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Snowy River Recovery

Snowy flow response monitoring and modelling

Contribution of unregulated tributaries to the ecological functioning of the main channel of rivers

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NSW Office of Water
Level 17, 227 Elizabeth Street
GPO Box 3889
Sydney NSW 2001

T 02 8281 7777 **F** 02 8281 7799

information@water.nsw.gov.au

www.water.nsw.gov.au

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Summary

The literature on the ecological role of unregulated tributaries relates mainly to regulated systems on which dams and other impoundments have been constructed and, within this, there is a bias towards influences on fish populations, with less emphasis on processes such as primary production, decomposition and nutrient cycling. In the Australian context, this bias is compounded by a paucity of studies specifically on the roles of tributaries.

The influx of water, sediment and organic material from tributaries into the main river channel can lead to abrupt changes in channel morphology, water volume, sediment characteristics and water quality, particularly at their confluences, which may interrupt the longitudinal connectivity of the main river channel. These changes include:

- the slope, width and depth of the main channel
- morphological features such as bars, fans and terraces
- size, shape and sorting of sediment on the riverbed
- hydraulic conditions within the water column
- near-bed flow velocity and shear stress
- turbidity, seston, nutrient and contaminant concentrations.

The magnitude and direction of change in these attributes depends on the volume and quality of the water, sediment and organic material delivered which, in turn, depend on the size of tributary, its pattern of discharge (i.e. continuous, periodic or ephemeral) and the biophysical characteristics of its catchment. Furthermore, the changes induced by flows from tributaries may be temporarily reversed by occasional floods in the main stem.

The effects of confluences on river morphology will vary with the shape of the drainage basin and the overall configuration of the channel network, including the number of tributaries, their spacing and angle as they intersect the main channel. The effects of confluences on sediment supply and morphological features may also be modified by fires, storms and floods.

Changes in channel morphology, hydraulic conditions, substratum composition and water quality that occur at confluences influence the wetted area, penetration of light, stability of the substratum, availability of micro-habitats and refugia, water chemistry and supply of food and nutrients. These, in turn, affect the distribution and abundance of biota, particularly those found in association with benthic habitats. The influx of organic matter, inorganic sediment and wood at tributary junctions may also alter the availability of food and can increase habitat heterogeneity with consequent effects on macroinvertebrate and fish diversity. The influx of water from tributaries may also transport seeds, aquatic macrophytes, macroinvertebrates, fish and their propagules/larvae into the main river channel.

In regulated river systems, influxes from unregulated tributaries may mitigate the downstream impacts of dams on thermal and hydrologic regimes, sediment processes and aquatic biota, but the extent to which they do this depends on the size of the tributaries in relation to the main-stem channel, their distance from the dam, and their discharge, sediment and water temperature characteristics. In such systems, management of tributary catchments to ensure good water quality and flow may be as important as managing flow in the main stream itself.

Introduction

This literature review attempts to provide a comprehensive summary of the contribution of unregulated tributaries to the ecological functioning of the main channel of rivers. The review considers the effects of tributaries in general and includes aspects such as flow variability, sediments, inorganic ions, nutrients, dissolved and particulate organic matter, and biota. The objective of the review is to assist the NSW, Victorian and Australian governments in understanding the potential benefits of providing environmental flows from tributaries into a regulated river. Example of this arrangement occurs across the Snowy Mountains scheme where tributaries downstream of major storages also have been regulated and offer an opportunity to provide an option for the delivery of environmental water.

The conceptual understanding of the dynamics of river systems has for many years been based on the River Continuum Concept (Vannote *et al*. 1980). According to this, rivers exhibit gradual downstream changes in hydrology and geomorphology which, in turn, implies gradual changes in biological processes and ecosystem function. Tributaries were recognised as no more than sites of disturbance to the downstream continuum. However, over time it has become increasingly apparent that the influence of tributaries is sufficiently disruptive to define what has been termed a river ’dis-continuum‘ (Ward and Stanford 1983, Perry and Schaeffer 1987). This led to the link discontinuity concept in which rivers are viewed as networks with tributary confluences constituting nodes linked together by intervening reaches of the river main stem (Rice *et al*. 2001). The concept was further developed in the network dynamics hypothesis, which considers river networks as populations of channels and their confluences (Benda *et al*. 2004b).

Much of the work done to date has focussed on understanding flow and mixing regimes at tributary and main stream confluences and the relationships between sediment transport, morphology and stratigraphy. Until relatively recently, less attention had been paid to the biological attributes of confluences (Rice *et al*. 2008a). At a slightly larger scale than the confluence itself, the confluence zone is considered to be an important site for storage of sediment and organic materials in the form of fans and terraces while, at the larger scale of reaches, main stream adjustments to the influx of water, sediment and organic materials are know to influence abiotic and biotic processes (Rice *et al*. 2008a).

These advances owe much to the development of spatially explicit sampling methodologies, including the use of high resolution digital elevation data allowing for accurate mapping of tributary networks. Improved sampling designs and analytical approaches, including modelling, which take into account the discontinuities caused by tributaries, rather than attempting to avoid them, have also become the norm (Torgersen *et al*. 2008). The result has been an increase in research into and understanding of the influence of tributaries on the physical and ecological functioning of rivers.

The literature on the ecological role of tributaries relates mainly to regulated systems, reflecting anthropogenic influences on most of the world’s freshwater supplies (Gregory, 2006, Poff and Zimmerman 2010). Furthermore, there is a bias towards the effects of tributaries on fish populations, which is probably due to their economic importance in many areas. There is less emphasis on processes such as primary production, decomposition and nutrient cycling. The emphasis on regulated systems is also evident in the Australian literature (e.g. Growns *et al*. 2009, Chester and Norris 2006, Growns and Growns 2001, Thoms and Sheldon 2000, Erskine 1985, Erskine *et al*. 1999, Pusey *et al*. 1998, Sherrard and Erskine 1991, Storey *et al*. 1991, Walker 1980), which is understandable, given that water is a scarce resource in much of Australia and most of the major river systems have been extensively altered by impoundments from which large amounts of water are abstracted for agriculture, industry and domestic use (Harris and Gehrke 1997). In the Australian context, this bias is compounded by a paucity of studies specifically on the roles of tributaries which, in most cases, must be inferred (e.g. Growns and Davis 1994, Erskine *et al*. 1999, Pusey *et al*. 1995, 1996).

This review examines the influences of unregulated tributaries on the main channel of rivers by considering their effects at the confluence where a tributary joins the channel, in the confluence zone, which may extend upstream and downstream for tens of metres in the case of a small river and downstream for several hundred metres in larger systems, and in the main channel downstream of the confluence zone, which again may extend from a few hundred metres to several kilometres. Since the emphasis is on physical and ecological effects of tributaries, no further consideration is given to methodological approaches.

Tributary effects in the confluence and confluence zones

Geomorphology and hydrology

The extent to which tributaries influence channel morphology in the main stem of a river is a function *inter alia* of the number of tributaries, their size and how they connect to the main channel. At the catchment scale, the downstream sequence of geomorphogically significant tributary confluences depends on the shape of the catchment and the structure of the network of interconnections of tributaries and the main channel. The extremes are heart-shaped catchments, in which significant confluences tend to occur all along the main channel, and rectangular or elongated catchments, where the number of significant confluences is much more limited (Benda *et al*. 2004a, b). However, local scale network geometry (kilometres) may modify large scale patterns depending on the geologic structure and the tectonic and erosional history of a sub-catchment (Benda *et al*. 2004a).

There is a threshold size below which a tributary may have little or no influence on the main channel. A review of 14 studies in the western United States and Canada indicated that tributaries with basins smaller than 1 km^2 have no effects on rivers with basins of 50 km^2 or larger (Benda *et al*. 2004a). Above this threshold, there is a linear relationship between the distances separating geomorphologically significant confluences and drainage area of the main river.

The principal way in which a tributary affects the main channel is by transport of sediment and debris to form alluvial fans, bars and terraces. The interaction of the tributary and main channel flows can substantially alter channel morphology both upstream and downstream of the confluence. Upstream effects (the zone of interference) include lower gradients, wider channel, increased bank erosion, more woody debris and finer substratum, while downstream effects (the zone of mixing) include steeper gradient, coarser substratum, deeper pools, formation of bars and greater frequency and intensity of disturbance (Benda *et al*. 2004b).

In Oregon coastal rivers, debris flows (wood, boulders and sediment) increase the physical heterogeneity of the confluence by increasing the roughness of the bed, trapping fine sediment and increasing the residence time of woody debris (Bigelow *et al*. 2007). However, if large amounts of fine sediment are deposited in the main stream, geomorphic heterogeneity may decrease, as was found in Creightons Creek in the Goulburn-Broken Catchment, central Victoria. In this stream, bank erosion resulted in a massive increase in bedload that affected the middle reaches of the system (Bartley and Rutherfurd 2005). In the Lower Hunter Valley Gippel (2004) found no consistent relationships between discharge and channel morphology at tributary junctions, although such relationships were apparent at a larger scale. Possible explanations for this include asynchrony in discharge between tributaries and the main stream, differences in the nature of sediments transported down different tributaries and interactions of flow with stream profiles below junctions.

Since the magnitude of effect of a tributary depends on the ratio of its flow to that of the main channel (Poff and Zimmerman 2010), it follows that factors that reduce the latter, such as abstraction of water and impoundments, will increase the influence of tributaries on the geomorphology of confluences. This explains the greater number of tributaries that have a significant effect in regulated rivers (Benda *et al.* 2004a). After construction of the Glenbawn Dam on the Upper Hunter River, the river channel contracted due to the formation of sediment bars immediately below the confluence of the first unregulated tributary (Erskine 1985). Sediment bars have also formed at the mouths of tributaries on the Snowy River below the Snowy Mountains Hydroelectric Scheme (Erskine *et al*. 1999). Similarly, after construction of the Windamere Dam on the Cudgegong River in New South Wales, main channel flow was greatly reduced and unregulated tributaries supplied most of the sediment to the main channel. As a result, sediment bars and in-channel benches formed at confluence sites (Benn and Erskine 1994). Bed aggradation and deposition of sediment at tributary junctions also occurred after construction of the Mangrove Creek Dam on the Hawkesbury River, New South Wales (Sherrard and Erskine 1991). A similar effect was found downstream of a dam on the Rheidol River in Wales, UK (Petts and Greenwood 1985). In contrast, floods in the main channel resulting from overtopping or controlled releases of water from dams can remove large amounts of sediment from confluences and transport this downstream (Rice *et al*. 2008).

Sedimentology

Confluences and proximal areas upstream and downstream of confluences are recognised as important sites for storage of sediment and organic materials in rivers (Rice *et al*. 2001). The dispersal of sediment at confluences is a function of flow dynamics, but also controls bed morphology which, in turn, feeds back upon sediment transport. Confluences, where coarse sediment enters the main channel, cause the downstream slope to increase (aggradation) while reducing upstream slope and sediment size due to a damming effect. Degrading confluences, where finer material is injected into the main stream, decrease the downstream slope, but have little or no upstream effect (Ferguson *et al*. 2006).

Several factors affect the way in which a tributary may affect main stream sediments at the confluence.

The angle at which a tributary enters the main stream may determine its effect. Studies on the River Ure, in North Yorkshire, UK, have shown that as confluence angle and discharge ratio increase, sediment from a tributary tends to become segregated from that of the main channel and flows around the confluence. Under these conditions, a tributary can partially dam a main stream forming a wider floodplain with greater lateral connectivity (Best 1988).

Tributary and main channel flows may not be synchronous, while sediment loads and rates of discharge may vary seasonally or from one flood event to another. Seasonal flushing of stored sediment, following increased rain in spring, is a significant feature of sediment dynamics in a small tributary of the Lachlan River in the Central Tablelands of New South Wales (Smith 2008). This has led some to advocate the integration of long-term data into mathematical models in order to predict the cumulative effects of tributaries on sedimentation (Rice *et al*. 2006, Ferguson and Hoey 2008).

Since alluvial fans near confluences are formed mainly during flood conditions, the extent of their up- and downstream influences varies in response to fires, storms and floods (Benda *et al*. 2004a). When there is little erosion in the watershed, depositional features at confluences tend to be eroded by floods, but expand again during erosional periods in the watershed.

Confluences tend to amplify the effects of disturbances in catchments. Close to confluences, both the frequency and magnitude of sediment fluctuations are higher than further downstream because of the saltatory nature of stream inputs (Bigelow *et al*. 2007).

The size of the catchment of a tributary has a direct bearing on the age of alluvial structures, with older structures being associated with smaller catchments that may be characterised by long periods of low flow punctuated by occasional infrequent flash floods. Alluvial structures at the mouths of large tributaries are generally younger because they are reworked by frequent discharge events (Benda *et* *al*. 2004a). Such differences in age have implications for the stability and nature of habitats that these structures may provide.

While it is clear that the contribution of water and sediments from tributaries directly affects the structure of the main channel, this is not always a one-way process. A recent study of the effects of floods in the River Rhine (Beckmann *et al*. 2005) showed that increased flow in the main channel reduced current velocities in tributaries by causing them to backup, resulting in the deposition of fine sediment.

Water quality

Just as tributary flows can contribute significantly to sediment and debris loads, they also affect water quality in the receiving channel. The most conspicuous effect is increased turbidity due to suspended solids. For example, turbidity increases and light penetration decreases immediately downstream of tributary confluences on the Colorado River (Stevens *et al.* 1997). Tributary flows can also cause variations in temperature, nutrients and contaminants, and create or disrupt gradients in the water chemistry in the main channel (Gooseff *et al.* 2008. Kiffney *et al*. 2006). Depending on local climatic conditions, the water temperature in a tributary may differ markedly from that in the main channel. Temperatures in slow flowing, shallow tributaries may be several degrees higher than in the main channel. For example, water in the Mutt River, a tributary of the upper Rhône River in Switzerland, has a wider temperature range and is usually much warmer than that in the Rhone itself, which is fed at that point primarily by melting ice (Knispel and Castella 2003).

Differences in temperature between tributaries and main channels may be exacerbated on regulated rivers depending on the release point from within the dam and location of the dam relative to the landscape. Hypolimnetic release of temperature-stratified water from lowland dams, such as Keepit Dam on the Namoi River (a tributary of the Darling), can depress river temperatures by up to 10ºC, but this effect is reduced to about 1ºC by contributions of warm water from downstream tributaries (Preece and Jones 2002). Water below a dam on the Green River, Utah, is several degrees colder than that in an unregulated tributary (Vinson 2001), while tributaries on the Murray River downstream of Lake Hume tend to be warmer than the main channel (Walker 1980). In higher altitude dams with epilimnetic releases via multi-level offtakes, the regulated river can be much warmer than the unregulated snow-melt tributaries (pers. com. S Williams).

Tributaries may also contribute to or break down thermal stratification in deep pools depending on the magnitude of the flows from the tributary relative to the cross sectional area and volume of the receiving waters of the main channel. Typically large events are required to break down thermal stratification (Reinfelds and Williams in prep).

Headwater streams transport organic matter including dissolved organic carbon, particulates and woody debris into larger channels (Bigelow *et al*. 2007, Gomi *et al*. 2002, Wipfli and Gregovich 2002), all of which directly affect water quality at the confluence. Furthermore, confluences are often sites of storage of benthic organic matter, particularly where large boulders and woody debris trap fine material (Bilby 1981), although much of this material is eventually transported downstream. Whether a confluence acts as a repository for benthic organic matter depends on its discharge ratio. In a study of the Acheron River in the central Highlands of Victoria, Wallis *et al*. (2009) found no systematic pattern in the distribution of suspended particulates at or around confluences, but they did find a positive relationship with discharge ratio and that tributaries contributed to an increase of about one third in the export of particulates during periods of high flow.

An area of research that has received increasing attention in recent years is the role that the hyporheic zone plays in a number of ecological processes in streams (Boulton *et al*. 2010). The hyporheic zone is the interstitial space in the sediments below a stream bed in which processes such as decomposition of organic material and recycling of nutrients occur. These, in turn, directly affect primary production in the surface waters of streams and hence their contributions to the ecology of the main channel (Mulholland and Webster 2010). Exchange of water between the overlying stream and the hyporheic zone has a significant influence on the quality of water transported by tributaries (Boulton *et al.* 1998).

While many influences of tributaries may be considered positive, there may also be negative impacts due to excessive amounts of sediment (Wood and Armitage 1997) causing increased turbidity which limits primary productivity, and inputs of contaminants, such as herbicides and pesticide residues (Muschal and Warne 2003, Webb and Walling 1992). In addition, elevated salinity is a problem in many parts of the world, including Australia. In the Hunter catchment in New South Wales, for example, streams are at risk from elevated salinity originating in natural marine sediments, but exacerbated by land use practices and mining (Muschal 2006). Saline streams entering the Hunter contribute to an increase in salinity and a decrease in water quality with potential impacts on invertebrates and fish (Hart *et al*. 1991). Macroinvertebrate species richness was negatively correlated with salinity in saline tributaries (Back Ck. and Bushy Ck.) of the Hopkins River in Victoria (Mitchell and Richards 1991). In the Murray River the concentrations of ions such as Cl^-, HCO_3^-, and Na^+ increase markedly downstream from the headwaters, with significant contributions to the ionic concentration coming from saline tributaries (Campaspe River and Barr Creek) (Herczeg *et al*. 1993).

Physical habitat

Tributaries have significant abiotic effects on the main stream, including changes in water volume, water chemistry, and the amounts of organic matter and sediment. These, in turn, influence the physical habitat at and near to their junction with the main channel. Tributaries affect the total wetted area, slope, width and depth of the main channel, as well as sediment characteristics, water temperature, hydraulics and flow (Rice *et al*. 2008a). Confluences are a source of habitat heterogeneity with the formation of sand banks, alluvial fans, deep pools, boulders and debris fields providing a variety of habitats for aquatic animals and plants. A significant relationship has been found between number of species and habitat complexity in Pranjip Creek in the Strathbogie Ranges of north central Victoria, with more species found in complex habitats (O'Connor 1991). In a survey of river basins in the Cascade Range, Washington, Kiffney *et al*. (2006) found that the amount of wood, the variability in median substrate size and concentrations of nitrogen and phosphorus and algal biomass were all higher at or immediately downstream of tributary confluences.

Disturbance in the catchments of tributaries can also influence the interaction between a tributary and the main channel. For example, burning of the catchment around streams in Idaho increased year-on-year variation in sediment loads, organic debris and large woody debris and affected the stability of habitats at confluences (Arkle *et al*. 2010).

The influence of tributaries in structuring physical habitats is also important in regulated rivers (Poff and Zimmerman 2010), but the extent to which unregulated tributaries decrease the influence of dams depends on the size of the tributaries, their distance from the dam, and their discharge, sediment and water temperature characteristics (Petts 1986). A confluence with a major tributary which increased flow in the main channel of the Canning River, Western Australia, allowed macroinvertebrate assemblages to recover after being depleted following construction of the Canning Dam (Storey *et al*. 1991). Downstream of the Glenbawn Dam (Hunter River), the streambed channel downstream of the first tributary narrowed and the banks became colonised by riparian vegetation, particularly willow (*Salix* spp.) (Erskine 1985). Similar effects have been observed near tributaries below Mangrove Creek Dam in the Hunter catchment, with tea trees (*Leptospermum* spp.) becoming established on in-stream sediment deposits following dam construction (Sherrard and Erskine 1991), and below Windamere Dam on the Cudgegong River where 'weeds' became established on sediment deposits (Benn and Erskine 1994). Impoundment also resulted in the development of sediment deposits below a dam on the Rheidol River, Wales, UK (Petts and Greenwood 1985).

Biology and ecosystem processes

The physical heterogeneity resulting from the interaction of tributaries and main channels has implications for the ecology of river systems because increased habitat heterogeneity leads to an increase in biodiversity (Downes *et al*. 1998). Benda *et al*. (2004b) have proposed that confluences are biological hotspots that contribute disproportionately to the biodiversity of river networks and subsequent studies appear to support this. Tributary size has a significant influence on macroinvertebrate diversity in a Finnish watershed, although small-scale influences on diversity around riffles were also important (Heino *et al*. 2005). In contrast, Heino and Mykra (2006) found a weak but significant relationship between landscape-scale stream classifications (small, medium and large streams) and macroinvertebrate diversity. They ascribed this to individualistic responses to environmental gradients, the occurrence of many macroinvertebrate taxa across all stream classifications and the fact that few species show strong stream fidelity.

Intermittent tributaries of the Arc Stream in south-eastern France had the highest taxonomic richness and contributed significantly to diversity in the main stream (Maasri *et al*. 2008). Sand banks that developed after the construction of a dam on the Glenelg River in Victoria supported macroinvertebrate diversity that, although similar to that in river runs and pools, contributed significantly to the diversity of a system that had been degraded by impoundment (Lind *et al*. 2009). Similarly, in the Agi-gawa River in Japan, the influence of a tributary partially compensated for dam-related environmental impacts on macrobenthic assemblages (Katano *et al*. 2009).

Confluences are often associated with increased productivity due to the supply of nutrients, drift and detritus from the tributary (Rice *et al*. 2008b). Habitat discontinuities at confluences were found to be associated with shifts in algal biomass and increases in sculpin and salmonid abundance (Kiffney *et al*. 2006). In the Solimões-Amazon main stream the diversity of electric fishes is greatest near confluences, particularly where a tributary provides nutrient and prey (Fernandas *et al*. 2004).

Because confluences are often characterised by distinct upstream, downstream and confluence environments, they support mobile species that exploit the juxtaposition of these habitats leading to increased complexity of riverine food webs (Power and Dietrich 2002). Examples include yellow-legged frogs (*Rana boylii*) which over-winter in tributaries of the South Fork Eel River in California, but return to the main stream to breed (Kupferberg 1996), possibly in response to higher algal productivity (Rice *et al.* 2008b). The opposite sequence, in which fish (humpback chub) migrate from the Colorado River into the Little Colorado to spawn, has also been noted (Gorman and Stone 1999). Seasonal changes in the ratios of may flies to caddis flies below the confluences of tributaries on the West River, Vermont, have been related to the movement of sediment from the tributaries (Svendsen *et al*. 2009). Tributaries may also act as refugia, as illustrated by the seasonal use of tributaries by fish in Alaskan rivers (Bramblett *et al*. 2002) and in the range Mountains of Trinidad (Fraser *et al*. 1995).

The unusual hydrology and morphology at confluences may provide opportunities for some animals. River dolphins, for example, show preferences for tributary junctions along the Mahakam River in Borneo and also in the Yangtze River, possibly because deep pools and scour holes trap fish on which they feed (Rice *et al*. 2008b). Such pools can also provide habitat for over-wintering steelhead (Nakamoto 1994).

The interaction between a tributary and the main channel is a two-way exchange in which flow in the main channel can influence physical conditions in a tributary. Beckmann *et al*. (2005) found that sediments in the mouth of tributaries in the Rhine were affected by floods, which reduced sediment particle size by decreasing water flow rates, and that the composition and diversity of macroinvertebrates were reduced.

It is clear that tributary confluences are special places with unusual physical characteristics that support an increased diversity of organisms compared to the main stream of many rivers. In addition, confluences and confluence zones also have significant influences on downstream conditions by altering channel structure and providing energy supplements in the form of organic material and nutrients. This in turn affects biological communities and ecological processes at the larger scales of river reaches and channel networks (Rice *et al*. 2008b).

Downstream effects of tributaries

Physical effects

Tributaries may cause discontinuities in water quality and flow in the main channel of rivers, resulting in punctuated downstream fining of sediment which divides the river into what have been termed sedimentary links (Rice and Church 1998). The extent to which the changes in channel morphology, water volume, sediment characteristics and water quality extend downstream from the confluence depends on a variety of processes. Influxes of sediment may result in the formation of large sand bodies that are moved downstream slowly by river flow (Bartley and Rutherfurd 2005). These sand bodies may reduce the capacity of the channel, decrease the variety of morphological features, smother in-stream habitat and reduce the coarseness of the substratum and its stability (Bartley and Rutherfurd 2005). They can also have beneficial effects, promoting the formation of wetlands which support a diverse range of other organisms and act as filters for nutrients (Lind *et al.* 2009).

Where a tributary contributes sediment to a main stream, there is usually some adjustment downstream to the slope of the stream bed and sediment grain size. For example, to accommodate the material load from a sediment-laden tributary, there may either be an increase in slope (aggradation) or a straightening of the channel (lower sinuosity). Conversely, downstream of clear water tributaries, slope may decrease (degradation) and the channel may become more sinuous (Ferguson and Hoey 2008). Both aggrading and degrading junctions can have an influence on bed grain size which extends for a considerable distance downstream (Ferguson *et al*. 2006). An alternative effect of clear water tributaries is armouring of the bed which occurs in rivers where fine grain sediments predominate and are scoured by tributary flows (Thorgersen *et al*. 2008). Therefore, the extent and nature of downstream adjustments depend on the relative amounts of water and sediment in the tributary and main stream, which is why tributaries may be more influential in regulated rivers.

One of the most common effects of tributary flow on main channels is an increase in channel width in the downstream receiving river. Studies have shown that width is fairly constant along individual channel links (reaches between tributary confluences), but increases occur past junctions in proportion to the length of the link (Richards 1980). Another common effect is that tributaries create discontinuities in slope and/or grain size such that slope and grain size tend to decrease along channel links, but increase abruptly at the start of the next link (Ferguson and Hoey 2008). Changes in water quality are common downstream of tributary confluences, but the extent of their influence depends on dilution, oxidation, chemical reactions, deposition and degradation and also vary with catchment hydrology, runoff and stream discharge (Rice *et al.* 2001).

Biological and ecosystem effects

One of the most important effects of tributaries is their contribution to sediments loads in the main channel. If the sediment is relatively coarse it will settle out close to the confluence. However, fine sediment will be transported downstream where it can have a marked impact on primary productivity and faunal diversity. Fine sediment reduces light penetration and photosynthetic activity and may damage macrophytes by abrasion of the leaves or by smothering. Fine sediments also adversely affect macroinvertebrates by changing substratum composition, increasing drift, and affecting respiration by clogging respiratory structures. On the other hand, taxa, such as Chironomidae, which use fine sediment for construction of tubes, may benefit under these conditions (Wood and Armitage

1997). The contribution of sediment from a major tributary of the Yahagi River in central Japan largely reversed the effects of a hydroelectric dam on macroinvertebrate assemblages (Takao *et al*. 2008).

In contrast to the above, tributaries can increase habitat heterogeneity and together with energy subsidies in the form of organic matter and nutrients, increase taxonomic diversity and productivity (Rice *et al*. 2001). Inputs of nutrients from agricultural land in the catchments of tributaries on the Swan River in Western Australia are thought to have significant effects, such as increasing primary production, on the ecology of the downstream parts of the river, including the estuarine reach (Peters and Donohue 2001). In the Colorado River, which is fragmented by a number of dams, species richness of riparian vegetation was found to increase as a function of distance downstream of dams in part through contributions of seeds from tributaries (Merritt and Wohl 2006). Tributaries on the Danube contribute significantly to zooplankton in the main channel (Bothar 1981 in Cellot 1996), while aquatic macroinvertebrate drift from tributaries has been shown to affect downstream assemblages in the Mississippi (Eckblad *et al*. 1984 in Cellot 1996, Scheaffer and Nickum 1986a), and in the Upper Rhône River in France, with seasonal variations in drift reflecting life cycle characteristics of the fauna rather than flow regime (Cellot 1996).

At the catchment scale, the degree of river-stream connectivity and variability in habitat features among tributaries are known to affect fish assemblage structure (Hitt and Angermeier 2008, Reyjol *et al*. 2008). Patterns in fish assemblages along the Napo River in Ecuador have been related to downstream gradients in turbidity, substratum and pH modified by the influence of tributaries (Ibarra and Stewart 1989). In a long-term study of paddlefish in the Missouri River, Pracheil *et al*. (2009) found a strong correlation between young-of-the-year recruitment in the main river and flow characteristics from an unregulated tributary. Wipfli and Gregovich (2002) estimated that in coastal rivers of Alaska, every kilometre of salmon-bearing channel receives energy inputs from tributaries sufficient to support up to 2000 young-of-the-year salmonids. The position of tributaries within the river drainage network has also been shown to influence the diversity of fish assemblages (Osborne and Wiley 1992; Slawski *et al.* 2008).

The diversity of electric fishes in the Amazon, apart from being greater immediately downstream of tributaries (section 2.2.5), increases in a downstream direction as each tributary contributes to overall diversity (Fernandas *et al*. 2004). This effect may be due in part to enhancement of local habitat heterogeneity and niche diversity downstream of tributaries (Rice *et al*. 2001). The distribution and diversity of fish in tropical rivers in Queensland is significantly associated with habitat structure (Pusey *et al*. 1995, Pusey and Kennard 1996), while in the Burdekin River, Queensland, fish community structure is also influenced by differences in habitat structure of main channel and tributary systems (Pusey *et al*. 1998). Backwaters in the Mississippi are important nursery areas for fish and support at least 13 families including Cyprinidae, Clupeidae and Sciaenidae. Larval fish drifting into the main stream are responsible for maintaining downstream populations (Scheaffer and Nickum 1986 b). Reproductive success of migratory teleosts downstream of a dam on the São Francisco River in Brazil, was restored in the section of the river below a major unregulated tributary (Sato *et al*. 2005). The reproductive success of endangered species, such as Macquarie perch (*Macquaria australiasica*) may also be enhanced by tributaries which provide spawning habitat, while galaxid (*Galaxis* spp.) populations are greater where the fish find refuge from predation by trout (*Salmo trutta*), such as above impoundments and in tributaries (Tilzey 1976).

As in the confluence and confluence zone, the downstream extent of the influence of tributaries on the main stream of rivers depends on the interaction of many factors. Arguably the most important of these are the relative size of the tributary and main river and the relative amounts of sediment that each one contributes. Tributaries with large relative flows and sediment loads will influence the main channel over greater distances than smaller tributaries. The major effects of tributaries include increasing habitat heterogeneity, providing energy supplements in the form of organic matter and nutrients and acting as refugia, nurseries and sources of recruits for faunal assemblages in the main channel. Tributaries are particularly important in regulated rivers because they can ameliorate the effect of impoundment by restoring more natural flows and providing habitat for fauna that may have been displaced from the main stream. In such systems, management of tributary catchments to ensure good water quality and flow may be as important as managing flow in the main stream.

Conclusions

The majority of the literature on the influences of tributaries on main channels of rivers is based on studies conducted in North and South America and to a lesser extent in Europe. The applicability of this information for Australian rivers is still untested. There have been numerous studies on river systems in Australia, usually with an emphasis on regulated systems, but there is surprisingly little information on the role of tributaries. This is clearly an area where further studies, specifically on the interactions between tributaries and main channels, would yield useful information for management. In particular, increased management of the flow regimes of unregulated tributaries via protection measures such as embargoing water resource development in undeveloped tributaries or setting of appropriate diversion limits on minimally hydrologically-affected tributaries may provide an improved mechanism for the rehabilitation of regulated rivers.

Known roles of tributaries

In summary, the review has highlighted the following general points:

- Tributaries have significant influences on the physical structure of rivers, including alteration of sediment loads and amounts of woody debris, stream bed morphology, channel width, flow regimes and water quality.
- Tributaries provide energy subsidies to the main channel in the form of organic carbon, nutrients, silica, and suspended particulates.
- By increasing habitat heterogeneity and acting as sources of recruitment, tributaries contribute to biological productivity and diversity.
- Tributaries act as refugia or as conduits for dispersal for a variety of aquatic fauna and contribute to recolonisation of the main channel after major disturbance events such as floods.
- Tributaries can ameliorate the effects of impoundment by restoring flow and water quality and providing favourable habitats for spawning

Major information gaps

As will be evident from this review, there have been numerous studies on the hydrology and ecology of rivers in Australia, with the majority focussing on regulated systems. There have also been some studies on the ecology and functioning of tributaries. Few of these, however, have highlighted the interactions between tributaries and river main stems in the ways commonly done for river systems in the Northern Hemisphere. The hydrology of Australian rivers varies greatly, ranging from high-flow tropical systems with strong seasonality, snowmelt dominated regimes with large peaks in spring and a predictable base flow, to low-flow systems draining arid areas, and are subject to intermittent flash floods and extremes of physical conditions. Kennard *et al* (2009) identifies 12 broad hydrological regimes for Australia. The variation in hydrological regimes across Australia limits the applicability of much of the information on river systems where rainfall and flows are more consistent. Consequently, there are still many gaps in our understanding of the role of tributaries in the ecology of rivers in this country. These include:

- The influence of temporal variations in the relative flows of tributaries and main stems on downstream ecology. For example, there is a need to relate long-term data on flows to the physical structure of stream beds as a basis for modelling the effects of tributaries under a variety of flow conditions.
- How environmental flows and their management affect the interactions between tributaries and river main stems.
- The effects of different patterns of land-use (e.g. agriculture, forestry and urban development) and the role of fire on flows and water quality in tributaries.
- The impact of increased abstraction and salination of water in tributaries on rivers.
- Linkages between hyporheic flow in tributaries, particularly breakdown of organic matter and recycling of nutrients, and productivity in river main stems.
- The role of tributaries as reservoirs of biodiversity in highly modified river systems.

Finally, while beyond the scope of this review, the development of conceptual models of the influence of tributaries on rivers, based on local conditions, would be useful in planning and management of water resources. Given the variety of conditions prevailing in Australia, it would be logical to develop regional models which would focus, for example, on the snowmelt rivers of the Australian Alps, the wet tropics, the east and south coasts, including Tasmania, the Western Australian coastal belt and the arid interior. These could become the basis for predictive models as the information gaps are filled.

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