Chapter 4
Impingement and Entrainment at SWRO Desalination Facility Intakes

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Abstract Seawater desalination intakes have potential to negatively impact marine life. The principal impacts of concern are broadly categorized into impingement and entrainment (I&E). Each represents an interaction between the marine organisms in the source water body and the intake screening technology used at the desalination facility. Impingement is the entrapment of larger organisms against the screen mesh by the flow of the withdrawn water. Entrainment is the passage of smaller organisms through the screening mesh. Concern over the impacts of I&E has formed the basis of a major portion of the environmental regulation of seawater intakes in the U.S. for power generation and other industrial uses. In addition, the impacts of I&E at seawater desalination intakes is growing as a global environmental concern. The withdrawal of seawater for desalination has impacts that cannot be eliminated; however, they can be minimized. There are well-recognized approaches for predicting the potential for I&E, for documenting the magnitude of I&E, and for assessing the impacts of I&E on natural populations. More importantly, the body of knowledge surrounding I&E and the means for minimizing its impacts is extensive. Although some impacts are unavoidable, various technological and operational methods, many of which have undergone extensive laboratory and field evaluation, are available and proven to improve the protection of marine life at desalination facility intakes. This chapter reviews the biology of I&E at seawater intakes, the sampling approaches for assessing and quantifying I&E, the methods for predicting the potential for I&E, the methods for assessing the impact of I&E on natural populations, and the common approaches and technologies available for minimizing I&E at seawater intakes.

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T.M. Missimer et al. (eds.), *Intakes and Outfalls for Seawater Reverse-Osmosis Desalination Facilities*, Environmental Science and Engineering,
DOI 10.1007/978-3-319-13203-7_4

4.1 Introduction

The operation of intakes at seawater reverse osmosis (SWRO) desalination plants has potential to negatively impact marine organisms near the intake structure. The most significant impacts can be broadly categorized as impingement and entrainment (I&E). Each represents an interaction between the organisms in the source water body and the desalination feedwater system and each is dependent on the size of the organism and the screen mesh of the intake screening technology. Impingement refers to the pinning of larger organisms (typically juvenile and adult stages) against the screen mesh by the flow of the withdrawn water while entrainment refers to the passage of smaller organisms (typically early life stages—eggs and larvae) through the screen mesh (Fig. 4.1). Another term, entrapment, refers to organisms that have entered a component of the intake system. These organisms have not yet been impinged on or entrained through the final downstream screening structure, but have no means of escape from the intake water system.

Commonly accepted definitions of entrainable and impingeable organisms, as they are used in the U.S., are given as:

> *Impingeable organism*—organism large enough to be retained by a mesh with a maximum opening of 14.2 mm—includes 9.5-mm mesh and 6.35 by 12.7 mm mesh (EPA 2014). This group includes larger, actively moving juvenile and adult organisms.
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> *Entrainable organism*—organism small enough to pass through a mesh with a maximum opening of 14.2 mm—includes 9.5-mm mesh and 6.35 by 12.7 mm mesh (EPA 2014). This group includes small organisms with limited to no

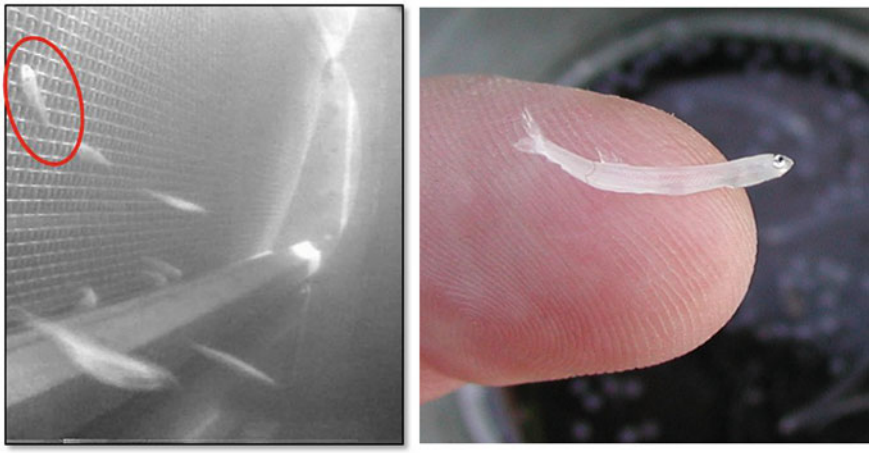

Fig. 4.1 Impingement of juvenile striped bass on a traveling water screen (*left*) and a larval fish representing a size that is potentially at risk of entrainment (*right*)

swimming ability. Some of these organisms (e.g., fish eggs) may be completely passive, lacking the ability to avoid the intake flow regardless of velocity.

The magnitude of impingement losses for any species from intake operation is a function of the organism's risk of exposure to the intake screen (number or proportion impinged and entrained) and the subsequent mortality of those organisms that were exposed (referred to as impingement or entrainment mortality). Impingement survival is very species-specific, with species that are considered "hardy" (e.g., species with heavy skeletal structure, thick scales, protective slimes) typically experiencing higher survival and those considered "fragile" (e.g., species with lighter skeletal structures, thinner scales, a tendency to lose scales readily when handled) (EPRI 2003a). In the desalination process, entrainment mortality is assumed to be 100 % (Foster et al. 2013; Pankratz 2004) except in cases where a portion of the withdrawn flow is diverted away from the treatment systems for brine dilution.

There are a number of factors that can directly or indirectly affect the probability and magnitude of I&E at seawater desalination intakes, most of which are interrelated. These include:

- *Intake location*—An intake in a more biologically productive area poses a greater risk of exposing marine life to I&E than one located outside of a biologically-productive area.
- *Ambient hydraulics*—An intake in an area with low ambient currents (e.g., tidal or ocean currents) poses a greater risk of I&E than one located in an area with relatively strong ambient currents that can sweep non-motile organisms away.
- *Water quality*—Extremes of temperature and low dissolved oxygen can negatively impact marine organism health, in turn compromising their ability to avoid exposure to the intake.
- *Species-specific morphology and physiology*—Physical attributes of the marine organisms can affect both their ability to avoid impingement and entrainment and to survive impingement.
- *Intake system design and operation*—An active intake screening system that collects and returns impinged organisms poses a greater risk of impinging organism than a passive intake screening system operating at a low velocity, which nearly eliminates the risk of impingement.

Minimizing environmental impacts to marine resources is often a regulatory concern, particularly in the U.S., but can also be driven by other mechanisms such as corporate environmental policy or project financing requirements (e.g., the Equator Principles). Given the high priority placed on preserving marine resources by many countries, it is important to have both accurate measurements of I&E impacts as well as effective mitigation approaches. Consideration of these impacts during pre-design phases for new SWRO facilities is also critical because the potential for I&E can be minimized through the careful selection of an intake location and intake screening technology. The location, screening technology, and intake design are also important from an economic perspective, as each can significantly impact capital and operational expenditures. For example, an intake constructed in a poorly selected location may result in greater than expected impingement. Such a scenario may require the facility operator to make either a physical or operational modification, typically at a high cost, to the intake to reduce impingement.

4.2 Environmental Regulation in the U.S

The U.S. is often considered to be one of the most environmentally-conservative countries and impingement and entrainment have received intense scrutiny, particularly at thermal electric power plants, since the 1970s. Although not explicitly covered by the same federal regulations developed for the thermal power industry, desalination facilities are commonly held to the same environmental performance standards; therefore, the following review of the principal federal regulation governing I&E in the thermal power industry is warranted.

Cooling water intake structures (CWIS) at thermal power plants fall under the federal Clean Water Act (CWA) which is administered by the U.S. Environmental Protection Agency (EPA). Section 316(b) of the CWA requires "*that the location, design, construction, and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impacts*" (EPA 2011). In 2004, rulemaking by the EPA established new guidelines for the implementation of Sect. 316(b) (the Rule), which required all CWIS to meet national performance standards relative to impingement mortality and, in some cases, entrainment. The rulemaking was parsed into several phases: Phase I covered new power plants, Phase II covered existing power plants, and Phase III covered new offshore oil and gas extraction facilities that withdraw 7575 m^3/d or more and use at least 25 % of the water exclusively for cooling. The Rule laid out benchmark performance standards for the reduction of impingement mortality (IM) and entrainment.

The Rule for existing thermal power plants was recently rewritten and a final 316(b) Rule was released in May of 2014 (EPA 2014). This final Rule supersedes the Phase II and Phase III rules and covers all facilities withdrawing at least 7575 m^3/d of cooling water from waters of the U.S. of which 25 % is used exclusively for cooling. All facilities falling under the final Rule have to address IM. The EPA has provided seven pathways for IM compliance; they include:

- Operate a closed-cycle recirculating system.
- Operate at a design through-screen velocity less than or equal to 0.15 m/s.
- Operate at an actual through-screen velocity less than or equal to 0.15 m/s.
- Operate an existing offshore velocity cap (i.e., those installed before October 14, 2014 and has to be 244 m offshore to qualify)
- Operate modified traveling water screens (requires a 2-year optimization study to ensure screens are working as best they can to minimize IM of non-fragile species)

- Operate a combination of technologies, management practices, and operational measures that meets the standards set forth in the following compliance alternative (also requires a 2-year optimization study as compliance alternative 5).
- Achieve a specific IM performance standard of no more than 24 % mortality of all non-fragile species for 12 months. The EPA stated that they do not expect many facilities to choose this compliance option; rather, this is a compliance path that can be used for innovative technologies developed in the future.

Due to site-specificity, the EPA has not issued a national entrainment performance standard. Instead, the EPA has left the determination for what constitutes best technology available (BTA) for entrainment to the permit writers. CWIS permitting in the U.S. is generally decentralized with most states having been delegated the authority to issue permits under the Clean Water Act. While all facilities are subject to a BTA determination relative to entrainment, only those facilities withdrawing greater than 473,176 m^3/d are required to submit additional studies that include evaluation of entrainment reducing technologies. These studies must evaluate closed-cycle cooling, the use of recycled water (to reduce intake flow and associated entrainment), and the technical feasibility of fine-mesh/narrow slot (2-mm) screens.

The biggest factor affecting whether an intake will be held to an entrainment performance standard is the location of the intake. Given that desalination facility intakes, by design, withdraw seawater, they are located in coastal marine and estuarine areas. Since coastal and estuarine areas are widely recognized as highly biologically productive (Agardy and Alder 2005) and are used for spawning and rearing of early life stages of marine organisms, protection against entrainment of early life stages is likely to be required.

The details of the final Rule and the approaches utilized by power generators to comply with the regulations are important to the desalination industry in the U.S. In nearly every case in the U.S., state regulators with jurisdiction over the desalination industry draw from the federal 316(b) Rule. Since the regulation of desalination impacts is handled at the state level in the U.S., there is potential for the regulations to vary among states.

4.3 Typical Intake Studies Required

A suite of biological studies are typically required by permitting authorities to support the assessment of potential intake-related I&E impacts as well as to determine the effectiveness of the intake screening system for minimizing these impacts. The studies can be broadly grouped into two categories: studies that provide data on the populations of organisms occurring near the intake that may be at risk of I&E (i.e., baseline characterization) and studies that provide data on the organisms that actually impinge on or entrain through the intake screening system (i.e., I&E characterization). Each study type is described briefly here, though greater detail on standard I&E studies is provided in Sect. 4.4.

4.3.1 Baseline Characterization Study

A baseline characterization study is designed to yield data on the species and life stages occurring in the source water body and which may be at risk of I&E. Baseline data are critical for setting the benchmark against which I&E impacts can be measured. Typical baseline characterization studies include the following components (EPA 2012):

- A review of existing pertinent data that would aid in identifying the species and life stages present;
- Identification of the species and life stages in the area and their relative abundance near the proposed intake location;
- Identification of the species and life stages most susceptible to impingement and entrainment (I&E);
- Identification of the primary periods of reproduction, larval recruitment, and peak abundances;
- Identification of the temporal (daily, seasonal) variations in abundance; and
- Supplemental field studies conducted to collect data that were not available must document the study methods, statistical power, QA/QC process, and data analysis approach.

4.3.2 Impingement and Entrainment Characterization Studies

Impingement and entrainment studies are designed to quantify the magnitude of I&E of organisms at an intake screening system. In the case of impingement, many studies are also designed to estimate the survival of organisms after impingement. Typical I&E studies include the following general components (EPRI 2004b):

- Review and summary of any historical I&E data that are available for the site under consideration;
- Identification of the species and life stages in the area that may be susceptible to I&E;
- Quantification of the current impingement and entrainment levels at the intake in question; and
- Characterization of the spatial and temporal variation (e.g., annual, seasonal, diel) in abundance.

Of impingement and entrainment, entrainment has been receiving greater scrutiny in the U.S. desalination industry. Since many entrainable-sized organisms are passive, planktonic particles, lacking the capacity to swim away from the hydraulic zone of influence of an intake, there is often a greater focus on designing intake systems with screening mesh/slot sizes sufficient to physically exclude these early life stages. Subsequently, much effort is expended addressing entrainment concerns in the U.S. In general, other countries put less of an emphasis on intake-related impacts as a whole, instead focusing on the potential impacts of concentrate discharge.

4.4 Measuring I&E

Direct measurements of I&E can be made through the collection of impingement and entrainment samples at a facility's seawater intake. Typically, impingement sampling studies are conducted over a sufficient time period (minimum of 12 months) to account for natural variations in abundance associated with seasons, time of day, tidal stage, etc. However, collecting two years of data can account for interannual variability in natural populations. Sampling frequency and magnitude will vary based on the study-specific objectives.

4.4.1 Impingement Sampling

Impingement sampling provides the opportunity to quantify the number of organisms impinged at a seawater intake. The difficulty in collecting impingement samples varies among screening technologies. For example, collecting impingement samples from a traditional traveling water screen which actively collects impinged organisms is much less difficult than trying to quantify impingement on cylindrical wedgewire screens that are designed to passively prevent impingement.

Collecting impingement samples from a traveling water screen is relatively straightforward. Debris and fish that impinge on and are subsequently rinsed from the screen are diverted into a sample collection system. Typically, the collection system is a mesh basket or net placed in the return sluiceway (Fig. 4.2), but can be more elaborate if it is not feasible to install impingement sampling equipment in the screen house (Fig. 4.3). Impinged organisms and debris are collected, sorted, and counted. The impingement rate can then be calculated based on the numbers of impinged organisms collected and the duration of sampling. It is also wise to collect water quality and environmental data as environmental conditions can impact impingement rates (EPRI 2004b).

In cases where the traveling water screens being sampled have been modified to include fish-friendly features, there is often interest in assessing impingement survival. Impingement survival requires that, after collection, the impinged organisms are held over a sufficient time period (e.g., 48 h) to determine any latent mortality attributable to the impingement and collection process.

Fig. 4.2 Impingement sampling equipment used inside a screen house (*left*)—traveling water screen housing is at left with fish return trough exiting through the side; collection basket is suspended in discharge of return trough. Post-collection latent impingement mortality holding system (*right*)

Fig. 4.3 Impingement survival sampling study. Impinged organisms are diverted from the screen's fish return trough (*left*) to a collection net (*middle*). Collected organisms are transferred to a holding facility (*right*) where they are held in flow-through tanks to assess latent impingement mortality. (Images courtesy Alabama Power Company)

4.4.2 Entrainment Sampling

As with impingement sampling, entrainment sampling provides the opportunity to quantify the number of smaller organisms that are entrained through the intake screening technology. Entrainment data are used to estimate the total annual impact of entrainment on the local populations of marine organisms.

In desalination plants, entrainment samples must be collected from locations upstream of the pumps. There are two upstream locations from which desalination facility entrainment samples can be collected: (1) with plankton nets from an area directly upstream of the intake screens (Figs. 4.4 and 4.5) or (2) with pumps from

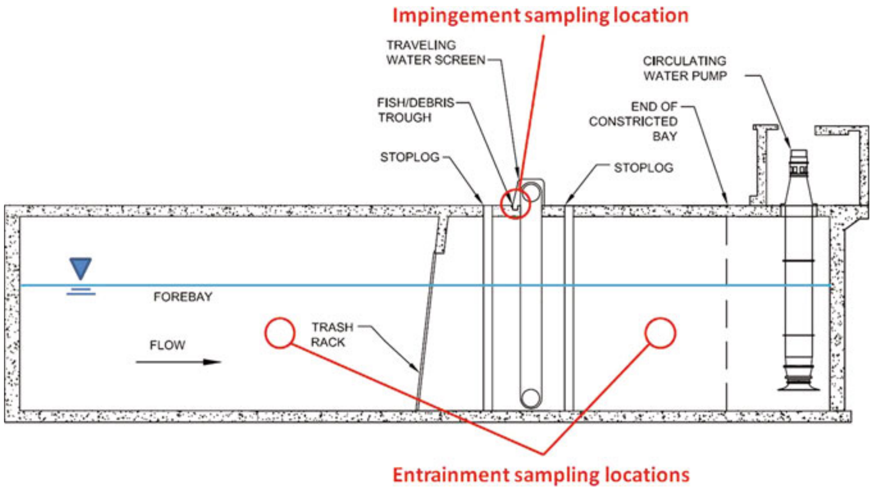

Fig. 4.4 Generalized entrainment sampling locations (impingement sampling location given for reference) within a typical seawater intake structure equipped with a trash rack and traveling water screens

an accessible area within the intake structure downstream of the screens, but still upstream of the pumps (Figs. 4.4 and 4.5). In cases where a portion of the withdrawn flow may be used for brine dilution and entrainment survival may be greater than zero, entrainment samples may be collected from a location downstream of the circulating water pump. Regardless of the sampling location, sampled water is typically filtered through a collection device with sufficiently small mesh (typically 335-μm mesh plankton nets) based on the size of the target organisms. An in-line flow meter is used to record the volume of water sampled. Entrained organisms are rinsed from the collection device, concentrated, and preserved. Samples are then transported to an ichthyoplankton processing laboratory where they are sorted, identified to the lowest taxonomic level practicable, and enumerated. Entrainment densities are then calculated based on organism abundance and sample volume (e.g., number of organisms per cubic meter).

Ideally, entrainment sampling is conducted over multiple years in order to account for inter-annual variability in organism abundance. Typically, samples are collected once per week or once every two weeks over a 12-month period in order to capture any seasonal variations in organism abundance. Sampling may be less frequent during time periods when ichthyoplankton are not present or only occur in very low abundances (e.g., winter months in temperate climates) (EPRI 2005). Daytime and nighttime sampling is also conducted to capture diel variations in organism abundance. Diel sampling also provides data on variations in organism abundance related to tidal cycle. Samples can also be composites comprised of multiple depths or discrete-depth samples which can aid in determining whether there is any vertical stratification of the entrained organisms. It may also be

Fig. 4.5 Entrainment sampling equipment. Bongo plankton nets for collecting ichthyoplankton samples upstream of the intake structure (*top left*); barrel sampler with integral plankton net for collecting pumped samples from within intake structure (*bottom left*; image courtesy ASA Analysis and Communication, Inc.); and fish eggs and larvae collected during entrainment sampling studies

desirable to monitor ambient current velocities near the intake so that any relationships between organism abundance and ambient hydraulic conditions can be determined.

In addition to sampling from the intake system, ambient biological samples should also be collected in the source water body near the intake location. These ambient samples serve to establish a concurrent baseline to which densities of entrained organisms can be compared and can serve as the basis for assessing the impacts of entrainment on local populations of organisms (see Sect. 4.6 for more on estimating impacts).

4.5 Predicting I&E

Predicting the potential biological effectiveness of an intake technology is important to facility operators, particularly given the high cost of modifying an intake after construction to provide greater protection to marine organisms. Using existing data, it is possible to estimate the potential biological efficacy of various intake screening alternatives.

The methods used to estimate an intake technology biological efficacy depends upon its mode of action (e.g., exclusion [passive mode] versus collection [active mode]). In addition, the site-specific intake design and operating characteristics, and the morphological, physiological, and behavioral characteristics of the organisms involved at the intake will impact the efficacy of a screening technology. Determining the potential efficacy of various intake screening technologies takes into account two principal components for which empirical data are often available: (1) physical exclusion and (2) impingement survival. The following sections describe these components in greater detail.

4.5.1 Physical Exclusion

For passive screening systems [e.g., cylindrical wedgewire screens (see Chap. 5)], physical exclusion is the principal factor to consider when estimating biological efficacy. It is commonly accepted that impingement on passive screens, which utilize low through-slot velocities, is virtually eliminated (Gulvas and Zeitoun 1979; Zeitoun et al. 1981), obviating the need to determine the potential for impingement survival.

The key factor in determining physical exclusion is organism size in relation to the screen mesh size or slot width. Several methods have been used to estimate physical exclusion by screens (e.g., Schneeberger and Jude 1981; Turnpenny 1981; PSEG 2004). All of these methods rely upon the sizes of organisms exposed to the intake and the underlying assumption that organisms with body depths greater than opening size of the screening mesh will not fit through the mesh. Often the larval head capsule depth (HCD) is used as the limiting dimension, because it is the widest non-compressible portion of the larval body (Fig. 4.6); (EPRI 2014).

Exclusion is a species-specific measure, as there is substantial variation in the morphometric characteristics among species. With larvae, the orientation of the organism at the time of contact with the screen will also influence its likelihood of being entrained. In addition, the ratio of ambient velocity to through-mesh velocity and the swimming ability of the larvae can impact the probability of entrainment

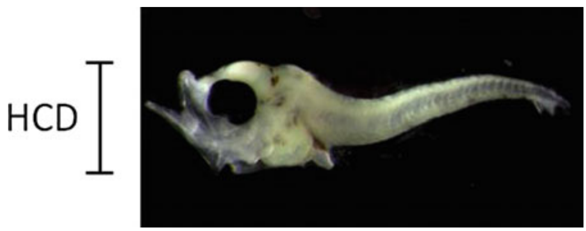

Fig. 4.6 Head capsule depth (HCD) of a larval fish

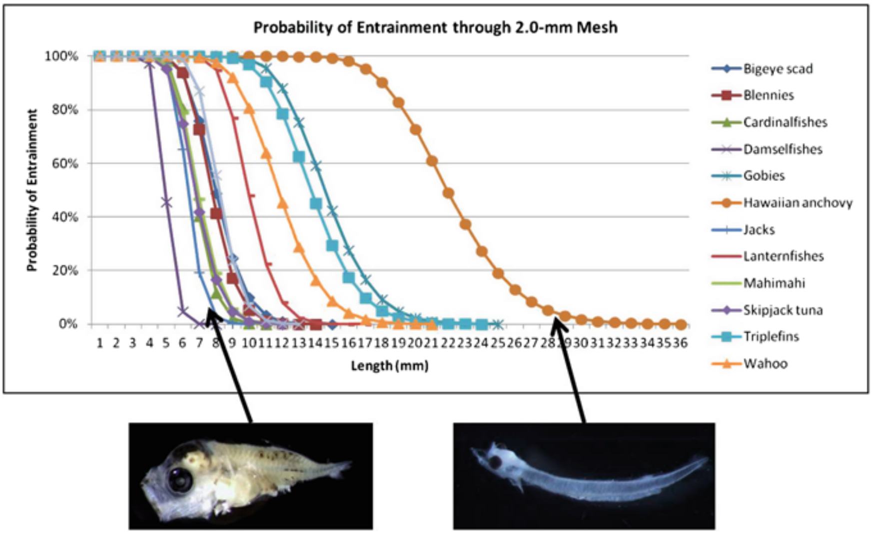

Fig. 4.7 Probability of fish entrainment through 2.0-mm mesh screening. Larvae with larger HCDs relative to body length (e.g., jacks, *bottom left*) are excluded at smaller lengths than larvae with smaller HCDs relative to body length (e.g., anchovies, *bottom right*). (Modified from Oney et al. 2013)

with wedgewire screens. In the case of juvenile and adult fish, exclusion can be estimated using the limiting body depth of the organisms (not always the HCD).

As fish length (or egg diameter) increases, the probability of entrainment decreases (Fig. 4.7). As shown in Fig. 4.7, species-specific differences in morphology factor heavily into determining the probability of entrainment. Fish with large HCDs are excluded at a shorter total body length than fish with small HCDs. It is important to note that other factors have been shown to increase exclusion (e.g., organism behavior, orientation of organisms, ambient hydraulics (EPRI 2003b; Heuer and Tomljanovich 1978; NAI 2011a, b; Weisberg et al. 1987); therefore, the physical exclusion component should be considered a conservative estimate.

4.5.2 Impingement Survival

Collection technologies, such as modified traveling water screens, handle the organisms during the collection and transfer process back to the source water body. This handling may impart additional stress, injuries, scale loss, or mortality to the organisms. Therefore, the second component of evaluating the effectiveness of a collection technology, is determining how well organisms survive the impingement, collection, and return process. The survival of these impinged organisms is dependent upon their biology (e.g., life stage, relative hardiness) and the screen operating characteristics (e.g., rotation speed, spraywash pressure) (WRRF 2014).

Impingement survival data are readily available for many species that are typically of concern at conventional thermal power plants in the U.S. (EPRI 2003a); however, other sites may have substantially fewer or no data on species that are targeted for protection near their intakes. The presence of existing data is also a function of the regulatory requirements for industrial water intake permits; parts of the world that have stringent regulatory requirements (e.g., the U.S.) are likely to have more historical impingement survival data than countries that are not required to monitor for intake-related impacts.

Ideally, impingement survival data is available for the intake technology under consideration and for each of the species and life stages of concern. However, this is seldom the case. More often, data are available for some species and lacking for others. In cases where impingement survival data are lacking for a particular species or life stage, surrogate data can be used provided the surrogate organism shares similarities with the species of concern.

4.6 I&E Impact Assessment

I&E monitoring studies collect raw data on the numbers or weight of organisms impinged or entrained. These raw numbers are converted to densities based on the sample volumes and can then be used to estimate total annual impacts. Total annual losses can be calculated for a full-scale intake under actual or maximum design withdrawal by multiplying the densities by the total volume of water withdrawn. Thus, three components are included in determining the impact of I&E; they are: (1) an estimate of the number of organisms impinged or entrained, (2) an estimate of survival after impingement or entrainment (assumed to be zero in the desalination process), and (3) an estimate of the population in the source water body (Cannon and Lauer 1976).

With total I&E losses calculated for a given intake, the next step is to convert those numbers to a value. Total annual losses are used to assess the impacts of I&E on local populations through a number of well-established impact assessment models. The resulting impact assessments can then be put in the context of their effect on local populations. EPRI (2002) categorizes, in increasing level of analysis complexity, the various levels of prospective (predictive) assessments as those that define I&E losses in terms of numbers of individuals or biomass lost ("individual loss"), in terms of the fractional loss in annual production from a population ("fractional loss"), or in terms of population-level changes resulting from long-term exposure to I&E loss. Of these three approaches, the most frequently used impact assessment models in the U.S. have been those that define impacts as individuals lost (demographic approach) or as a fractional loss to populations (proportional mortality approach). Table 4.1 provides a summary of the commonly-used demographic and proportional mortality approaches to assessing I&E impacts.

4.6.1 Demographic Approach

Demographic models convert lost organisms to equivalent numbers of adults. Demographic approaches are germane to assessing entrainment impacts. Projecting a certain number of adults that equate to a certain number of eggs or larvae requires the use of detailed life history data such as natural mortality rates for each life stage, fecundity, age-at-maturity, and life span (EPRI 2004a). The principal demographic approaches include those that equate the numbers of eggs and larvae lost to entrainment to an equivalent number of adults (adult equivalent loss), equivalent biomass lost (biomass foregone), or to the number of mature females that would be required to compensate for the loss (fecundity hindcast).

Demographic approaches are relatively simple provided there are sufficient life history data available for the species of concern (Table 4.1). Converting losses of early life stages of organisms makes estimating the value of the loss easier since adult organisms are more easily understood in fisheries management terms and typically have a true market value (i.e., commercial and recreational).

4.6.2 Conditional Mortality Approach

The conditional mortality approach, also known as the empirical transport model (ETM) was originally proposed in the 1980s to estimate losses from power plant cooling water intakes (Boreman et al. 1978). The ETM compares the number of organisms entrained to the total number at risk of entrainment in the source water body and results in an estimate of the proportional mortality caused by entrainment (Steinbeck et al. 2007).

The ETM approach has a distinct advantage in that it does not require the detailed life history data of demographic approaches (Table 4.1). However, upfront data collection may be more intensive since sampling must also be conducted in the source water body to: (1) characterize the abundance and composition of source water larval populations and (2) characterize the hydrodynamic/oceanographic conditions that could impact a larva's risk of being exposed to entrainment.

Once I&E impacts have been defined, a determination will be rendered on whether the magnitude of the impacts warrants mitigation. The outputs from impact assessments provide the basis for conducting a cost-benefit analysis to determine whether changes to the intake are justified. For impacts that cannot be addressed with intake modifications, compensatory mitigation is typically used. Such mitigation of I&E impacts is typically achieved through restoration of spawning or nursery habitat for the affected organisms. The size of habitat is designed to offset for the numbers of organisms lost due to the operation of the intake.

Table 4.1 Description of the common I&E impact assessment approaches, their data requirements, and their advantages and disadvantages

	Demographic approach		Conditional mortality approach
	AEL	FH	Empirical transport model
Description of model	Uses larval losses (entrained organisms) to estimate the equivalent number of adult fishes that would have been lost to the population	Uses larval losses (entrained organisms) to estimate the number of sexually-mature adult females whose reproductive output has been lost	Estimates the proportion of organisms in the source water body population that will be lost to entrainment, while accounting for spatial and temporal variability in distribution and vulnerability of each life stage to water withdrawals
Requires biological sampling of entrained organisms?	Yes		Yes
Requires biological sampling of organisms in source waterbody?	No		Yes
Requires oceanographic data on currents near intake?	No		Yes
Requires life history data?	Yes		Limited
Advantages	Adult fish are easily understood in fisheries management context		Model output lends itself well to calculating mitigation in terms of area of production foregone (APF)
	Does not require biological sampling of organisms in source water body		Requires only limited life history information, specifically, an estimate of the duration over which an organism is vulnerable to entrainment
Disadvantages	Requires detailed life history data that are sometimes unavailable, incomplete, or uncertain		Requires collection of oceanographic data (currents) as model input (if not otherwise available)
	Accurate data on the status of the adult population are required to assess the impact of lost adults		Requires biological sampling of source water body in addition to intake sampling

4.7 Minimizing I&E

I&E impacts resulting from the operation of seawater intakes cannot be eliminated; however, they can be minimized through the proper location, design, and selection of the best performing intake screening technology. In the recently released final 316(b) Rule, EPA (2014) describes four approaches for reducing I&E at existing power generating facilities: (1) reduce flow, (2) install technologies or operational procedures to gently exclude organisms or collect and return them to the source water body without harm, (3) locate the intake to a less biologically rich area (i.e., greater distance offshore or greater depth), or (4) reduce intake velocity.

4.7.1 Flow Reduction

Reducing flow is a viable means for reducing entrainment impacts since entrainment is proportional to flow when considering passive life stages of organisms with no swimming ability. Whether reducing flow has a similar benefit for reducing IM remains to be conclusively demonstrated. Nieder (2010) concluded that, in general, volumetric flow rate is not a strong predictor of adverse environmental impacts. In particular he states "*there is little direct*, *proportional relationship between impingement and cooling water capacity use*". Rather, impingement has been shown to be more episodic and more closely related to other environmental variables such as temperature (EPRI 2003c).

Reducing flow at a seawater desalination facility may not be a viable option as reduced inflow will result in reduced production of potable water. However, the following approaches could be considered to reduce seawater needs at desalination facilities:

- Increase recovery rates such that less feedwater is required
- Reduce ancillary water demands (e.g., additional flow withdrawn for concentrate dilution)
- Consider other feedwater sources that have no real potential for I&E impacts (e.g., subsurface intakes)

4.7.2 Exclusion and Collection Technologies

Intake technologies designed to reduce I&E can generally be categorized into four groups based on their mode of action (WRRF 2014). These categories include: behavioral systems, which take advantage of natural behavior patterns to attract or repel fish; exclusion systems, which physically block fish from passage; collection systems, which actively collect fish and return them to a safe release location; and diversion systems, which divert fish to a bypass for return to a safe release location.

Exclusion and collection technologies have received the greatest focus for their application in reducing I&E at seawater intakes. These two categories of intake technologies are discussed below in greater detail.

4.7.2.1 Exclusion Technologies

Exclusion technologies include systems that passively prevent the passage of organisms based on their size. Their potential effectiveness can be determined based on the size distribution of the organisms that may come in contact with it, i.e., exclusion technologies function on the premise that a screen will physically exclude organisms equal to or greater than its mesh size. Exclusion systems are also typically designed with low intake velocities to minimize the risk of impingement.

Cylindrical wedgewire screens are one of the most popular exclusion technologies for reducing I&E impacts at large seawater intakes (Fig. 4.8). Cylindrical wedgewire screens are typically designed with a small slot size (≤3 mm) and a low through-slot velocity (e.g., 0.15 m/s) to reduce entrainment impacts (see Chap. 5 for more on passive screens). By nature of the low through-slot velocity and small hydraulic zone of influence, these screens have also been shown to essentially eliminate impingement (Gulvas and Zeitoun 1979; Zeitoun et al. 1981; Tenera 2010). The biological and engineering performance of cylindrical wedgewire screens is optimized when there is sufficient ambient velocity to carry organisms and debris away from the screen face (EPRI 2006).

A number of pilot-scale studies have been conducted to determine the potential for cylindrical wedgewire screens to minimize I&E at seawater desalination facilities on the California coast. Tenera (2007) completed a pilot-scale biological evaluation of a 2.4-mm cylindrical wedgewire screen (0.09 m/s through-screen velocity) for the Marin Municipal Water District proposed desalination facility in northern California. Results from the pilot-scale testing indicated that the risk posed by entrainment resulting from a full-scale desalination facility (30 MGD) would be low to ambient populations of fish (0.02–0.06 % entrainment-related mortality). Tenera (2010)

Fig. 4.8 Cylindrical wedgewire screen designs. Bilfinger Water Technologies screen with Hydroburst backwash cleaning system (*left*) and Intake Screens, Inc. screen with rotating, brush-cleaned screen drums (0.5-mm slot width) (*right*)

completed a similar pilot-scale evaluation of a 2.0-mm cylindrical wedgewire screen (0.10 m/s through-screen velocity) in Santa Cruz, California. While the results indicate that the screens were very effective at reducing the potential for impingement, the magnitude of entrainment reduction was limited to approximately 20 % compared to an open intake. The authors concluded that the abundance of very small larvae (with HCDs less than the 2-mm slot size) may have affected the results.

4.7.2.2 Collection Technologies

Collection technologies are designed to either actively or passively collect organisms or direct them to a bypass. Their potential effectiveness can be determined in much the same way as discussed above for exclusion systems; however, since the organisms are being actively collected, it is necessary to know how well they survive the collection and return process. Therefore, while the potential efficacy of exclusion systems can be determined based on the size of the organisms in relation to the size of the mesh, the potential efficacy of collection systems also has to take into account injury and mortality that may be imparted by the collection and return process.

Modified traveling water screens (TWS) are one of the most commonly used collection technologies for reducing I&E impacts at large seawater intakes. Modified TWS represent an improvement over conventional TWS in that they include various fish-friendly components including fish lifting buckets at the bottom of each screen basket, low-pressure spray wash systems, and fish return systems (Fig. 4.9). In addition, such screens are designed to rotate continuously to reduce impingement duration and improve survival. The survival of organisms through a collection system is species- and life stage-specific, but in many cases can be high (EPRI 2003a). Modified TWS utilizing smaller mesh sizes may reduce entrainment of early life stages, though survival of impinged early life stages is generally poor (EPRI 2010).

Modified TWS are used extensively throughout the U.S. to reduce impingement mortality and entrainment (IM&E). The mesh size selected will determine the size of the organisms that will be retained (i.e., impinged). Recent moves towards the use of finer-mesh modified TWS means that the numbers of impinged organisms increases. For example, organisms that would entrain through a coarse-mesh (e.g., 9.5-mm) screen would impinge on a mesh of 3 mm. In the case of seawater desalination facilities where entrainment mortality is assumed to be 100 %, using smaller mesh to impinge smaller organisms could constitute an overall improvement in biological performance provided IM is less than 100 %.

4.7.3 Location

The location of the withdrawal point can confer an environmental benefit to marine organisms. Offshore withdrawal points have been shown to reduce I&E impacts simply by moving the intake to a place where there are fewer organisms (EPA 2014).

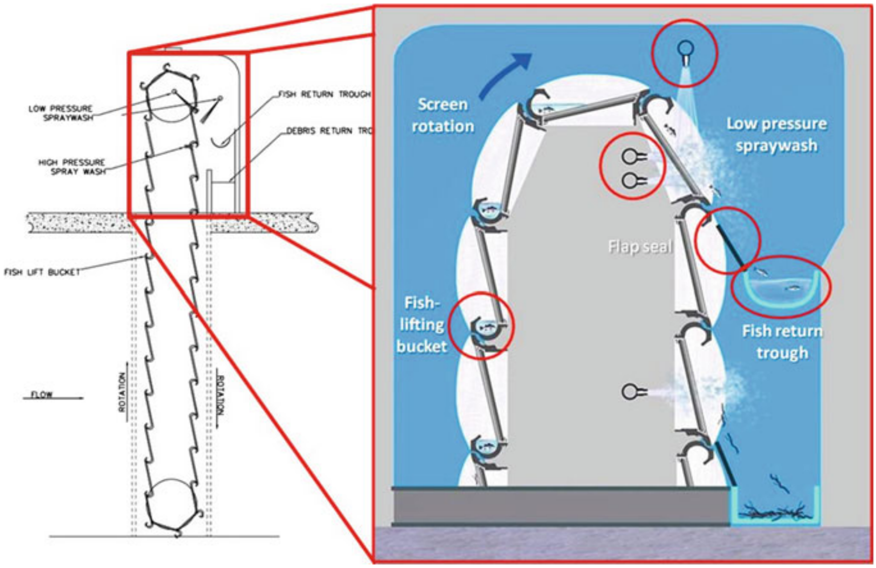

Fig. 4.9 Modified traveling water screen (through-flow design) with fish-friendly features indicated in the exploded view. (Image Courtesy Evoqua Water Technologies)

It is commonly accepted that the nearshore and estuarine zones where many large industrial water intakes are located are more biologically productive and are likely to have higher densities of organisms that could become impinged or entrained in the intake flow (EPA 2014). Moving an onshore withdrawal point offshore can have a beneficial biological effect provided the offshore location is in an area of low fish density (i.e., not a valuable spawning or nursery area). The offshore location has potential to reduce entrainment due to its location in less productive water.

Relative to impingement, nearly all offshore intakes include a velocity cap of some sort. A velocity cap is a behavioral deterrent technology that changes what would otherwise be vertical flow vectors at an uncapped offshore intake riser to horizontal flow vectors. A velocity cap is an effective means for reducing IM because it has been shown that horizontal flow vectors are more easily sensed and avoided by fishes (Beck et al. 2007; Lifton and Storr 1978; Weight 1958). A velocity cap, however, does not reduce entrainment of free-floating eggs and larvae, which are unable to distinguish the hydraulic cues or do not sufficient swimming ability to avoid them.

4.7.4 Intake Velocity

Reducing intake velocity can reduce IM. A through-screen velocity of 0.15 m/s has been determined to be protective of impingeable sized fishes (EPA 2014; EPRI 2000).

Practically speaking, for the same flow rate, reducing the intake velocity means that the open screening area must be increased. Screening area can be increased either through use of larger mesh or more screens.

4.8 Discussion and Conclusions

Impingement and entrainment have received intense focus in the thermal power generating industry in the U.S. and have become an increasing concern at other industrial water intakes, including at SWRO desalination facilities. As was presented in this chapter, the majority of the information available on the topic of I&E has been obtained by power generators, typically in response to permit requirements. Nonetheless, SWRO desalination facilities are likely to be held to similar environmental performance standards and in some cases will have to comply with standards that could be more restrictive. This scenario is currently playing out in California and New York, as some SWRO desalination plant developers face I&E-related state regulations that are more stringent than the federal-level 316(b) ones. Beyond the U.S., the topic of impacts associated with the operation of large SWRO desalination intakes has also been receiving greater attention of late, particularly in countries that rely heavily on seawater desalination, such as the Kingdom of Saudi Arabia and Australia (Chaps. 2 and 3).

The withdrawal of seawater has impacts that cannot be eliminated; however, they can be minimized. The presence and magnitude of I&E at a given site need to be documented with biological sampling. Biological sampling at the intake and in the source water body provides the basis upon which the magnitude of the I&E can be determined. In the absence of site-specific empirical data, it is also possible to estimate the biological performance of various intake technologies by considering existing data. Ultimately, though, the magnitude I&E must be defined to be able to determine what it means on a population-scale for the species being affected.

The body of knowledge surrounding I&E and the means to minimizing its impacts on natural populations of marine organisms is extensive. Various technological and operational methods have undergone comprehensive laboratory and field evaluations to refine their biological efficacy.

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