Are our urban streams on fire? Using studies on fire to learn about the Urban Stream Syndrome

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Key Points

- Fire disturbs stream ecosystems in a similar way to urbanization and can help us to disentangle the importance of flow from other stressors
- A comparison of urban and fire effects on stream ecosystems supports the assertion that altered flow is the key stressor of the Urban Stream Syndrome
- Studies on fire suggest that urban biota will be increasingly stressed by climate change

Abstract

The Urban Stream Syndrome is a term applied to describe the multiple impacts urbanisation has on aquatic ecosystems. Altered hydrology is considered to be the dominant stressor driving the syndrome. However, the current focus on hydrology may overshadow the importance of other stressors, such as poor water quality and a degraded riparian zone. Separating the effects of altered flow from other stressors is difficult in urban studies, because stressors typically change concomitantly. One novel way to learn is by comparing urban streams to streams affected by fire. Fire causes similar hydrologic symptoms to urbanisation, but can have reduced impacts if the riparian zone remains intact. Importantly, the effects of fire are independent of non-nutrient pollution. Thus fire can provide an insight into the role of hydrologic versus trophic and pollution disturbance in urban streams. Here we use the literature to compare and contrast the effects of urbanisation and fire on streams. We find marked similarities in symptoms between fire affected and urban streams, reinforcing the view that altered flow is the dominant stressor. However, we note some differences which suggest pollution and riparian vegetation exert some influence, even in flow-disturbed systems. We encourage researchers to explore novel ways to advance our understanding of the Urban Stream Syndrome.

Keywords

urbanisation, fire, stream health, macroinvertebrates, waterway management, land use

Introduction

Urban streams are highly degraded, exhibiting a suite of symptoms termed the Urban Stream Syndrome (USS) (Walsh et al. 2005a). Symptoms include increased flow volume and variability, elevated nutrients and pollutants, increased water temperature and conductivity, and the loss of sensitive species (Klein 1979, Walsh et al. 2005b). Altered flow, driven by directly connected impervious area, is considered to be the key stressor driving the USS, particularly in south-eastern Australia (Walsh et al. 2005b, Walsh et al. 2007, Imberger et al. 2014, Vietz et al. 2014). However, most urban studies struggle to separate the effect of altered flow from that of altered water quality, riparian influences and instream habitat because these ecosystem components typically degrade together along an urban gradient (Walsh et al. 2005a). The covariation of stressors is currently limiting the ability of research to determine the key stressors of urban streams, and hampers our ability to implement targeted management actions. What is needed are novel approaches to increase our understanding. One way to learn is by comparing the symptoms of urbanisation to those caused by fire.

Urbanisation and fire both disturb freshwater systems. However, while urbanisation is chronic, cumulative, and promotes homogenisation (McKinney 2006), fire is short-lived, often patchy and promotes heterogeneity across the landscape (Malison and Baxter 2010, Pillsbury et al. 2011). While the time frames and mechanism of disturbance differ, the ecological consequences of urbanisation and fire on streams are strikingly similar. For example, both urbanisation and fire lead to an increase in the volume and flashiness of stream flow, channel change, increased sedimentation and nutrients (Gresswell 1999, Minshall 2003). However, differences also occur. For example, fire typically does not lead to increases in man-made pollutants, i.e. heavy metals, hydrocarbons, pharmaceuticals, as urbanisation does. Also fire may not always lead to destruction of the riparian zone (Klose et al. 2015). Differences between fire- and urban-affected streams may help us to separate the influence of altered flow from that of altered non-nutrient pollutants. Similarly, differences between streams with burnt and unburnt riparian zones could reveal the extent to which riparian restoration can deliver improvements to urban stream health in the face of altered flow, sediment and nutrient regimes.

This paper compares and contrasts the effects of urbanisation and fire on stream ecosystems using existing scientific literature. We use this summary to learn about the relative importance of different ecosystem drivers of the USS. We expect that if flow is the overriding driver of the USS that urban- and fire-affected streams will display very similar symptoms; whereas, if riparian vegetation and man-made pollution are important factors shaping the USS that urban- and fire-affected streams will display different symptoms, for example, different macroinvertebrate assemblages. We also use studies on fire to provide an insight into the recent heterogeneity in the USS, and finish by discussing the implications of fire-related learnings on the rehabilitation of urban streams.

Urbanisation vs fire: similarities and differences

Urbanisation and fire elicit a number of similar and different responses from stream ecosystems. Some of the differences may be due to differences in the severity and magnitude of disturbance effects, the timing of sampling post-disturbance in fire-affected studies along with the frequency of fire, and the types of sampling and analytical methodologies used. However, in general we consider that the patterns presented here to be relatively robust for several reasons. Firstly, because considerable research has been done in both of these ecological fields and general patterns have already been identified by prior reviews and syntheses (see Paul and Meyer (2001), Walsh et al. (2005a) for urban studies and Minshall et al. (1989, 2003), Gresswell (1999) and Verkaik et al. (2013) for fire studies). In addition, most of the research on fire has been conducted on severe or large fires (Bixby et al. 2015), reducing the likelihood that non-fire related variation is obfuscating patterns.

Urbanisation and fire have similar effects on stream ecosystems. Physical changes include increased flow volume and flashiness (Gresswell 1999, Coombs and Melack 2013, Klose et al. 2015), widened and deepened channels (Roby 1989, Minshall et al. 1997), increased in sedimentation (Roby and Azuma 1995, Gresswell 1999, Coombs and Melack 2013) and increased light, temperature and nutrients (Gresswell 1999, Noske et al. 2010, Coombs and Melack 2013) (Table 1). Energetic changes include a shift in the basal resources supporting the food web of small streams from detrital (allochthonous) systems towards algal (autochthonous) systems (Minshall et al. 1989, Mihuc and Minshall 2005, Reid and Thoms 2012, Tuckett and Koetsier 2016). Biotic changes include a decrease in total macroinvertebrate species richness, the predominance of chironomid species (Mellon et al. 2008, Roby and Azuma 1995, Verkaik et al. 2015, Walsh et al. 2005a), and a varied response from instream algal communities. The varied algal response is a consequence of increased algal production driven by increased light and temperature associated with the destruction of riparian vegetation, and decreased algal production brought about by increased substrate disturbance and turbidity associated with increased scouring flows (Paul and Meyer 2001, Minshall et al. 2001, Mellon et al. 2008).

Although there are similarities, urbanisation and fire create a number of different effects on stream ecosystems. For example, fire, unlike urbanisation does not lead to increase in non-nutrient pollutants instream, unless fire retardant chemicals have been sprayed (Verkaik et al. 2013). Also, while urbanisation causes a decrease in woody debris associated with the clearing of riparian vegetation and desnagging, fire can lead to an increase in instream woody debris as burnt trees fall into the stream or because of tree fall associated with bank collapse (Young 1994, Minshall et al. 1997, but see Vaz et al. 2015). Furthermore, while urbanisation reduces both aquatic and terrestrial connectivity via the construction of roads and flow regulating structures, fire only affects riparian connectivity, and only in instances when the riparian zone is burnt (Vieira et al. 2004). Importantly, while urban land clearing and destruction of the riparian corridor leads to a reduction in particulate organic matter (Walsh et al. 2005b), and an increase in light and at times algal production (Roy et al. 2005), fire may, or may not, create these symptoms in accordance with the extent and severity to which the riparian zone is burnt (Cooper et al. 2015, Verkaik et al. 2015). Urbanisation and fire also lead to nuanced differences in the invertebrate assemblage. For while urbanisation leads to an assemblage dominated by physico-chemically tolerant species such as chironomids and oligochaetes (Paul and Meyer 2001, Walsh et al. 2005b), fire leads to an assemblage dominated by colonising species, i.e. those that can cope with frequent physical disturbance, such as chironomids, simuliids and Baetid mayflies (Minshall et al. 2001, Vieira et al. 2011, Verkaik et al. 2013).

Table 1. The ecological consequences of urbanization and fire on stream ecosystem components

Component	Urbanisation	Fire
Hydrology	• Increased flow volume, Increased flashy flows, Increased frequency of flow pulses, increased overbank flow, reduced baseflow	• Increased flow volume and peak discharge, baseflow response not reported
Geomorphology	• Increased incision and widening of channel • Increased sedimentation in short term, but reduced sedimentation in long term	• Channel incision and channel widening often occurs, but not always • Increased sedimentation
Riparian	• Reduction in understorey vegetation and riparian canopy, and terrestrial detritus	• Mixed response depending on whether or not it is burnt. If burnt, reduced canopy cover and litter.
Connectivity	• Reduced aquatic and riparian connectivity	• Little change
Energetics	• Reduction in coarse organic matter • A shift towards autochthonous energy away from allochthonous sources	• Variable response of organic matter • A shift towards autochthonous energy away from allochthonous sources
Water chemistry	• Higher water temperature, greater fluctuations in temperature • Lower dissolved oxygen concentrations, particularly during low flow periods • Increased concentrations of heavy metals, pesticides, hydrocarbons, pathogens and personal care products • Elevated nutrient concentrations (N,P)	• Increase in water temperature • Variable response of oxygen • Most systems experience an increase ions; however, some do not • No change in man-made pollutants • Elevated nutrient concentrations (N,P), but not always
Woody debris	• Loss of woody debris	• Variable response. Many studies report an increase, but some report a decrease or no change
Algae	• Mixed response for algal biomass and productivity	• Mixed response of algal biomass and productivity
Invertebrates	• Decline in species richness • Mixed response for density/biomass • Assemblage dominated by tolerant species, sensitive species, EPT families rare • Detritivore (shredder) species are often lacking	• General decline in species richness, although a few studies have found little change • Mixed response for density/biomass • Assemblage dominated by opportunistic species, i.e. short-lived, fast colonising species, such as chironomids, simuliids and Baetidae and species that have good dispersal • Variable response of shredders/detritivores

Using fire to learn about the drivers of the Urban Stream Syndrome

The similarities and differences between urbanisation and fire can help us to disentangle the principal drivers of urban stream health. If altered flow, and associated increase in sedimentation and nutrients, is the overriding driver of the USS then both urban- and fire-affected streams should display similar symptoms, including parallel changes to the biotic assemblage. Our study provided general support for the dominant role of flow, as there were strikingly similar ecological responses to these very different disturbances, including similar changes to the macroinvertebrate assemblage. The importance of flow, and hydrologic processes more broadly, was further supported by the fact that the severity of stress to both urban and fire-affected streams is linked to the proportion of the catchment that has been built (Walsh et al. 2005a) or burnt (Gresswell 1999), and the fact that ecological changes to streams in burnt catchments are greatest after spates of rainfall (Minshall et al. 1997, Vieira et al. 2004, Verkaik et al. 2013). It appears therefore that while urbanisation and fire are created by very different land use change, i.e., urbanisation is associated with the building/paving of land surface and fire is associated with the burning of vegetation, that both stressors lead to similar hydrologic consequences, i.e. increased runoff and decreased infiltration and evapotranspiration.

We were particularly interested in the macroinvertebrate response to urbanisation and fire, because it provides a synthesis of abiotic alterations, hence provide a good description of general stream condition/health (Rosenberg and Resh 1993). Our study revealed that both urbanisation and fire lead to a decrease in taxonomic diversity and a dominance of chironomid species. If man-made pollutants were playing an important role in shaping the assemblage of urban streams, we would have expected to find a greater number of pollution sensitive species, such as EPT taxa, in fire-affected streams. While we cannot rule out that elevated water temperatures associated with fire caused the loss of these sensitive taxa in fire-affected streams, their general absence (aside from the Baetiidae) from both urban and fire-affected streams suggests that flow-driven disturbance is driving changes in the macroinvertebrate assemblage. Increasing substrate disturbance and sedimentation associated with erosive urban flows is often presented as an important mechanism leading to the decline of EPT taxa (see review by Harrison et al. (2007)). The presence of Baetiids, a colonising family sensitive to heavy metal pollutants, in fire-affected streams but not in urban streams does suggest that water pollution is exerting some influence, albeit secondary on urban streams.

Studies on fire also indicate that the riparian zone can exert some influence on stream function even in the face of catchment-wide increases in runoff. We learnt the most from a recent Californian study which compared stream condition in unburnt sites against burnt sites with and without burnt riparian zones. This study revealed that riparian vegetation in burnt catchments limited algal productivity, maintained the basal resource of food webs as detrital rather than algal, and hastened the recovery of shredder invertebrates (Cooper et al. 2015, Klose et al. 2015). These changes were mediated via reduced light and temperature, and increased inputs of leaf litter (Cooper et al. 2015, Klose et al. 2015). Many of the aforementioned relationships have been found in urban studies (Roy et al. 2005). However, most urban studies have found that these trophic changes have little influence on the invertebrate assemblage (Roy et al. 2005, Walsh et al. 2007). In urban streams with intact riparian zones, the recovery of the invertebrate assemblage may be limited not only by frequent flow and sediment stress and reduced landscape connectivity, but also by a the predominance of non-native leaf litter which degrades rapidly in the face of elevated nutrient concentrations (Imberger et al. 2008, Rosemond et al. 2015).

Fire, heterogeneity in the Urban Stream Syndrome and other learnings relevant to the management of urban streams

There is growing recognition of heterogeneity within the USS (Booth et al. 2016), and recent studies have highlighted the importance of climate and landscape attributes (soil type, slope, vegetation) to the manifestation and severity of the USS (Hale et al. 2016, Utz et al. 2016). Studies on fire provide support for this advancement. Indeed, fire researchers frequently highlight the importance of landscape attributes such as physiography (slope, soil type), vegetation and climate on the magnitude of stream disturbance post fire (Gresswell 1999, Townsend and Douglas 2000, Verkaik et al. 2013, Verkaik et al. 2015). Broad agreement between these disciplines stems from the universal influence of climate and physiography on runoff; i.e. runoff will be greater in high gradient streams (Minshall et al. 1997); when geomorphic sensitivity, i.e. erodibility, is high (Swanson 1981); and when rainfall is frequent and severe (Vieira et al. 2004). The agreement across disciplines highlights the importance of local and regional factors to the manifestation of the USS and reiterates the importance of local context to the management and repair of urban streams.

The importance of climate to flow-related disturbance in both urban and fire-affected streams alike, infers that climate change may alter the severity of urban stream symptoms and how we manage streams moving forward. While little research has been done on climate change and urban streams (but see Mantyka-Pringle et al. (2014)) we can learn from studies on fire. A recent comparison of fire effects across different biogeographic regions revealed that macroinvertebrate assemblages are disturbed more in regions experiencing drought and protracted low flow (south-eastern Australia) (Verkaik et al. 2015). Researchers propose that low flows exacerbate fire disturbance by limiting opportunities for recolonization (i.e. drift) and by increasing physico-chemical stress (Verkaik et al. 2015). If applicable to urban streams, this finding suggests that climate change will magnify the stress caused by urbanization. A recent study in Austin, Texas (USA), which found that macroinvertebrates in streams with low flow permanence were more stressed by urbanization than those in streams with high flow permanence (King et al. 2016), supports this assertion. However, there still remains the possibility that a decrease in rainfall frequency associated with a drying climate will relax flow stress and actually lead to an improvement in the condition of urban streams. Indeed, a recent study from Melbourne (Australia), reported that urban stress to some macroinvertebrate families is reduced when flow (average annual discharge or antecedent discharge) is lower (Walsh and Webb 2016). Long-term studies are needed to identify the actual consequence of climate change on urban streams; however, in the interim it may be useful for researchers and managers in highly seasonal climates to consider temporal shifts in urban stressors (as per Bailey and Ahmadi (2014)). Managing flow during wet seasons and managing water quality, particularly temperature and nutrients, during dry seasons is a precautionary approach with merit.

Studies of fire can provide other insights relevant to urban stream restoration. For example, studies of fire have found that increased flow volume associated with increased catchment runoff can moderate the water temperature increases associated with the loss of the riparian zone (Helvey et al. 1976). This learning suggests that stormwater harvesting and infiltration may exacerbate elevated urban water temperatures, unless they are matched by riparian restoration. Repairing large continuous tracts of riparian vegetation particularly in narrow, east-west oriented streams that will deliver the greatest shading and temperature benefit to streams. Studies on fire also tell us that riparian restoration can reduce algal production, even in the presence of elevated nutrient concentrations (Klose et al. 2015); this suggests that riparian zones can be used to minimize the buildup of nuisance algae in urban waterways. Lastly, studies of fire indicate that recovery of the processes that control large woody debris (LWD) are much slower than other ecological components, and may take multiple decades to repair (Gresswell 1999). Therefore, it is important to start repairing riparian zones sooner rather than later so that trees have long enough to grow and die to create natural wood recruitment. Manual additions of LWD can also achieve faster recovery of instream wood volume.

Conclusion

Covariation of stressors along an urban gradient hampers our ability to determine the most influential factors degrading urban streams. Using knowledge from other disciplines, such as fire-ecology, can fast track our learning. Our comparison of urban- and fire-affected streams provides another line of evidence, albeit indirect, that flow is indeed a key driver of the USS. The comparison with fire confirms that the ecological stress associated with urbanisation is likely to differ among systems in line with differences in climate and physiographic setting. As we learn more about the USS we may discover that the importance of different stressors change seasonally. We challenge researchers to come up with novel ways to separate covariant stressors. Separating chemical stress from flow along a drainage network could be achieved by comparing the occupancy of species that are robust to physical disturbance, but sensitive to pollution, such as *Baetid* mayflies. Creative solutions will help to advance our understanding and ultimately improve our ability to repair urban streams.

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