

Hydrological impacts of biological invasions

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Abstract

The quantity and distribution freshwater are fundamental to many ecosystem services, including water supply, flood attenuation, habitat provision, electricity generation, navigation and recreation. Non-native plants and animals can degrade hydrological services through their physiology, morphology, behavior and interactions with other species, which can be compounded when non-native species are ecosystem engineers or transformers. Using the hydrological cycle and drawing on key global examples, this chapter outlines seven main ways in which non-native species can disrupt hydrological services and how these impacts can be managed. Non-native plants may alter local and regional climates by modifying land-atmosphere transfers of heat and moisture, surface roughness and albedo, and concentrations of aerosol particles. Differences in native and non-native water use can alter catchment runoff (usually reducing water yield), especially when non-native vegetation covers extensive areas (e.g. mesquite, eucalypts). Non-native plant invasion may alter the seasonal availability of water because of differences in the timing and duration of water use (e.g. deciduous natives vs evergreen invaders). Non-native animals and plants can change ground surface and soil characteristics, altering surface and subsurface flows, infiltration rates and water residence times (e.g. earthworms, beavers). Species that invade wetlands, lakes and rivers can trap sediment, narrowing flow channels and reducing flood attenuation (e.g. tamarisk, sagittaria, mimosa). Some plant growth forms and animal behaviors can cause channel collapse, increase sediment erosion

and alter flow paths (e.g. willows, coypu). Non-native species can modify water passage and flow velocities by altering geomorphology and hydraulics (e.g. salvinia, zebra mussels). Invasive species management remains difficult because of feasibility and conflicting values of species (e.g. ecology vs economy, upstream vs downstream effects). An ecosystem services framework may help reconcile the differential impacts that non-native species have in time, space and on the delivery of various services.

1. Introduction

With an estimated value exceeding US \$2.8 trillion per annum (Costanza, d'Arge et al. 1997), hydrological services relate to the supply and regulation of freshwater. The timing and magnitude of runoff, flooding and groundwater recharge are fundamental to many ecosystem services. To optimize the supply of some of these services (e.g. navigation, water supply, hydropower), the hydrological cycle has been modified through the construction of dams, channelization and diversion of rivers, and transformation of river floodplains. Changes in land use, increases in water storage capacity and extraction, flow stabilization and loss of wetlands have affected hydrology and regulation of freshwaters (MA 2005). Currently, global freshwater use exceeds long-term accessible supplies by as much as 25%, made possible through overuse of groundwater and interbasin water transfers (i.e. catchments, watersheds, MA 2005). Although such actions have increased the availability of some services, they have reduced the availability of others, including services in other times and locations.

Though less dramatic than massive engineering works that transform river ecosystems, biological invasions can compromise and threaten hydrological services. By changing land cover and water use, geomorphology and hydraulics, non-native plants and animals can alter the quantity of water and its distribution in time and space. The relative importance of invasion-induced changes to hydrology is likely to increase as the demand for, and scarcity of, hydrological services intensifies, the latter a result of human population growth and global environmental change (Costanza, d'Arge et al. 1997; MA 2005; Vörösmarty, McIntyre et al. 2010). Compounding these trends, biological invasions are increasing both in number and impact, and will likely

further stretch an already stretched system. Understanding, managing and ameliorating negative effects of non-native species on hydrology is therefore crucial.

Based around the hydrological cycle and drawing on key examples from across the world, this chapter outlines seven main ways in which non-native species invasions can disrupt hydrological services and how these impacts can be managed. Although hydrological services are integrally linked with services that relate to water quality, soil formation, nutrient cycling and waste treatment, the focus of this chapter is on the supply and regulation of freshwater. Examples are restricted to non-native animals and plants reflecting the focus of research conducted to date, but it is important to note that disease and pathogens can also affect hydrological services (Strayer 2010).

2. What are hydrological services and how are they provided?

Hydrological services relate to the supply and regulation of freshwater, particularly its quantity and availability in time and space. Hydrological services can be divided into four categories: 1) supporting services that support ecosystems, biota and other types of ecosystem services; 2) provisioning services that relate to water as a resource itself, whether it is used on- or off-site; 3) regulating services that encompass the role of water in mitigating damage to human life and property; and 4) cultural services, which include the spiritual, social and aesthetic values of freshwater environments (Table 1, MA 2005; Brauman, Daily et al. 2007).

The distribution and amount of water in a landscape is driven by the hydrological cycle (Fig. 1). Falling as precipitation, freshwater can be intercepted by vegetation and cloud cover before reaching the ground, where it can directly contribute to surface runoff or can infiltrate the soil to join subsurface and groundwater storage and flows. Water can evaporate from all storages, and may be transpired back to the atmosphere by plants. Water can reach river channels and water bodies directly from precipitation or through surface runoff, subsurface flows and base flows, with the speed of water flow generally declining in that order. The length of time that water spends in a particular flow path or storage is called its residence time. Shorter residence times reflect that a volume of water is conveyed over a shorter period of time, resulting in shorter floods with higher peaks that come soon after a rainfall event. Once in a water body or watercourse, water may be stored, evaporated, used by organisms or will flow to downstream coastal ecosystems.

For the provision of ecosystem services, it can help to either maintain or disrupt the natural hydrological cycle. The hydrological cycle is often disrupted to ensure the optimal provision of some hydrological services (e.g. continual access to a steady flow of water for irrigation, Catford, Downes et al. 2011). Even though the total amount of water in the cycle remains the same, such modification alters the balance of water amongst the various storages and flows. Changes to the storage or flow of water at any point in the cycle will therefore affect water regulation and the hydrological services of the entire catchment. Although seemingly less radical than overall changes in water quantity, changes in the temporal and spatial characteristics of water availability can have a larger effect on service provision as many hydrological services rely on the consistency of water access and supply.

3. Ways in which biological invasions disrupt hydrological services

Invasion impacts are defined as a measurable change in the state of an invaded ecosystem that can be attributed to non-native species (Ricciardi, Hoopes et al. 2013). Non-native species impact hydrology through changing the amount, location and seasonality of water use, and through changes to the physical environment, which affect patterns, volumes and velocities of water flow. As well as these direct effects, non-native species can indirectly alter the quantity and regulation of water through their interactions with other species, including native biota, and through feedback effects on local and regional climates. There are seven main ways in which species can alter hydrology and the hydrological cycle (Table 2, Fig. 1); the first two mechanisms relate to water quantity, and the remaining five mechanisms affect water regulation. These mechanisms are not mutually exclusive and many of them co-occur.

3.1 Local and regional climate

Non-native plants can change evapotranspiration rates, local temperatures, surface roughness, concentrations of aerosol particles and surface albedo by modifying the characteristics of vegetation and land cover. Most research about the effects of vegetation on climate have focused on vegetation clearing, but increases in vegetation biomass, especially of woody vegetation with high evapotranspiration rates, may alter local and regional rainfall patterns by changing transfers of heat and moisture between the land and atmosphere (van Dijk and Keenan 2007). Though further research is required to ascertain relationships between vegetation and local rainfall (Vanclay

2009), large expanses of non-native trees could change the amount and seasonality of rainfall in an area by increasing i) the amount of water stored in the air and atmosphere, ii) surface roughness and iii) concentrations of aerosol particles, which provide condensation nuclei. Despite the potential for increased precipitation, increases in tree abundance will still typically result in lower water yields (the amount of water remaining after evapotranspiration) locally as well as regionally (van Dijk and Keenan 2007).

3.2 Water use

The most commonly cited impact of biological invasions on hydrology is through the increased use of water by non-native plants (Charles and Dukes 2007; van Wilgen, Reyers et al. 2008). Although riparian and instream plant use can increase, the greatest effects on water quantity are brought about by non-native vegetation that covers extensive areas of catchments where the majority of runoff is produced (Calder and Dye 2001; MA 2005). Woody shrubs and trees that have invaded South Africa have reduced the water yield from upland fynbos ecosystems by 30% (and national runoff by 7%, van Wilgen, Reyers et al. 2008), with an estimated annual cost of US \$68 million (Charles and Dukes 2007). Tamarisk (also known as salt cedar) *Tamarix* spp. have exerted similar impacts in the southwestern US, where they consume 1.4-3.0 billion m³ more water than native riparian species (Pejchar and Mooney 2009). Subsequent changes to water supply, hydropower generation and flood risk are estimated to cost US \$133-285 million per annum (Charles and Dukes 2007). Woody species belonging to genera *Pinus*, *Eucalyptus*, *Acacia*, *Prosopis* and *Tamarix* are thought to exert such impacts because their deep roots enable them to access soil moisture and groundwater that native vegetation cannot (Pejchar and Mooney 2009). However, such effects are not limited to woody species. Invasion of yellow star thistle *Centaurea solstitialis* L. into annual grasslands of the western US has increased summer water use by 105-120 mm per annum (Levine, Vilà et al. 2003). Similarly, conversion of native tussock grasslands to non-native pastures in upland areas of New Zealand has halved yearly runoff volumes (Holdsworth and Mark 1990).

Non-native plants can reduce water yields by increasing interception, evapotranspiration and water storage in plant tissues through higher biomass, productivity, evapotranspiration rates and leaf area indexes, and because they add or change the structural complexity of vegetation (Pejchar and Mooney 2009).

Grasslands converted to forest have resulted in a 45% average reduction in stream flow (Brauman, Daily et al. 2007) and tamarisk can increase annual evapotranspiration by 300-460 mm (Levine, Vilà et al. 2003). One of the reasons for higher water yields in tall tussock (bunch) grasslands in New Zealand compared with non-native dominated forest and pasture ecosystems is attributed to the anatomy of the native tussock leaves where transpiration is minimized and water droplets are intercepted from fog (Holdsworth and Mark 1990). Plants that photosynthesize using the C3 pathway typically use more water than C4 plants, which use more water than CAM plants. Young plants use more water than mature plants because of their faster growth rates, so when new populations of non-native plants invade and colonise an area, water use will be particularly high (Brauman, Daily et al. 2007).

Invasion may not always lead to declines in runoff though. Non-native grasses that have invaded the midwestern US have shallower roots than the native perennial grasses that they have replaced, potentially reducing water use (Pejchar and Mooney 2009). Non-native animals have a negligible direct effect on water quantity, but can affect plant water use through herbivory and by altering species composition (Ehrenfeld 2010).

3.3 Seasonality of water use

Non-native plants that differ in phenology to native plants may alter the seasonal availability of water because of differences in the timing and duration of water use (Levine, Vilà et al. 2003; Ehrenfeld 2010). For example, non-native annual grasses in California transpire for a short period in late winter and spring, whereas native perennial grasses also transpire in summer (Levine, Vilà et al. 2003). The invasion of evergreen plants in areas formerly dominated by deciduous, or seasonally dormant, plants (e.g. non-native evergreen trees into seasonally dormant South African grasslands, van Wilgen, Reyers et al. 2008) and vice versa has resulted in seasonal changes in water use that reflect plant phenology. Reflecting their greater tolerance of warmer conditions and lower water availability than C3 plants, C4 and CAM plants are predicted to increase in abundance with climate change. Though the hydrological impact of these predicted changes in vegetation will likely be dwarfed by the changes in climate that facilitate them, seasonal shifts in water uptake are likely to occur.

4) Ground surface and soil texture modification

Non-native animals and plants can alter the physical features of the ground surface and soil, altering surface and subsurface flows, infiltration rates, soil bulk density and water holding capacity, and water residence times. As well as their physical structure affecting patterns of water flow and local storage, plants can affect soil texture and organic content, and their decomposed roots can provide passages for subsurface water flow. Animals that burrow, dig or live in the soil can similarly alter surface and subsurface storage and flows. The European earthworm *Lumbricus terrestris* L., highly invasive in temperate and boreal regions of North America, changes the structure of the soil by creating permanent vertical burrows in the mineral layer, and increasing soil porosity and bulk density (ISSG 2015). As well as altering river hydrology, hydraulics and geomorphology through dam construction, non-native beavers *Castor canadensis* Kuhl reduce riparian forest cover in southern South America where they forage up to 120 m from rivers (Anderson, Pastur et al. 2009). Deforestation by beavers in Chile and Argentina has increased erosion because of exposed slopes (Lizurralde, Escobar et al. 2004) and has effectively converted closed southern beech *Nothofagus* forest to grass and sedge meadows, which are often dominated by non-native herbs (Anderson, Pastur et al. 2009; ISSG 2015).

5) *Wetland encroachment, channel narrowing and sedimentation*

Terrestrial non-native plants can invade wetlands and floodplains, especially if natural flooding has declined (Catford, Downes et al. 2011), trapping sediment and reducing their capacity to absorb and attenuate floods. Wetland plants can encroach water channels, slowing water velocities and facilitating sedimentation. Originally from the southern US, the aquatic macrophyte sagittaria *Sagittaria platyphylla* (Engelm.) J.G. Sm invades wetlands and drainage, irrigation and river channels in southeastern Australia (Catford, Downes et al. 2011). Growing in water about 0.3 m deep, the emergent form of the plant spreads clonally via stolons, which extend out into water depths of up to 1.5 m where it grows in its submerged form. As sediment accumulates over time, the species is able to gradually spread out into the main river channel, diverting, slowing and impeding water flow (Fig. 2). Giant sensitive tree *Mimosa pigra* L. also reduces water flow and increases silt levels in rivers (ISSG 2015). Tamarisk species are estimated to cost US\$53 million per annum because of channel narrowing (Pejchar and Mooney 2009).

6) *Destruction and erosion of channel form*

Growth form of plants and behavior of animals can cause channel collapse, sediment erosion and change flow paths. Burrows of the South American coypu *Myocastor coypus* Molina introduced into North America, Europe, Africa and Asia, undermine riverbanks, and its dykes and consumption of plants roots and rhizomes promote channel instability and erosion (ISSG 2015). In Australia, non-native willow trees (*Salix* spp.) can modify banks, and obstruct and divert stream flow with their dense growth above- and below-ground growth.

7) *Water movement in channel*

Non-native species can modify flow dynamics by altering the morphology and hydraulics of waterways. Prolific growth of non-native plants and bivalves can block channels and infrastructure, impeding water movement, navigation, waste disposal and hydropower generation, as well as affecting water quality and providing suitable conditions for mosquito breeding (Pejchar and Mooney 2009). Submerged and floating macrophytes (e.g. salvinia *Salvinia molesta* D.Mitch., water hyacinth *Eichornia crassipes* (Mart.) Solms, Eurasian milfoil *Myriophyllum spicatum* L., American elodea *Elodea canadensis* Michx.) are among the worst weeds in the world (ISSG 2015). Their dense growth reduces water speeds, deepens channels, increases sedimentation rates, reduces erosion rates and increases flood risk (Strayer 2010). In the Hudson River in the northeastern US, the floating European water chestnut *Trapa natans* L. reaches densities ten times that of the native American eelgrass *Vallisneria spiralis* L. that it replaced, reducing water flows, impeding river access and negatively impacting recreation and native animals (Strayer 2010). North American beavers, invasive in Europe, Russia and South America, directly alter the flow dynamics of rivers, with marked effects on water movement and flood risk (ISSG 2015).

Globally invasive zebra mussel *Dreissena polymorpha* Pallascan block pipes and other infrastructure (Pejchar & Mooney (2009), but their hard surfaces can effectively armour channels too, potentially increasing water velocities in wider channels. In some systems, water velocities and flow increase following a reduction in native plant densities. Grazing by golden apple snails *Pomacea canaliculata* Lamarck in southeast Asian wetlands and rusty crayfish *Orconectes rusticus* Girard in North American rivers have reduced the density of macrophytes. New Zealand mudsnails *Potamopyrgus antipodarum* Gray can reach population densities of tens to hundreds

of thousands of individuals per square metre and can consume up to 75% of gross primary production (ISSG 2015).

4. Feedbacks between hydrological modification and invasions

Animals and particularly plants clearly affect hydrology and water regulation through their morphology, physiology and behavior (albeit inconsistently, Vilà, Basnou et al. 2010), but this is not a one-way relationship. The hydrological characteristics of an ecosystem are necessarily a strong determinant of the resident biota because of organisms' behavioral and ecophysiological requirements. Native species may have adapted to the historical hydrological characteristics of their ecosystem, so hydrological modification can prompt a decline in their abundance and vigour, and may directly or indirectly facilitate invasion (Catford, Downes et al. 2011). Evidence suggests that hydrological modification has led to a decline in the abundance of native plants in River Murray wetlands in southeastern Australia, and has subsequently facilitated invasion by less specialized non-native species (Catford, Downes et al. 2011).

Ecosystems with modified hydrology seem particularly susceptible to invasion by non-native species, which may then go on to change hydrology further (Strayer 2010). Species that alter environmental conditions in their favour are referred to as ecosystem engineers (animals) or transformers (plants). Beavers and zebra mussels are obvious examples, as is *sagittaria* in that it facilitates sedimentation, which then provides more habitat suitable for its colonisation and spread (Fig 2). In some cases, it can be difficult to ascertain whether invaders are drivers, passengers or transformers of environmental change (Lindenmayer, Wood et al. 2015). Such a situation is seen in the southwestern US with the invasion of tamarisk along rivers. Although the majority of evidence seems to imply that tamarisk is a passenger of hydrological modification because it is able to reach groundwater that native woody species cannot, tamarisk has probably exacerbated hydrological change by lowering water tables further (Stromberg, Lite et al. 2007; Ehrenfeld 2010). In terms of management, it is important to determine whether invasion promotes a change in hydrology or whether hydrology facilitates invasion. Transformers and ecosystem engineers often require simultaneous

species and environmental control because of the positive feedback between invasion and environmental change (Lindenmayer, Wood et al. 2015)

5. Managing invasion impacts on hydrological services: can the concept of ecosystem services help?

Non-native species can disrupt hydrological services, but the perception of such changes can vary, with some changes perceived positively and others negatively (Pejchar and Mooney 2009; Pyšek, Jarošík et al. 2012). In areas where deforestation has led to salinization, non-native trees with deep roots and high rates of evapotranspiration may help alleviate negative effects of salinization by lowering water tables. However, deep-rooted trees that lower water tables and deplete groundwater reserves are highly undesirable in formerly treeless areas (Brauman, Daily et al. 2007). Non-native species that trap sediment can be perceived as harmful in some situations (Fig. 2), but they can also help to counteract bank destabilization and elevated rates of erosion that may be the result of independent changes in land and water use (Pejchar and Mooney 2009). Such tradeoffs are not restricted to ecosystem services that relate to freshwater.

Conflicts between non-native species' (often negative) impacts on ecology versus their (often positive) impacts on society and the economy are keenly felt and difficult to reconcile (Pejchar and Mooney 2009; van Wilgen, Khan et al. 2011). First introduced to India in 1857, mesquite *Prosopis juliflora* (Sw.) DC. was actively planted in the 19th and 20th centuries and now occurs throughout the arid and semi-arid regions of the country (Tewari, Pasiecznik et al. 1993) where it has increased water use, dramatically decreasing catchment runoff (Fig. 3). Deliberate plantings of wattle, eucalypt and pine species have culminated in similar effects. Reducing the abundance of these species would improve water security, especially in downstream ecosystems, but it would come at a marked cost to local communities that have come to rely on these species for timber, fuel and other products. Mesquite accounts for over 70% of firewood in rural parts of tropical arid and semi-arid India, and is also a major fuel source in urban areas (Shackleton, Le Maitre et al. 2014), so its control would be met with resistance (Fig. 3). Quantifying the relative value of these different ecosystem services could potentially help to reconcile this conflict, provided that disadvantaged parties are appropriately compensated. Quantifying the values of ecosystem services and the impacts of biological invasions is not easy, however.

Accurate assessment of the relative costs and benefits of non-native species and ecosystem services relies on: 1) isolating the effects of non-native species from other factors that might affect ecosystem services; 2) quantifying the cost of different ecosystem services and ecological impacts in a single currency; 3) accounting for acute and chronic, onsite and offsite, and immediate and delayed effects of non-native species; and 4) predicting the likely value of ecosystem services and likely impacts of invasive species in the future such that appropriate discount rates can be applied.

Even with perfect knowledge, policy and management options might be limited. Jurisdictional boundaries can make enforcement and cooperation difficult, as costs and benefits to ecosystem services are often geographically displaced, especially when dealing with rivers and their catchments. Activities in the upper regions of the Mekong River catchment in China may be most felt in the five countries downstream, for instance. Even with support for non-native species control, effective approaches may be unavailable, especially in aquatic ecosystems. There has been some success controlling non-native plants (e.g. biological control of *Salvinia molesta* by the salvinia weevil, *Cyrtobagous salviniae*, ISSG 2015), but many control programs have been unsuccessful in freshwater ecosystems (Strayer 2010), no doubt hampered by access issues and restrictions on chemical use in aquatic environments.

One of the few examples of a highly coordinated national-scale approach to invasive species control is the Working for Water program in South Africa. With water demand outstripping supply in over half of South Africa's water management areas, this innovative program was initiated by the national government in 1995 to alleviate both poverty and water stress: people were employed to cut down invasive woody species with the aim of reducing water use and restoring hydrological services (van Wilgen, Reyers et al. 2008). Despite clearing 1.2 million hectares of non-native trees within the first eight years of the program, much of the landscape is still dominated by invasive trees. This case study highlights the difficulties in controlling invasive species and keeping up with their rates of spread even when levels of support for control are high (van Wilgen, Forsyth et al. 2012).

Conclusion

The magnitude of non-native species' impacts on water resources and hydrology is probably underestimated because of a lack of impact-based research (Pyšek, Jarošík et

al. 2012), particularly at the ecosystem level (Ricciardi, Hoopes et al. 2013), and the difficulties of isolating invasion-impacts from other impacts on hydrology. Nevertheless, there is ample evidence indicating that non-native species, especially plants that cover extensive areas, can have profound effects on hydrological services. Some of these species have become iconic case studies that have captured the attention of natural resource managers and policy makers. Despite this, water-demanding trees in South Africa and India, ecosystem-engineering invertebrates in North America, and habitat-transforming macrophytes in Asia and Australia have nevertheless proved difficult to manage. This can reflect conflicting values of the species and impediments to their control. Provided that certain challenges are met, the concept of ecosystem services may provide a framework for reconciling the differential impacts that non-native species have in time, space and on the delivery of various services.

The limited success in controlling invasive woody species in South Africa, despite a control effort that could rarely, if ever, be matched, is sobering. Although biological control may be able to lessen impacts in some cases, the most effective way to prevent hydrological impacts of similar magnitudes is to identify and manage high-risk species, and the conditions that facilitate their invasion, ahead of time. Invasion ecology researchers appear to have embraced this need, as the escalating number of studies focusing on invasive species impacts, impact metrics and impact-based species traits attests. Ascertaining the cumulative effects of multiple non-native species, which could potentially be controlled collectively, will be important for optimizing management efficacy.

As the demands for, and scarcity of, freshwater resources and hydrological services heighten (Costanza, d'Arge et al. 1997; Vörösmarty, McIntyre et al. 2010), and the likelihood and impacts of invasion increase, there will be increasing need for identifying, managing and ameliorating the impacts of invasive species on the quantity and regulation of water.

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List of figures

Figure 1 Hydrological cycle showing the seven main ways that non-native species impact the quantity and regulation of freshwater. Features marked by numbers relate to impacts described in Table 2: 1) Local and regional climate, 2) Water use (trees vs grass), 3) Seasonality of water use (evergreen vs deciduous trees), 4) Ground surface and soil texture modification (tree branches altering surface flow), 5) Wetland encroachment, channel narrowing and sedimentation (macrophytes on channel edge), 6) Destruction and erosion of channel form (mammal burrow undercutting riverbank), 7) Channel water flow (bivalves armouring channel).

Figure 2 a) *Sagittaria Sagittaria platyphylla* (Engelm.) J.G. Sm encroaching on a tributary of the River Murray, Victoria, Australia (emergent form visible) with b) submerged form spreading into deeper water via stolons from emergent plants. Photographs by JAC.

Figure 3 a) Impenetrable monoculture stands of mesquite *Prosopis juliflora* (Sw.) DC. that extend over vast tracts of land in Punjab, northern India; b) local people harvesting mesquite timber in Tamil Nadu, southern India; c) Dense stand of blue gum *Eucalyptus globulus* Labill. with an understorey of gorse *Ulex europeaus* L. in Ooty, southern India; d) person collecting blue gum leaves to sell for oil production in Ooty. These two non-native tree species reduce catchment water supplies across India, but are valued for timber, seeds, oil and other products. Photographs by JAC.

Table 1 Hydrological services grouped into four major categories with examples of non-native species impacts (MA 2005; Brauman, Daily et al. 2007). Refer to Table 2 for more examples.

Hydrological services	Non-native species impacts
Supporting services	
<ul style="list-style-type: none"> - Water, nutrients and sediment for other ecosystems - Habitat and dispersal vector for biota 	<p>North American beavers can transform the structure and function of entire ecosystems by altering the physical, chemical and geomorphological characteristics of rivers and riparian zones. Impacts include: higher rates of erosion by converting forests to meadows; increases in nutrient availability from wood debris in waterways, leading to increases in primary productivity and changes in invertebrate assemblages; dams acting as barriers to dispersal and indirectly changing water temperature; indirectly facilitating other non-native species that are better suited to the modified environmental conditions than native species (Lizurralde, Escobar et al. 2004; Anderson, Pastur et al. 2009; ISSG 2015).</p>
Provisioning services	
<ul style="list-style-type: none"> - Transport and navigation - Waste removal and dilution - Hydroelectricity generation - Freshwater products (e.g. fish) - Municipal, industrial, agricultural, commercial water use - Thermoelectricity generation 	<p>Zebra mussels clog water intake screens and pipes of municipal water supplies and hydroelectric companies, degrades the quality, taste and odor of potable water, and can lead to bioaccumulation of organochlorine and heavy metals in fish and ducks that prey on them (Pejchar and Mooney 2009).</p>
Regulating services	
<ul style="list-style-type: none"> - Flood attenuation - Drainage - Saltwater intrusion - Sedimentation and erosion 	<p>Dense populations of submerged and floating macrophytes (e.g. salvinia, Eurasian water-milfoil) increase flood risk by reducing flow velocities and water passage, and increasing rates of sedimentation and reducing rates of erosion (Strayer 2010).</p>

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- Dryland salinization

Cultural services

- Spiritual and religious
 - Education
 - Tourism
 - Recreation
- The diatom, didymo or rock snot *Didymosphenia geminata* (Lyngbye) M. Schmidt, has impeded the recreational, tourism and aesthetic value of invaded rivers in New Zealand (ISSG 2015). The whole South Island of New Zealand was declared a controlled area in 2005 requiring that all equipment (boats, fishing gear, clothes) used in an infected waterway must be cleaned before use in another waterway.
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