Section 3

FLUVIAL PROCESSES WITH SPECIAL EMPHASIS ON GLACIAL RIVERS

An Annotated Bibliography

Compiled for the
Region II FRPA Riparian Management Science & Technical Committee

by
Jason E.B. Mouw
Alaska Department of Fish and Game, Sport Fish Division

SUMMARY

Glacial rivers are perhaps some of the most physically diverse ecosystems on earth and are characterized by tremendous habitat complexity that shifts in space and time at a wide variety of scales. They are characterized by a highly variable flow regime and extreme suspended sediment concentrations (Milner and Petts, 1994). Glacial rivers typically adopt one or both of two general channel forms: braided or anastomosed. Braiding is typically referred to as the channel state in which splitting channels flow around bars or islands that are contained between dominant floodplain banks. Anastomosis refers to a split channel form in which multiple channels flow around rather permanent vegetated islands that are not flooded at bankfull discharge. Braided rivers are characterized by relatively high stream power (due to a high channel slope), high rates of erosion, deposition, and channel change. Anastomosing rivers are characterized by lower channel slope gradients, and perhaps higher rates of deposition.

In general, glacial rivers flow with cold water, yet due to their aquatic habitat complexity they are characterized by high thermal heterogeneity (Malard et al. 2001) that supports a wide variety of fish species and their various life history stages and strategies. This physical habitat complexity is driven by cut and fill alluviation. These fluvial processes are driven by bank erosion and lateral and point bar accretion. Though the cause of channel form in glacial systems is still debated, there are several important factors that contribute. First, due to high levels of suspended sediment, glacial rivers develop a braided or anabraching (split channel form) in order to maximize hydraulic efficiency to optimize the conveyance of water and sediment. Next, these forms also merely result from “flashy” hydrologic regimes that frequently lead to overbank flows and floodplain head cutting (Tabata and Hickin, 2003). In Region II, Alaska, ice and wood jams also have a strong influence on causing multiple channel networks and initiating important

floodplain habitat processes that influence fish and wildlife habitat (Smith and Pearce, 2002, Prowse and Conly, 2002).

Each attribute of the highly variable flow regime is important to the form of gravel-bedded river systems (Heritage et al. 2001). High flows have the competence to conduct great geomorphic work on a river's flood plain, whereas low flows seasonally denude imbedded surfaces and cause local incision of the bed surface layer (Parker, 1990). Though low and high flows have substantial influence, effectiveness of processes that control geomorphic form in river systems is a function of their distribution in time and their magnitude. It does not follow, therefore, that the infrequent high magnitude events are the most significant. Rather the more moderate events that recur rather frequently, such as the bankfull flow perform the greatest amount of geomorphic "work" (Wolman and Miller, 1960).

Until quite recently, most concepts of river systems were based on the assumption that rivers are stable, single threaded systems that are isolated from adjacent flood plains. It is now recognized that glacial rivers are characterized by flow and sediment regimes that lead to expansive flood plains within which a great mosaic of aquatic habitats are embedded, and that the river is connected with those habitats. This hydrologic connectivity, either through surface connection or hyporheic exchange flow, is critical to maintaining floodplain function and biodiversity (Bornette el al. 1998, Ward et al., 1999, Sheldon et al. 2002).

REFERENCES

Boulton, A.J., Findlay, S., Marmonier, P, Stanley, E.H., and Valett, H.M. 1998. The functional significance of the hyporheic zone in streams and rivers. Annual Review of Ecology and Systematics 29: 59-81.

The hyporheic zone is an active ecotone between the surface stream and groundwater. Exchanges of water, nutrients, and organic matter occur in response to variations in discharge and channel slope and hydraulic conductivity of bed sediments. Upwelling ground water supplies stream organisms with nutrients whereas downwelling stream water provides dissolved oxygen and organic matter to benthic animal communities in the hyporheic zone. Dynamic gradients exist at a hierarchy of scales and vary in space and time. At the microscale, gradients in redox potential control chemical and microbially mediated nutrient transformations that occur in the hyporheic zone. At the reach scale, hydrologic exchange and geomorphically controlled water flux time are reflected in gradients in hyporheic faunal composition, uptake of dissolved organic carbon, and nitrification. The hyporheic corridor concept describes gradients at the catchment scale, extending to alluvial aquifers kilometers from the main channel. Across all scales, the functional significance of the hyporheic zone relates to its activity and connection with the surface stream.

Emmet, W.W., and Wolman, M.G. 2001. Effective discharge and gravel-bed rivers. Earth Surface Processes and Landforms. 26: 1369 – 1380.

Effectiveness in geomorphology may be associated with transport (work) and with landform. Bedload transport may relate to both. Determination of that discharge which transports more bedload than any other entails assessment of the magnitude and frequency of bedload transport. This involves arraying daily mean discharges, computing the bedload for each unit of discharge, and determining the discharge that transports the most bedload. For those rivers in which the relationships of bedload discharge to water discharge are not dominated by very large-size particles and where daily mean discharges are an adequate description of streamflow characteristics, a large body of data demonstrates that this discharge is often analogous to bankfull discharge and often has a frequency of recurrence of one to two years. Rivers with constraints on the mobility of bed material, typically armored channels with steeper than average relationships of bedload discharge to water discharge, may have an effective discharge occurring at higher stages and greater recurrence intervals than bankfull discharge. Bedload discharges were measured at five snow-melt dominated, gravel-bedded rivers in the northern Rocky Mountains, USA; drainage areas at the sites ranged from about 55 to 4950 km2 and bankfull discharges ranged from about 6·5 to 650 m3 s-1. Median bed-surface particles, d50, ranged from 40 to 173 mm, and d90 ranged from 132 to 310 mm. Exponents of the bedload ratings, indicating the steepness of the relationship of bedload discharge to water discharge, ranged from 2·30 to 5·06. Values of the exponent correlated well with values of either d50 or d90 of the bed-surface material and demonstrate the effect of the bed-surface material on the bedload rating. Effective discharge was determined for each site. The ratio of effective discharge to bankfull discharge, Qe/Qb, ranged from 0·98 to 1·31. The values of Qe/Qb correlated well with exponent values from the bedload ratings. Data indicate that, as the exponent of the bedload rating increases from typical to more steep values, effective discharge increases from near-bankfull discharge to, in the present study, about 1·3 bankfull discharge. This represents about a doubling of the recurrence interval.

Heritage, G.L., Broadhurst, L.J., and Birkhead, A.L. 2001. The influence of contemporary flow regime on the geomorphology of the Sabie River, South Africa. Geomorphology 38: 197 – 211.

The existence of a channel-forming, `dominant' or `bankfull' discharge has been applied, with some success, to a variety of alluvial river systems in temperate areas. This paper presents the results of an investigation into the relationship between flow magnitude and frequency, and the geomorphological units of the Sabie River in the Mpumalanga Province, South Africa. The river is perennial, however, it exhibits an extreme seasonal flow regime. The river has been subject to incision (100,000–10,000 years ago), which exposed bedrock areas as topographic highs within a wide macro-channel. Zones of deposition have created alluvial sections resulting in a morphologically diverse river system. Stage–discharge relationships have been observed and constructed for 23 monitoring sites on the Sabie River. These have been used in conjunction with a 62-year calibrated simulated daily discharge record, to generate inundation frequencies for the morphological units present at each site. This includes results using annual maximum series data and time spans for activation, using the continuous daily flow data. The results reveal that the overall form of the cross-section is not related to a single channel-forming discharge, instead, a complex relationship exists whereby the section is influenced by the entire flow regime. The results do however suggest a poorly defined division of morphological units within the incised macro-channel, namely, those influenced by perennial, seasonal and infrequent flows. This relationship is best demonstrated by the morphological units associated with the perennial, active channels in alluvial sections, which correlate with the low flow regime (1–2-year return period on the annual maximum series), and larger macro-channel deposits which are related to rarer higher flows. Climatic wet and dry cycles, human influences and the physical effect of bedrock in the macro-channel further complicate the inundation pattern, resulting in disequilibrium conditions between channel form and contemporary flow regime on the Sabie River. Macro-channel sedimentary deposits, in particular, show no consistent relationship with a particular segment of the flow regime, being inundated by flows of between a 10- and 50-year return period.

Malard, F., Mangin, A. Uehlinger, U. and Ward, J.V. 2001. Thermal heterogeneity in the hyporheic zone of a glacial flood plain. Canadian Journal of Fisheries and Aquatic Sciences 58: 1319-1335.

This paper demonstrates an unexpectedly high level of thermal heterogeneity for a glacial river flood plain in space and throughout seasons. Whereas shallow alluvial groundwater had little influence on surface water temperatures, water upwelling from deep substratum interstices and hill slope water had a significant influence on surface water temperatures. In summer, sites influenced by upwelling were cooler and in winter the same sites were warmer than sites controlled by bedrock, or characterized by downwelling.

Milner, A.M., and Petts, G.E., 1994. Glacial rivers: physical habitat and ecology Freshwater Biology 32: 295 – 307.

The physical habitat and ecology of glacial rivers remains relatively unstudied. This review examines the unique attributes of the flow and sediment regimes of glacial rivers. Peak stream flow differs from snowmelt systems in that the peak is delayed and there is a strong diel rhythm associated with flow pulses. Downstream from glaciers temperatures increase, channels become more stable, and valley floors become older.

Parker. G. 1990. Surface-based bedload transport relation for gravel rivers. Journal of Hydraulic Research 28: 417-436.

This paper discusses the dynamic seasonal nature of river bed particle size distributions. At low flows the bed surface layer coarsens while the opposite is true during higher flows. This should be particularly true for glacial streams that run clear in winter, yet are extremely turbid in summer and fall.

Poole, G.C., Stanford, J.A., Frissel, C.A., and Running, S.W. 2002. Three-dimensional mapping of geomorphic controls on floodplain hydrology and connectivity from aerial photos. Geomorphology 48: 329-347.

The Nyack flood plain of the Middle Fork Flathead River, MT, USA is a 9-km anastomosed alluvial montane flood plain. Upstream from the flood plain, the river is unregulated and the catchment virtually pristine. A patchy mosaic of vegetation and channels exists on the flood-plain surface. The surface and subsurface geomorphic structures of the flood plain facilitate high hydrologic connectivity (water flux between the channel and flood plain) marked by complex seasonal patterns of flood-plain inundation, extensive penetration of channel water laterally into the alluvial aquifer, and spring brooks formed by ground water erupting onto the flood-plain surface. After delineating and classifying flood-plain "elements" (vegetation patches and channel reaches) on the flood plain, we analyzed field-based elevation survey data to identify expected relationships among flood-plain element type, surface scour frequency, and flood-plain elevation. Data analyses show that scour frequency was inversely proportional to the elevation of the flood plain above river stage, except when localized geomorphic controls such as natural levees prevent normal high flows from inundating and scouring relatively low flood-plain elements. Further, while different flood-plain element types occupy distinct elevation zones on the flood plain, the elevation of each zone above the river channel varies with localized channel entrenchment. We found that topographic variation among flood-plain elements is greater than the variation within elements, suggesting that coarse-scale flood-plain topography can be characterized by delineating flood-plain elements. Field data document strong associations between specific classes of flood-plain elements and preferential ground-water flow paths in the upper alluvial aquifer. Combined with preexisting ground penetrating RADAR (GPR) surveys, these data intimate a sinuous lattice of preferential ground-water flow paths (buried abandoned streambeds) in the upper alluvial aquifer at approximately the same elevation as the main channel's streambed. Using aerial photo interpretation and the identified relationships among element-types, elevation, and preferential ground-water flow paths, we developed a quantitative, three-dimensional characterization of surface and subsurface geomorphology across the entire flood plain to support a heuristic modeling effort investigating the influence of flood-plain geomorphology on spatio-temporal patterns of surface and ground-water flow and exchange under dynamic hydrologic regimes.

Prowse, T.D., and Conly, F.M. 2002. A review of hydroecological results of the Northern River Basins Study, Canada. Part 2. Peace-Athabasca Delta. River Research and Applications. 18: 447-460.

The Peace-Athabasca Delta (PAD) in northern Canada is one of the world's largest freshwater deltas. Concern developed over the ecological health of this system in the early 1970s following regulation of its main headwater tributary, the Peace River. Continued drying of the delta into the 1990s resulted in the initiation of two major science programs, the Northern River Basins Study and the Peace-Athabasca Delta Technical Studies. Recognizing the importance of water to restoring and maintaining biological productivity and diversity of the PAD, a series of studies was initiated to explain the reasons for the protracted drying and to design methods to restore flooding. These studies demonstrated that open-water floods from the Peace River were unlikely to flood the ecologically sensitive perched basins within the PAD. Moreover they discovered that most large-scale overbank flooding resulted from ice-jams formed during spring break-up. Increases in freeze-up ice levels due to enhanced winter flows from the reservoir and a decrease in spring snowmelt runoff from downstream tributaries were suggested as being responsible for a decline in the frequency and severity of ice-jam floods. Based on results from numerical modeling studies of ice-jams, a flow augmentation strategy was designed to aid the formation of ice-jams near the PAD. Results of a test trial based on this strategy are presented. An update is also provided about ecological studies conducted since the delta was recharged by floodwaters in 1996.

Sheldon, F., Boulton, A.J., and Puckridge, J.T. 2002. Conservation value of variable connectivity: aquatic invertebrate assemblages of channel and floodplain habitats of a central Australian arid-zone river, Cooper Creek. Biological Conservation 103: 13-31.

Rapidly expanding water resource development in arid and semi-arid zones of Australia threatens the flow regime and ecological integrity of the few large dryland rivers and their immense floodplains. Efforts to manage and conserve the surface waters of these rivers are hampered by limited scientific data on the ecology of their flora and fauna and on their responses to the high natural variability of flow regime that typifies dryland rivers. Irregular floods connect channel and floodplain wetlands to differing degrees and for varying periods of time but the ecological significance of this connectivity is poorly understood. On Cooper Creek, a large dryland river in central Australia, we explored the degree to which assemblage composition varied with connectivity and hydrological regime. Shortly after protracted regional flooding, we sampled aquatic macroinvertebrate assemblages from the principal microhabitats in 12 channel and floodplain wetlands. Ephemeral and temporary lakes tended to have fewer taxa than semi-permanent channel or terminal lake habitats. Although hydrological connection had only recently been lost for some wetlands, there was already evidence of divergence in aquatic macroinvertebrate assemblage composition. Disruption of the natural variability in connectivity and hydrological regime by excessive water abstraction or river-flow regulation threatens the ecological integrity and aquatic macroinvertebrate biodiversity of dryland rivers. Preservation of the irregular flow regime and sporadic connectivity underpins conservation of the mosaic of floodplain wetlands that play such a crucial role in the ecosystem functioning of rivers such as Cooper Creek.

Smith, D.G., and Pearce, C.M. 2002. Ice jam-caused fluvial gullies and scour holes on northern river flood plains. Geomorphology 42: 85-95.

Two anomalous fluvial landforms, gullies and scour holes, eroded into flood plains bordering meandering and braiding river channels have not been previously reported. We observed these features along the Milk River in southern Alberta, Canada, and northern Montana, USA, which has a history of frequent (50% probability of recurrence) and high-magnitude (12% probability of recurrence greater than bankfull) ice jam floods. Gullies have palmate and narrow linear shapes with open-ends downvalley and measure up to 208 m long×139 m wide×3.5 m deep (below bankfull). Channel ice jams reroute river water across meander lobes and cause headward gully erosion where flow returns to the main channel. Erosion of the most recent gully was observed during the record 1996 ice breakup flood and ice jams. Scour holes (bowl-shaped, closed depressions), eroded by water vortices beneath and between grounded ice jam blocks, measure up to 91 m long×22 m wide×4.5 m deep. Ice jam-caused gullies may be precursors to the formation of U-shaped oxbow lakes and multiple channels, common in many northern rivers.

Tabata, K.K., and Hickin, E.J. 2003. Interchannel hydraulic geometry and hydraulic efficiency of the anastomosing Columbia River, Southeastern British Columbia, Canada. Earth Surface Processes and Landforms. 28: 837 – 852.

The morphodynamics of the anastomosing channel system of upper Columbia River in southeastern British Columbia, Canada, is examined using an adaptation of conventional hydraulic geometry termed interchannel hydraulic geometry. Interchannel hydraulic geometry has some of the characteristics of downstream hydraulic geometry but differs in that it describes the general bankfull channel form and hydraulics of primary and secondary channels in the anastomosing channel system. Interchannel hydraulic geometry generalizes these relationships and as such becomes a model of the geomorphology of channel division and combination. Interchannel hydraulic geometry of upper Columbia River, based on field measurements of flow velocity and channel form at 16 test sections, is described well by simple power functions: wbf = 3·24Qbf0·64; dbf = 1·04Qbf0·19; vbf = 0·30Qbf0·17. These results, with other related measurements of flow resistance, imply that channel splitting leads to hydraulic inefficiency (higher flow resistance) on the anastomosing Columbia River. Because these findings differ from those reported in studies elsewhere, we conclude that hydraulic efficiency does not provide a general explanation for anabranching in river channels.

Ward, J.V., K. Tockner, and F. Shiemer. 1999. Biodiversity of floodplain river ecosystems: ecotones and connectivity. Regulated Rivers: Research and Management 15: 125-139.

A high level of spatio-temporal heterogeneity makes riverine floodplains among the most species-rich environments known. Fluvial dynamics from flooding play a major role in maintaining a diversity of lentic, lotic and semi-aquatic habitat types, each represented by a diversity of successional stages. Ecotones (transition zones between adjacent patches) and connectivity (the strength of interactions across ecotones) are structural and functional elements that result from and contribute to the spatio-temporal dynamics of riverine ecosystems. In floodplain rivers, ecotones and their adjoining patches are arrayed in hierarchical series across a range of scales. At a coarse scale of resolution, fringing floodplains are themselves complex ecotones between river channels and uplands. At finer scales, patches of various types and sizes form habitat and microhabitat diversity patterns. A broad spatio-temporal perspective, including patterns and processes across scales, is needed in order to gain insight into riverine biodiversity. We propose a hierarchical framework for examining diversity patterns in floodplain rivers.

Various river management schemes disrupt the interactions that structure ecotones and alter the connectivity across transition zones. Such disruptions occur both within and between hierarchical levels, invariably leading to reductions in biodiversity. Species richness data from the connected and disconnected floodplains of the Austrian Danube illustrate this clearly. In much of the world, species-rich riverine/floodplain environments exist only as isolated fragments across the landscape. In many large rivers, these islands of biodiversity are endangered ecosystems. The fluvial dynamics that formed them have been severely altered. Without ecologically sound restoration of disturbance regimes and connectivity, these remnants of biodiversity will proceed on unidirectional trajectories toward senescence, without rejuvenation. Principles of ecosystem management are necessary to sustain biodiversity in fragmented riverine floodplains.

Williams, G.P. 1978. Bankfull discharge of rivers. Water Resources Research 14: 1141-1154.

This is a classic review paper that discusses the various definitions of bankfull discharge and its recurrence interval. This stage of flow is widely accepted to be important for channel maintenance and engaging important fluvial processes that maintain and create aquatic habitat. Bankfull discharge is generally equaled or exceeded every 1.5 years.

Wolman, M.G., and Miller, J.P. 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology 68:54-74.

Effectiveness of processes that control geomorphic form in river systems is a function of their distribution in time and their magnitude. It does not follow, therefore, that the infrequent high magnitude events are the most significant. Rather the more moderate events that recur rather frequently, such as the bankfull flow perform the greatest amount of geomorphic "work".

Wolman, M.G. and Leopold, L.B. 1957. River flood plains: some observations on their formation. Geological Survey Professional Paper 282-C.

This classic paper discusses the formation of flood plains on gravel-bed rivers. Floodplain formation and development was discussed as driven by bank erosion and lateral bar accretion rather than by overbank deposits.