THE ECOLOGICAL AND SOCIO-ECONOMIC IMPACTS OF INVASIVE ALIEN SPECIES ON INLAND WATER ECOSYSTEMS

PREFACE

This document is an assessment of the ecological and socio-economic impacts of invasive alien species (IAS) on inland water ecosystems. This assessment examines the trends in biotic invasion of inland water ecosystems, reports on known ecological and socio-economic impacts of IAS on inland water ecosystems, and provides guidance and information on resources that can help minimize the impact of IAS on inland water ecosystems. This ecosystem assessment is a response to paragraph 6 (d) of the Convention on Biological Diversity (CBD) Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) recommendation VI/5 in which the decision was made, in accordance with paragraph 29 (b) of decision V/20 and paragraphs 1 and 9 of VI/5, to initiate assessments on the impacts of IAS.[1] The report also supports decision VI/23 of the sixth Conference of Parties (COP), which urged research and assessments on the causes and consequences, as well as the prevention and management of IAS.[2]

The Global Invasive Species Programme (GISP) was contracted to lead this assessment and to work with Parties and other bodies to provide an international perspective on the issue. This assessment greatly benefited from contributions made by a team of technical and policy experts who attended an experts' consultation hosted by GISP and The Nature Conservancy (TNC) in July 2003 in Washington, D.C., USA.[3] We are particularly grateful to the following individuals for participating in the experts' consultation and contributing to the production of this assessment and the associated information document, as well as those experts who reviewed the assessment and further enriched its content:

Participants in experts' consultation: Dr. Angela Arthington, Griffith University, Australia; Dr. Alejandro Arrivillaga, Universidad del Valle, Guatemala; Dr. Ann Bartuska, The Nature Conservancy, USA; Dr. Nina G. Bogutskaya, Russian Academy of Sciences, Russia; Dr. Nick Davidson, The Ramsar Convention on Wetlands, Switzerland; Dr. Roger Day, CAB International, Kenya; Ms. Pam Fuller, US Geological Survey, USA; Dr. Geoffrey Howard, IUCN, Kenya; Dr. Roberto Mendoza–Alfaro, Universidad Autónoma de Nuevo Leon, Mexico; Mr. Marshall Meyers, Pet Industry Joint Advisory Council, USA; Dr. Dan Polhemus, Smithsonian Institution, USA; Dr. Alphis Ponniah, WorldFish Center, Malaysia; Dr. Jason F. Shogren, University of Wyoming, USA; Dr. Marcos Silva, Secretariat of CBD, Canada.

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[1] http://www.biodiv.org/doc/meeting.asp?lg=0&wg=sbstta-07
[2] www.biodiv.org/decisions/default.asp?lg=0&dec=VI/23
[3] A full report of the experts consultation is included as an addendum to this document (Meyerson et al. 2004).

The assessment was funded by the CBD and the U.S. Environmental Protection Agency. The Nature Conservancy and Smithsonian Institution provided in-kind support. This assessment consists of seven sections:

I *Introduction*. Status of inland water ecosystems; definition of IAS; tension between benefits and impacts of IAS on inland water ecosystems; trends in biotic invasions of inland water ecosystems; and pathways analysis.

II *Ecological Impacts*. Overview of available data on ecological impacts of IAS on inland water ecosystems; relevant case studies; and gaps in knowledge and research needs.

III *Socio-Economic Impacts*. Overview of available data on socio-economic impacts of IAS on inland water ecosystems by market and non-market factors; relevant case studies; and gaps in knowledge and research needs.

IV *Strategies for Prevention and Control of Invasive Alien Species.* Overview of options; and guidance for minimizing the impacts of IAS on inland water ecosystems through prevention, early detection and rapid response, and management including eradication, control, and monitoring programs.

V *Conclusions and Recommendations.* Summary of general findings from this assessment and recommendations by experts.

VI *Literature Cited.* List of literature referenced in this report.

VII *Appendices*.

Owing to the complexity and relatively recent recognition of the IAS issue, as well as the lack of historical monitoring and environmental impact assessments globally, there is relatively little reliable information on the ecological and socio-economic impacts of IAS on inland water ecosystems. The findings of this assessment have been compiled from a wide-range of studies conducted by scientists, natural resource managers, and economists around the world.

Although this report addresses inland water ecosystems collectively, the processes and impacts of biological invasion differ among and within rivers, lakes, wetlands and estuaries. Case studies are provided to illustrate these differences.

I INTRODUCTION

Status of Inland Water Ecosystems

Inland water ecosystems are defined by the CBD as ecosystems that encompass habitats with a variety of physical and chemical characteristics, including bogs, marshes and swamps, which are traditionally grouped as inland wetlands, and inland seas, lakes, ponds, rivers, streams, groundwater, springs, cave waters, floodplains, backwaters, oxbow lakes, and small containers such as pitcher plants and even tree holes (UNEP/CBD/SBSTTA/8/8/Add.1/ph 6/2002). Appendix A provides a summary of the importance and uniqueness of inland water ecosystems as well as the vulnerability of inland water ecosystems to IAS.

The decline of inland water biodiversity has reached alarming rates, making inland water species among the most threatened of all taxa. In North America, their rate of extinction is five times more rapid than that of terrestrial animals and at a level similar to tropical forest species (Ricciardi and Rasmussen 1999). Approximately 20% of the world's freshwater fish species are at risk of extinction (Moyle and Leidy 1992). Similar declines are found in almost every country, but actual rates of biodiversity loss globally may be much higher since there is a paucity of data on the status of most species and even less on entire freshwater communities and ecosystems. Available data suggest that inland water ecosystems have been degraded worldwide. For example, 85% of inland water ecosystems in Latin America and the Caribbean are in critical, endangered or vulnerable condition (Olson et al. 1998). This extinction crisis will become more problematic in the near future as human populations and economies grow, placing increasing demands on inland water ecosystems for water, hydropower, transportation, food and wastewater disposal[4].

The introduction of IAS is considered to be a leading cause of species endangerment and extinction in freshwater systems (Claudi & Leach 1999; Harrison and Stiassny 1999; Sala et al. 2000). An *invasive alien species* (IAS) is defined as "an *alien species* (a species, subspecies, or lower taxon, introduced outside its natural past or present distribution; includes any part, gametes, seeds, eggs, or propagules of such species that might survive and subsequently reproduce), whose introduction and/or spread threaten biological diversity."[5] For example, IAS are thought to cause or contribute to more than 70% of native North American freshwater species extinctions during the twentieth century (Williams et al. 1989). A survey of 31 fish introduction studies in Europe, North America, Australia, and New Zealand found that in 77% of the cases, native fish populations were reduced or eliminated following the introduction of alien fish species (Ross 1991). One hundred and sixty seven of México's roughly 500 freshwater fish have been listed at some degree of risk, and 76 are the result, at least in part, of IAS (Contreras-Balderas et al. 2002a). In Australia, invasive alien fish species are the leading cause in the decline of 22 species of native fish classified as endangered, vulnerable or rare (Wager and Jackson 1993).

Tension Between Benefits and Impacts of Alien Species on Inland Water Ecosystems

Not all alien species are invasive. Every introduction likely has some influence on the host ecosystem, but most influences are thought to be benign, or their impacts are undetectable, especially at early stages of establishment. Some IAS may not cause ecological damage and many, especially fish, provide economic

[4] Some models suggest that water withdrawals will increase 50% in developing countries and 18% in developed countries during the next 25 years, placing even greater pressures on inland water ecosystems and potentially leading to severe water shortages across two-thirds of the total world human population by the year 2025 (Szollosi-Nagy *et al*. 1998).

[5] The definition for *invasive alien species* was developed at the CBD's sixth Conference of the Parties (DecisionVI/23).

benefits, while others cause ecological harm arising from their invasive behaviour but produce substantial social, economic, and cultural benefits. For example, some of the most dramatic trade-offs between economic benefits and ecological costs involve introductions of common carp (*Cyprinus carpio*), one of the most widely introduced species in inland water ecosystems. In 2002, over 2.8 million tons of common carp were produced through aquaculture –mostly in developing countries (FAO pers. comm.). Native species have suffered in lakes and rivers where this species has been introduced. By feeding in the soft benthic substrates of lakes and rivers, common carp increase siltation and turbidity, decreasing water clarity and harming native flora and fauna (Fuller et al. 1999; Koehn et al. 2000). Common carp have been associated with the decline and local disappearance of native fishes in Argentina, Australia, Venezuela, Mexico, Kenya, India, and elsewhere (Welcomme 1988).

Significant international instruments have recently been established that address the issue of intentional introduction of alien species, such as the UN Food and Agriculture Organization (FAO) Code of Conduct for Responsible Fisheries [see www.invasivespecies.gov for additional international instruments]. Such international codes and conventions call for risk assessments prior to species introductions and the creation of accessible IAS information resources that include biological and ecological attributes of alien species, and their potential for invasive behaviour and ecological impacts. One such example is the FAO Database on Introductions of Aquatic Species (DIAS), designed to serve as an important initial summary and registry of introduced species (DIAS 1997).

Case study illustrating use of international codes of practice to manage alien species introductions: Papua New Guinea (PNG) is classified as a low income, food deficit country by the Food and Agriculture Organization (FAO) of the United Nations. Although PNG has abundant natural resources, a rugged terrain, poor infrastructure and dense rainforests offer few practical possibilities for food production for 80% of the population that live in inland areas. Extensive inland water ecosystems do provide a means for rural communities to use fishery resources, but in PNG they have unusually low levels of freshwater fish species diversity and in particular many of the productive niches available are not fully utilised. In response to pressure to use alien species for fishery enhancement of under-productive inland waters, PNG and the United Nations Development Programme undertook a stock enhancement programme that involved the application of the ICES/EIFAC codes of practice on alien species (Turner 1988; ICES 1995). These codes called for an initial assessment of the need to introduce alien species and their likely environmental and socio-economic impact. The codes also called for the establishment of an independent panel of experts to advise on the risk and benefits of the introduction. These assessments led to the conclusion that several species of alien fishes could be introduced into specific drainages to provide added food security in remote areas. The introduced alien species were selected on the basis of expected minimal impact on the native biodiversity and maximum socio-economic benefits. In particular, top-level predatory species were avoided and those feeding in major under-utilised vacant niches were preferred. Following the approval of species, import, quarantine and culture for grow-out were undertaken as prescribed by the codes. The species were introduced into the Sepik and Ramu drainages between 1993 and 1997. A brief study of selected fishing communities in the catchments was undertaken in 2002 (Kolkolo 2003) and revealed that all but two of the species introduced have established viable populations and are generating food and income for rural communities in the Sepik and Ramu catchments.

Trends in Biotic Invasion of Inland Water Ecosystems

Rapid increases in the volume of international trade and tourism, combined with the emphasis on free trade have increased the likelihood of the intentional or unintentional movement of IAS. In many cases, customs and quarantine practices that were developed to protect countries from human and agricultural diseases and pests are inadequate safeguards against species that threaten native inland water biodiversity. The result has been an increasing trend of biotic invasions with impacts on the economic, political, ecological and cultural systems of developing and developed countries alike (e.g., Ricciardi 2001).

Information on the status of inland water biodiversity is severely lacking in many countries, making it difficult to evaluate and predict trends in biotic invasions. Moreover, it is usually not until the invasion becomes noticeable or has ecological/economic/social consequences that observations are recorded or investigated. Coverage of accidental introductions (e.g., through ship ballast water, or escapes from aquaculture facilities) is particularly poor and these events have generally been recorded only when important impacts on fisheries or the receiving environment have occurred. One resource documenting species introductions is the FAO Database on Introductions of Aquatic Species (DIAS) that records the number of aquatic species introduced or transferred from one country to another. Although the global coverage of this database is far from complete for alien species introductions, it is the most thorough dataset yet to be compiled on this topic. Europe has the highest percentage of recorded introductions in DIAS (25.1%), followed by Asia (16.4%), Africa and Oceania (each with 14.7%), South and Central America (14.1%); Middle East (8.4%), and North America (6.3%).

FishBase, developed by FAO and WorldFish Center in collaboration with other organizations, represents one of the most comprehensive databases on fin fish distributions and ecology world-wide[6] and has incorporated information from DIAS on fin fish. At present there are 2,904 reported inland water fish introductions recorded in FishBase and about half of these introductions have become established as self-sustaining populations in the wild. Aquaculture has been cited as the main reason for introducing fin fish into inland water systems with 40% of the documented introductions highlighting the significance of movement of alien species for aquaculture. One-third of the established aquaculture fin fish species were reported to have adverse ecological impacts (Bartley and Casal 1999). The top five species established for aquaculture are: common carp (*Cyprinus carpio)*, Mozambique tilapia (*Oreochromis mossambicus)*, rainbow trout (*Oncorhynchus mykiss)*, largemouth bass (*Micropterus salmoides)* and brown trout (*Salmo trutta).*

Pathways Analysis of IAS into Inland Water Ecosystems

The introduction, establishment and spread of IAS into inland water ecosystems depends on a vast number of socio-economic, political, cultural, and ecological factors. These range from the source, transport, and demand for goods and services, to the human alteration of inland water systems for water management projects (e.g., dams, diversions, inter-basin water transfers), to the vagility and adaptability of IAS to new ecosystems. For example, human migration has long served as a source of species introductions as people tend to bring familiar plants and animals with them to their new homes and unintentionally have also brought diseases and pest species. While demand for food resources increases hand in hand with human population growth, industries such as aquaculture will continue to increase production in existing areas as well as new areas. As this growth occurs, the likelihood for aquaculture to serve as a pathway for IAS will also increase. In the same way, as wealth grows in different regions around the globe, demand for alien plants and animals is likely to increase, resulting in more IAS introductions through horticulture and aquarium trades, as well as through increased tourism and demand for exotic recreational activities.

Appendix B summarizes numerous intentional and unintentional pathways of entry for IAS into inland water ecosystems that arise based on the factors outlined above. Aquaculture is the prime example of a

[6] Although a large portion of the scientific literature focuses on invasive alien fish species, the list of known biotic invaders of inland water ecosystems globally, both intentional and accidental introductions, is long and includes the full spectrum of freshwater taxonomic groups from vertebrates (fishes, amphibians, reptiles, birds and mammals) to invertebrates (insects, unionids, crustaceans), to freshwater plants, algae and micro-organisms. Therefore, no such group can be treated as a low invasion risk.

pathway of intentional introductions of IAS. In 2001, global aquaculture production in inland waters was 22.4 million tons in comparison to inland capture fisheries of 8.8 million tones (FAO 2002), indicating the enormous level of aquaculture production in inland waters. While aquaculture has the potential to provide low-cost protein to those who need it most, it is not without cost to ecosystems and society. There is increasing evidence that aquaculture has contributed to the degradation of water quality and habitat structure in production areas, and is a major pathway for the introduction of IAS (Santiago 1994; McCrary et al. 2001). In order to maximize the full potential and benefits of aquaculture, we must minimize the risks of introducing species that could become invasive through comprehensive risk assessment prior to introduction. The further spread of aquaculture species known to be highly invasive also needs to be curbed or prohibited.

The ornamental fish trade is the second largest sector for intentional introductions of IAS into inland water ecosystems and is almost completely based on alien species, although some countries (e.g., Australia) are tending towards trade in native species. However, the records of introductions and subsequent establishment are rarely documented in developing countries and hence not adequately captured by DIAS or FishBase (Alphis Ponniah pers comm.). These are often very small scale operations which can lead to the mis-perception that due to their small physical size and production potential the risk of releasing an IAS is negligible. The market for ornamental fisheries is a rapidly changing one because of the demand for new species and varieties are rarely documented nor formally regulated.

II. ECOLOGICAL IMPACTS

The ecological impacts of IAS on inland water ecosystems vary significantly depending upon the invading species, the extent of the invasion, and the vulnerability of the ecosystem being invaded (Appendix C summarizes a range of ecological impacts of IAS on inland water ecosystems). Loss and degradation of biodiversity due to IAS can occur throughout all levels of biological organization from the genetic and population levels to the species, community, and ecosystem levels, and may involve major alterations to physical habitat, water quality, essential resources and ecological processes. These impacts can vary in terms of the lapse of time between the initial introduction and subsequent spread of an IAS, its severity of impact, the likelihood of synergistic interactions with other threatening processes, and the potential for initiation of a cascade of effects ramifying throughout an entire ecosystem (Wilcove et al. 1998; Levine 2000; McNeely *et al.* 2001).

IAS generally reduce the abundance of native inland water species through predation, hybridization, parasitism, or competition for resources, and may alter community structure and ecosystem processes, such as nutrient cycling, energy flow or the hydrodynamic properties of a particular inland water ecosystem. The effects of IAS on inland water ecosystems overall can be summarized into eight general categories: alteration of hydrologic regime; alteration of water chemistry regime; alteration of physical habitat and habitat connectivity; biological community impacts; species population impacts; genetic impacts; and alteration of ecosystem structure and processes (e.g., food web structure and energy flow).

Case study illustrating genetic impacts: Once IAS are successfully established, interactions between IAS and native species during reproduction can result in severe impacts on native species populations. Erosion of native gene pools can occur directly through hybridization, potentially resulting in sterile offspring and an associated decrease in population size, introgression or gene swamping of the native species genome by a more productive IAS, or indirectly through competition resulting in reduced populations and hence diminished sources of genetic material. The most conspicuous examples of the consequences of genetic interactions are hybridization events followed by erosion of the gene pool of native species, such as hybridization between invasive alien rainbow trout (*Oncorhynchus mykiss)* and native trout populations (cutthroat trout, *Oncorhynchus clarki*) (Campton 1987), and between invasive alien mallard ducks (*Anas platyrhynchos*) and the New Zealand gray duck (*Anas superciliosa superciliosa*), the Hawaiian duck

(*Anas wyvilliana*), and the Florida mottled duck (*Anas fulvigula fulvigula*) (Ryhmer and Simberloff 1996).

Case study illustrating population/species impacts followed by cascading ecosystem impacts: The Louisiana crayfish (*Procambarus clarkii*) is native to the south central part of the United States. Global introductions of *P. clarkii* have had widespread negative consequences, such as the displacement of native crayfish, caused by a deadly crayfish plague *(Aphanomyces astaci)* that previously devastated European freshwater crustaceans. *Procambarus clarkii* is a hardy, competitive, and aggressive species with a high reproduction rate. It is also physically destructive, burrowing through the walls of earthen dams and causing damage to floodplain levees. This species contributes to public health and veterinary health problems because it is an intermediate host for several parasitic helminths of vertebrates. The introduction of *P. clarkii* causes a cascade of ecological impacts throughout invaded freshwater ecosystems. Dramatic changes have occurred in invertebrate assemblages in response to depression of the biomass and productivity of benthic algae and aquatic macrophytes, which in turn have led to decreased fish populations (Mendoza case study in Meyerson et al. 2004).

Case study illustrating community level impacts followed by cascading ecosystem impacts: The quilted melania (*Thiara granifera)* and the red rimmed melania (*Melanoides tuberculata)* are freshwater snails native to subtropical and tropical areas of northern and eastern Africa and southern Asia. Their competitive abilities are superior to other freshwater snails, and their introduction into North America has led to the decline or disappearance of several native snail populations (Contreras-Arquieta and Contreras-Balderas 1999). Quilted and red-rimmed melania not only out-compete native species but are resistant to predation thereby reducing food availability to molluscivore fishes. The present spread of these IAS pose threats both to the native freshwater snails and molluscivore fishes, and to sports fish, commercially important aquaculture species, and humans. They are also vectors for several dangerous invasive alien parasites such as the Chinese liver fluke (*Clonorchis sinesis)*, oriental lung fluke (*Paragonimus westermani)*, *Philophtalmus sp.* (eye fluke of birds, which occasionally infects mammals), and *Centrocestus formosanus,* a trematode with infective stages that penetrate the gills of fish in high numbers, causing severe damage and even death. *Centrocestus formosanus* has caused serious infections in cultured fish in Florida and Mexico and in wild fish stocks in Texas, affecting several threatened or endangered fishes such as the Fountain darter (*Etheostoma fonticola)*, Devils River minnow (*Dionda diaboli)*, Rio Grande darter (*Etheostoma grahami)*, Proserpine shiner (*Cyprinella proserpina)*, Comanche Springs pupfish (*Cyprinodon elegans)* and Pecos gambusia (*Gambusia nobilis)* (Mitchell et al. 2000; Mendoza case study in Meyerson et al. 2004).

Case study illustrating ecosystem impacts and an invasion complex: Bermuda grass (*Cynodon dactylon)*, an IAS introduced into the southeastern U.S. for livestock forage and lawns, has also taken its toll on freshwater habitat. Bermuda grass forms a carpet on stream bottoms and increases the resistance of substrates to disturbance during floods, eliminating the scoured habitat preferred by native fish and invertebrate spawning habitat. It also creates habitat for the fathead minnow and other invasive alien fish that compete with native species and facilitates establishment of watercress (*Rorippa nasturtium-aquaticum)*, aquatic buttercups (*Ranunculus sp.)* and other invasive plants. The result is a short-circuit of the natural successional trajectory because Bermuda grass creates an "invasion complex" or invasional “meltdown” (Simberloff and Von Holle 1999) in which one invading species facilitates the establishment and spread of additional invaders (Ricciardi 2001). A very similar sequence of disturbances has been documented in Australian tropical streams invaded by South American para grass (*Brachiaria mutica*), introduced as a pasture species for cattle. The proliferation of such grasses under conditions of reduced canopy cover greatly influences stream environments by trapping sediment and channelising flows, leading ultimately to channel contraction until low-frequency, high-intensity, flood events re-establish normal channel dimensions (Bunn *et al.* 1998). In the short-term, proliferation of pasture grasses leads to a suite of changes in habitat structure, water quality, food web structure and fish diversity (Arthington et al. 1983, Bunn *et al.* 1997, 1998). In addition, the living tissue of submerged C_4 grasses such as para grass (i.e., those which fix carbon from carbon dioxide via the Hatch-Slack photosynthetic pathway) contributes very little to aquatic food webs (Bunn *et al.* 1997), and the ungrazed senescent leaf material collects on the stream bed where it remains unprocessed by secondary consumers, forming a thick anoxic organic ooze intolerable to both fish and invertebrates (Pusey and Arthington 2003). The diversity of invertebrate prey is much reduced and fishes are forced to alter foraging behaviour or consume prey items not normally found in the diet. Finally, streams infested with para grass often support alien poeciliid fishes such as *Gambusia holbrooki* and species of *Xiphophorus* (Arthington et al. 1983; Pusey et al. 2000).

Case study illustrating ecosystem wide / habitat impacts: Common carp (*Cyprinus carpio*) were introduced into the Murray-Darling River System in Australia. Carp biomass was estimated to reach 3,144 kg ha^{-1}, with fish densities up to 1 fish m^{-2}, and in some locations on the Murray and Murrumbidgee Rivers, they account for over 95% of fish (Gehrke et al. 1995). At such high densities, the direct physical impacts of carp may include bank erosion, increased turbidity and elevated nutrient concentrations caused by substrate disturbance and by excretion. These alterations to physical and chemical conditions have ecological consequences, such as increased phytoplankton density in response to elevated nutrient levels, and reduced aquatic macrophyte growth (a consequence of disturbance of the substrates that support submerged aquatic vegetation, especially delicate species). Reduced plant biomass and cover may affect important habitat conditions for invertebrates and fish, and also fish food resources (Arthington 1991; Koehn et al. 2000). The massive biomass shifts that occur in rivers infested with carp represent major redirection of energy flow through the aquatic ecosystem.

Other threats to inland water ecosystems such as water use, surrounding land use, and overharvesting/ fisheries management, may create conditions that favour IAS introductions by decreasing the resistance of the ecosystem to invasion (see Appendix A section on vulnerability of inland water ecosystems to IAS invasion). IAS can be more competitive and efficient at utilizing resources made available by disturbances than native species.

Not all IAS impacts are equally detectable and in some cases it may not be clear what symptoms to look for (Allendorf 1991; Gaffney and Allen 1992). For example, a large volume of literature exists on changes in species composition resulting from predation, but this does not necessarily mean that it is the primary impact of IAS introductions; predation is much easier to detect than genetic effects or allelopathy, for example. In addition, distinguishing between impacts caused by IAS and those caused by other environmental threats is a major challenge. The introduction of Nile perch (*Lates niloticus*) into Lake Victoria is one outstanding example. Initially the decline of haplochromine cichlid populations was attributed almost completely to predation by Nile perch. Later, it was discovered that increased eutrophication through pollution and over-exploitation may have also played a role in the decline of haplochromine cichlids (Pitcher and Hart 1995).

Knowledge Gaps & Research Needs

In many instances little or no knowledge of baseline conditions exists prior to the biological invasion of an inland water ecosystem. Further, taxonomy is often inadequately understood and therefore cannot support quarantine and management action. At the ecosystem level, more data is needed to quantify the effects of IAS on ecological processes such as food web structure and energy flow. At the genetic level, hybridization appears in some cases to enhance invasiveness, but this needs to be established through formal investigations. For example, hybrid vigour may have enhanced the spread of carp and tilapia strains in Australia. Other important research questions that need to be addressed include the following: What patterns and processes characterize the distribution and spread of invasive alien micro-organisms? How do genetic traits and hybridization affect the likelihood of a species becoming invasive? What are the key factors driving ecosystem resistance to invasions and the capacity to recover from invasions?

What are the high priority taxonomic difficulties that should be addressed first? How can we predict invasibility? How can the impacts of IAS be distinguished from the consequences of other stresses such as loss of habitat and hydrological connectivity, flow regulation, loss of riparian functions and water pollution?

These gaps in knowledge present challenges for constructing useful conceptual models to guide the planning of experimental research, prevention, management, monitoring, and control of IAS in inland water ecosystems.

III. SOCIO-ECONOMIC IMPACTS

IAS impacts are not restricted to ecosystems; they also affect local economies. IAS have adversely impacted numerous industries, such as fisheries, tourism, and water production. For example, sea lamprey (*Petromyzon marinus)* has caused significant economic and commercial losses to Great Lakes fisheries in the US and Canada. It has been estimated that if sea lamprey was not controlled, the loss of fishing opportunities and indirect economic impacts could be greater than $500 million USD annually (Spaulding and McPhee 1989). However, as discussed previously, economic benefits sometimes can be derived from species that are invasive to an ecosystem. The challenge is to balance the benefits and costs, both economic and ecological, to ensure sustainable use of inland water ecosystems.

Relationship Between Economics & Invasive Alien Species

Human activities to increase economic productivity and well-being have contributed to both the introduction and vulnerability of inland water ecosystems to IAS (Dalmazzone 2000). Our daily choices can facilitate the introduction of IAS, which can eventually lead to a reduction in ecosystem and economic productivity and overall well-being. For example, the introduction of the largemouth black bass into Lago de Pátzcuaro and Lago Chapala in México has established commercial and sports fisheries, at the cost of the local and highly appreciated pescado blanco and charal fisheries (Elizondo-Garza and Fernández-Méndez 1995), with high economic losses and social changes. It is important to understand the relationship between economic choices and ecosystem health so that economic incentives can be used to mitigate the impacts of IAS, and ensure that both ecosystems and economies are safeguarded. Ultimately, when countries protect their ecosystems from IAS, they also protect human health, production standards, access to overseas markets, a sense of security and cultural identity (NZIER 2000), and their native biodiversity.

Impacts

The socio-economic impacts of IAS fall into two broad categories: market impacts (e.g., changes in prices), and non-markets impacts (e.g., changes in ecosystem services). Market impacts imply reduced productivity of commodities sold within the marketplace. For inland water ecosystems affected by IAS, these production losses include decreases in fisheries and aquaculture production, decreases in the availability and accessibility of water for industries, decreases in the navigability of lakes and rivers, and declines in property values (Halstead et al. in press).

Non-market impacts due to IAS in inland waters can include potential risks to human capital due to premature deaths, declines in social capital[7] due to increased transaction costs[8], and declines in natural

[7] Social capital is typically thought of as the relationships between people integral to sustain trust in societies. These relationships facilitate the building of social institutions, such as non-governmental organizations, new government institutions, etc. IAS reduce ecosystem services and can cause greater demands on governments, as a result weakening social capital. This can have adverse impacts in countries that are already weak in social capital.

capital due to the loss of ecosystem services[9]. Estimating the value of these non-market impacts can be difficult and costly[10]. Nonetheless, the potential impacts of alien species introductions and the reversibility of these impacts should be considered even if they are not quantifiable at this time.

In addition to the impacts that affect the functions of economies and ecosystems, the distribution of these impacts must be considered. All humans rely on freshwater for their survival. Many depend on inland water ecosystems for their livelihood. The distribution and types of impacts due to IAS in inland water ecosystems can be inequitable. Some ecosystems are more prone to invasion than others due to human disturbances that may have occurred in the ecosystem, e.g., river impoundment, and as a result will incur more costs. People are therefore affected differently by IAS depending on where they live, their source of livelihood, and the range of control and eradication strategies available to them. IAS in inland water systems have variable impacts on different sectors of society. Those within lower income brackets may experience more severe impacts from IAS than those at a higher income level. Subsistence level producers may have fewer options to manage IAS, and may value marginal prevention and control measures more than the wealthy (Shogren 2000). Moreover, the control or eradication of an IAS is not always a public good[11], since sometimes it serves only a small sector of society. Therefore, governments should evaluate the ability of various societal groups to adapt to/mitigate the impacts incurred from IAS when determining how to most efficiently allocate resources.

Finally, since a time lag can occur before an introduced species is recognized as an IAS, there is the challenge of intergenerational equity. If a strategy benefits the current generation but imposes large costs on future generations, then it is unlikely that there will be a way to compensate the later generation. Therefore, before an introduction is made, consideration should be given to both the short-term and the long-term costs and benefits, to all groups of people.

Case study illustrating market, nonmarket impacts and geographic inequity of impacts: *Tamarix sp.*, commonly known as salt cedar, is an invasive riparian weed in the southwest United States, Australia and Mexico. It can raise the salinity of the soil making it inhospitable to native plant species (Jackson et al. 1990). *Tamarix* was introduced as an ornamental plant from Eurasia over 100 years ago, but has only recently been recognized as invasive, demonstrating both the lag effect and intergenerational nature of some IAS. *Tamarix* consumes water on average 35% more rapidly than native vegetation, causing the water table to drop, desert springs to dry up and lowering the level of lakes (McDonald 1968; Vitousek 1986; Loope et al. 1988; Johns 1990). It also causes a reduction in the width and depth of river channels, thus reducing the water-holding capacity of waterways and increasing the frequency and severity of over bank flooding (Graf 1978; Graf 1980; Blackburn et al. 1982). Zalaveta's (2000) study on the economic impacts of *Tamarix* found that municipal, agricultural, hydroelectric power generation, and river recreation sectors were affected resulting in market and non-market impacts. It is estimated that $16-44 million USD per year of hydropower generation is lost through *Tamarix* invasion. Zavaleta found that it would be less expensive to combat *Tamarix* than to look for alternative mechanisms to obtain water (Zavaleta 2000).

Case study illustrating market impacts: The golden apple snail (*Pomacea canaliculata*) was introduced intentionally into Asia in 1980 to be cultured as a high-protein food source for local consumption as well

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[8] Transaction costs are those costs incurred in the process of caring out an activity, such as lawyers fees, personnel time, costs for meetings, etc.

[9] Examples of ecosystem services for inland water ecosystems include drinking water, waste removal, crop irrigation, food sources, and water filtration.

[10] Since non-market impacts do not have an explicit market price, researchers estimated potential impacts through implicit price as revealed by tools such as contingent valuation, hedonic pricing, and travel cost methods. This requires careful study and surveying that may require more resources, e.g., time and money, than available and as such is not always feasible.

[11] Public goods are those goods that no one is excluded from and that everyone can consume; for instance, air is a public good.

as for export. It has since invaded Asian rice agro-ecosystems, spreading through extensive irrigation networks, feeding voraciously on rice seedlings. According to a case study in the Philippines, actual production losses amounted to between 70,000 – 100,000 tons of paddy, valued at $ 12.5 – 17.8 million USD in 1990. The total cost of the golden apple snail in 1990 to Philippines rice farmers was estimated between $28 and 45 million USD. This estimate included the loss of yields, in combination with costs pertaining to the control measures adopted (i.e., hand-picking, application of molluscicides) and costs for seedling replanting, but did not include non-market impacts such as health issues arising from pesticide usage and non-target impacts on biodiversity (Naylor 1996).

Case study illustrating market impacts and the benefit of control: Wherever water hyacinth (*Eichhornia crassipes)* has been introduced outside of its native range, it has created dense floating mats that restrict fishing and transport, reduce the availability of water for drinking, irrigation and power generation and affects biodiversity. A 1999 survey, in Benin demonstrated the economic impacts of water hyacinth on local economies before and after water hyacinth was controlled using biological control agents (mottled water hyacinth weevil (*Neochetina eichhorniae)* and chevroned water hyacinth weevil *(Neochetina bruchi))*. The principle activities of the men surveyed were fishing and agriculture. They reported that water hyacinth impacted fishing. The women, whose principle activities were transport and trading, reported that trade was most affected. In addition, many of the women said that the time that it took to trade was increased because water hyacinth slowed river navigation, making it take longer to get to the market. During the height of the water hyacinth infestation, men reported their annual income dropped from $1,984 to $607 USD, after the control of water hyacinth their income rose to $1,160 USD per person. Women were most impacted in trading of fish; they saw their income drop from $519 to $137 USD per person during the major infestation. Trade in food crops was reduced from $310 to $193 USD per person. At the time of the survey, the fish trade had not recovered, while the food crop trade had dropped to 92% of its pre-water hyacinth infestation level. The researchers estimated that the economic loss due to water hyacinth was $2,151 USD per household, while the benefit from the biological control was $783 USD per household. This study clearly demonstrates that the impacts of IAS can have significant impacts on local economies and that when IAS are controlled it improves not only the ecosystem but the economy (De Groote et al. 2003).

Case study illustrating market level impacts: Leung et al. (2002) developed a quantitative bioeconomic modeling framework to examine risks from introduced alien species to economic activity and the environment. Their Stochastic Dynamic Programming model identifies optimal allocation of resources to prevention versus control, acceptable invasion risks, and consequences of invasion to optimal investments. They applied the model to zebra mussels, and showed society could benefit from prevention of zebra mussels based on market values of damage to industry by spending up to $336,000 USD/yr to prevent invasions into each lake with a power plant. In contrast, they argued that the US Fish & Wildlife Service spent $825,000 USD in 2001 to manage all aquatic invaders for all US lakes. Their results suggest that more investment in prevention toward inland water invasions appears warranted.

Knowledge Gaps & Research Needs

Policymakers need information on the benefits and costs of IAS in order to make informed management decisions. Studies are usually only conducted on those species that have an overwhelming impact on both the ecosystem and economy. In addition, the majority of the economic studies tend to be for a handful of inland water species in developed countries. Monitoring is often not conducted after an introduction making it difficult to determine the ecological and economic impacts of a species. Research is needed to define the links between the socio-economic and environmental sectors, including the feedback loops between them, to assist in developing decision support tools.

IV. STRATEGIES FOR PREVENTION, EARLY DETECTION AND RAPID RESPONSE, AND MANAGEMENT OF INVASIVE ALIEN SPECIES

The significant ecological and socio-economic impacts of IAS on inland water ecosystems dictate that efforts must be made to prevent and control their further spread. The strategies to minimize the impacts of IAS are known, however the countries' ability to address IAS varies. Efforts should be made to tailor IAS management strategies to each ecosystem and economy. Generally these strategies fall into the categories of prevention, early detection and rapid response, and management. *Guiding Principles for the Prevention, Introduction and Mitigation of Impacts of Alien Species that Threaten Ecosystems, Habitats or Species* (CBD Decision VI/23) and *Invasive Alien Species a Comprehensive review on the efficiency and efficacy of existing measures for their prevention, early detection, eradication and control* (UNEP/CBD/SBSTTA/6/7/2000) are some primary resources on this topic. In addition, the following resources found at www.invasivespecies.gov provide guidance for developing and implementing effective, strategic programs for the prevention, eradication, and/or control of IAS. Several of these resources provide case studies or provide suggestions for overcoming socio-political, financial, scientific, technical, and technological challenges to the implementation of IAS prevention and management programs. The following is a summary of strategies specific to inland water ecosystems regarding the prevention, early detection and rapid response, and management of IAS. Additionally, international codes of practice such as developed by FAO and partners (Turner 1988; ICES 1995; FAO 1995) provide a mechanism for responsible decision making.

Prevention

Prevention of the introduction of IAS is the first and most cost-effective measure against IAS because once an introduced species has become established it can be extremely difficult or more often impossible to eradicate. Intact ecosystems are the best preventative measure against IAS, as IAS often thrive in disturbed ecosystems. In inland water ecosystems, human induced changes on land and in the adjoining waterways have contributed to the majority of IAS invasions, since these changes can adversely affect native species and their ecosystems making them more susceptible to impacts from IAS. Ecosystem restoration as well as integrated river basin management are therefore important components to maintaining healthy inland water ecosystems. Moreover, as a result of the interconnected nature of inland water ecosystems, information sharing between managers within and between countries is vital to prevent and/or slow further invasions.

Recognizing that the ecosystem services of inland waters are integral to local economies and that intentional/unintentional introductions occur, risk assessments are crucial to safeguard introductions. Careful monitoring/inspection of known pathways of introduction for inland waters such as the live food fish trade, aquaculture, aquarium releases, and stocking should be undertaken. The development and use of codes of conduct and best management practices, such as the FAO Codes of Conduct for Responsible Fisheries and the International Standards for Phytosanitary Measures produced by IPPC, are important tools for industry and managers to use when determining whether to introduce an alien species into inland waters.

Exclusion methods based on IAS pathways of entry into inland water ecosystems rather than on individual species provide the most efficient way to concentrate IAS preventative efforts. Effective strategies for pathway closure include: interception of IAS species based on regulations enforced with inspections and fees; treatment of material suspected to be contaminated with IAS; prohibition of particular commodities in accordance with international regulations; and public education to support the prevention of the introduction of IAS including awareness raising of the reasons for the restrictions, regulatory actions, and the environmental and economic risks involved.

For transboundary inland water ecosystems, regional country co-operation is essential for effective IAS preventative strategies as efficiency can be increased by sharing information, ensuring consistency in related policies, legislation and practice, and cooperation on risk assessments. Identification of IAS and pathways of entry that are of concern to two or more countries and determination of priorities for multi-lateral cooperation is an important step towards harmonization. Information exchange on national standards and regulatory frameworks regarding aquatic IAS is crucial to identify gaps and share lessons learned.

Building political will for implementation of preventative measures is a significant challenge, particularly when the negative impacts have not yet occurred or there is a conflict of interest between parties that desire the IAS introduction and those who oppose it. Had the zebra mussel (*Dreissena polymorpha*) been prevented from entering North America by purging of ballast water at sea or by treatment of ballast water by chemicals or ultraviolet light, extinction threats to many freshwater species would be far lower than they currently are (Ricciardi et al. 1988). In addition, billions of dollars of industrial damage from clogged water pipes would have been avoided.

Early Detection and Rapid Response

Once an IAS has colonized an inland water ecosystem, the best course of action is early detection and rapid response. Experience and research have shown that taking action on new invasions early is most effective. In order to detect new invasions it is important to have baseline surveys and consistent monitoring programs in place. Ongoing routine surveys and assessments should have a component that monitors IAS.

Monitoring can be expensive and time consuming, which often makes it difficult to gain political support. In addition, national monitoring and early warning systems are often weak or lack co-ordination. Limitations to early detection and rapid response of IAS include lack of information about species already present (baseline data) and lack of accessible information systems. In many cases, institutional fragmentation limits the capacity of environment, phytosanitary and health authorities to cooperate on rapid response mechanisms. Moreover, some countries have no legal mandate to conduct monitoring or control IAS unless a species is first designated a pest or a noxious species, and even then monitoring is usually poorly implemented or non-existent.

Several emergency models, such as fire response, natural disaster response, health emergencies, and military emergencies have potential as models for response to IAS invasions in inland water ecosystems. To be effective, each early detection and rapid response plan should incorporate the following key aspects: a) Community awareness and outreach as to the possible presence of potential invaders and their likely impacts. Outreach greatly enhances public understanding of the impacts of IAS and the practicalities and risks of various management options. Volunteer community support in early detection and eradication programs, especially in regard to monitoring of inland water ecosystems, is critical for success given the lack of resources in many countries for institutionalized programs; b) Instruction for community volunteers in the use of preventive technologies and control measures; c) Communication of the human health and ecological risks associated with control technologies is essential. In addition, a cost-benefit analyses of these strategies should be implemented to determine the most effective response strategy; d) Community support and the political will to undertake rapid response activities must be in place prior to an emergency in order to guarantee the cooperation that is essential to successful eradication and control programs; e) Clear lines of authority for appropriate action with immediate access to emergency funding in order to shorten the timeline between detection and action; f) An established system of priorities, and tested protocols with manuals and guidelines to serve as decision-support tools;

and g) Monitoring of outcomes and analysis of successes and failures so that adaptive management approaches can be applied and new techniques and technologies integrated.

Owing to the interconnectedness of inland waters, it is important that early detection and rapid response plans involve all interested and responsible parties. This will require regional collaboration between countries sharing inland water ecosystems. Where integrated river basin management plans exist or other regionally collaborative activities are in place, efforts should be made to ensure that early detection and rapid response of IAS are components of such plans.

Management: Eradication, Control and Monitoring

Although eradication of IAS in inland water ecosystems can be difficult, particularly within a large drainage network where system wide eradication would be necessary, it should not be ruled out. An analysis of the barriers to success and incentives for eradication should be undertaken, including analysis of transboundary systems where coordinated actions between countries are needed. A successful eradication program must engage the local community. If the community obtains a significant benefit from the species, then eradication may not be possible, and containment may be the only option. However, if the community stands to benefit from eradication, their involvement is more likely and could prove invaluable. Databases of successful eradications as well as failures should be developed to allow information sharing and technological and strategic development. Examples of successful eradications in inland water ecosystems include the eradication of coypu (*Myocastor coypus)* in the United Kingdom (see case study below), and hydrilla (*Hydrilla verticillata*) and tamarisk (*Tamarix ramosissima*) eradications in the south-western United States and southern Australia.

The goal of controlling IAS has been either to contain the species within a geographical area or to suppress the overall abundance of the species down to some pre-determined level. Mechanical, chemical and biological control are used separately or collectively to contain the distribution of the invading species. Inland water ecosystems currently have fewer control methods available to them compared to terrestrial ecosystems because of the dispersed nature of these ecosystems. Mechanical control involves directly removing individuals of the IAS either by hand or using machinery (i.e., fishing, pulling weeds) or draining of the waterbody that has become infested. It is highly specific to an IAS, and is often very labour intensive. Chemical control involves the application of pesticides or defoliants to IAS. Chemical control is often very effective as a short-term solution. Major drawbacks of chemical control are its high cost and non-target impacts on native species. Local communities often object to the application of chemicals because of perceived health consequences. Biological control involves the intentional use of organisms (e.g., natural predators and pathogens, sterile individuals) to suppress IAS populations. Although not without its problems, when it is successful, biological control is highly cost effective, permanent, and self-sustaining.

Monitoring is needed to ensure the long-term success of control and eradication of IAS. The public can play an important role in both control and monitoring if they are made aware of the benefits/costs of IAS. In order to effectively manage inland waters, managers need to have access to information about alien species that could prove to be a threat. Information-sharing and collaborative programs are important domestically, regionally and internationally in order to prevent the further spread of IAS. Baseline surveys and monitoring are essential sources of information for managers, as well as crucial to the early detection and rapid response of IAS.

Case study eradication of coypu in the United Kindgom: Coypu (*Myocastor coypus*) is a large South American rodent that was originally imported for their fur in the 1920s to the United Kingdom. However, these fur farms were poorly managed and several coypus escaped, establishing themselves in wetlands similar to their native South American swamps (Gosling 1989). As the coypus reproduced, their increasing population began to take its toll on native wetlands, altering their hydrology and vegetative composition resulting in the loss of native wetland species (Gosling 1989). By the late 1950s, there were as many as 200,000 coypus in the United Kingdom. The Ministry of Agriculture began a three-year eradication campaign, with the aim to reduce the population significantly in two or three years and confine the survivors to the Norfolk Broads. Their trapping strategies were effective in decreasing the population size of coypu, but they were not successful in the eradication of this species (Gosling 1989). The Coypu Research Laboratory was established by the Ministry of Agriculture, which spent almost two decades studying the population ecology of the coypu. Researchers constructed coypu population models that took into account birth and death rates, number of trappers, weather conditions and other variables to determine an appropriate eradication strategy. The Coypu Control Organization was established in 1981 with 24 trappers and 3 supervisors to eradicate the 5,000 plus coypu population in the United Kingdom (Gosling 1989). Incentives were created so that trappers were rewarded for finishing the job earlier, rather than prolonging it so their employment was lengthened. By April 1986 there were fewer than 40 coypu in the United Kingdom (Gosling 1989). The last 40 were difficult to capture, but by April 1987 the last breeding group was found. The coypu eradication program demonstrates that eradication is possible, but significant research and perseverance from all those involved are vital (Gosling 1989).

V. CONCLUSIONS AND RECOMMENDATIONS

Invasive alien species are a leading cause of biodiversity loss in inland water ecosystems (Sala et al. 2000). Their ecological impacts span all levels of biological organization from the genetic level impacts to ecosystem level and may involve cascading ecosystem-wide impacts. Economic impacts of IAS on inland water ecosystems are varied with both market impacts and non-market impacts. Pathways of IAS entry into inland water ecosystems are numerous and often there are few regulations or controls on their transport and entry. Intentional introductions for aquaculture, ornamental aquarium trade, and fisheries are the leading pathways of entry. The costs and benefits of these IAS introductions are mixed as alien species are often a major source of income for local communities. At the same time, IAS may degrade the natural resources upon which communities depend. There is limited experience in the prevention, eradication and control of IAS in inland water ecosystems with fewer methods available than for the control of invasive species in terrestrial systems. Given the vulnerability of inland water ecosystems to IAS invasions and the projected increases in human population growth, with associated needs for inland water ecological services, action needs to be taken now if we wish to maintain healthy inland water ecosystems that are critical not only to our survival but to the survival of all species on Earth.

Recommendations

1. Attempts to develop tools to predict where a species is likely to become invasive have had some success for inland water ecosystems, for example, the global information system of Ricciardi et al. (2000), and the genetic algorithm for rules prediction based on environmental factors (Kolar and Lodge 2002). However, predictions that a species will not become invasive are doomed to failure; every species can become invasive under some circumstances. Therefore, the precautionary approach should be adopted by treating every alien species as potentially invasive until there is evidence to indicate otherwise.

2. Prevention of introduction of IAS into inland water ecosystems should be a priority for every country to ensure ecological and socio-economic well-being. Maintaining healthy ecosystems and implementing strategies that are effective at closing off pathways of transport and entry should be pursued. Risk assessments should be conducted on all new proposed intentional alien species introductions and every alien species should be assessed to be of low ecological and socio-economic risk prior to its introduction into an inland water ecosystem.

3. Many countries, especially those that share inland water ecosystems (i.e., transboundary inland water ecosystems), are at different stages in their efforts to address the problem of IAS; apply relevant laws differently; and have varied technical capacities and levels of financial resources. An integrated river basin management approach to the prevention and control of IAS should be implemented where feasible to enable countries to make the issue a significant priority and build capacity by developing mutually supportive legal, policy and monitoring frameworks, sharing information and technical capacity, and using limited resources efficiently. For example, in Europe, the Water Framework Directive is intended to provide for integrated management of all inland waters and the European Inland Fisheries Advisory Commission has adopted international codes on alien species (Turner 1988).

4. Involvement of local and indigenous communities and other relevant stakeholders should be promoted at all levels of the identification, prevention and control of IAS in inland water ecosystems. Given the lack of awareness and resources in developing countries to deal with IAS, there needs to be stronger support from the CBD process on awareness and outreach. South Africa's Working for Water Programme is an example of the benefit of bottom-up management approaches and community empowerment. This model may provide an example for holistic water management to the rest of Africa (Van Wilgen et al. 1998).

5. Implementation of monitoring programmes to ensure adequate baseline data as well as evidence of the long-term success of early detection and rapid response, eradication and control efforts is vital to the successful abatement of IAS threats. The use of volunteer community support in the establishment and maintenance of these monitoring programmes is critical given the lack of resources in many countries for institutionalised programs. Programmes such as WaterWatch and FrogWatch in Australia could serve as models for community involvement in monitoring and surveillance.

6. National and regional legislation and policy initiatives should be developed to enable the early detection of IAS in inland water ecosystems and implementation of rapid response programmes. Clear lines of authority for rapid response should also be incorporated into response plans.

7. Research should be targeted at knowledge gaps and research priorities identified in this report, specifically: baseline monitoring of inland water ecosystems and their native species; economic development of native species; in-depth studies on the impacts of IAS on inland water ecosystems; development of innovative mechanical, chemical and biological control techniques; assessment of the benefits and costs of IAS; and modeling of feedback links between ecological and economic systems to aid in the estimation of risk posed by alien species.

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VII. APPENDICES

Appendix A	Overview of Inland Water Ecosystems
Appendix B	Examples of Pathways of Entry of Invasive Alien Species into Inland Water Ecosystems
Appendix C	Examples of the Ecological Impacts of Invasive Alien Species on Inland Water Ecosystems

Appendix A

Overview of Inland Water Ecosystems

Importance and Uniqueness of Inland Water Ecosystems

The most critical component for human survival is access to a sufficient supply of freshwater. In addition, freshwater ecosystems provide us with ecological services such as hydropower, drinking water, waste removal, water filtration, crop irrigation and landscaping, transportation, manufacturing, food source, recreation, nutrient transport/cycling and religion and a spiritual sense of place, that form the basis of our economies and social values. However, freshwater is in very limited supply. Approximately 2.5% of the Earth's water is freshwater, most of which is locked in polar ice caps, stored in underground aquifers (many with recharge cycles measured in millennia), or part of soil moisture and permafrost (McAllister et al. 1997). Only 0.01% of the Earth's water is available as freshwater rivers and lakes which occupies only 0.8% of the Earth's surface (McAllister et al. 1997). These inland water ecosystems support all terrestrial and freshwater life and contain 2.4% of all known existing species, a species richness per unit area that is higher than terrestrial and marine environments[12] (McAllister et al. 1997).

Inland water ecosystems vary in their spatial extent, have indistinct boundaries, and can be hierarchically nested within one another depending on spatial scale (e.g., headwater lakes and streams are nested within larger coastal river systems). Perhaps the most distinguishing features of inland water ecosystems from terrestrial ecosystems are their variability in form and their dynamic nature. Inland water ecosystems are extremely dynamic in that they often change their location (e.g. a migrating river channel) and when they exist (e.g. seasonal ponds) in an observable time frame. Inland water ecosystems are nearly always connected to and dependent upon one another, and as such they form drainage networks that constitute even larger ecological systems. Inland water ecosystems exist in many different forms, depending upon their underlying climate, geology, vegetation, and other features of the watersheds in which they occur. In very general terms, however, inland water ecosystems fall into three major groups (Table A1): standing-water ecosystems (e.g. lakes and ponds); flowing-water ecosystems (e.g., rivers and streams); and freshwater-dependent ecosystems that interface with the terrestrial world (e.g., wetlands and riparian areas). Although the terms inland water ecosystem and freshwater ecosystems are often used interchangeably, it should be noted that there is not an exact correspondence between the two, as a number of inland water ecosystems are saline such as the Salton Sea and Great Salt Lake (UNEP/CBD/SBSTTA/3/7/ph 9/1997).

[12] The richness of inland water species includes a wide variety of plants, fishes, mussels, crayfish, snails, reptiles, amphibians, insects, micro-organisms, birds, and mammals that live beneath the water or spend much of their time in or on the water. Many of these species depend upon the physical, chemical, and hydrologic processes and biological interactions found within inland water ecosystems to trigger their various life cycle stages (e.g., spawning behavior of a specific fish species might need to be triggered by adequate flooding at the right time of the year, for a sufficient duration, and within the right temperature range, etc.; seed germination of a particular plant might require a different combination of variables).

Table A1. Distribution of inland water ecosystems by continent (modified from Korzun et al. 1978). All estimates are approximations and vary according to the methods used to derive them.

	Africa	**Europe**	**Asia**	**Australia**	**N. Am.**	**S. Am.**
Large lakes (km^3)	30,000	2,027	27,782	154	25,623	913
Rivers (km^3)	195	80	565	25	250	1,000
Wetlands (km^2)	341,000	'Eurasia' 925,000		4,000	180,000	1,232,000

Many inland water ecosystems, notably rivers and large lakes, are transboundary in nature. Their ecological boundary is their entire watershed which may cross several political boundaries. Large rivers in particular may flow through many different countries (i.e., headwaters in one country with its mainstem in another country), and also act as the borders between contiguous countries. Because of this, and the fact that activities in one part of a watershed may have effects throughout a watershed (often in another country), such as introduction of IAS, these inland water ecosystems may require more complex political strategies for prevention, eradication and /or control of IAS than terrestrial ecosystems.

Vulnerability of Inland Water Ecosystems to Invasive Alien Species

Biological invasions are more important drivers of biodiversity change in freshwater systems than in terrestrial systems (Sala et al. 2000). They are expected to be the number one driver of biodiversity change in lakes over this century because of the pattern of human settlement around freshwater and the insular/discrete nature of these inland water ecosystems. Our livelihood and our cultures are intimately linked to inland waters. The majority of the world's population makes its home adjacent to these systems, making them extremely vulnerable to IAS invasion. Remote areas with less human disturbance receive fewer IAS than areas that are in the middle of trade routes or that host immense human settlement and activity (Drake et al. 1989).

Generally, inland water ecosystems with high ecological integrity have a higher resistance to biotic invasion than inland water ecosystems that have been degraded through human alteration for water use. The resultant degradation in water quantity and quality of inland water ecosystems caused by dams, inter-basin water transfers, effluent release etc., increase the vulnerability of inland water ecosystems to IAS invasion (Heinz Center 2003). For example, the Workshop on Freshwater Biodiversity held in Selbu, Norway, June 1997 in support of the third meeting of SBSTTA reported that thermal pollution which may occur in connection with industrial uses may *inter alia* lead to invasion by IAS, which may cause changes in ecosystem function. Dams provide lentic habitats that are not favourable to the local riverine species but are highly appropriate for IAS as seen in reservoirs in México (Contreras-Balderas 1976), and many other places around the world (Ackerman et al. 1973).

Appendix B

Examples of Pathways of Entry of Invasive Alien Species into Inland Water Ecosystems

(Modified from Carlton 2001)

Pathway of Entry	**Means of Introduction** I= Intentional, U=Unintentional
Aquaria (Private)	1. (I/U) Aquaria/garden pond plants and animals escape / released into the environment. [1,2,3,4,5,6,7,8]
	2. (U) Pathogens, parasites, algae associated with aquaria plants / pets escape into the environment. [9,10,11]
	3. (I) Introduction of fish for ornamental purposes into private garden ponds. [2,11,12,13]
Aquaria (Public)	1. (I/U) Display organisms escape / released into the environment.
	2. (I/U) Organisms transported with display species escape / released into the environment.
Bait	1. (I/U) Live bait and/or its live packaging (e.g., aquatic plants) released / escaped into the environment. [2,4,5,11,14,15]
	2. (U) Organisms associated with live bait / packaging released into the environment. [14]
Biological Supply	1. (I/U) Organisms intended for scientific study released into the environment. [2,16]
	2. (I/U) Organisms used for classroom study escape / released into the environment.
	3. (I/U) Organisms associated with study specimens escape/ released into the environment.
Shipping Vessels (land, water and air transport)	1. (U) Organisms released when ships discharge ballast water. [11,17,18]
	2. (U) Organisms attached to interior or exterior structures and equipment (i.e., “fouling organisms”) released into the environment.
	3. (U) Organisms contaminating cargo (e.g., wood casks, water containers) released into the environment.

Supporting references: [1] West 1910; [2] Fuller et al. 1999; [3] Bamabaradeniya 2002; [4] Fuller 2003; [5] Contreras-Arquieta and Contreras-Balderas 1999; [6] Contreras-Balderas 1999; [7] Contreras-Balderas and Ludlow 2003; [8] Copp et al. 1993; [9] Hoffman and Schubert 1986; [10] Shotts and Gratzek 1984; [11] Yamamoto and Tagawa 2000; [12] Arthington et al. 1999; [13] Copp et al. 2002; [14] Sherfy 2000; [15] Winfield et al. 1996; [16] Hutchinson and Williams 1994; [17] Ruiz and Carlton 2003; [18] Carlton and Geller 1993; [19] Johnson et al. 2001; [20] Wheeler 1974; [21] Smith et al. 1998; [22] Penczak 1999; [23] Pethiyagoda 1994; [24] McCrary et al. 2001; [25] Lightner 1993; [26] Kennedy 1975; [27] Robertson and Austin 1994; [28] Farr-Cox et al. 1996; [29] Gozlan et al. 2002; [30] Gozlan et al. 2003a; [31] Gozlan et al. 2003b; [32] Riedel 1965; [33] McKaye et al. 1995; [34] Stott 1977; [35] Holcik 1991; [36] Bambaradeniya 2001; [37] Crossman and Cudmore 1999; [38] Mills et al. 1999; [39] Mosisch and Arthington 1998.

Pathway of Entry	Means of Introduction I= Intentional, U=Unintentional
Cargo	1. (I) Organisms released into the environment.
	2. (U) Organisms contaminating cargo (e.g., wood products) released into the environment.
Dry Docks / Jetties	1. (U) Organisms attached to structures that have been relocated.
	2. (U) Organisms released when ballast water is discharged.
Floating Debris	1. (U) Organisms moving on garbage (e.g., bottles, buoys, nets, packaging) that have been relocated.
Fisheries & Game (Recreational)	1. (U) Introduction of organisms transported on hulls, motors and trailers of recreational boats. [11 19]
	2. (I/U) Release of organisms for sporting purposes, including organisms intended to serve as their forage (e.g., tadpoles for bass). Also included are associated organisms (e.g., pathogens) that are unintentionally released. [2 4 6 20 21 22 23 24]
	3. (U) Escape of fisheries stocks, game species (e.g., bullfrogs), and their associated organisms during transport, transplantation and/or holding for growth. [6]
	4. (U) Introduction of organisms associated with relocated fishing gear (e.g., lines, nets, floats).
	5. (I/U) Introduction of aquatic plants and associated material to enhance habitat fisheries / game stocks.
	6. (U) Release of organisms (esp. pathogens and parasites) from waste produced by processing of fish/game. [25]
	7. (U) Release of organisms (esp. pathogens and parasites) along with introduced fish. [25 26 27]
Food (aquaculture & agriculture)	1. (U) Escape of animals and their associated organisms from holding facilities / transport containers. [11 24]
	2. (I/U) Release of organisms by private citizens for propagation and harvest. Includes associated organisms. [2 4 6 11 28 29 30 31]
	3. (I) Government sanctioned release of organisms for propagation and harvest. [2 4 6 23 32 33]
	4. (I/U) Organisms associated with food packaging and released into the environment when packaging is discarded.
Horticulture & Flora Culture	1. (I/U) Introduction of plants and associated organisms into gardens, waterways, and riparian areas.
	2. (U) Introduction of organisms associated with water and soil storage / transport media.
Pest Control	1. (I/U) Release of organisms as biological control agents. Includes their associated organisms. [2 4 6 11 34 35 36]

Pathway of Entry	Means of Introduction I= Intentional, U=Unintentional
Restoration	1. (I/U) Introduction of organisms (esp. plants and fish) and their associated organisms for habitat restoration / conservation purposes. [2,4,6,36]
	2. (U) Release of organisms associated with re-introduced or established native species. [2,4]
Water Diversion Projects	1. (I/U) Movement of organisms into new aquatic systems as a result of projects designed to redirect the flow of water (e.g, inter-basin water transfer, canals, dams, and diversions. [6,37,38]
Recreation	1. (U) Introduction of organisms associated with relocated recreational gear (e.g., SCUBA tanks, rafts, inner tubes, ATVs, hiking boots, etc.). [39]
	2. (I/U) Movement of organisms along transportation corridors - roads, trails, etc.
Natural Dispersal & Hitchhiking	1. (I/U) Dispersal of organisms under their own influence or aided by other organisms (e.g., birds moving snails from one wetland system into another). [2,4,6]
Military and Development Actions	1. (U) Introduction of organisms associated with transport of military and development aid.
Drinking Water Shipments	1. (U) Introduction of organisms associated with bottled water.
Smuggling	1. (I) Illegal transport of organisms. [6]

Appendix C

Examples of the Ecological Impacts of Invasive Alien Species on Inland Water Ecosystems

Ecological Factors	Impacts
Change in Physical Habitat	Loss of native habitat. [1,2,3,4,5,6,7,8,9,10,11,12]
Change in Hydrologic Regime	Alteration of surface water flow regime. [6,7,8,9,13,14,15,16,17]
	Alteration of groundwater regime. [18,19,20,21]
	Alteration of soil moisture regime. [10]
	Alteration of evapotranspiration regime. [10,18,19,20,21]
Change in Water Chemistry Regime	Alteration of dissolved oxygen concentration(s). [4,11,22,23]
	Alteration of dissolved mineral concentrations. [14]
	Alteration of dissolved organic matter. [4,11,23]
	Alteration of turbidity. [1,4,24,25,26,27]
Change in Connectivity	Alteration of lateral connectivity (e.g., river – floodplain connectivity), longitudinal connectivity (e.g., upstream - downstream connectivity), vertical connectivity (e.g., river - groundwater connection through the hyporheic zone). [6,11,12]
Biological Community Impacts	Loss of native species diversity. [1,8,13,23,28,29,30,31,32,33]
	Alteration of native trophic structure and interactions. [1,4,5,8,11,23,26,30,31,34]
	Alteration of native biomass. [1,11,26,35,36,37]
Species Population Impacts	Loss of or decrease in native species populations through predation. [1,4,10,38,39]
	Loss of or decrease in native species populations through competition for food, shelter, habitat and other important resources. [1,4,32,40,41,42,43,44,45,46,47]
	Loss of or decrease in native species populations through pathogens / parasites carried by invasive alien species. [2,4,26,48,49]

Supporting references: [1] Taylor et al. 1986; [2] McCrary et al. 2001; [3] Crivelli 1983; [4] Yamamoto and Tagawa 2000; [5] Lougheed et al. 1997; [6] Bunn et al. 1998; [7] Simberloff and Van Holle 1999; [8] Bunn et al. 1997; [9] Arthington et al. 1983; [10] Jackson et al. 1990; [11] Gopal 1987; [12] Lovich and de Gouvenain 1998; [13] Edwards and Contreras-Balderas 1991; [14] Contreras et al. 2002b; [15] Graf 1978; [16] Graf 1980; [17] Blackburn et al. 1982; [18] McDonald 1968; [19] Vitousek 1986; [20] Loope et al. 1988; [21] Johns 1990; [22] Holcik 1991; [23] Pusey and Arthington 2003; [24] Taylor et al. 1984; [25] Elizabeth et al. 1992; [26] Koehn et al. 2000; [27] Gehrke et al. 1995; [28] Oguto-Ohwayo and Hecky 1991; [29] Wheeler 2000; [30] Godinho and Ferreira 1998; [31] Ricciardi 2003; [32] Contreras 1976; [33] Bambaradeniya 2002; [34] Starling et al. 2002; [35] Reinthal and Stiassny 1991; [36] Leveque 1997; [37] Rodiles 1977; [38] Batjakas et al. 1997; [39] Gouddswaard et al. 2002; [40] Moyle 1976; [41] Arthington 1991; [42] Krueger and May 1991; [43] Pethiyagoda 1994; [44] McKaye et al. 1995; [45] Twongo 1995; [46] Arthington and Lloyd 1989; [47] Arthington and Marshall 1999; [48] Cowx 1997 [49] Kou et al. 1981; [50] Arthington and Bluhdorn 1994; [51] Fausch and White 1981; [52] He and Kitchell 1990; [53] Crowl et al. 1992; [54] Chevassus 1979; [55] Campton 1987; [56] Carvalho and Hauser 1995; [57] Echelle et al. 1997; [58] Hanfling and Harley 2003; [59] Echelle and Connor 1989; [60] Waples 1991; [61] Gaffney and Allen 1992; [62] Wilde and Echelle 1992; [63] Ashbaugh et al. 1994; [64] Echelle and Echelle 1994; [65] Echelle and Echelle 1997; [66] Rhyme and Simberloff 1996.

Ecological Factors	**Impacts**
	Dispersal / relocation of native species populations through over-crowding and aggressive behaviour. [1,2,11,50,51]
	Decrease in reproduction rate and fecundity of native species populations. [52,53]
	Decrease in growth rates of native species populations. [1,52,53]
	Alteration of behaviour in native species populations. [23,51,52,53]
Genetic Impacts	Loss of genetic variability through hybridization. [1,26,52,54,55,56,57,58]
	Loss of genetic variability through introgression / gene-swapping (i.e., erosion of the native species population's gene pool). [33,42,57,59,60,61,62,63,64,65,66]