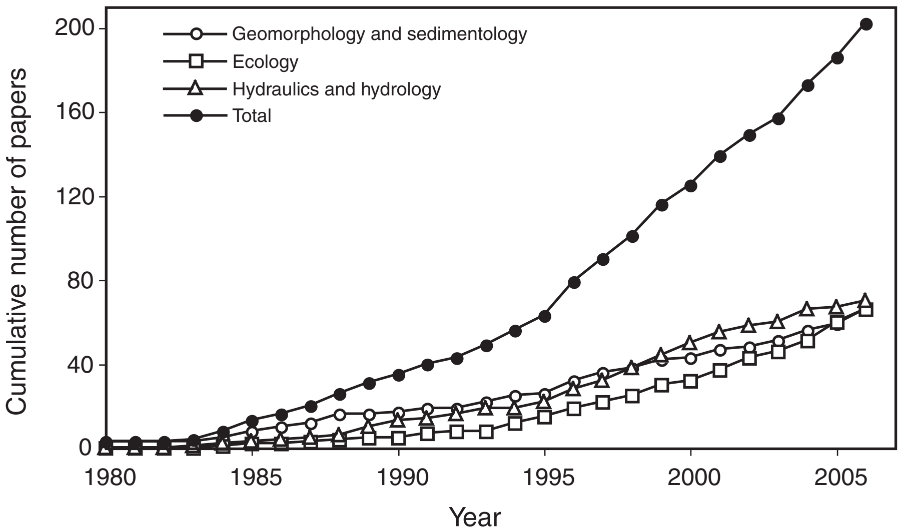

Figure 1.1 The growth in research publications that deal with confluences and tributaries. Network research is not included. Because of the cross-disciplinary nature of many papers, the classification into sub-disciplines is imperfect. Searches were made for the period 1980–2007 using the ISI Web of Science, Science Citation Index – Expanded (http://portal.isiknowledge.com/). A primary search was made of titles, abstracts and keywords using the Boolean expression '(confluence* OR tributar*) AND (river* OR channel*)'and subsequent searches explored other likely terms. Results from these searches were then scrutinized and only those papers where tributaries or confluences were the primary subject matter or where they were used explicitly to explain observed phenomena were retained. Large numbers of papers that studied a particular river system including one or more of its tributaries or confluences but which did not focus on the properties or processes of confluences or tributaries were excluded. Because many papers on water chemistry across drainage basins fall into this category, the 'hydraulics and hydrology' classification does not include any water quality papers.

the smallest scales, research at river confluences examined the distinctive flows, morphologies, sedimentary assemblages and habitats that make confluence sites important local features. Most attention has been directed towards understanding flow mixing at junctions (Gaudet and Roy, 1995; Best and Ashworth, 1997; Biron *et al.*, 2004; Rhoads and Sukhodolov, 2004; Ding and Wang, 2006) and relations between sediment transport, morphology and stratigraphy (Biron *et al.*, 1993; Kenworthy and Rhoads, 1995; Ashworth, 1996; Leclair and Roy, 1997; Paola, 1997; Roy and Sinha, 2005; Boyer *et al.*, 2006). The biological attributes of confluences have received some attention (Cellot, 1996; Kupferberg, 1996; Franks *et al.*, 2002; Fernandes *et al.*, 2004; Kreb and Budiono, 2005; Kiffney *et al.*, 2006), as have the dynamics of ice jams at confluences (Prowse, 1986; Ettema *et al.*, 1997; Shen *et al.*, 2000; Ettema and Muste, 2001). At this scale, improved understanding informed, and was informed by, studies of confluences in braided rivers (Ashmore, 1991; Ashworth *et al.*, 1992; Best and Ashworth, 1997), which, arguably, has laid the foundation for recent investigations of the dynamics of river bifurcations (Dargahi, 2004; Federici and Paola, 2003; Khan *et al.*, 2000; Parsons *et al.*, 2007).

At a slightly larger scale, the confluence zone has been recognized as an important site of storage and staging for clastic and organic materials in fans and terraces (Albertson and Patrick, 1996; Brierley and Fryirs, 1999; Florsheim *et al.*, 2001; May and Gresswell, 2004; Gomez-Villar *et al.*, 2006). Ecological research at this scale suggests that tributary channels in the vicinity of confluences can provide important biological resources including, for example, refugia from high water temperatures (Bramblett *et al.*, 2002; Cairns *et al.*, 2005) and main-stem predators (e.g. Fraser *et al.*, 1995). It has been proposed that such factors, along with enhanced morphological heterogeneity in this confluence zone, may create hotspots of elevated biodiversity (Benda *et al.*, 2004a). At the larger, reach scale, main-stem adjustments to tributary fluxes of water, sediment and organic materials have been shown to structure the longitudinal operation of various abiotic and biotic processes leading to step-changes or gradient shifts in, for example, bed material grain size (Dawson, 1988; Rice and Church, 1998), longitudinal profile (Rice and Church, 2001; Hanks and Webb, 2006) and macroinvertebrate ecology (Perry and Schaeffer, 1987; Rice *et al.*, 2001). Earlier work on tributary influences has been extended to investigate what controls the magnitude of tributary impacts (Rice, 1998; Benda *et al.*, 2004b; Ferguson *et al.*, 2006; Rice *et al.*, 2006).

Understanding confluence dynamics and tributary impacts at these various scales is crucial for scaling-up knowledge of river processes to the drainage network scale: understanding the operation of the nodes in a network is necessary in order to develop network-scale models and tools. Indeed, there is increasing awareness that river system science requires a better integration of process knowledge across a range of spatial scales and particular emphasis is being placed on understanding network-scale functions (e.g. Paola *et al.*, 2006). Building on early work that focused on the topological properties of river networks (see Abrahams, 1984, for a review), a large body of research over the past 30 years has focused on the fractal properties and scaling relations of networks and the way in which these properties and relations are connected to basin hydrological response (see Rodríguez-Iturbe and Rinaldo, 1997). This line of research has matured into the investigation and modelling of process dynamics at river network scales, for example in geomorphology (Gasparini *et al.*, 1999; Binnie *et al.*, 2006; Sklar *et al.*, 2006; Bigelow *et al.*, 2007) and lotic ecology (Poole, 2002; Power and Dietrich, 2002; Benda *et al.*, 2004a; Grant *et al.*, 2007; Thorp *et al.*, 2006; Bertuzzo *et al.*, 2007). Other emerging topics include the role of network structure in pollutant dispersion and the relation of channel networks on other planets to those on Earth – topics that are covered in the latter section of this volume.

Key aims of the book

Work on confluence dynamics, tributary impacts and network-scale functions is, then, alive and well and involves experimental work in the field and laboratory, numerical modelling and large-scale empirical field investigations. This endeavour is frequently cross-disciplinary, challenging traditional boundaries between ecology, engineering, geomorphology, hydrology and sedimentology and emphasizing that river network form and functions control the spatio-temporal patterns of many physical, chemical and biotic processes at the Earth's surface (Paola *et al.*, 2006). At the onset of the second century of modern fluvial studies, our key aim in this book is to present a multidisciplinary, multiscale perspective on confluences, tributaries and river networks. Our intention is that by bringing together work on confluence dynamics and tributary–main stem interactions with network-scale perspectives, the reader will be better positioned to explore the links between processes across these scales. We have tried to draw out these linkages explicitly wherever possible. We hope that the book will provide a foundation upon which integrative effort can be built so that a truly network-scale understanding of river systems can be developed. A recurrent theme, raised by numerous authors, is the need for the continued collection of field and experimental data with which to develop and test our models of confluence, tributary and network processes, and we hope that the areas for further investigation highlighted herein will direct this effort. Also, by presenting the material here in book form, we hope to maximize the involvement of the wider community and facilitate the incorporation of new confluence, tributary and network understanding into the management of river processes and services.

Sections of the book

The book is organized into three parts: (I) River Channel Confluences, (II) Tributary–Main-stem Interactions and (III) Channel Networks. Each section begins with a short introductory essay that includes an overview of the papers in that section, so we refrain from providing such an overview here. Individual chapters focus on the core themes of research and knowledge as well as some topics that have received less attention (e.g. confluence and tributary management). Each chapter provides a review of current understanding, presents new research and considers where future efforts should be directed. We do not claim that the volume is comprehensive, and some topics, such as the structure and dynamics of distributary drainage networks, are not covered here. We do feel, however, that the book has sufficient scope to introduce the novice and scholar alike to many important issues at the forefront of research on river confluences, tributaries and networks. It is hoped that the book as a whole will provide a timely synthesis of a rapidly growing and important field of study but will also bring forward new and stimulating ideas that will shape a coherent and fruitful vision for future work.

References

Abrahams AD. 1984. Channel networks: a geomorphological perspective. *Water Resources Research* **20**: 161–188.

Abrahams AD, Campbell RN. 1976. Source and tributary-source link lengths in natural channel networks. *Geological Society of America Bulletin* **87**: 1016–1020.

Abrahams AD, Updegraph J. 1987. Some space-filling controls on the arrangement of tributaries in dendritic channel networks. *Water Resources Research* **23**: 489–495.

Albertson PE, Patrick DM. 1996. Lower Mississippi River tributaries: Contributions to the collective science concerning the 'Father of Waters'. *Engineering Geology* **45**: 383–413.

Ashmore PE. 1991. How do gravel-bed rivers braid?*Canadian Journal of Earth Sciences* **28**: 326–341.

Ashworth PJ. 1996. Mid-channel bar growth and its relationship to local flow strength and direction. *Earth Surface Processes and Landforms* **21**: 103–123.

Ashworth PJ, Powell DM, Prestegaard KL, Ferguson RI, Ashmore PE, Paola C. 1992. Measurements in a braided river chute and lobe. 2. Sorting of bedload during entrainment, transport, and deposition. *Water Resources Research* **28**: 1887–1896.

Benda L, Andras K, Miller D, Bigelow P. 2004a. Confluence effects in rivers: Interactions of basin scale, network geometry, and disturbance regimes. *Water Resources Research* **40**: W05402.

Benda L, Poff NL, Miller D, Dunne T, Reeves G, Pess G, Pollock M. 2004b. The Network Dynamics Hypothesis: How channel networks structure riverine habitats. *BioScience* **54**: 413–427.

Bertuzzo E, Gatto M, Maritan A, Rodriguez-Iturbe I, Rinaldo A. 2007. River networks and ecological corridors: Reactive transport on fractals, migration fronts, hydrochory. *Water Resources Research* **43**: W04419. DOI: 10.1029/2006WR005533.

Best JL. 1986. The morphology of river channel confluences. *Progress in Physical Geography* **10**: 157–174.

Best JL. 1988. Sediment transport and bed morphology at river channel confluences. *Sedimentology* **35**: 481–498.

Best JL, Ashworth PJ. 1997. Scour in large braided rivers, and the recognition of sequence stratigraphic boundaries. *Nature* **387**: 275–277.

Bigelow PE, Benda LE, Miller DJ, Burnett KM. 2007. On debris flows, river networks, and the spatial structure of channel morphology. *Forest Science* **53**: 220–238.

Binnie SA, Phillips WM, Summerfield MA, Fifield LK. 2006. Sediment mixing and basin-wide cosmogenic nuclide analysis in rapidly eroding mountainous environments. *Quaternary Geochronology* **1**: 4–14.

Biron P, Roy AG, Best JL, Boyer CJ. 1993. Bed morphology and sedimentology at the confluence of unequal depth channels. *Geomorphology* **8**: 115–129.

Biron PM, Ramamurthy AS, Han S. 2004. Three-dimensional numerical modeling of mixing at river confluences. *Journal of Hydraulic Engineering, ASCE* **130**: 243–253.

Boyer C, Roy AG, Best JL. 2006. Dynamics of a river channel confluence with discordant beds: Flow turbulence bed load sediment transport and bed morphology. *Journal of Geophysical Research – Earth Surface* **111**: F04007. DOI: 10.1029/2005JF000458.

Bramblett RG, Bryant MD, Wright BE, White RG. 2002. Seasonal use of small tributary and main-stem habitats by juvenile steelhead, coho salmon, and Dolly Varden in a southeastern Alaska drainage basin. *Transactions of the American Fisheries Society* **131**: 498–506.

Brierley GJ, Fryirs K. 1999. Tributary-trunk stream relations in a cut-and-fill landscape: A case study from Wolumla catchment, New South Wales, Australia. *Geomorphology* **28**: 61–73.

Bruns DA, Minshall GW, Cushing CE, Cummins KW, Brock JT, Vannote RL. 1984. Tributaries as modifiers of the river continuum concept: Analysis by polar ordination and regression models. *Archive Hydrobiologie* **99**: 208–220.

Cairns MA, Ebersole JL, Baker JP, Wigington PJ, Lavigne HR, Davis JA. 2005. Influence of summer stream temperatures on black spot infestation of juvenile Coho salmon in the Oregon Coast Range. *Transactions of the American Fisheries Society* **134**: 1471–1479.

Cellot B. 1996. Influence of side-arms on aquatic macroinvertebrate drift in the main channel of a large river. *Freshwater Biology* **35**: 149–164.

Church M, Kellerhals R. 1978. On the statistics of grain size variation along a gravel river. *Canadian Journal of Earth Sciences* **15**: 1151–1160.

Dargahi B. 2004. Three-dimensional flow modelling and sediment transport in the River Klaralven. *Earth Surface Processes and Landforms* **29**: 821–852.

Dawson M. 1988. Sediment size variation in a braided reach of the Sunwapta River, Alberta, Canada. *Earth Surface Processes and Landforms* **13**: 599–618.

Ding Y, Wang SSY. 2006. Optimal control of open-channel flow using adjoint sensitivity analysis. *Journal of Hydraulic Engineering, ASCE* **132**: 1215–1228.

Ettema R, Muste M. 2001. Laboratory observations of ice jams in channel confluences. *Journal of Cold Regions Engineering* **15**: 34–58.

Ettema R, Fujita I, Muste M, Kruger A. 1997. Particle-image velocimetry for whole-field measurement of ice velocities. *Cold Regions Science and Technology* **26**: 97–112.

Federici B, Paola C. 2003. Dynamics of channel bifurcations in noncohesive sediments. *Water Resources Research* **39**: 1162.

Ferguson RI, Cudden JR, Hoey TB, Rice SP. 2006. River system discontinuities due to lateral inputs: Generic styles and controls. *Earth Surface Processes and Landforms* **31**: 1149–1166.

Fernandes CC, Podos J, Lundberg JG. 2004. Amazonian ecology: Tributaries enhance the diversity of electric fishes. *Science* **305**: 1960–1962.

Flint JJ. 1980. Tributary Arrangements in Fluvial Systems. *American Journal of Science* **280**: 26–45.

Florsheim JL, Mount JF, Rutten LT. 2001. Effect of base level change on floodplain and fan sediment storage and ephemeral tributary channel morphology, Navarro River, California. *Earth Surface Processes and Landforms* **26**: 219–232.

Franks CA, Rice SP, Wood PJ. 2002. Hydraulic habitat in confluences: An ecological perspective on confluence hydraulics. In *The Structure, Function and Management Implications of Fluvial Sedimentary Systems*, Dyer FJ, Thoms MC, Olley JM (eds). International Association Hydrological Sciences Publications, Wallingford, UK: **276**, 61–67.

Fraser DF, Gilliam JF, Yip-Hoi T. 1995. Predation as an agent of population fragmentation in a tropical watershed. *Ecology* **76**: 1461–1472.

Gasparini NM, Tucker GE, Bras RL. 1999. Downstream fining through selective particle sorting in an equilibrium network. *Geology* **27**: 1079–1082.

Gaudet JM, Roy AG. 1995. Effect of bed morphology on flow mixing length at river confluences. *Nature* **373**: 138–139.

Gomez-Villar A, Alvarez-Martinez J, Garcia-Ruiz JM. 2006. Factors influencing the presence or absence of tributary-junction fans in the Iberian Range, Spain. *Geomorphology* **81**: 252–264.

Grant EHC, Lowe WH, Fagan WF. 2007. Living in the branches: Population dynamics and ecological processes indendritic networks. *Ecology Letters* **10**: 165–175.

Hanks TC, Webb RH. 2006. Effects of tributary debris on the longitudinal profile of the Colorado River in Grand Canyon. *Journal of Geophysical Research-Earth Surface* **111**: F02020.

Horton RE. 1945. Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin* **56**: 275–370.

Kennedy BA. 1984. On Playfair's law of accordant junctions. *Earth Surface Processes and Landforms* **9**: 153–173.

Kenworthy ST, Rhoads BL. 1995. Hydrologic control of spatial patterns of suspended sediment concentration at a stream confluence. *Journal of Hydrology* **168**: 251–263.

Khan AA, Cadavid R, Wang SSY. 2000. Simulation of channel confluence and bifurcation using the CCHE2D model. *Proceedings of the Institution of Civil Engineers-Water Maritime and Energy* **142**: 97–102.

Kiffney PM, Greene C, Hall J, Davies J. 2006. Gradients in habitat heterogeneity, productivity, and diversity at tributary junctions. *Canadian Journal of Fisheries and Aquatic Sciences* **63**: 2518–2530.

Knighton AD. 1980. Longitudinal changes in size and sorting of stream bed material in four English Rivers. *Geological Society of America Bulletin* **91**: 55–62.

Kochel RC, Baker VR. 1982. Palaeoflood hydrology. *Science* **215**: 353–361.

Kreb D, Budiono YK. 2005. Conservation management of small core areas: Key to survival of a critically endangered population of irrawaddy river dolphins *Orcaella brevirostris* in Indonesia. *Oryx* **39**: 178–188.

Krumbein WC. 1942. Flood deposits of the Arroyo Seco, Los Angeles County, California. *Geological Society of America Bulletin* **53**: 1355–1402.

Kupferberg SJ. 1996. Hydrologic and geomorphic factors affecting conservation of a river-breeding frog (*Rana boylii*). *Ecological Applications* **6**: 1332–1344.

Leclair SF, Roy AG. 1997. Variability of bed morphology and sedimentary structures at a discordant river confluence during low flows. *Geographie Physique et Quaternaire* **51**: 125–139.

Lyell C. 1830. *Principles of Geology*. John Murray: London.

Mackay JR. 1970. Lateral mixing of Liard and Mackenzie Rivers downstream from their confluence. *Canadian Journal of Earth Sciences* **7**: 111–124.

May CL, Gresswell RE. 2004. Spatial and temporal patterns of debris-flow deposition in the Oregon Coast Range, USA. *Geomorphology* **57**: 135–149.

Miller JP. 1958. *High Mountain Streams: Effects of Geology on Channel Characteristics and Bed Material.* Memoir 4, State Bureau of Mines and Mineral Resources, New Mexico Institute of Mines and Mining Technology, Socorro, New Mexico.

Mosley MP. 1976. An experimental study of channel confluences. *Journal of Geology* **84**: 535–562.

Paola C. 1997. When streams collide. *Nature* **387**: 232–233.

Paola C, Foufoula-Georgiou E, Dietrich WE Hondzo M, Mohrig D, Parker G, Power ME, Rodriguez-Iturbe I, Voller V, Wilcock P. 2006. Toward a unified science of the Earth's surface: Opportunities for synthesis among hydrology, geomorphology, geochemistry, and ecology. *Water Resources Research* **42**: 10.1029/2005WR004585.

Parsons DR, Best JL, Lane SN, Orfeo O, Hardy RJ, Kostaschuk R. 2007. Form roughness and the absence of secondary flow in a large confluence–diffluence, Rio Parana, Argentina. *Earth Surface Processes and Landforms* **32**: 155–162.

Perry JA, Schaeffer DJ. 1987. The longitudinal distribution of riverine benthos: A river discontinuum?*Hydrobiologia* **148**: 257–268.

Petts GE. 1984. *Impounded Rivers: Perspectives for Ecological Management.* John Wiley and Sons: Chichester.

Petts GE, Greenwood M. 1985. Channel changes and invertebrate faunas below Nant-y-Moch dam, River Rheidol, Wales, UK. *Hydrobiologia* **122**: 65–80.

Playfair J. 1802. *Illustrations of the Huttonian Theory of the Earth.* Dover: London.

Poole GC. 2002. Fluvial landscape ecology: Addressing uniqueness within the river discontinuum. *Freshwater Biology* **47**: 641–660.

Power ME, Dietrich WE. 2002. Food webs in river networks. *Ecological Research* **17**: 451–471.

Prowse TD. 1986. Ice jam characteristics, Liard-Mackenzie Rivers confluence. *Canadian Journal of Civil Engineering* **13**: 653–665.

Rhoads BL. 1987. Changes in stream channel characteristics at tributary junctions. *Physical Geography* **8**: 346–361.

Rhoads BL, Sukhodolov AN. 2004. Spatial and temporal structure of shear layer turbulence at a stream confluence. *Water Resources Research* **40**: W06304.

Rice SP. 1998. Which tributaries disrupt downstream fining along gravel-bed rivers? *Geomorphology* **22**: 39–56.

Rice SP, Church M. 1998. Grain size along two gravel-bed rivers: Statistical variation, spatial pattern and sedimentary links. *Earth Surface Processes and Landforms* **23**: 345–363.

Rice SP, Church M. 2001. Longitudinal profiles in simple alluvial systems. *Water Resources Research* **37**: 417–426.

Rice SP, Greenwood MT, Joyce CB. 2001. Tributaries, sediment sources and the longitudinal organisation of macroinvertebrate fauna along river systems. *Canadian Journal of Fisheries and Aquatic Sciences* **58**: 824–840.

Rice SP, Ferguson RI, Hoey T. 2006. Tributary control of physical heterogeneity and biological diversity at river confluences. *Canadian Journal of Fisheries and Aquatic Sciences* **63**: 2553–2566.

Richards KS. 1980. A note on changes in channel geometry at tributary junctions. *Water Resources Research* **16**: 241–244.

Rodríguez-Iturbe I, Rinaldo A. 1997. *Fractal River Basins: Chance and Self-Organization.* Cambridge University Press: Cambridge.

Roy AG, Woldenberg MJ. 1986. A model for changes in channel form at a river confluence. *Journal of Geology* **94**: 402–411.

Roy NG, Sinha R. 2005. Alluvial geomorphology and confluence dynamics in the Gangetic plains, Farrukhabad-Kannauj area, Uttar Pradesh, India. *Current Science* **88**: 2000–2006.

Roy AG, Roy R, Bergeron N. 1988. Hydraulic geometry and changes in flow velocity at a river confluence with coarse bed material. *Earth Surface Processes and Landforms* **13**: 583–598.

Shen HT, Su JS, Liu LW. 2000. SPH simulation of river ice dynamics. *Journal of Computational Physics* **165**: 752–770.

Shreve RL. 1967. Infinite topologically random channel networks. *Journal of Geology* **77**: 397–414.

Sklar LS, Dietrich WE, Foufoula-Georgiou E, Lashermes B, Bellugi D. 2006. Do gravel-bed river size distributions record channel network structure? *Water Resources Research* **42**: DOI: 10.1029/2006wr005035.

Sternberg H. 1875. Untersuchungen über längen- und Querprofil geschiebeführender Flüsse. *Zeitschrift für Bauwesen* **25**: 483–506.

Taylor EH. 1944. Flow characteristics at rectangular open channel junctions *Transactions of the American Society of Civil Engineers* **109**: 893–912.

Thorp JH, Thoms MC, Delong MD. 2006. The riverine ecosystem synthesis: Biocomplexity in river networks across space and time. *River Research and Applications* **22**: 123–147.

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