Dana, vol. 12, pp. 83-97, 2000

Evidence for a decline in the abundance of the American eel, *Anguilla rostrata* (LeSueur), in North America since the early 1980s*

*William A. Richkus & Kevin Whalen***
Versar, Inc., 9200 Rumsey Road, Columbia, MD 21045, USA
richkuswil@versar.com

Abstract

A large and dramatic decline in the numbers of yellow American eel ascending an eel passage facility at the R.H. Saunders Hydroelectric Generating Station on the St. Lawrence River was observed between 1982 and 1993. Commercial landings of American eel in both Canada and the USA have also declined significantly over the last ten years. In this project we evaluated whether eel abundance had declined over this same time period throughout North America. We contacted resource and fisheries management agencies and fisheries researches along the East Coast of the USA and Canada to locate and acquire long term data sets useful for evaluating abundance trends. Data sets of potential value were those extending over the period 1984 through 1995 that were collected in a consistent manner and that could be converted into annual abundance indices of some type (e.g., CPUE). Sources of the useful data sets identified varied widely and included beach seine surveys, impingement sampling at power generating station, commercial fishing, research collections, and monitoring programs. Given the numerous limitations in the data sets acquired, we analyzed for trends using a non-parametric technique. Statistically significant negative trends in abundance were found in data sets from Ontario (Canada), Quebec (Canada), New York (USA) and Virginia (USA). No statistically significant increases in abundance were found. The preponderance of data suggests that there has been a continent-wide decline in eel abundance. We discuss potential factors contributing to the decline, including changes in oceanic conditions, pollution and habitat degradation, recruitment and growth overfishing, and hydroelectric facility impacts. However, the observed declines could also result from unusually high recruitment during the 1970s.

Keywords: American eel, abundance, trends, fisheries, environmental effects.

Introduction

There has been substantial concern among US and Canadian fisheries agencies in the last ten years over the perceived downward trend in abundance of American eel (Castonguay *et al.* 1994a, Peterson 1997). Declining trends in abundance of American eels were first noted and publicized for St. Lawrence River counts of yellow eels passing the ladder at the R.H. Saunders Generating Station, where a greater than 100-fold decline in average daily counts of yellow eels was observed between 1982 and 1993.

*This paper is abstracted from a portion of an EPRI report prepared by the authors under contract to EPRI, 3412 Hillview Avenue, Palo Alto, CA 94304, USA. The full report is entitled: American Eel (*Anguilla rostrata*) Scoping Study: A literature and data review of life history, stock status, population dynamics and hydroelectric impacts, EPRI, Palo Alto, CA: 1999. TR-111873. Preparation of this paper was also supported by funding from EPRI to Versar, Inc.

**Present affiliation of Kevin Whalen is: Federal Energy Regulatory Commission, Washington, D.C. Views expressed by Kevin Whalen are his own and do not represent official views and policies of the Federal Energy Regulatory Commission.

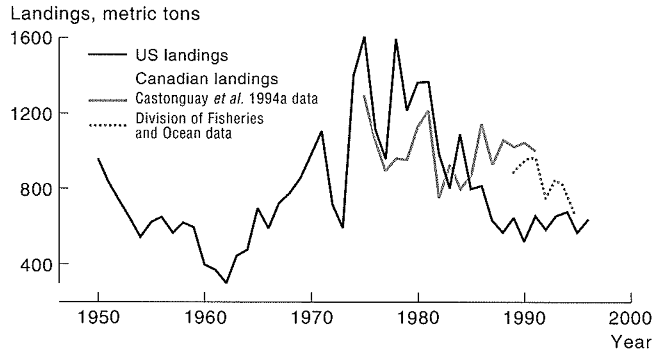

Figure 1. Time series of US and Canadian landings of American eel. Discrepancy in Canadian estimates for overlapping years is unexplained.

In addition, annual commercial landings of American eel in both the USA and in Canada have declined substantially over the past ten to fifteen years (Figure 1). However, substantial deficiencies in the landings, effort and catch composition data preclude the use of the recorded commercial harvest data to evaluate trends in eel abundance throughout their range (EPRI, 1999). The large declines in yellow eel recruitment in the St. Lawrence River were worrisome to fisheries managers because that watershed, based on its large size, may support a large stock of mostly female eels that could comprise a substantial proportion of the total fecundity of the American eel panmictic stock (Castonguay *et al.* 1994a, Lary & Busch 1997). In this project, we sought to identify long-term data sets that would allow us to determine if eel abundance had declined in areas of their range outside of the St. Lawrence River watershed.

Data documentation and approach

Valuable data pertaining to trends in abundance of American eel, documented in Peterson (1997), provide frames of reference beyond the R.H. Saunders ladder data for documenting the status of American eel in Canada. To date, however, no corroborating evidence for a population decline in American eel has been presented from USA data and no quantitative comparative summary analyses of trends of all existing data have been completed. We compiled existing data sets and identified new data sets to analyze time series trends in abundance of American eel. The limitations associated with these time series data are detailed in EPRI (1999). Only data sets providing reasonably consistent, reliable, and non-biased sampling were included in the analysis. Data sets were analyzed that represented a geographical range from Nova Scotia, Canada, to Virginia, USA, and included life stages ranging from glass eels and elvers to yellow and silver-phase eels (Table 1). Our sources of data varied widely and included beach seine surveys, impingement sampling, commercial fishing, research collections, and monitoring programs. Further details and background information can be found in the references cited for those data sets compiled from published reports (Table 1). Descriptions of the unpublished data sets compiled are described as follows:

New Hampshire commercial eel pot fishery. Data obtained from the Marine Fisheries Division of New Hampshire Fish and Game were annual statewide catch per unit effort (CPUE) commercial landings, consisting of summed total weights landed divided by the summed total pot hours of effort. From two to seven rivers contributed to the annual CPUE data reported.

Potomac River, Virginia, commercial eel pot fishery. Data provided by the Potomac River Fisheries Commission were summed annual pounds caught in the Potomac River divided by the product of the number of eel pots fished each year and the number of days worked. Pot mesh size for both New Hampshire and Potomac River eel fisheries was presumed to be that dictated by the regulations of each state.

Hudson River, New York, beach seine and fall shoal survey programs. Data were summarized in 1995 Hudson River, New York, year-class report as part of the Hudson River estuary monitoring program (Ecological Analysts 1998). Data were from beach seine and fall shoal surveys completed at various sites between the George Washington Bridge and Troy Dam. Beach seine surveys were completed biweekly from mid-June through October to target young-of-the-year (YOY) species using shore-zone nursery areas. Fall shoal surveys were completed biweekly from July to October. The beach seine survey used a 30.5-m bag beach seine (sampling area = 450 m^2). Beach seine survey CPUE data presented are total number of eels collected per year divided by the number of samples collected ($\approx$1,000 per year). The fall shoal survey used a 1.0-m^2 Tucker trawl (channel strata) and 3.0-m beam trawl (shoal and bottom strata). Fall shoal survey CPUE data presented are total numbers of eels collected each year divided by the volume of water sampled.

Hudson River, New York, impingement sampling program. Data from the Hudson River, New York, were from impingement sampling at the Roseton and Danskammer power plants and represent summed annual total catch. Each year impingement sampling was typically completed once per week. Additional samples were sometimes collected prior to the late 1980s in accordance with state permitting requirements. Additional sampling events were infrequent and believed not to represent a significant source of bias in the data. The Roseton and Danskammer stations are located in close proximity to river mile 107 on the Hudson River in a tidal area, well above the zone of saltwater intrusion. Both Roseton and Danskammer are fossil-fueled steam electric generating stations using once-through cooling systems.

North Anna River, Virginia, electrofishing surveys. Data were provided by Virginia Power Company on annual electrofishing/electroseining surveys completed in North Anna River, which is part of the York River system, Virginia. Sampling was completed annually between 1981 and 1996. We used data from fall collections (September-October) as fall was the most consistent seasonal period sampled over time. The data reported are relative abundance estimates (number of eels/70 m of shocking distance) first averaged over site and then month.

The significance of trends in abundance was determined using a Mann-Kendall nonparametric trend analysis (van Belle & Hughes 1984). Trends in abundance for each data set were tested over the same time period, 1984-1995, which corresponded with the period of greatest decline observed at the R.H. Saunders ladder on the St. Lawrence River (1982-1993, Casselman *et al.* 1997). Few of the data time series available provided quantitatively reliable information to compare abundance trends over a longer time period. As discussed below, the cyclic and sometimes erratic nature of eel recruitment may affect conclusions regarding decreases in abundance. Clearly, the scope of inference of our analysis is limited to the time period selected. Longer time scales or different time intervals may result in different conclusions regarding stock status.

Table 1. Summary of data sources used in Mann-Kendall trend analysis of eel abundance time series. Significance was determined at $\alpha = 0.05$; n.s. = not significant. Sources are arranged approximately from north to south. Name of contact individual providing unpublished data is given in 'Source' column. Number in parenthesis for 'Available years' column is number of data points available for analysis within the selected 1984 to 1995 time frame. 'Figure' column refers to figure number where data appear in graphical form. All significant relationships between measures of abundance over time were negative.

State/ Province	Location	Source	Available years	Collection method	Eel life stage(s)	Mann-Kendall trend analysis (1984-1995)	Figure
Nova Scotia	East River, Sheet Harbor	Jessop 1996, pers. comm.	1990-1997 (6)	Irish elver trap	Elver	n.s.	4
Ontario	St. Lawrence River	Casselman *et al.* 1997	1974-1995 (12)	Fish ladder	Yellow	$p < 0.001$	2
Ontario	Lake Ontario	Casselman *et al.* 1997	1984-1996 (12)	Commercial electrofising	Yellow	$p < 0.001$	2
Quebec	St. Lawrence River (lower)	Axelsen 1997	1979-1995 (12)	Weir trapping	Silver/ yellow	$p < 0.01$	2
New Hampshire	Statewide	Marine Fisheries Division; N.H. Fish & Game (C. Rogers)	1988, 1990-1997 (7)	Commercial eel pot	Yellow	n.s.	4
New York	Hudson River	1995 year-class report for the Hudson River Estuary Monitoring Program	1985-1995 (11)	Beach seine survey	Yellow	$p < 0.01$	2
New York	Hudson River	1995 year-class report for the Hudson River Estuary Monitoring Program	1985-1995 (11)	Fall shoal survey	Yellow	n.s.	2
New York	Hudson River, Roseton	Central Hudson Gas & Electric Company (CHGECo) (W. Mancroni)	1973-1996 (12)	Impingement sampling	Silver/ yellow	n.s.	2
New York	Hudson River, Danskammer	CHGECo (W. Mancroni)	1974-1996 (12)	Impingement sampling	Silver/ yellow	$p < 0.001$	2
New Jersey	Little Sheepshead Creek	Able & Fahey 1998	1989-1994 (6)	Bridge netting	Glass eel	n.s.	4

Table 1 continued

Virginia/ Maryland	Potomac River	Potomac River Fisheries Commission (P. Holbrook)	198-1997 (8)	Commercial eel pot	Yellow	n.s.	4
Virginia	North Anna River	Virginia Power Company (N.H. Wooding)	1981-1997 (12)	Electrofishing/ electroseining	Yellow	$p < 0.01$	2
Virginia	VIMS trawl survey; rivers and estuaries	Geer & Austin 1997	1954-1996 (12)	Trawl sampling	< 180 mm	n.s.	3
Virginia	VIMS trawl survey; rivers and estuaries	Geer & Austin 1997	1954-1996 (12)	Trawl sampling	181-350 mm	n.s.	3
Virginia	VIMS trawl survey; rivers and estuaries	Geer & Austin 1997	1954-1996 (12)	Trawl sampling	> 350 mm	$p < 0.05$	3
Virginia	VIMS trawl survey; rivers and estuaries	Geer & Austin 1997	1954-1996 (12)	Trawl sampling	All lengths combined	n.s.	3

Results and discussion

Significant negative trends in abundance of American eel were found in data sets from Ontario, Quebec, New York, and Virginia, the full extent of the geographical range tested (Table 1, Figure 2A-F). Evidence for a decline in the St. Lawrence River is indicated by the declining trend in daily passage at the R.H. Saunders ladder (Figure 2A, Casselman *et al.* 1997) and the related decline in commercial electrofishing catches of yellow eels in Lake Ontario (Figure 2B, Casselman *et al.* 1997). A significant decline in abundance was also evident in commercial weir trapping of silver eels in the lower St. Lawrence River (Figure 2C). On the Hudson River, New York, a significant negative trend was observed in the beach seine survey collections (Figure 2D), but not for fall shoals survey sampling (Figure 2D). Impingement catches of eels on the Hudson River showed significant declines at Danskammer, but not at Roseton (Figure 2E). In Virginia, a significant negative trend was found in the North Anna River (Figure 2F) and for eels >350 mm collected in the Virginia Institute of Marine Sciences (VIMS) trawl survey (Figure 3C). The observation of significant declining trends in New York and Virginia, more southerly regions of North America, provides evidence independent of the St. Lawrence River for a decline in American eel from 1984 to 1995. Other regional indices of eel abundance in Canada, including electrofishing surveys completed on the Miramichi and Restigouche rivers (New Brunswick), as well as from the Morrell River (Prince Edward Island), also show evidence for declining trends in eel abundance (Chaput 1997).

There was no evidence of a declining trend for glass eels in New Jersey, elvers in Nova Scotia, or for yellow eels in commercial pot fisheries in New Hampshire or Virginia (Figure 4A,B). These data sets had the fewest number of points available for analysis and none had data available for dates preceding 1988 when sharp declines in

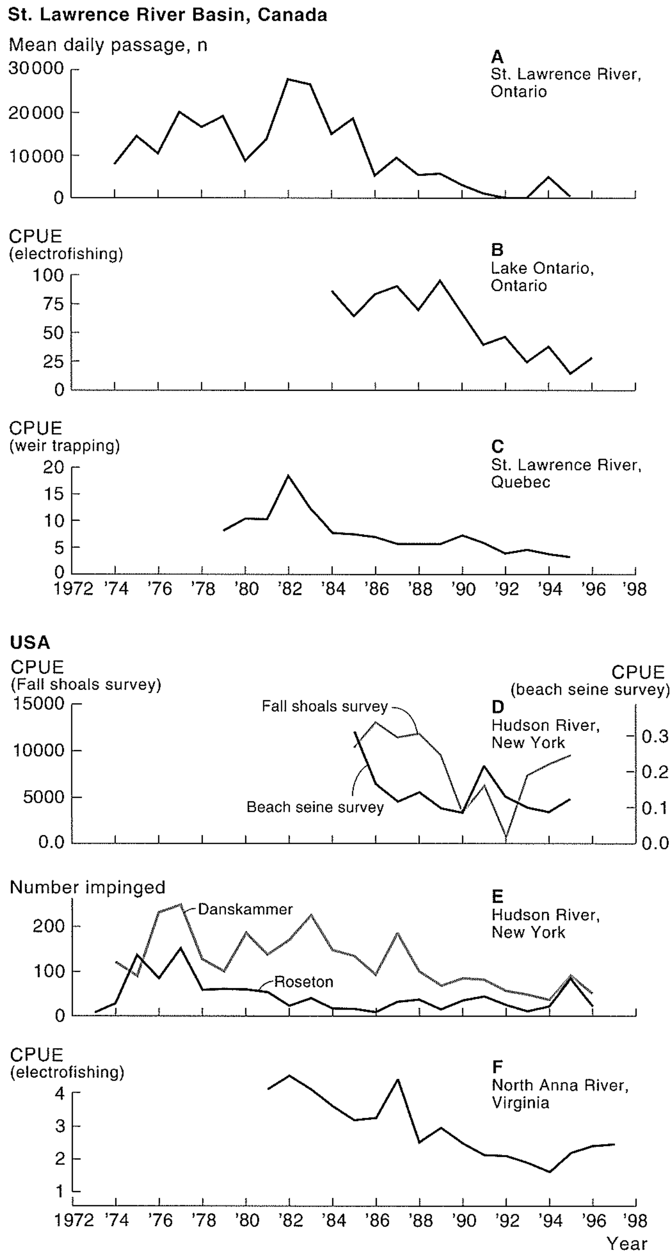

Figure 2. Time series data for American eel abundance from different regions of North America. Data set descriptions and results of Mann-Kendall analysis of trends between 1984 and 1995 are given in Table 1.

abundance were observed in other data sets (e.g., North Anna River, Virginia). No significant trend in abundance was observed for <180 mm and 181-350 mm eels in the Virginia Institute of Marine Sciences (VIMS) trawl survey (Figure 3A,B). Other time series data from 1988 to 1996 for several smaller St. Lawrence River tributaries (Caron & Verreault 1997a) show neither positive nor negative trends in eel abundance.

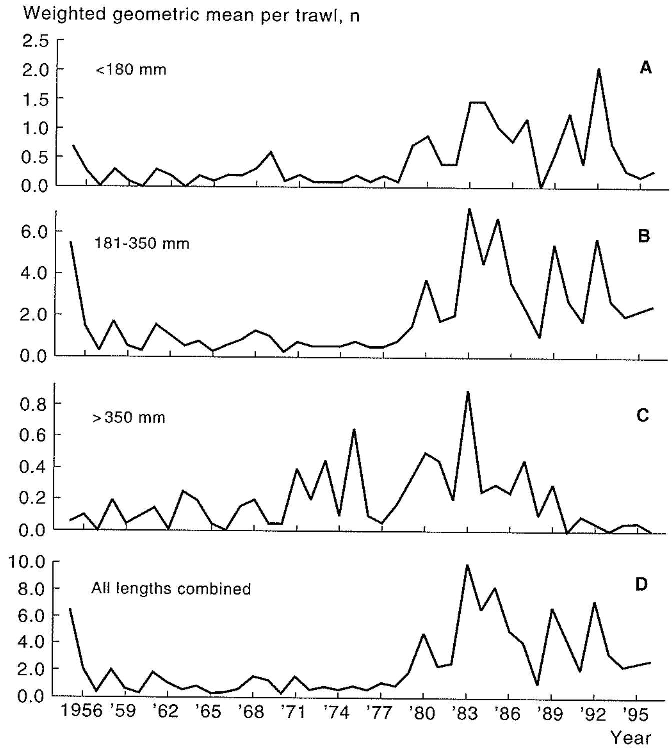

Figure 3. Time series data from Virginia Institute of Marine Science trawl surveys completed between 1956 and 1996. Data are weighted geometric mean per trawl and are presented by size category of eel. Results of Mann-Kendall analysis of trends between 1984 and 1995 are given in Table 1.

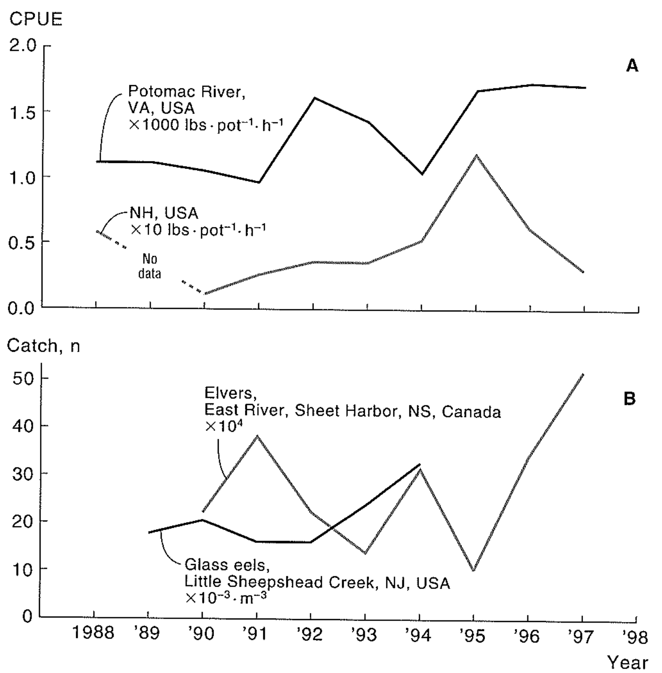

Figure 4. A: Time series CPUE data for the Potomac River, Virginia, and New Hampshire (statewide) landings of commercial eel pot fisheries for juvenile eels. B: Time series catch data for glass eels collected in Little Sheepshead Creek, New Jersey, and for elvers recruiting to the East River, Sheet Harbor, Nova Scotia. Results of Mann-Kendall analysis of trends between 1984 and 1995 are given in Table 1.

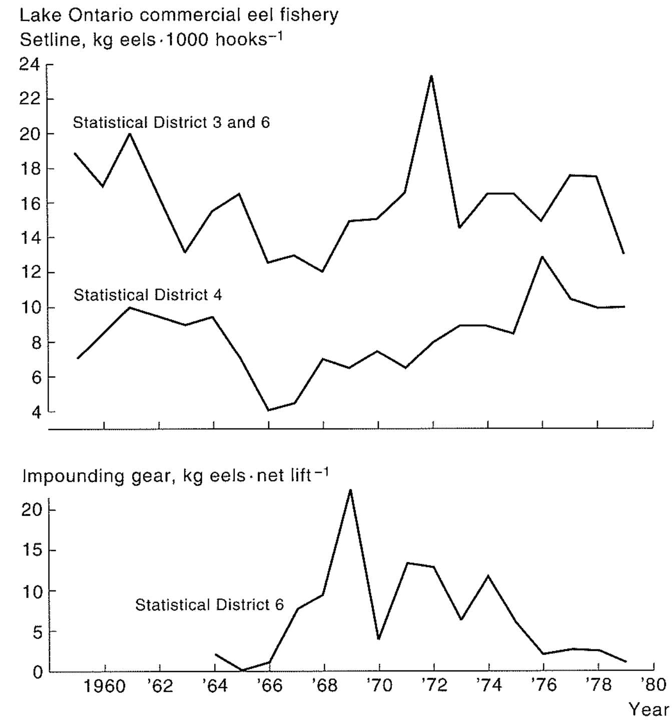

Figure 5. Time series CPUE data for various statistical districts for the Lake Ontario commercial eel fishery. Trends were not statistically analyzed, however, no significant trends in abundance were evident.

In the VIMS data, the large inter-annual variability in catch for eels <350 mm is problematic for the analysis of trends (Figure 3A,B). Other plots for longer time series, such as for various statistical districts in the Lake Ontario commercial eel fishery between 1954 and 1980, exemplify large annual variability present in eel time series data (Figure 5, Stewart *et al.* 1997). Such variability may reflect year class size variation, as we discuss further below.

That all available and reasonably reliable abundance indices do not demonstrate a declining trend suggests there may be localized factors (e.g., recruitment and growth overfishing, localized passage blockages) that may interact with larger-scale processes such as a decrease in oceanic recruitment to influence trends in abundance. For example, on the Richelieu River, a tributary of the St. Lawrence River, a significant declining trend in the catch of silver eels most likely reflects the long-term effect of restricting upstream passage to Lake Champlain (Figure 6, Axelsen 1997). Localized blockages of upstream passage in tributaries in larger river systems that cause recruitment failure of silver eels (Axelsen 1997) may affect trends in silver eel catch at downstream locations. Declining trends in abundance for data sets based primarily on silver eels, such as the lower St. Lawrence River time series (Figure 2C), may therefore reflect the collective effect of reduced juvenile recruitment to the river and recruitment failure stemming from restricting the passage of eels to important upstream habitats.

A major limitation of the data available for trend analysis was that the size, age and phase composition of the majority of the samples were not reported. Only the R.H. Saunders ladder totals and Lake Ontario electrofishing data are exclusively yellow-phase eels. Beach seine surveys and impingement sampling on the Hudson River may have included both yellow and silver-phase eels. Electrofishing sampling on the North Anna River in Virginia was completed in September and/or October and therefore could have also included silver-phase along with yellow eels in the collection. Mixing silver and yellow-phase eels (i.e., migratory and resident population components) in collections could confound time series abundance estimates. Annual estimates were typically averaged over broad seasonal periods; thus, the potential effect of mixing migratory and resident components may have been negated. In general, as noted above, there was very little annual variability in data sets showing a significant declining trend in abundance, which greatly enhanced the statistical power to observe meaningful trends.

While data in Figure 2A-F provide evidence in several areas for a decline in eel abundance since the early 1980s, the longer-term data sets also indicate that cyclic variation is prominent. Cyclic variation also occurs in data sets for European eels *Anguilla anguilla* (L.) (Vøllestad & Jonsson 1988). As Casselman *et al.* (1998) pointed out for the R.H. Saunders ladder counts on the St. Lawrence River, annual trends in eel abundance may be significantly influenced by strong year classes. In the St. Lawrence River, yellow eels may recruit to upstream areas over a number of years and thus a strong year class of eels recruiting to the lower St. Lawrence may have a long-term influence on trends in abundance at upriver locations. Annual trends in abundance could be deceiving if annual catches are comprised of ages of eels that are not constant. Once a strong year class recruits through a system, abundance will be expected to naturally decline, with the magnitude of the decline proportional to the relative strength of the year class and the time period over which upriver recruitment occurs.

This pattern is exemplified in time series abundance data on upstream migrating eels from the Conowingo fish lift located on the lower Susquehanna River, Maryland (SRAFRC 1991, 1992, 1993; Figure 7). High abundance of eels in 1974-1976 and on a smaller time scale in 1981 (Figure 7) drive the perception of decrease in abundance in subsequent years. Elvers accounted for the high abundance of eels in 1974 (C. Frese,

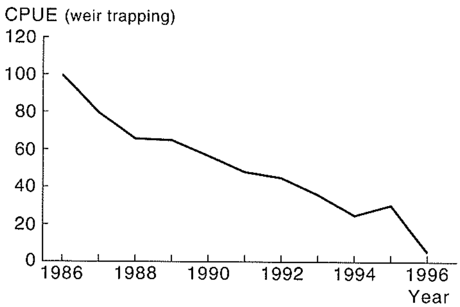

Figure 6. Time series weir CPUE data for Richelieu River, Quebec, a St. Lawrence River tributary, showing a decreasing trend in primarily silver eel abundance.

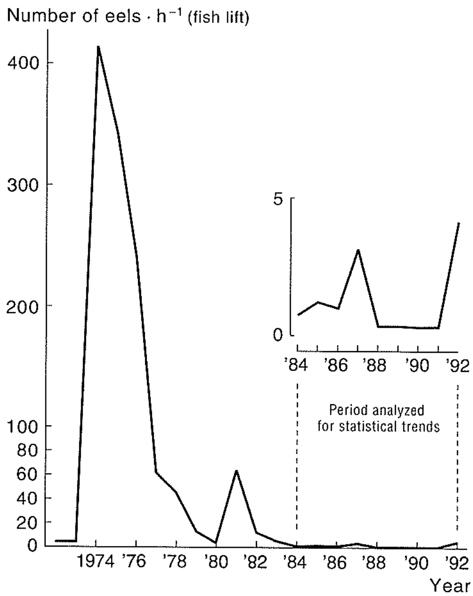

Figure 7. Annual trends in number of upstream migrating American eels lifted per hour of fishing at the Conowingo fish lift(s) on the lower Susquehanna River, Maryland (SRAFRC 1991, 1992, 1993).

Normandeau Associates, Inc., pers. comm.). Given the corroborating evidence reported above, the failure of eels to occur in high abundance after 1981 in the Susquehanna River, particularly the absence of large numbers of elvers, may indicate as in other systems, that American eel are in a depressed and/or declining state. As Casselman *et al.* (1998) pointed out for the St. Lawrence River and as the Susquehanna River data exemplify, it will be important to consider how natural cyclic population patterns, such as the influence of strong year classes, may influence the time scale and thus the perception of the magnitude of the stock decline in eels.

Potential explanations for stock decline

The wide distribution of the American eel, including the division of its life history between freshwater and ocean habitats, necessitates considering an equally wide range of potential factors to explain declines in abundance. The four hypotheses explored by Castonguay *et al.* (1994a) as potential causes for the decline of American eel included oceanic influences, pollution, overfishing, and habitat fragmentation and alteration (including hydroelectric development).

Parasitic infection. Recently, concern has been expressed over the high infection rates (20-40%) by the parasite *Anguillicola crassus*, an Asian nematode found in American eels from the Chesapeake Bay and Hudson River (Secor *et al.* 1998). Local infestations such as those reported in the Potomac River, Virginia, may be very high (≈90%, Bay Journal, September 1998). The parasite is a blood-feeding worm that reproduces in an eel's swim bladder. Hatching larval worms may bore through, rupture, and thus functionally damage the swim bladder. The extent to which *A. crassus* is established along the eastern coast is not currently known and thus the effect that infestations may have on eel stocks is unknown (Barse & Secor 1999).

Oceanic factors. Evidence for the role of oceanic factors in the decline of American eel has been discussed previously by Castonguay *et al.* (1994b). Briefly, they postulated that changes in the strength and distribution of ocean currents observed in the 1980s could affect the distribution and successful recruitment of leptocephali to North America. The finding of a similar decline for European eels supported the suggestion of the importance of far-reaching factors (of global proportions) that may influence eel recruitment. We found no new information on the role of oceanic factors in the decline of American eel since Peterson (1997), where Castonguay reiterates his arguments published in 1994. Several physical oceanography papers (e.g., Kelly & Gille 1990, Kelly & Watts 1994) indicate that the positioning of ocean currents cited by Castonguay *et al.* (1994b) as potentially causing low recruitment of eels, may in fact result in increased rather than reduced transport in areas critical to the dissemination of eel larvae to North America. These findings question Castonguay *et al.* (1994b)'s hypothesis, but they do not diminish the importance of the point Castonguay *et al.* (1994b) raised concerning the potential oceanic influence on the decline of American eel.

The broad latitudinal distribution of eels and the immense scale and expanse of the ocean environment they occupy as larvae substantially complicates the ability to link variability in the ocean environment to variability in glass eel or elver recruitment. The spawning and maturation strategy of eels (e.g., immense fecundity of individual females) would appear to be adapted for larval recruitment that is largely random (Mc-

Cleave 1998). The random nature of eel life history in the ocean coupled with the practical limitations of linking biological and physical process at such a large scale may certainly obfuscate the role of the ocean in affecting stock abundance. Given that eel recruitment to freshwater and coastal areas is inherently bound to oceanic processes, further research is warranted to understand the effect of variation in Gulf Stream transport on elver recruitment and to determine how decadal-scale (or longer) changes in ocean climate and/or annual-scale (or shorter) changes in ocean weather influence larval recruitment. Of particular interest will be determining what oceanic conditions are associated with strong glass eel and elver year classes that may have far-reaching influences on freshwater trends in stock abundance.

Pollution. The potential scope of the effect of pollution on American eel is difficult to ascertain directly. In the St. Lawrence system, one vector that had been explored is the chronic exposure of eels to contaminated sediments in Lake Ontario (Hodson *et al.* 1994). Eels may spend an extended period in fresh water before maturing and migrating and may therefore be chronically exposed to toxins. The benthic habitat of eels may also make them particularly susceptible to uptake from polluted sediments. The bioaccumulation of toxins and storage in lipid tissue could put eels at risk to toxicity when such tissues are metabolized during the presumably arduous return migration to the Sargasso Sea (Hodson *et al.* 1994). Additionally, bioaccumulated toxins, which are typically preferentially stored in lipid tissue, may be mobilized and deposited in lipid-rich egg tissue (Ankle *et al.* 1989) and result in developmental failure of larvae (Niimi 1983).

A second vector for a pollution effect on eels is through direct exposure to highly contaminated waters. In the St. Lawrence River, Dutil *et al.* (1987) estimated that as many as 100 metric tons of silver eels were found dead during the migration seasons of 1972 and 1973 as a result of pollution. The effect was limited to silver eels, suggesting some special susceptibility for metamorphosed eels (Dutil 1984). Dutil *et al.* (1987) showed exposure of eel gill membranes to contaminated water resulted in large changes in the functional gill morphology, which led to pathological osmotic stress. Body burdens were not correlated with osmotic stress indicating the vector of mortality was likely the topical exposure of gills to contaminated water. Recent research indicates osmoregulatory ability of eels is affected by pesticides (Sancho *et al.* 1997). Other analyses of St. Lawrence River eels have found very little evidence for signs of external disease (Dutil *et al.* 1997).

Recent improvements in environmental toxin levels, such as has occurred in Lake Ontario (Hodson *et al.* 1994), may minimize the potential for chronic exposure to affect migrating eels and the development of eel larvae. However, many areas throughout the natural range of American eels in North America still contain contaminated sediments and waters (e.g., northern Hudson River, New York) and there is little understanding of how extant contamination may affect recruitment success of eels.

Recruitment and growth overfishing. Fisheries target all freshwater stages of the eel. Elvers are highly exploitable because of their localized concentration and abundance during upstream migration and older yellow eels are susceptible because they remain for extended periods in fresh water and estuarine areas, and are exposed to fishing mortality for many years. Several lines of recent research on elvers and silver eels support the presumption that fisheries exploitation rates on both juvenile and adult eels are very high. Studies from Canada have estimated fisheries exploitation rates on elvers as high as 30% (Giuseppe 1997) and harvest rates of near 17% for silver eels (Caron & Verreault 1997a). Given the numerous examples in the fisheries literature for the effects of overharvest on populations, it is unlikely such high exploitation rates on both juvenile and silver eels could be sustained indefinitely if the entire panmictic population were vulnerable to such fishing pressure. However, the widespread distribution of American eel throughout North America, and the often localized nature of fisheries for this species suggests that eel stocks in some regional areas may go unexploited or be very lightly fished. In addition, in our earlier discussion of recruitment, we noted that there may be a maximum number of elvers recruited into a system beyond which there is no additional recruitment to the silver eel life stage (Vøllestad & Jonsson 1988), suggesting that there may be surplus elvers moving into individual water bodies that could be harvested without impacting the regional abundance of eels or the population. It may be argued that, until natural mortality rates at all life stages are better known, prudent conservation favors protection of silver eels, since exploitation of this sexually mature life stage has the most direct effect on potential population fecundity. Recruitment overfishing for a panmictic catadromous species is essentially impossible to prove. Evidence from other long-lived, late maturing species where data are more tractable indicates very clear negative population consequences of over exploitation, particularly where fishing mortality rates may approach or exceed natural rates of mortality.

Other evidence for the effect of commercial fishing on American eel is from growth overfishing observed in the Chesapeake Bay (Hedgepeth 1983). Hedgepeth (1983) suggested that the amount of fishing pressure in an area was the primary factor explaining the size distribution of eels. The effect of commercial exploitation on eels has not been quantified, but evidence for growth overfishing indicates the significant role that fisheries have in affecting the age and size structure as well as sex ratios of local eel stocks which could, in turn, result in impact to the population.

Hydroelectric facility impacts

The complexity of eel life history makes it very difficult to establish the cumulative magnitude of the impact of hydroelectric facilities and other man-made barriers throughout the eel's geographical range on the status of the population. Clearly, eels within watersheds on which multiple hydroelectric facilities are sited are most likely to show significant hydroelectric impacts, particularly with regard to the cumulative mortality to silver eels associated with passage through multiple project turbines. However, the migratory behavior of eels and their behavior upon encountering hydroelectric projects is too poorly characterized to quantify cumulative multi-project losses. In addition, watershed-specific impacts to silver eels would have to be aggregated across all watersheds to assess the potential consequences to the population, an assessment which, to date, has not been done.

Impacts during upstream movement and on habitat colonization are even more poorly defined. Castonguay *et al.* (1994a) note that the recent decline in the eel stock has occurred many decades after the majority of the major hydroelectric projects within the eel's geographical range were constructed, making it unlikely that these projects could be a major causative factor in the continent-wide decline, although some specific projects clearly have affected some specific stocks (e.g., Richelieu River, Figure 6). However, a counter argument to the significance of hydroelectric impacts (e.g., Lary &

Busch 1997) is that although hydro projects may not be the causative factor in the initiation of the decline, they are a contributory factor, which should be mitigated in the face of the decline. Lary *et al.* (1998) recently presented an overview of the extent of barriers to migration, including hydro development, in several regions of North America encompassing the natural distribution of American eel. Using several assumptions regarding the passage of eels around barriers, they suggested that throughout the US, barriers in fresh water, including hydroelectric developments, have substantially restricted the access of eels to large portions of freshwater habitat. This modeling result was not ground-truthed with actual data on eel distribution and abundance or peer-reviewed, so its validity is unknown. Further analysis (i.e., ground-truthing) and development of geographical models of historic and existing eel habitat would be necessary to establish the model's validity. Linking geographical and population models may provide a means to simulate the benefits to the eel population of mitigating restricted upstream and downstream passage.

In summary, our analysis showed there is evidence from several widely distributed regions of North America supporting a conclusion for a decline in stock abundance of American eel from 1984 to 1995. All trends that were statistically significant showed declining abundance and no positive trends in abundance were observed. There were no statistically significant trends in abundance for glass eels or elvers, but the time series for these life stages may have been too short to provide meaningful results. Other data sets showing no statistically significant changes in abundance over time (e.g., VIMS data for eels <350 mm) generally had very high inter-annual variability. In contrast, data sets showing statistically significant declines had comparatively little annual variability, which substantially enhanced the statistical power of the tests performed to assess the population decline. Further analysis of how local factors may relate to, and influence, perceptions of large scale, population-level effects of depressed recruitment would be of value.

Acknowledgements

Preparation of this manuscript was funded through a contract from EPRI, Palo Alto, California, USA. We express our appreciation to our EPRI Contract Administrator, Dr. Doug Dixon.

References

Able, K.W. & J.P. Fahey, 1998. The first year in the life of estuarine fishes in the middle Atlantic Bight. – Rutgers University Press, New Brunswick, New Jersey. 240 pp.

Ankle, G.T., D.E. Tailed & J.P. Gipsy, 1989. Maternal transfer of bioactive polychlorinated aromatic hydrocarbons in spawning chinook salmon (*Onchorynchus tschwaytscha*). – Marine Environmental Research *28*: 231-234.

Axelsen, F., 1997. The status of the American eel (*Anguilla rostrata*) in Quebec. – *In* R.H. Peterson (ed.): The American eel in eastern Canada: stock status and management strategies, pp. 121-133. Proceedings of Eel Workshop, January 13-14, 1997, Quebec City, Quebec. Canadian Technical Report of Fisheries and Aquatic Sciences *2196*.

Barse, A.M. & D.H. Secor, 1999. An exotic nematode parasite of the American eel. – Fisheries *24*(2): 6-11.

Caron, F. & G. Verreault, 1997a. Estimation du stock d'anguille d'America (*Anguilla rostrata*) argent en devalaison days le bas Saint-Laurent et son taus d'exploitation en 1996. – *In* R.H. Peterson (ed.): The American eel in eastern Canada: stock status and management strategies, pp. 94-105. Proceedings of Eel Workshop, January 13-14, 1997, Quebec City, Quebec. Canadian Technical Report of Fisheries and Aquatic Sciences *2196*.

Caron, F. & G. Verreault. 1997b, Le reseau sentineled de l'anguille. – *In* R.H. Peterson (ed.): The American eel in eastern Canada: stock status and management strategies, pp. 144-160. Proceedings of Eel Workshop, January 13-14, 1997, Quebec City, Quebec. Canadian Technical Report of Fisheries and Aquatic Sciences *2196*.

Casselman, J.M., L.A. Marcogliese & P.V. Hodson, 1997. Recruitment index for the upper St. Lawrence River and Lake Ontario eel stock: a re-examination of eel passage at the R.H. Saunders hydroelectric generating station at Cornwall, Ontario, 1974-1995. – *In* R.H. Peterson (ed.): The American eel in eastern Canada: stock status and management strategies, pp. 161-169. Proceedings of Eel Workshop, January 13-14, 1997, Quebec City, Quebec. Canadian Technical Report of Fisheries and Aquatic Sciences *2196*.

Casselman, J. M., L. A. Marcogliese & P. V. Hodson. 1998. The American eel, *Anguilla rostrata*, stock of the upper St. Lawrence River and Lake Ontario: long-term trends, decreasing abundance, cause and effect. American eel biology and management symposium, August, 26, 1998. American Fisheries Society annual meeting, Hartford, Connecticut. Unpublished abstract.

Castonguay, M., P.V. Hodson, C.M. Couillard, M.J. Eckersley, J.-D. Dutil & G. Verreault, 1994a. Why is recruitment of the American eel, *Anguilla rostrata*, declining in the St. Lawrence River and Gulf? – Canadian Journal of Fisheries and Aquatic Sciences *51*: 479-488.

Castonguay, M., P.V. Hodson, C. Moriarty, K.F. Drinkwater & B.M Giuseppe, 1994b. Is there a role of ocean environment in American and European eel declines? – Fisheries Oceanography *3*(3): 197-203.

Chaput, G.C., 1997. Relative value of elver versus eel fisheries. Pages – *In* R.H. Peterson (ed.): The American eel in eastern Canada: stock status and management strategies, pp. 62-67. Proceedings of Eel Workshop, January 13-14, 1997, Quebec City, Quebec. Canadian Technical Report of Fisheries and Aquatic Sciences *2196*.

Dutil, J.D., 1984. Electrolyte changes of serum and muscle, and related mortalities in maturing, *Anguilla rostrata*, migrating down the St. Lawrence estuary, Canada. – Helgoländer wissenshaftliche Meeresuntersuchungen *37*: 425-432.

Dutil, J.D., M. Beaner & S.D. McCormick, 1987. Osmoregulatory and ionoregulatory changes and associated mortalities during the transition of maturing American eels to a marine environment. – American Fisheries Society Symposium *1*: 175-190.

Dutil, L.T., C.M. Couillard & D. Balancer, 1997. A processing plant survey of external lesions of American eels, *Anguilla rostrata*, from Lake Ontario and the St. Lawrence River, Canada. – Preventive Veterinary Medicine *31*: 19-32.

Ecological Analysts, Inc. (EA). 1998. 1995 year class report for the Hudson River Estuary monitoring program. Prepared for Consolidated Edison Company of New York, Inc.

EPRI, 1999. American eel (*Anguilla rostrata*) Scooping Study: A literature and data review of life history, stock status, population dynamics, and hydroelectric facility impacts. – EPRI, Palo Alto, CA. TR-111873. 144 pp.

Geer, P.J. & H.M. Austin, 1997. Time-series evaluation of American eel, *Anguilla rostrata*, in the Virginia portion of Chesapeake Bay. – Virginia Marine Resource Report. VIMS, Glouchester, VA, USA. 31 pp.

Giuseppe, B.M., 1997. American eel elvers and their fishery in the Scotia-Fundy area of Atlantic Canada: an overview. – *In* R.H. Peterson (ed.): The American eel in eastern Canada: stock status and management strategies, pp.134-143 . Proceedings of Eel Workshop, January 13-14, 1997, Quebec City, Quebec. Canadian Technical Report of Fisheries and Aquatic Sciences *2196*.

Hedgepeth, M.Y., 1983. Age, growth and reproduction of American eels, *Anguilla rostrata*, Lacier, from the Chesapeake Bay area. – M.S. Thesis, The College of William and Mary. 91 pp.

Hodson, P.V., M. Castonguay, C.M. Couillard, C. Desjardins, E. Pelletize & R. Macleod, 1994. Spatial and temporal variations in chemical contamination of American eels, *Anguilla rostrata*, captured in the estuary of the St. Lawrence River. – Canadian Journal of Fisheries and Aquatic Sciences *51*: 464-478.

Jessop, B.M., 1996. The biological characteristics and efficiency of deep-net fishing for, American eel elvers in the East River, Chester, Nova Scotia. – Report of the Joint Project Agreement Elver Fisheries Study, F286-5-0418. 14 pp.

Kelly, K.A. & S.T. Gille, 1990. Gulf stream surface transport and statistics at 69EW from the Gestate altimeter. – Journal of Geophysical Research C, Oceans, *95*: 3149-3161.

Kelly, K.A. & D.R. Watts, 1994. Monitoring Gulf Stream transport by radar altimeter and inverted echo sounders. – Journal of Physical Oceanogaphy *24*: 1080-1084.

Lary, S.J. & W.D.N. Busch, 1997. American Eel, *Anguilla rostrata*, in Lake Ontario and its tributaries: distribution, abundance, essential habitat and restoration requirements. – Administrative Report No. 97-01. U.S. Department of the Interior, Fish and Wildlife Service, Lower Great Lakes Fishery Resources Office, Amherst, N.Y. 27 pp.

Lary, S. J., W. D. N. Busch &C. M. Castiglione. 1998. Distribution and availability of Atlantic coast freshwater habitats for American eel (*Anguilla rostrata*). American eel biology and management symposium. August, 26, 1998. American Fisheries Society annual meeting, Hartford, Connecticut. Unpublished abstract.

McCleave, J. D. 1998. Oceanic variability as an influence on American eel reproduction and glass eel recruitment: a series of speculations. American eel biology and management symposium, August, 26, 1998. American Fisheries Society annual meeting, Hartford, Connecticut. Unpublished abstract.

Niimi, A.J., 1983. Biological and toxicological effects of environmental contaminants in fish and their eggs. – Canadian Journal of Fisheries and Aquatic Sciences *40*: 303-312.

Peterson, R.H. (ed.), 1997. The American eel in eastern Canada: stock status and management strategies. Proceedings of Eel Management Workshop, January 13-14. 1997, Quebec City, QC. Canadian Technical Report of Fisheries and Aquatic Sciences 2196. 174 pp.

Sancho, E., M.D., Fernando & E. André, 1997. Inhibition of gill NA+, K+-OUTPACE activity in the eel, Anguilla anguilla, by Fenitrothion. – Ecotoxicology and Environmental Safety *38*: 132-136.

Secor, D., J. Baker & A. Barse. 1998. Estuarine gradients in contamination and *Anguilla crassus* infestations in Hudson River American eels. American eel biology and management symposium, August, 26, 1998. American Fisheries Society annual meeting, Hartford, Connecticut. Unpublished abstract.

Stewart, T. J., J.M. Casselman & L.A. Marcogliese, 1997. Management of the American eel, *Anguilla rostrata*, in Lake Ontario and the upper St. Lawrence River. – *In*R.H. Peterson (ed.): The American eel in eastern Canada: stock status and management strategies, pp. 54-61. Proceedings of Eel Management Work-shop, Quebec City, Quebec. Canadian Technical Report of Fisheries and Aquatic Sciences *2196*.

SRAFRC (Susquehanna River Anadromous Fish Restoration Committee), 1991. Restoration of American shad to the Susquehanna River. – Annual progress report 1990. USFWS, Harrisburg, PA, USA. 112 pp.

SRAFRC (Susquehanna River Anadromous Fish Restoration Committee), 1992. Restoration of American shad to the Susquehanna River. – Annual progress report 1991. USFWS, Harrisburg, PA, USA. 127 pp.

SRAFRC (Susquehanna River Anadromous Fish Restoration Committee), 1993. Restoration of American shad to the Susquehanna River. – Annual progress report 1992. USFWS, Harrisburg, PA, USA. 143 pp.

van Belle, G. & J.P. Hughes, 1984. Nonparametric tests for trend in water quality. – Water Resources Research *20*: 127-136.

Vøllestad, L.A. & B. Jonsson, 1988. A 13-year study of the population dynamics and growth of the European eel, *Anguilla anguilla*, in a Norwegian river: evidence for density-dependent mortality, and development of a model for predicting yield. – Journal of Animal Ecology *57*: 983-997.