Chapter 5
Hydrological Impacts of Biological Invasions

Jane A. Catford

Abstract The quantity and distribution of 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 functions through their physiology, morphology, behaviour, 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 and 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 and 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 behaviours 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

J.A. Catford (✉)
School of BioSciences, The University of Melbourne, Melbourne, VIC 3010, Australia

Fenner School of Environment and Society, The Australian National University, Canberra, ACT 2601, Australia

Department of Ecology, Evolution and Behavior, University of Minnesota, Saint Paul, MN 55108, USA

Biological Sciences, University of Southampton, Southampton SO17 1BJ, UK
e-mail: j.a.catford@soton.ac.uk

M. Vilà, P.E. Hulme (eds.), *Impact of Biological Invasions on Ecosystem Services*, Invading Nature - Springer Series in Invasion Ecology 12,
DOI 10.1007/978-3-319-45121-3_5

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 versus economy, upstream versus 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.

Keywords Catchment • Ecosystem engineer • Flood • Habitat provision • Hydrological cycle • Land use • Water supply

5.1 Introduction

Hydrological services relate to the supply and regulation of freshwater and have an estimated value exceeding US $2.8 trillion per annum (Costanza et al. 1997). The timing and magnitude of runoff, flooding, and groundwater recharge are fundamental to many ecosystem services. To optimise the supply of some of these services (e.g., navigation, water supply, and hydropower), the hydrological cycle has been modified though the construction of dams, channelisation and diversion of rivers, and transformation of river floodplains. Changes in land use, increases in water storage capacity and extraction, flow stabilisation, and loss of wetlands have affected hydrology and the regulation of freshwaters. 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., between catchments / watersheds). Such actions have increased the availability of some services, but they have reduced the availability of others, including services in other times and locations.

Although less dramatic than massive engineering works that transform river ecosystems, biological invasions can compromise and threaten hydrological services. By changing land cover, 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 as a result of human population growth and global environmental change (Costanza et al. 1997; Millenium Ecosystem Assessment 2005- MEA 2005 hereafter; Vörösmarty et al. 2010). Compounding these trends, biological invasions are increasing in both number and impact, and will likely further stretch an already overextended 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).

5.2 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 5.1).

The distribution and amount of water in a landscape is driven by the hydrological cycle (Fig. 5.1). Falling as precipitation, freshwater can be intercepted by vegetation and cloud cover before reaching the ground. Upon reaching the ground, water can directly contribute to surface runoff or can infiltrate the soil, contributing to 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 may 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 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.

Table 5.1 Hydrological services grouped into four major categories with examples of non-native species impacts

Hydrological services		Non-native species impacts
Supporting services	Water, nutrients and sediment for other ecosystems	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 et al. 2004; Anderson et al. 2009; ISSG 2015).
	Habitat and dispersal vector for biota	
Provisioning services	Transport and navigation	Zebra mussels clog water intake screens and pipes of municipal water supplies and hydroelectric companies, degrade 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).
	Waste removal and dilution	
	Hydroelectricity generation	
	Freshwater products (e.g., fish)	
	Municipal, industrial, agricultural, commercial water use	
	Thermoelectricity generation	
Regulating services	Flood attenuation	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).
	Drainage	
	Saltwater intrusion	
	Sedimentation and erosion	
	Dryland salinisation	
Cultural services	Spiritual and religious	The diatom didymo or rock snot (*Didymosphenia geminata*) 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.
	Education	
	Tourism	
	Recreation	

Refer to Table 5.2 for more examples (MEA 2005; Brauman et al. 2007)

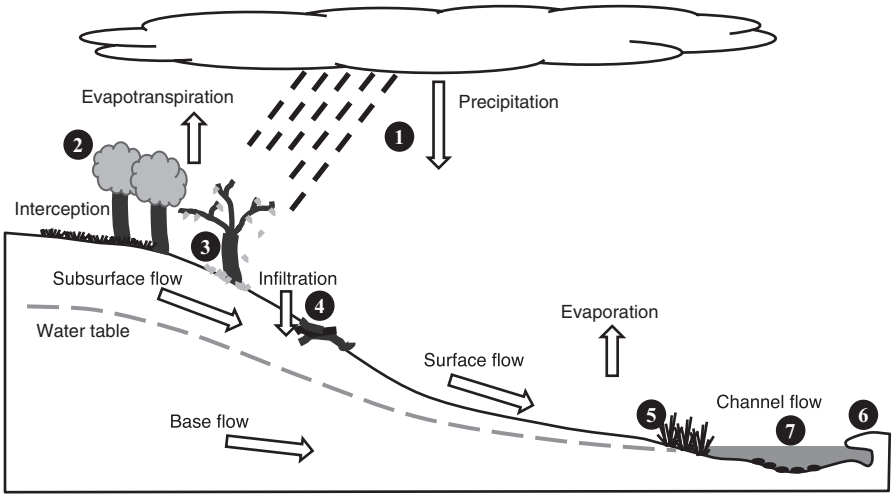

Fig. 5.1 Hydrological cycle showing the seven main ways that non-native species impact the quantity and regulation of freshwater. Features marked by *numbers* relate to impacts described in Table 5.2: (*1*) local and regional climate; (*2*) water use (trees vs. grass); (*3*) seasonality of water use (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); and (*7*) channel water flow (bivalves armouring channel)

5.3 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 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 5.2; Fig. 5.1): 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.

Table 5.2 Seven main ways that non-native species can affect the quantity and regulation of water, mechanisms through which they do so, and likely impacts on the hydrological cycle

Invader effects	Mechanisms of impact	Impacts on hydrological cycle	Species characteristics	Examples
Water quantity				
(1) Local and regional climate	Non-native plants change surface roughness, temperature and albedo, and land–air transfers of heat and moisture	Indirect, cumulative changes to precipitation and evaporation in catchment	Different structural form to native vegetation; high transpiration rates; darker foliage	Invasion of grasslands and heathlands by non-native trees
(2) Water use	Non-native plant populations increase interception and evaporation because of differences in their morphology, structure and population densities compared to native species	Increased evapotranspiration and water storage in plants; greater portion of water intercepted by vegetation aboveground and immediately evaporated; lower runoff	Novel life forms change vegetation structure; low intraspecific competition allows species to reach high densities	Pasture grasses; giant reed, *Arundo donax*; non-native trees
	Per capita water use of non-natives differs from natives because of their life stage (young plants use more water), growth rates or photosynthetic pathway (C3 plants use more water than C4 and CAM plants)	Differences in water use alters runoff, especially during plant growth season	Short life spans; rapid population growth; age distribution of population (e.g., dominance of juveniles); photosynthetic pathways	Blue gum, *Eucalyptus globulus*
	Non-native plants have greater access to soil moisture and groundwater than native plants	Lowers water table; reduces aquifer recharge, groundwater storage and base flows	Deep roots; expansive root system; high root biomass; novel life form (e.g. tree in heathlands)	Tamarisk; mesquite, *Prosopis* species; mimosa; pines; wattles, *Acacia* species
	Non-native animals and pathogens reduce biomass and productivity of native vegetation	Lower water use, interception and evapotranspiration increase water availability and decrease water residence time; higher flood risk	Herbivores that reduce vegetation productivity	Rabbits and other terrestrial herbivores

Water regulation				
(3) Seasonality of water use	Timing of growth of non-native plants differs from native plants	Seasonal changes in water availability	Different growth season to native plants (e.g., C3 vs C4 and CAM plants, deciduous vs. evergreen)	Willows and poplars in Australia; yellow star thistle, *Centaurea solstitialis*, in USA
(4) Ground surface and soil texture modification	Non-native species change physical structure of ground and infiltration capacity of soil	Changes to runoff flow paths and velocities; changes in surface water ponding and infiltration location and rates; changes in water residence time, storage and flows	Plants: distinct from natives in type and amount of biomass, chemical composition and amount of litter, dead wood, root structure, root biomass, and timing of leaf senescence	Plants that differ in structure or biomass from native vegetation
			Animals: behavior related to burrowing, digging; soil-dwelling invertebrates	Animals: earthworms, including common earthworm, *Lumbricus terrestris*; rabbits
(5) Wetland encroachment, channel narrowing and sedimentation	Non-native plants trap sediment and encroach channels, wetlands and floodplains	Reduces flood attenuation and water residence times; alters hydraulics, flow paths and velocities; results in flashier hydrographs, faster runoff, and increased flood risk; impedes navigation	Plant structure and morphology that reduces flow speeds and traps sediment; plastic or variable growth form; capacity for clonal spread	Tamarisk; mimosa; giant reed, *Arundo donax*; sagittaria; common reed, *Phragmites australis*
(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	Altered channel morphology, sediment size and hydraulics changes patterns and velocities of water flow	Plants: different root structure and morphology from natives.	Plants: willows and poplars
			Animals: burrowing, dam building, benthic feeders.	Animals: pigs; carp; beavers; coypu, *Myocastor coypus*; Chinese mitten crab, *Eriocheir sinensis*

(continued)

Table 5.2 (continued)

Invader effects	Mechanisms of impact	Impacts on hydrological cycle	Species characteristics	Examples
(7) Channel water flow	Non-native species clog waterways and infrastructure	Slows and impedes water flow; increases water pondage; impedes navigation and hydropower production	Plants: floating or submerged plants that can form dense stands (often monocultures); clonal; rapid population growth	Plants: salvinia; water hyacinth; Eurasian water-milfoil
			Animals: habitat-forming	Animals: bivalves
	Non-native bivalves armour channel	Reduction in channel roughness increases flow velocity, reduces storage times, and increases flood risk downstream	Bivalves with hard surfaces	Freshwater mussels, e.g., zebra mussel and quagga mussel from *Dreissena* genus
	Grazing by non-native animals reduces abundance of aquatic macrophytes	Reduces channel roughness; increases erosion, sediment suspension and transport; results in increased flow velocities, flashier hydrographs, and increased flood risk downstream	Voracious herbivores	Carp; coypu, *Myocastor coypus*; golden apple snail, *Pomacea canaliculata*; rusty crayfish, *Orconectes rusticus*

Changes in water quantity mostly affect supporting and provisioning services, whereas changes in water regulation mostly affect provisioning and regulating services. Cultural services can be affected by any change depending on the human values of a given system. Characteristics of non-native species that may be linked with species impacts on hydrology are noted (some hypothesised, some observed), along with some iconic examples where they exist. Water regulation refers to the distribution and flows of water in space and time. Refer to ISSG (2015) for authorities of species names. Table compiled using information from: Holdsworth and Mark 1990; Calder and Dye 2001; MEA 2005; Charles and Dukes 2007; van Wilgen et al. 2008; Deo et al. 2009; Pejchar and Mooney 2009; Ehrenfeld 2010; Vilà et al. 2010; ISSG 2015 and references there in

5.3.1 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 has 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). Although 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 (1) the amount of water stored in the air and atmosphere, (2) surface roughness, and (3) 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).

5.3.2 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 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; MEA 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 et al. 2008), with an estimated annual cost of US$68 million (Charles and Dukes 2007). Tamarisk (also known as salt cedar), *Tamarix* spp., has exerted similar impacts in the southwestern USA, where tamarisk trees consume 1.4–3.0 billion m^3 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 the 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 the yellow star thistle, *Centaurea solstitialis*, into annual grasslands of the western USA has increased summer water use by 105–120 mm per annum (Levine 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 et al. 2007), and tamarisk can increase annual evapotranspiration by 300–460 mm (Levine 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 minimised 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 et al. 2007).

Invasion may not always lead to declines in runoff, however. Non-native grasses that have invaded the midwestern USA 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).

5.3.3 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 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 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 et al. 2008) and vice versa has resulted in seasonal changes in water use that reflect plant phenology. C4 and CAM plants are predicted to increase in abundance with climate change because they are more tolerant of warmer and drier conditions than C3 plants. Although 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.

5.3.4 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. The physical structure of plants can affect patterns of water flow and local storage, but plants can also 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*, 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 (Invasive Species Specialist Group 2015) (ISSG 2015 hereafter). As well as altering river hydrology, hydraulics, and geomorphology through dam construction, the non-native beaver, *Castor canadensis*, reduces riparian forest cover in southern South America where individuals forage as far as 120 m from rivers (Anderson et al. 2009). Deforestation by beavers in Chile and Argentina has increased erosion because of exposed slopes (Lizurralde 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 et al. 2009; ISSG 2015).

5.3.5 Wetland Encroachment, Channel Narrowing, and Sedimentation

Terrestrial non-native plants can invade wetlands and floodplains, especially if natural flooding has declined (Catford 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 USA, the aquatic macrophyte *Sagittaria platyphylla* invades wetlands and drainage, irrigation, and river channels in southeastern Australia (Catford 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 as great as 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. 5.2). The giant sensitive tree, *Mimosa pigra*, 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).

Fig. 5.2 (**a**) *Sagittaria platyphylla* 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 Jane A. Catford)

5.3.6 Destruction and Erosion of Channel Form

The growth form of plants and behaviour of animals can cause channel collapse and sediment erosion, and can change flow paths. Burrows of the South American coypu, *Myocastor coypus*, introduced into North America, Europe, Africa, and Asia, undermine riverbanks and embankments. Coypu further increase channel instability and erosion by eating plant roots and rhizomes (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.

5.3.7 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*; water hyacinth, *Eichornia crassipes*; Eurasian milfoil, *Myriophyllum spicatum*; and American elodea, *Elodea canadensis*) are among the worst weeds in the world (ISSG 2015). Their dense growth reduces water speed, deepens channels, increases sedimentation rates, reduces erosion rates, and increases flood risk (Strayer 2010). In the Hudson River in the northeastern USA, the floating European water chestnut, *Trapa natans*, reaches densities ten times that of the native American eelgrass, *Vallisneria americana*, which it has replaced, thereby 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).

The globally invasive zebra mussel, *Dreissena polymorpha*, blocks pipes and other infrastructure (Pejchar and 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*, in southeast Asian wetlands and rusty crayfish, *Orconectes rusticus*, in North American rivers has reduced the density of macrophytes. New Zealand mudsnails, *Potamopyrgus antipodarum*, 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).

5.4 Feedbacks Between Hydrological Modification and Invasions

Animals, and particularly plants, clearly affect hydrology and water regulation through their morphology, physiology, and behaviour (albeit inconsistently; Vilà 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 organism behavioural 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 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, which has subsequently facilitated invasion by less specialised non-native species (Catford et al. 2011).

Ecosystems with modified hydrology seem particularly susceptible to invasion by non-native species, which may then go on to alter 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. 5.2). In some cases, it can be difficult to ascertain whether invaders are drivers, passengers, or transformers of environmental change (Lindenmayer et al. 2015). Such a situation is seen in the southwestern USA 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 et al. 2007; Ehrenfeld 2010). In terms of management, it is important to determine whether invasion promotes a change in hydrology or whether hydrological modification facilitates invasion. Transformers and ecosystem engineers often require simultaneous species and environmental control because of the positive feedback between invasion and environmental change (Lindenmayer et al. 2015).

5.5 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 as positive and others as negative (Pejchar and Mooney 2009; Pyšek et al. 2012). In areas where deforestation has led to salinisation, non-native trees with deep roots and high rates of evapotranspiration may help alleviate negative effects of salinisation by lowering water tables. However, deep-rooted trees that lower water tables and deplete groundwater reserves are highly undesirable in formerly treeless areas (Brauman et al. 2007). Non-native species that trap sediment can be perceived as harmful in some situations (Fig. 5.2), but they can also help to counteract bank destabilisation 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 (van Wilgen et al. 2011). First introduced to India in 1857, mesquite, *Prosopis juliflora*, was actively planted in the nineteenth and twentieth centuries and now occurs throughout the arid and semi-arid regions of the country (Tewari et al. 1993), where it has increased water use, dramatically decreasing catchment runoff (Fig. 5.3). 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 more than 70 % of firewood in rural parts of tropical arid and semi-arid India, and is also a major fuel source in urban areas (Shackleton et al. 2014), so its control would be met with

Fig. 5.3 (**a**) Impenetrable monoculture stands of mesquite, *Prosopis juliflora*, 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*, with an understory of gorse, *Ulex europaeus*, 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 Jane A. Catford)

resistance (Fig. 5.3). Quantifying the relative value of these different ecosystem services could potentially help to reconcile this conflict, provided that disadvantaged parties are appropriately compensated. However, quantifying the values of ecosystem services and the impacts of biological invasions is not easy.

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 considering 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 more than 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 et al. 2008). Despite clearing 1.2 million hectares of non-native trees within the first 8 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 et al. 2012).

5.6 Conclusions

The magnitude of non-native species impacts on water resources and hydrology is probably underestimated because of a lack of impact-based research (Pyšek et al. 2012), particularly at the ecosystem level (Ricciardi 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 proved difficult to manage, which can reflect the 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-focused species traits attests. Ascertaining the cumulative effects of multiple non-

native species, which could potentially be controlled collectively, will be important for optimising management efficacy.

As the demands for, and scarcity of, freshwater resources and hydrological services heighten (Costanza et al. 1997; Vörösmarty 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.

Acknowledgments I thank P. Hulme and M. Vilà for inviting me to contribute this chapter, B. van Wilgen for very helpful feedback that enabled me to improve it, Inderjit for sharing his knowledge of non-native plant invasions in India (and showing me some of them), and the IUCN's Invasive Species Specialist Group for giving me access to the pre-release beta version of the Global Invasive Species Database. Funding was provided by the Australian Research Council (DE120102221) and the ARC Centre of Excellence for Environmental Decisions.

References

Anderson CB, Pastur GM, Lencinas MV et al (2009) Do introduced North American beavers *Castor canadensis* engineer differently in southern South America? An overview with implications for restoration. Mamm Rev 39:33–52

Brauman KA, Daily GC, Duarte TK et al (2007) The nature and value of ecosystem services: an overview highlighting hydrologic services. Annu Rev Environ Resour 32:67–98

Calder IR, Dye P (2001) Hydrological impacts of invasive alien plants. Land Use Water Resour Res 1:1–12

Catford JA, Downes BJ, Gippel CJ et al (2011) Flow regulation reduces native plant cover and facilitates exotic invasion in riparian wetlands. J Appl Ecol 48:432–442

Charles H, Dukes J (2007) Impacts of invasive species on ecosystem services. Biological invasions. In: Nentwig W (ed) Biological invasions, vol 193, Ecological studies. Springer, Berlin/Heidelberg, pp 217–237

Costanza R, d'Arge R, de Groot R et al (1997) The value of the world's ecosystem services and natural capital. Nature (Lond) 387:253–260

Deo RC, Syktus JI, McAlpine CA et al (2009) Impact of historical land cover change on daily indices of climate extremes including droughts in eastern Australia. Geophys Res Lett 36:L08705

Ehrenfeld JG (2010) Ecosystem consequences of biological invasions. Annu Rev Ecol Evol Syst 41:59–80

Holdsworth D, Mark A (1990) Water and nutrient input: output budgets: effects of plant cover at seven sites in upland snow tussock grasslands of Eastern and Central Otago, New Zealand. J R Soc N Z 20:1–24

ISSG (2015) Global Invasive Species Database. Invasive Species Specialist Group, IUCN (The World Conservation Union)

Levine JM, Vilà M, D'Antonio CM et al (2003) Mechanisms underlying the impacts of exotic plant invasions. Proc R Soc Lond B Biol 270:775–781

Lindenmayer DB, Wood J, MacGregor C et al (2015) A long-term experimental case study of the ecological and cost effectiveness of invasive plant management in achieving conservation goals: Bitou Bush control in Booderee National Park in eastern Australia. PLoS One 10:e0128482

Lizurralde M, Escobar J, Deferrari G (2004) Invader species in Argentina: a review about the beaver (*Castor canadensis*) population situation on Tierra del Fuego ecosystem. Interciencia 29:352–356

Millenium Ecosystem Assessment (2005) Ecosystem and human well-being. A framework for assessment. Island Press, Washington, DC

Pejchar L, Mooney HA (2009) Invasive species, ecosystem services and human well-being. Trends Ecol Evol 24:497–504

Pyšek P, Jarošík V, Hulme PE et al (2012) A global assessment of invasive plant impacts on resident species, communities and ecosystems: the interaction of impact measures, invading species traits and environment. Glob Change Biol 18:1725–1737

Ricciardi A, Hoopes MF, Marchetti MP et al (2013) Progress toward understanding the ecological impacts of nonnative species. Ecol Monogr 83:263–282

Shackleton RT, Le Maitre DC, Pasiecznik NM et al (2014) *Prosopis*: a global assessment of the biogeography, benefits, impacts and management of one of the world's worst woody invasive plant taxa. AoB Plants 6 pii: plu027

Strayer DL (2010) Alien species in fresh waters: ecological effects, interactions with other stressors, and prospects for the future. Freshw Biol 55:152–174

Stromberg JC, Lite SJ, Marler R et al (2007) Altered stream-flow regimes and invasive plant species: the *Tamarix* case. Glob Ecol Biogeogr 16:381–393

Tewari JC, Pasiecznik NM, Harsh LN et al (1993) *Prosopis* species in the arid and semi-arid zones of India. The Prosopis Society of India conference. The Prosopis Society of India and the Henry Doubleday Research Association, Central Arid Zone Research Institute, Jodhpur, Rajasthan, India

van Dijk AIJM, Keenan RJ (2007) Planted forests and water in perspective. For Ecol Manag 251:1–9

van Wilgen BW, Reyers B et al (2008) A biome-scale assessment of the impact of invasive alien plants on ecosystem services in South Africa. J Environ Manag 89:336–349

van Wilgen BW, Khan A, Marais C (2011) Changing perspectives on managing biological invasions: insights from South Africa and the Working for Water programme. In: Fifty years of invasion ecology: the legacy of Charles Elton. Wiley, New York, pp 377–393

van Wilgen BW, Forsyth GG, Le Maitrea DC et al (2012) An assessment of the effectiveness of a large, national-scale invasive alien plant control strategy in South Africa. Biol Conserv 148:28–38

Vanclay JK (2009) Managing water use from forest plantations. For Ecol Manag 257:385–389

Vilà M, Basnou C, Pyšek P et al (2010) How well do we understand the impacts of alien species on ecosystem services? A pan-European, cross-taxa assessment. Front Ecol Environ 8:135–144

Vörösmarty CJ, McIntyre PB, Gessner MO et al (2010) Global threats to human water security and river biodiversity. Nature (Lond) 467:555–561