Chapter 17

Estuarine Fisheries and Aquaculture

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17.1 Introduction

Estuaries are highly productive ecological systems that support extensive fisheries and aquaculture activities around the world (Kapetsky 1984). The term “fisheries” refers to the capture of wild aquatic organisms which include not only finfish, but also shellfish and other invertebrates (Box 17.1). In contrast, aquaculture involves the farming of animals or plants in aquatic environments.

Estuarine fisheries and aquaculture play an essential role in global seafood production (FAO 2018d). Over half of humanity lives in coastal areas (Vitousek et al. 1997) and many coastal populations rely on fisheries and aquaculture products as a major source of animal protein and micronutrients (Kawarazuka and Béné 2011; Hall et al. 2013; Tacon and Metian 2018). Estuaries are the source of an estimated 16 percent of non-oceanic, global fisheries yield (Houde and Rutherford 1993), and aquaculture is one of the fastest growing food animal production industries in the world, accounting for almost half of global seafood supply (Campbell and Pauly 2013; FAO 2018d). Current and anticipated impacts of human population growth and climate change on estuarine-based fisheries and aquaculture pose a threat to global food security and nutrition, particularly in developing countries (FAO 2018c, d; Teh and Pauly 2018). Estuaries are critical to the success of many fisheries because they serve as habitat during all or certain stages in the life cycle of many wild populations (Pihl et al. 2002; Able 2005). Some species found in estuaries are lifelong residents of estuaries, whereas other species use estuaries as nursery or juvenile habitat while spending the majority of their lives in the ocean or freshwater (see Chapter 12). Also, high secondary productivity makes estuaries important foraging grounds for many piscivorous stocks (see Chapter 15). Some of the largest and economically important fisheries in the world target estuarine-dependent species such as menhaden, herrings, breams, mullets, temperate basses, salmonids, crabs, flatfish (e.g., sole, plaice, and flounder), eels, shads, sturgeons, shrimp, and clams (Costa et al. 2002; Wilson 2002; Pérez-Ruzafa and Marcos 2012). Pihl et al. (2002) estimated that nearly 40% of commercially exploited fish species in Europe use estuaries at some stage in their life cycle. In the United States, estuaries serve as habitat for over 80% of commercially caught fish,
## Box 17.1 Fisheries and Aquaculture Terms

**FISHERIES**—the capture of wild aquatic organisms which include not only finfish, but also shellfish and other invertebrates for use as human food, fishmeal (animal feed, often for farmed fish), oil, medicine, and other products. Fisheries may be subdivided into commercial (or “industrial”), recreational, artisanal (small-scale commercial), and subsistence sectors.

**AQUACULTURE**—the breeding, rearing, and harvesting of aquatic organisms in water, primarily for use as human food. MARI-CULTURE is a subset of all aquaculture that is restricted to brackish and marine waters.

**STOCK**—a wild fishable population of aquatic organisms that is typically self-sustaining, geographically isolated from others of the same species, and managed as a distinct unit.

**YIELD**—the amount of products generated from fisheries or aquaculture activities, typically measured by weight.

**RECRUITMENT**—fish in a given stock that have grown large enough or migrated to new areas such that they have become vulnerable to capture fisheries. This term may also be used more generally to describe production of juvenile fish.

**CATCH- PER- UNIT-EFFORT**—the amount (number or biomass) of fish caught as a function of a standard unit of fishing effort.

**STOCK ASSESSMENT**—the process of collecting and analyzing biological and fishery information to estimate stock abundance and the stock’s response to fishing.

**COHORT**—a group of fish born during the same spawning season or other time frame meaningful to that species.

**REFERENCE POINTS**—A benchmark used in fisheries management against which stock biomass and fishing mortality rate can be compared. Reference points often focus on either the desired state of the fishery called the “target” (e.g., fishing mortality that will produce sustainable yield), or a state of the fishery that should be avoided called a “threshold” or “limit.”

**NATURAL MORTALITY**—Natural mortality includes any cause of death that cannot be attributed to the effects of fishing, especially such processes as predation and disease.

**FISHING MORTALITY**—The rate at which fish are being removed from the population due to fishing activities.

**STOCK STATUS**—a formal determination made describing the condition of the stock based on the results of a stock assessment or other analyses of available data. Although multiple stock status determinations exist, the most common are: (i) the stock is/is not experiencing “overfishing” (i.e., the rate of fishing mortality is higher than our fishing mortality threshold or limit reference point), and (ii) the stock is/is not “overfished” (the stock size is lower than our biomass threshold or limit reference point).

**BYCATCH**—Incidental catch of nontarget species during fishing activities that is either retained or discarded at sea.

**LANDINGS**—Portion of the commercial fishery catch that is brought back to port and sold (or given away in case of subsistence or recreational fisheries).

and over 50% of recreational catches come from estuaries (National Research Council 1997; National Marine Fisheries Service 2017).

Given the migratory nature of many fish populations, estuaries have broad, regional impacts that extend far beyond their physical borders. For migratory species, conditions in estuaries can affect the entire population. For example, if growth and survival conditions for juvenile grey mullet (*Mugil cephalus*) in Chinese estuaries is poor, mullet will produce sustainable yield, or a state of the fishery that should be avoided called a “threshold” or “limit.”

In this chapter, we begin by providing an overview of global patterns and potential drivers of estuarine fisheries and aquaculture yields. We then transition into a description of the types of information used to monitor and assess wild fish dynamics in estuaries. We conclude with an overview of fisheries and aquaculture management in estuaries with a focus on current and future challenges.

### 17.2 Estuarine Yield

Although fisheries and aquaculture yields may vary, estuaries are typically more productive than other types of ecosystems (Kapetsky 1984; Pérez-Ruzafa and Marcos 2012). High yields are driven by a number of physical, biological, and anthropogenic factors, including high primary productivity and proximity to
17.2.1 Global Patterns

Estuaries are thought to be highly productive in terms of fisheries and aquaculture yields, yet quantifying that yield is a challenge because many countries do not distinguish estuarine from coastal ocean or freshwater production statistics (Pérez-Ruzafa and Marcos 2012; FAO 2018d). Houde and Rutherford (1993) estimated that approximately 16% of non-oceanic global fisheries yield is derived from estuaries. Approximately 36% of global aquaculture yield can be attributed to coastal and marine areas, which include estuaries; however, extensive farming of species that are estuarine-dependent in the wild also occurs in inland ponds in which salinity is controlled (Macintosh 1994; FAO 2018d).

Highly productive estuaries are found in many tropical, subtropical and temperate regions around the globe (Kapetsky 1984; Pérez-Ruzafa and Marcos 2012). Some of the highest reported estuarine yields come from the large estuaries of the Northwest Atlantic (Pérez-Ruzafa and Marcos 2012). For example, the 250,000 km² of the Gulf of St. Lawrence, Canada, yielded fisheries catches of 400,000 tonnes (hereafter t), plus 90,000 t from aquaculture in 2016 (Fisheries and Oceans Canada). In that same year, approximately 200,000 t of fisheries yield was reported from the 165,000 km² area of the Chesapeake Bay in the USA (NOAA Fisheries). Among coastal lagoons, the highest catch-per-unit-effort from capture fisheries has been reported in the Northwest Atlantic, East Indian Ocean, Pacific Southwest (Australia), and Mediterranean Sea regions (Pérez-Ruzafa and Marcos 2012).

Although aquaculture is expanding worldwide, Asia far exceeds other regions in terms of marine and brackish seafood production (Campbell and Pauly 2013; FAO 2018d). China’s coastal provinces of Liaoning, Shandong, Fujian, and Guangdong alone produced more farmed seafood than any other maritime country between 2000 and 2010 (Campbell and Pauly 2013). Even when China is excluded, Asia remains the continent producing the most farmed seafood due to high yields in countries such as India, Indonesia, and Viet Nam (Campbell and Pauly 2013).

17.2.2 Physical, Biological, and Evolutionary Drivers

High fisheries and aquaculture yields from estuaries are generally explained by their high primary production (Nixon 1982, 1988; see also Chapters 1 and 4). High primary production is driven by physical factors such as: (i) the availability of organic matter inputs via rivers (Yáñez-Arancibia et al. 1985a, b; Day et al. 1997; Bianchi et al. 1999); (ii) shallowness, which is conducive to rapid remobilization of nutrients (Jones 1982; Nixon 1982; Deegan 2002); and (iii) velocity and volume of water exchanges between the sea and the estuarine system, which also affects fish populations directly via recruitment (Deegan et al. 1986; Yáñez-Arancibia et al. 2007). In addition, high yields are driven by proximity of estuaries to ports and human settlements which makes them convenient for aquaculturists in particular, but also for fishers (Houde and Rutherford 1993; Macintosh 1994).

The impact of primary production and other environmental influences on fisheries and aquaculture yields vary across ecosystems. Estuaries have been found to be twice as productive for aquaculture as coastal seas and freshwater systems (Macintosh 1994). Fisheries yields from estuaries also are, overall, higher than the yields from other exploited marine and fresh water ecosystems, whether one considers the mean or the median as a measure of central tendency (Table 17.1; Kapetsky 1984). However, estuaries do not have uniformly high fisheries yields, and, indeed, the frequency distribution is strongly skewed, indicating numerous instances of unproductive estuaries (Figure 17.1). The extremely productive estuaries in Figure 17.1 may benefit from a number of positive factors, including:

1. Nearby coastal habitat supplying high recruitment (Pauly 1986a);
2. Fertilization from rivers, agricultural runoff, or human sewage, and through water exchanges with the ocean (Kapetsky 1984);
3. A management regime that makes the best of incoming recruitment.

Some factors that likely explain the occurrence of the unproductive estuaries in the long tail of this nearly log-normal distribution are:

1. Extreme salinity and temperature fluctuations, turbidity, anoxic conditions, or toxic discharges;

<table>
<thead>
<tr>
<th>Systems</th>
<th>Median</th>
<th>Mean</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal lagoons</td>
<td>5.1</td>
<td>11.3</td>
<td>107</td>
</tr>
<tr>
<td>Continental shelves</td>
<td>4.8</td>
<td>5.9</td>
<td>20</td>
</tr>
<tr>
<td>African/Asian reservoirs</td>
<td>4.2</td>
<td>7.5</td>
<td>41</td>
</tr>
<tr>
<td>Coral reefs</td>
<td>4.1</td>
<td>4.9</td>
<td>15</td>
</tr>
<tr>
<td>River floodplains</td>
<td>3.2</td>
<td>4.0</td>
<td>33</td>
</tr>
<tr>
<td>Reservoirs (United States)</td>
<td>1.3</td>
<td>2.4</td>
<td>148</td>
</tr>
<tr>
<td>Natural lakes</td>
<td>0.5</td>
<td>2.8</td>
<td>43</td>
</tr>
</tbody>
</table>

Source: Kapetsky (1984)/FAO.
2. Very shallow sills, preventing high recruitment;
3. Excessive illumination or turbidity, both of which can lead to reduced primary productivity (Qasim 1970, 1973);
4. Insufficient fishing effort (Bayley 1988), a condition that is increasingly rare.

A major component of high fisheries production in many estuaries is high natural recruitment (Day et al. 1989; Yáñez-Arancibia et al. 1993, 1994; Mann 2009). High recruitment in estuaries generally leads to high fishery catches once these animals are large enough to interact with fishing gear. One reason for this high recruitment is that many of the fish species of importance in estuarine environments are either (i) r-selected sensu (Pianka 2011), that is, relatively small, fast growing, with a high production/biomass (P/B) ratio or (ii) the juveniles of K-selected species, that is, the fast growing, high production stage fishes whose adult form, however, typically occurs outside estuaries. The high P/B ratios of the constituent species are not the only explanation for the generally high production of estuarine fish communities. The high biomasses themselves, that is, the high carrying capacities of these ecosystems in terms of seasonal food availability to fishes due to high primary and secondary production, also play a crucial role.

In areas where estuarine systems have maintained themselves over long periods (i.e., the Gulf of Mexico), evolutionary mechanisms have emerged that have stabilized and refined such seasonal programming, making the fish population in question gradually more dependent on the estuarine system for the maintenance of high biomass. In other areas where the estuarine system does not persist or is not regularly open to juvenile migration (i.e., along the coast of Northwestern Africa, the Pacific coast of Mexico, and the eastern coast of East Australia), the use of lagoons seems to be more a matter of random movements along the coast and of inshore movements. This implies (i) a lower conversion of primary and secondary production into fish flesh and hence (ii) lower biomasses of coastal fishes. However, the practical difficulties in separating random along-shore/inshore movements from evolutionary, fine-tuned, aimed movements toward and within estuaries, and the difficulties involved in precise field estimation of biomass and conversion efficiencies, make rigorous testing of the hypothesis difficult. Indeed, this may be the main reason for the continuing debate on the degree of dependence of coastal fishes on estuaries (Able 2005; Litvin et al. 2018).

### 17.3 Fish Population Dynamics and Its Four Factors

The yield from both fisheries and aquaculture practices are impacted by estuarine conditions and the life history characteristics of the fished species. In the case of aquaculture, yields are a function of the quality of seed animals, culture practices, and environmental conditions, such as the quality of the water in the production area. However, determining the yield that can be sustainably removed from a wild population is much more difficult because the animals are not constrained to one location and the initial conditions of the stock are often unknown.

To estimate fishing mortality rates and set sustainable quotas for a given fishery, scientists conduct a stock assessment in which fish populations are monitored and the resulting data either examined or, when possible, used to build a statistical model that estimates fish stock size, fishing mortality rates, and management reference points. The goal of this section is to provide an overview of the basic concepts of fish population dynamics used in fisheries stock assessment. Although we refer to the dynamics of fish populations throughout this section, many of these same concepts and the same or similar techniques can be applied to shellfish and other exploited animal populations as well.
17.3.1 Russell’s Axiom

Fish population dynamics are often represented by means of Russell’s axiom, that is:

\[ B_t = B_0 \left( R + G \right) - \left( M + F \right) \]

which states that a well-defined stock of biomass \( B_t \) will have, after an arbitrary period \( \Delta t \), the biomass \( B_0 \) as a result of positive processes \( R = \text{recruitment} \); \( G = \text{growth} \) that have added to the stock, while negative processes \( M = \text{natural mortality}; F = \text{fishing mortality} \) have reduced it (Russell 1931; Ricker 1975). The four processes included in Eq. (17.1), plus some peripheral processes also considered by fishery biologists (Figure 17.2), have been studied extensively and described in a mathematically tractable form by numerous authors (Ricker 1954; Beverton and Holt 1957; Schaefer 1957; Ricker 1975; Guillard 1983; Pauly 1984; Hilborn and Walters 1992; Pauly 1998; Quinn and Deriso 1999). In this section, we present a few of the models that have resulted from these efforts, specifically those that have been used to characterize fish dynamics in estuarine systems. The four factors shall be examined in the sequence: growth, natural mortality, fishing mortality, and related factors (mainly catch/effort), with recruitment being last, because it is the most complex factor to investigate, model, and predict.

17.3.2 Growth of Fishes

Information on how fish grow is an important component of fish population dynamics for several reasons. First, the relationship between length and age tells us how early in life an animal might become susceptible to fishing mortality and, if associated maturity data are available, how many chances the fish might have to spawn before being caught. Differences in growth between sexes and across a species’ range are important for managers to consider when setting regulations such as minimum size limits. Second, quantitative relationships between the length and age of fish are commonly used to convert length data to age data for use in stock assessment models. The most common data collected on animals that have been caught is length because it is easy and inexpensive to obtain. However, most stock assessment models used to estimate changes in stock size and fishing mortality over time are constructed such that they track fish by age because it is easy to mark the transition from one age to another at the turn of the year.

The relationship between length and age can be quantified using the standard von Bertalanffy curve (von Bertalanffy 1938) which has the form:

\[ L_t = L_\infty \left( 1 - e^{-K(t-t_0)} \right) \]

where \( L_t \) is length at age \( t \); \( L_\infty \) is the asymptotic length, that is, the average length the fish would attain if they lived indefinitely; \( K \) is a parameter expressing how fast \( L_\infty \) is approached and has the dimension of time\(^{-1} \) (e.g., year\(^{-1} \)); \( t \) is age; and \( t_0 \) is the theoretical age at length zero if the fish always grew according to the equation. An example is presented in Box 17.2.

Although the von Bertalanffy growth equation works well in many circumstances, it does not account for seasonality in fish growth patterns. Estuarine environments are highly seasonal, more so than the open marine environment to which they are connected. Thus, the food types (Chavance et al. 1984; Aguirre-Leon and Yañez-Araribio 1986), food consumption (Figure 17.3), and hence, the growth of estuarine fishes are bound to oscillate seasonally, whether the fish in question undertake seasonal migrations in and out of estuaries or not. The typical dominant source of seasonal oscillations, however, is water temperature, which exerts a profound influence on the metabolic processes of poikilotherms and hence on their growth (Pauly 2010). Even in tropical and subtropical waters, animals such as the checkered puffer fish (Sphoeroides testudineus) display seasonal growth oscillations (Pauly and Ingles 1981; Longhurst and Pauly 1987).

Various authors have modified the von Bertalanffy growth equation to accommodate seasonal growth (Hoenig and Chaudhury Hanumara 1982; Longhurst and Pauly 1987; Soriano and...
Fish Population Dynamics and Its Four Factors

Jarre 1988; Pauly 2010). These growth models can accommodate stronger growth oscillations in “winter,” all the way up to a very short period of zero growth, for example, when temperatures are lowest (Pauly 2010). However, these models cannot accommodate longer periods of zero growth. An alternative model that can accommodate a period of growth stagnation, i.e., no-growth time (NGT; Pauly et al. 1992) is proposed below. To fit this model, the time axis is divided into one growth and one NGT over each period of one year. Then, during growth time, we have

\[ L_t = L_\infty \left[ 1 - \exp(-\omega) \right], \]  

(17.3)

in which \( L_t \) is the length at age \( t \), and where,

\[ \omega = K'(t' - t_s) + \frac{K}{2\pi} \left[ \sin \frac{2\pi}{1 - NGT} (t' - t_s) - \sin \frac{2\pi}{1 - NGT} (t_s - t) \right]. \]  

(17.4)

where, \( t' \) is obtained by subtracting the total amount of NGT that the fish experienced from the age \( t \) since \( t = 0 \), and \( t_s \) is the parameter adjusting a seasonal cycle to start at \( t = 0 \). Note that the seasonal growth itself (outside of NGT) is described by a sine wave curve with period \( 1 - NGT \), and that the unit of \( K' \) is \((year^{-1})^{-1}\) instead of year\(^{-1}\). A program in R to fit Eq. (17.4) to length-at-age data was published by Ogle (2017). An application example for this model is given in Figure 17.4. The model predicts a no-growth time of about three months (January to March) for the European seabass (Dicentrarchus labrax) in l’Etang d’Or, France (Quignard 1984; Beauchot 1987), a feature that other seasonal growth models could not have detected.

Resulting growth curves illustrate how southern black bream growth rates have slowed over time and the average asymptotic length is smaller.

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<tr>
<td>( L_\infty ) (TL, mm)</td>
<td>424</td>
<td>351</td>
<td>288</td>
</tr>
<tr>
<td>( K ) (year(^{-1}))</td>
<td>0.29</td>
<td>0.28</td>
<td>0.25</td>
</tr>
<tr>
<td>( t_s ) (year)</td>
<td>-0.19</td>
<td>-0.28</td>
<td>-0.76</td>
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One potential driver of this change in growth is thought to be hypoxia, which typically results in reduced metabolism (Pauly 2010). Also, density-dependent effects may be at play given that the fish in question have increasingly tended to aggregate inshore, where oxygen levels remain high.

**Box 17.2 Case study: changes in growth of southern black bream in response to environmental degradation.**

Southern black bream (Acanthopagrus butcheri) is a fish endemic to the southern coast of Australia that spends its entire life in its natal estuary and that has highly plastic biological characteristics, including growth. Since the early 1990s, the estuaries in which southern black bream reside have experienced extensive habitat degradation. Fisheries scientists have observed concurrent, significant changes in southern black bream growth. For example, estimated values for \( L_\infty \) and \( K \) parameters of the von Bertalanffy growth equation (Eq. 17.2) for male bream have both declined over time.

[Figure 17.3 An example of seasonal changes in the stomach contents and hence, presumably the food consumption of a lagoon fish, the silver perch Bairdiella chrysoura, in Terminos Lagoon, Mexico. Source: Adapted from data in Chavance et al. (1984).]

The growth of fishes within estuaries relative to that of conspecifics (members of the same species) growing in other habitats appears to be a function of (i) the type of estuary and/or of habitats being compared, (ii) the species of fish, and (iii) the life stage of the fish species. Shallow, eutrophic estuaries lead to improved growth compared with that of deep
estuaries which are strongly influenced by the marine regime (Chauvet 1984; Chauvet 1988). With regard to Mediterranean species such as gilthead sea bream (*Sparus aurata*) and European sea bass, estuarine habitats appear to lead to higher growth rates among juveniles and young adults (Figure 17.5), while among the larger, older specimens of these two species, growth within estuaries is at best equivalent to, and generally less than, that in the marine environment (Chauvet 1988). Fast growth of juveniles and smaller maximum sizes of adults are not incompatible. Indeed, rapid juvenile growth due to availability of abundant food and high habitat temperatures generally goes along with smaller maximum adult sizes (Longhurst and Pauly 1987; Pauly 2010).

Habitat quality may also affect fish growth rates. In some French estuaries, fish size was found to be greater in systems with high eutrophication and ecotoxicity levels than in less impacted systems, suggesting that low habitat quality may increase fish growth rate at the expense of larval survival (Brehmer et al. 2013). In other systems, recent growth was found to be slower for fish in waters with high sediment metal concentrations (Gilliers et al. 2006; Amara et al. 2007; Amara et al. 2009). However, these results are not universal and may depend on the species of interest and types of contaminants to which fish are exposed (Gilliers et al. 2004). Other poor habitat conditions such as low dissolved oxygen levels have been shown to reduce growth rates (Campbell and Rice 2014; Cottingham et al. 2014). However, water temperature still has an overwhelming impact on growth, as mentioned above, and must be accounted for first before using fish growth as a metric of habitat quality (Searcy et al. 2007).

### 17.3.3 Natural Mortality

Natural mortality includes any cause of death that cannot be attributed to the effects of fishing, including such processes as disease and predation. The effects of natural mortality on a *cohort* of fish can be modeled using:

\[ N_t = N_0 e^{-Mt}, \]

where \( N_t \) and \( N_0 \) are the numbers of fish at the beginning and end, respectively, of a period \( \Delta t \), and \( M \) is the instantaneous rate of natural mortality during that period. In fisheries science, mortality rates (both natural and fishing mortality) are typically

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“bonga” *Ethmalosa fimbriata* (Clupeidae) occur in West Africa. One form reaches lengths of up to 30 cm and is found along the coast, large estuaries, and open coastal lagoons; the other form occurs only within closed lagoons and is limited to a length of about 15 cm (Longhurst and Pauly 1987). Note that these effects are independent of, and added to, the size-based artificial selection that is imposed by a long-term fishery, and which ultimately results in small adults (Conover and Munch 2002; Pauly 2002).

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reported as either annual or instantaneous rates; annual mortality is the percentage that dies in one year, whereas, instantaneous mortality refers to the fraction dying over a very short time interval.

Estimates of $M$ are typically derived from either empirical data collection programs such as tagging or other mark-recapture studies (Pine et al. 2003), or $M$ can be estimated using information about the species’ life history (Pauly 1980; Then et al. 2014). Across fish species, natural mortality of fishes is strongly correlated with other aspects of their life history such as growth, which is demonstrated in the model

$$M = \left(K^{0.65} T^{0.46}\right) L_\infty^{-0.28}$$

where $L_\infty$ is total length in centimeters, $K$ is in year$^{-1}$ and $T$, the environmental temperature, is in degree Celsius (Pauly 1980). Hence, estuarine fishes which tend to have higher and lower environmental temperature, is in degree Celsius (Pauly 1980).

Many natural or anthropogenic factors may cause catastrophic mortalities in estuaries, including the following:

1. Eutrophication, leading to nighttime depletion of oxygen and/or benthic production of $H_2S$, which can be released into the water column by storms (Luther et al. 2004; Pollock et al. 2007);
2. Harmful algal blooms (Landsberg 2002);
3. Hypersalinity (Gunter 1952; Whitfield 2005; Whitfield et al. 2006);
4. Cold or hot spells, particularly effective in shallow estuaries (Gunter 1952; Thronson and Quigg 2008);
5. Pollution from land-based sources such as agricultural run-off and pesticides (Davis et al. 2017; O’Mara et al. 2017).

Catastrophic mortalities are difficult to incorporate into standard population dynamics models and have indeed not generally been considered explicitly in fisheries management. Their probability of occurrence and prevention are complicating aspects of estuarine fisheries and aquaculture management.

### 17.3.4 Fishing Mortality and Catch-per-unit-effort

Fishing mortality is the rate at which fish are being removed from the population due to fishing whether commercial, subsistence or recreational. The mortalities considered here include any death caused by fishing activities whether the animal is caught and retained, dies after being discarded (Zeller et al. 2018), or dies after interacting with the fishing gear in some other way (Avila et al. 2018). Catch statistics and biological data such as size and age of fish caught are collected, whenever possible, to monitor fishing activities and help quantify the effect that fishing is having on the population.

In the previous section, we used Eq. (17.5) to describe the effects of natural mortality on a population; however, that model assumed fishing mortality was not an influential driver of population dynamics. In situations where fishing is occurring, the rates of natural mortality ($M$) and fishing mortality ($F$) can be added to yield the total mortality rate ($Z$) and used to model the exponential decline in population abundance over time such that:

$$N_j = N_i e^{-ZM},$$

where

$$Z = M + F.$$  

We can convert this from an instantaneous rate to an annual catch rate ($A$), using:

$$A = 1 - e^{-Z}.$$  

Equations (17.7–17.9) form the backbone of many stock assessment models used to estimate fishing mortality and stock size (Quinn and Deriso 1999). Changes in the age composition of catch data are often used to estimate mortality with Eqs. (17.7–17.9), a simple example of which is shown in Box 17.3. In many situations, though, age composition of the catch is unknown. Thus, fisheries scientists often examine trends in catch to monitor changes in the underlying population (Froese et al. 2012).

Fishery catch is a function of both the size of the population available to be caught and the amount of effort expended. Catch can be described mathematically as follows:

$$C = q \cdot f \cdot B,$$  

where

$q$ = catchability coefficient

$f$ = fishing mortality

$B$ = population biomass
where \( C \) is the fisheries catch in weight during a given period, \( B \) is the mean biomass during that same period, and \( q \) is a scaling coefficient called catchability that represents the fraction of a fish stock caught by a defined unit of the fishing effort, \( f \). This definition implies that \( C/f \) (the catch per unit of effort, or CPUE) is proportional to the biomass, an assumption that generally holds, but which does not apply in some cases, especially in schooling fish (Hilborn and Walters 1992). If \( q \) remains constant, CPUE can be used to monitor stock trends when absolute biomass is unknown (Figure 17.6). Effort is often gear-specific and can be based on a variety of metrics such as number of fishers, days at sea, number of hooks set, hours trawled, or hours of trap soak time. In estuaries, fishery CPUE tends to decline rapidly as the density of fishers increases, implying that, past a certain level, increased fishing effort results in smaller catches (Figure 17.7a).

CPUE should be interpreted with some caution, though, because \( q \) often changes over time due to the tendency of fishers to move to areas of high density, environmental changes that drive movement of fish outside the surveyed range, etc. (Wilberg et al. 2010). In such circumstances, the relationship between catch and biomass is not proportional across the time.

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**Box 17.3 Estimation of fishing mortality using catch-at-age data: a case study of yellow perch (Perca flavescens) in the upper Chesapeake Bay.**

Typically, fish produce many juveniles, but few survive to old age given mortality factors such as predation, disease, and fishing. The model presented in Eq. (17.7) describes the exponential decline in abundance of fish within a given cohort over time. To obtain a rough estimate of the total mortality experienced by a stock, we apply a method called a “catch curve” which assumes the rate of decline in catch-at-age either for a cohort of fish or within a given year is indicative of the total mortality (Quinn and Deriso 1999).

For example, the distribution of yellow perch catch-at-age from the 2015 commercial harvest in the upper Chesapeake Bay shows that catch of fish is low for ages 2–3, increases for age 4, then largely declines across the remaining ages 5–10+. Yellow perch younger than age 5 are not yet fully exposed to the fishery, meaning they are typically too small to be reliably caught in the nets used by fishermen. Therefore, we will focus our analysis on catch of ages 5+ fish that are fully selected to the gear.

Taking the natural logarithm of catches for ages 5+ linearizes the data such that the slope of a line drawn through these points, with the sign changed, is an estimate of the total instantaneous mortality rate on the population; in this example, total mortality (\( Z \)) = 0.55 year\(^{-1}\).

Based on observed catch-at-age in other areas of the Chesapeake Bay that are closed to fishing, the natural mortality rate for yellow perch in this area was estimated to be 0.25 year\(^{-1}\). Therefore, according to Eqs. (17.8 and 17.9), the instantaneous fishing mortality rate is equal to 0.30 year\(^{-1}\), and the annual harvest rate is 0.42 or 42% of the population.

**Source:** Paul Pailis, Maryland Department of Natural Resources.

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**Figure 17.6** Trend in catch-per-unit-effort (CPUE) of Atlantic croaker (Micropogonias undulatus) in a trawl survey of the Chesapeake Bay mainstem, 2002–2016. Effort is measured as the area swept by the trawl net. If catchability (\( q \)) has been constant over the time series, this CPUE trend should reflect trends in total abundance in the survey area, indicating that croaker have largely been in decline since 2004. **Source:** Based on Virginia Institute of Marine Science (2016).
series and CPUE may provide misleading information about true stock trends (Erisman et al. 2011). In general, though, CPUE information is welcome when interpreting fishery statistics; indeed, the inclusion of fishing effort has been shown to add considerably to model precision when predicting yields in estuarine systems (Figure 17.7b).

Despite the simplicity of Eqs. (17.7) and (17.9), estimating the fishing mortality that occurs in estuaries is a significant challenge for several reasons, including:

1. Estuaries do not encompass the complete life cycle of many species that inhabit them. Species that are not permanent residents of estuaries may be subject to different natural and fishing mortalities in the riverine systems or coastal oceans that they inhabit during different times in their lives (Bayley 1988). Thus, to estimate the amount of fishing mortality that occurs in a given estuary, we must know both the proportion of the total fishery that occurs in an estuary and the rates and times at which fish move in and out of estuaries throughout their lives. However, estuarine migration rates require extensive, expensive tagging studies and are thus unknown for many species.

2. Most fisheries statistics collection programs do not distinguish between fish of the same species caught in estuaries versus the nearby coastal ocean, as mentioned in Section 17.2.1 (Bayley 1988). Thus, the application of classical methods of fish population dynamics and fishing management to estuarine fisheries without consideration of the entire stock is often inappropriate, even if isolated elements of these resource systems can be described by these classical methods (Lam Hoai and Lasserre 1984).

3. Similarly, the scattered and often small-scale nature of fisheries operations in estuaries generally makes the routine collection of CPUE data too costly. Hence, such data are lacking for most estuaries (Kapetsky 1984) or are largely unreliable (Bayley 1988).

4. The methods that may be most appropriate for assessing estuarine stocks, which have the advantage of not requiring estimates of fishing effort, do require information on the age of fish caught, which can be obtained in a cost-effective manner only for the most important species in major estuarine fisheries.

In summary, the methodologies to monitor and assess the dynamics of estuarine fish stocks have largely been developed; however, the data required to conduct these analyses are often lacking due to funding restrictions and the complex nature of many estuarine fish stocks and small-scale estuarine fisheries.

17.3.5 Recruitment

Fisheries scientists use information on recruitment to determine how many new fish will become available to the fishery and how sustainable catch advice provided to managers might change as a result of high or low juvenile fish production. This often proves to be a difficult task because fish recruitment is highly variable and can fluctuate 10-fold among years in an apparently random or even chaotic fashion (Hjort 1914; Houde 2009).

Recruitment is thought to be a function of the size of the adult spawning portion of the stock. In general, recruitment increases with increasing spawning stock size until it either levels off (Figure 17.8a; Beverton and Holt 1957) or declines again at large stock sizes due to processes such as cannibalism or nest site competition (Ricker 1954). A suite of different mathematical models linking production of recruits to size of the spawning stock have been described, all of which assume recruitment declines at low stock size (Sharp and Csirke 1983; Quinn and Deriso 1999).

In practice, though, fisheries scientists have discovered that recruitment is highly unpredictable and is often poorly correlated with spawning stock size (Houde 2009). In addition, extended periods of unexplained high or low recruitment produced by a range of spawning stock sizes often baffle fishermen,
Understanding fish recruitment in estuaries is further complicated by the diversity of ways in which fish species use estuaries in the recruitment portion of their life cycles (see also Section 17.1 and Chapter 12). Three main groups of fishes occur in estuaries: (i) resident species: those which spend their entire life cycles within an estuary; (ii) seasonal migrants: those which enter estuaries during a more or less well-defined season from either the marine or the fresh water side and leave it during another season; and (iii) occasional visitors: those which enter and leave an estuary without a clear pattern within and among years. To these three basic groups, two other groups may be added: (iv) marine, estuarine-related species, which spend their entire life cycle in the upper shelf under the influence of an estuarine plume; and (v) fresh water, estuarine-related species, which spend their entire life cycle in the fluvial-deltaic zone in the upper reaches of estuarine systems.

The degree to which fish use estuaries can affect our ability to monitor and predict recruitment dynamics. Estuarine residents pose the least challenge because both the spawning stock and recruits can be directly monitored within estuaries if resources are sufficient. However, most estuarine fishes are seasonal migrants that spawn outside estuaries; young fish are either flushed into estuaries while still in the planktonic stage, or swim as early juveniles into estuaries against the outgoing current (Figure 17.9), either due to their effort to stay close inshore or due to coastal wanderings in search of food (Pauly 1982; Quignard 1984; Chauvet 1988). The relative level of recruitment into estuaries by seasonal migrants is thus determined by a combination of the overall number of potential recruits along the coast and oceanographic and estuarine conditions that allow fish to enter estuaries. For other migratory species, recruits may not rely on estuaries as nursery sites, but estuaries serve as important foraging grounds during a later stage in their life cycle; by associating with productive estuarine systems at some life stage, a high standing stock can be maintained (Yáñez-Arancibia and Sanchez-Gil 1988).

Outside estuaries, numerous marine species spend their entire life cycle in the upper shelf deriving benefits from estuarine plumes. For example, a significant fraction of the secondary production in the western Gulf of Mexico’s “fertile crescent” (Mississippi River mouth to the northern tip of the Yucatan Peninsula, and including some areas the Atlantic coast of Central America) is derived from estuarine ecosystems, including areas on the shallow shelf influenced by estuarine plumes (Darnell 1990; Sánchez-Gil and Yáñez-Arancibia 1997; Chesney and Baltz 2001; Yáñez-Arancibia 2005; Sánchez-Gil et al. 2008). Characteristics of these estuaries are high riverine discharge rates, large fresh water surpluses, and low water residence times. Much of the production and subsequent trophic transfer may therefore occur outside the physical boundaries of the estuaries, that is, in association with plumes of fresh water over the inner continental shelves. These contrasting sources—estuary and shelf—of trophic delivery to the fishery forage base, and ultimately to larger consumers, is one cause of uncertainty on how we view the functions of estuaries and the shelf ecosystem they influence.
Thus, high fisheries production may be attributable in part to the estuary-like conditions prevailing in large parts of the inner continental shelf during high river discharge periods, as relatively a few fish species are wholly adapted to life cycles within estuarine systems.

17.4 Management of Estuarine Fisheries and Aquaculture

Both fishing and aquaculture activities in estuaries involve the use of natural resources. This implies the need for management because common-property, open-access natural resources systems, given competing users, cannot produce high, sustained yields if left to themselves (Hardin 1968). Since the advent of modern industrial fishing fleets, fish stocks have tended to quickly become overfished unless they are managed, and in some cases even when they are (Pauly et al. 2002). When unregulated, aquaculture practices can also result in low yields, polluted waters, and toxic products (Ottinger et al. 2016). This section outlines the general principles of fisheries and aquaculture management in estuaries and concludes with a summary of future challenges.

17.4.1 Fisheries Management

Fisheries management is a process by which the current and future behavior of participants in the fishery is controlled in an attempt to ensure sustainable use of the resource. The process, which often starts too late when stocks are already depleted (Ludwig et al. 1993), typically begins with a recognition or statement of a problem and the gathering and analysis of available data, sometimes in the form of a formal stock assessment. Estimated trends in quantities such as fishery catch and effort, stock biomass, fishing mortality, and recruitment are used by fisheries scientists to establish the stock status and suggest sustainable catch levels. Managers then consider that information when making decisions about setting regional quotas, or catch limits, and how to allocate the resource among participants.

Fisheries management action is implemented through the establishment and enforcement of regulations. Fisheries agencies that are granted management authority to set fishery regulations vary by country, but can include local, provincial/state, and national governments as well as international organizations with multiple countries as members. Fisheries management actions typically involve putting restrictions on: (i) access to the resource either through licensing or closure of specific areas to fishing, (ii) number of gears, (iii) type of gear deployed, (iv) timing of effort deployment, or (v) some combination of these (Pauly et al. 2002). Without such restrictions, stocks often collapse, leading to negative ecological and socioeconomic consequences, including food web alterations (Pauly et al. 1998) and food insecurity (Pauly et al. 2005).

Estuarine fisheries possess several characteristics that complicate management compared with many freshwater or marine fisheries. First, the seasonality of estuaries poses unique management challenges. A number of investigations have demonstrated the existence of complex, seasonally changing relationships between fisheries yields and high nutrient loads, fresh water inputs, shallow depths, large areas of tidal mixing, coastal vegetated area, surface area of estuarine systems, and the resulting high productivities that are typical of estuaries and estuarine plume ecosystems (Deegan et al. 1986; Nixon 1988; Sánchez-Gil and Yáñez-Arancibia 1997; Yáñez-Arancibia et al. 2007). Thus, management decisions must account for this seasonal pulsing habitat, and the protection of its different components, including the aquatic
vegetation, in the context of comprehensive environmental planning. Coastal fisheries resources are an expression of ecosystem functioning and to assure the persistence of such resources, the protection and conservation of essential habitats is the key.

However, fisheries management agencies often have limited or no jurisdiction over many activities that affect fish habitat in estuaries such as channel dredging, agricultural runoff, shoreline development, or hydropower plant operations. In some cases, controlling fishing practices alone may not be sufficient to maintain robust stocks. Thus, fishery management plans often include habitat management goals that other agencies can use to guide their actions. In some circumstances, fisheries scientists or managers are consulted before certain actions are taken that might affect fish habitat. However, in many circumstances, fisheries professionals are not consulted on estuary management issues or given authority to maintain or enhance fish habitat, making management of fish habitat in estuaries particularly challenging given they often contain or are in close proximity to major ports, shipping lanes, hydropower plants, agriculture production, and human population centers.

Also, the predominance of migratory species in estuaries that inhabit these systems for only part of their life cycle means that estuarine fisheries often require complex inter-jurisdictional management (i.e., the cooperative or complementary management of the same fishery across multiple agencies). For example, many part-time residents, particularly anadromous and catadromous species, in the Chesapeake Bay require the coordination of up to six different agencies to regulate all the different fisheries that interact with the species across its entire range and life history, both in and outside estuaries (Table 17.2; Chesapeake Bay Fisheries Ecosystem Advisory Panel (NCBO) 2006). If any one of these agencies, including those with jurisdictions limited to areas outside estuaries, does not maintain sustainable fishing practices, the entire stock and the estuarine fisheries that rely on it may be negatively affected.

Finally, it is also important to recognize that many fisheries around the globe, particularly in estuaries, are not industrial but small in scale. Approximately 25% of current global fisheries catch are from small scale fisheries sectors, either artisanal, subsistence, or recreational (Figure 17.10; Pauly and Zeller 2016). One of the major trends in global fisheries is increased competition between small-scale and large-scale fisheries due to overfishing (Pauly 2006; FAO 2015). Yet small-scale fisheries tend to directly benefit more people and their livelihoods, and generally have fewer negative environmental effects.

**TABLE 17.2** A summary of fishery management plans (FMPs) adopted, and regulations established by the 8 fisheries management agencies and organizations with authority to regulate the harvest of 10 example estuarine fishes/crustaceans that inhabit the Chesapeake Bay, USA. FMP indicates which agency/organization has adopted an FMP in their region. C and R indicate an agency has set commercial or recreational fisheries regulations, respectively, in their waters. Note that several different agencies may have complementary (or competing) FMPs for the same species and that multiple agencies can set their own independent regulations for the same species within their jurisdictions. Blue crab and white perch are the only lifelong resident species in the Chesapeake Bay on this list with all others being diadromous or seasonal migrant species.

<table>
<thead>
<tr>
<th>Species</th>
<th>ASMFC</th>
<th>MAFMC</th>
<th>SAFMC</th>
<th>DCF</th>
<th>DMDNR</th>
<th>PFBC</th>
<th>PRFC</th>
<th>VMRC</th>
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<tbody>
<tr>
<td>American eel</td>
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<td>C/R</td>
<td>R</td>
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<tr>
<td>Atlantic croaker</td>
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<tr>
<td>Atlantic sturgeon</td>
<td>FMP</td>
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<tr>
<td>Black sea bass</td>
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<td>C/R</td>
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<tr>
<td>Blue crab</td>
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<tr>
<td>Bluefish</td>
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<td></td>
<td>C/R</td>
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<tr>
<td>Spanish mackerel</td>
<td>FMP</td>
<td>FMP</td>
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<td>C/R</td>
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<tr>
<td>Striped bass</td>
<td>FMP</td>
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<tr>
<td>Summer flounder</td>
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<td>C/R</td>
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<tr>
<td>White perch</td>
<td>C/R</td>
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<td>C/R</td>
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* The Chesapeake Bay Program regional partnership maintains a Blue Crab Fishery Management Plan, but does not have management authority to set regulations.
* An FMP for white perch was drafted in 1990, but never formally adopted by Maryland Department of Natural Resources.

ASMFC Atlantic States Marine Fisheries Commission; MAFMC Mid-Atlantic Fishery Management Council; SAFMC South Atlantic Fishery Management Council; DCF District of Columbia Fisheries Management Branch; MD DNR Maryland Department of Natural Resources; PFBC Pennsylvania Fish and Boat Commission; PRFC Potomac River Fisheries Commission; VMRC Virginia Marine Resources Commission.

Source: Adapted from Chesapeake Bay Fisheries Ecosystem Advisory Panel (2006).
Reconstructed global catch broken down into large-scale (industrial) and small-scale (artisanal, subsistence, recreational) sectors. Source: Data from Sea Around Us.

and socioeconomic side effects (Zeller et al. 2016; Zeller et al. 2017). Given the difficulty of monitoring small-scale fisheries, their contribution to national fish supply tends to be greatly underestimated compared to that of industrial fisheries, leading to undervaluation of their importance to communities (Zeller et al. 2007). For example, reconstructed marine fish catch statistics from Cambodia, Malaysia, Thailand, and Viet Nam showed that small-scale sector catches were underestimated by an average of two times (Teh and Pauly 2018). Until small-scale fisheries catches are consistently monitored independent of industrial catches, small-scale fisheries will continue to be undervalued (Pauly and Charles 2015) and overall fishing pressure underestimated (Teh and Sumaila 2011) in estuaries and other aquatic systems.

Estuarine fisheries management involves not just the regulation of targeted fishing on individual stocks, but also monitoring and control of the potential negative impacts fisheries can have on the broader ecosystem, including nontargeted catch, estuarine habitats, and the estuarine food web.

Fishers often catch species that were not targeted and this is called bycatch. Bycatch may be retained, or may be discarded because they are undesirable, usually for economic reasons (Zeller et al. 2018). Note that not all bycatch is discarded, and that targeted species may be discarded as well. When the amount of catch allowed for a targeted species is limited by a quota, some fishers may discard all or a portion of their catch to make space for bigger and hence more valuable fish of the same species; this process is called high-grading, and it is illegal.

Discarded bycatch can include not just fish, but many species of shellfish, marine mammal, coral, seabird, or sea turtle. The degree to which discarded animals can survive capture and handling varies by species and life stage and is a significant source of uncertainty in estimation of fishing mortality (Davis 2002). Some animals are quite resilient, while others such as Mexico’s endemic porpoise, the vaquita (*Phocoena sinus*), are at the brink of extinction due to them being bycatch of a fishery for a giant croaker, the totoaba (Taylor et al. 2017). Also, the bycatch of juvenile fish in estuaries varies seasonally but can have serious negative impacts on the recruitment of both target and nontarget stocks (Blaber et al. 2000). The monitoring and regulation of discard mortality is a major challenge in fisheries management because fishers are typically not required to report fish they do not land and sell. In particular, many estuarine-related fisheries employ gears or techniques that are nonspecific for their target species; for example, shrimp trawling results in high discard to landings ratios that range from 2 to 10+ kg discarded per kg shrimp kept (Alverson et al. 1994; Pauly and Zeller 2016). Also, derelict fishing gear that has been lost or abandoned can continue to “ghost fish” or cause bycatch mortality due to accidental ingestion of plastic debris or entanglement (Coe and Rogers 2012).

Another way in which fishing affects estuarine ecosystems is through direct habitat disturbance or destruction. Although the degree of impact may vary across gear types, dredges and trawls tend to have the largest effect on benthic communities, turbidity, and disturbance or destruction of sensitive habitats such as seagrass beds and oyster reefs that serve as nursery and foraging habitat (Blaber et al. 2000). The rate of recovery of estuarine habitats from fishery disturbance depends largely on the substrate type, frequency of disturbance, and degree of tidal flow (DeAlteris 1988; DeAlteris et al. 1999; Collie et al. 2000).

Without careful management, fisheries can induce unintended trophic alterations that impact community structure and functioning of estuarine food webs. Aquatic systems have experienced a gradual transition in the catch of largely long-lived, high trophic level, piscivorous fish toward short-lived, low trophic level invertebrates and planktivorous pelagic fish, a process that has been termed “fishing down aquatic food webs” (Pauly et al. 1998; Pauly et al. 2000; Liang and Pauly 2017). Northern temperate regions of the globe such as the North Atlantic where fisheries are most developed have experienced the most severe sequential collapse and replacement of upper trophic level fisheries (Pauly et al. 1998; Essington et al. 2006), although some countries in lower latitudes such as India and Brazil have also experienced striking rates of trophic level declines in estuarine and marine fisheries (Bhathal and Pauly 2008; Freire and Pauly 2010).

The overall functioning of estuarine ecosystems can be altered by fishing activities as well. For example, the Chesapeake Bay estuary was once home to extensive reefs of the eastern oyster (*Crassostrea virginica*) which helped to filter vast quantities of water (Newell 1988). With the advent of oyster dredging in the 1870s, oyster reefs and subsequent fishery catches rapidly declined to low levels within 60 years (Rothschild et al. 1994; Jackson et al. 2001). Given continued overfishing, habitat destruction, and disease, the population has not recovered and is estimated to be at approximately 0.3% of its historic, unfished state (Wilberg et al. 2011), leaving the ability of oysters to help mitigate the effects of anthropogenic eutrophication greatly diminished. Ending overfishing and rebuilding oyster populations in the
Bay could help restore habitat for numerous finfish species (e.g., reef-obligate gobies, blennies, and toadfish), improve submerged aquatic vegetation abundance, increase denitrification, and reduce the quantity of suspended solids and phytoplankton (Cerco and Noel 2007).

### 17.4.2 Aquaculture Management

Management of aquaculture in estuaries is in many ways similar to land-based agriculture in that it involves activities such as regular stocking, intervention in the rearing process to enhance production, feeding, and predation control (NOAA 2006). Unlike most capture fisheries, aquaculture can involve the permitting or leasing of some static area of the aquatic ecosystem to culturists, and the ownership of the farmed stock by individuals or corporations.

Aquaculture regulations focus on a few key issues: (i) species to be cultivated; (ii) water quality, (iii) water use, (iv) land use for associated hatchery/processing activities, (v) hatchery management; (vi) feed types; (vii) types and placement of artificial substrates or cages; and (viii) processing (DeVoe and Hodges 2002). In some countries, aquaculture management involves control of hatchery and culture practices on land for seeding or stocking, aquatic zoning and location siting procedures, leasing and permitting of the water column or bottom to private companies by government agencies, monitoring of water quality impacts, and regular testing of seafood products to protect human health. Like fisheries, the degree of regulatory control over aquaculture practices varies widely among nations (Boyd and Schmittou 1999).

Although aquaculture management standards are increasing around the world, enforcement of regulations is often lax (Wood and Mayer 2007).

Aquaculture management has several issues that often pose greater challenges in estuaries than fresh or marine waters, including use conflicts and coordination across multiple jurisdictions. Estuarine aquaculture activities are typically stationary farms that involve the use of artificial structures such as racks, stakes and lines, or cages and pens (Macintosh 1994; Bostock et al. 2010). These semipermanent structures placed in the water create use conflicts with other traditional estuary activities and interests such as commercial fisheries, navigation, shoreline development, and recreation (DeVoe and Hodges 2002; Harvey and McKinney 2002; Klinger and Naylor 2012). Balancing the competing interests of aquaculture and other human activities in estuaries requires comprehensive coastal zone management and planning (DeVoe and Hodges 2002; Cataudella et al. 2015).

As with estuarine fisheries management, aquaculture activities, when regulated, are often subject to oversight by multiple authorities that regulate everything from navigational hazards posed by aquaculture gear to treatment of farmed stock with pharmaceuticals. For example, aquaculture practices in US estuaries must comply not only with local and state government regulations, but also with that of seven different federal agencies, including the US Army Corps of Engineers, US Environmental Protection Agency, US Fish and Wildlife Service, NOAA Fisheries, US Food and Drug Administration, US Department of Agriculture, and the US Coast Guard (DeVoe and Hodges 2002).

The management of aquaculture in estuaries involves not only the regulation of culturing activities, but also the monitoring and control of potential impacts on the broader ecosystem. Primary concerns include changes in water quality and estuarine habitats, structure and functioning of the estuarine community, and human health. See Box 17.4 for a case study example of the aquaculture of milkfish (Chanos chanos) and its ecosystem impacts.

Estuarine habitats can be altered by aquaculture activities particularly when gear displaces or destroys local sea grass beds, mangroves, or wetlands (Páez-Osuna 2001; DeVoe and Hodges 2002). Aquaculture also has the potential to disturb the local sediment, induce changes in benthic community structure (Findlay et al. 1995; Simenstad and Fresh 1995), and cause localized eutrophication and sediment deposition through the concentrated release of feces by sedentary or penned farmed animals, particularly in areas with low flow (Páez-Osuna 2001; Testa et al. 2015). When localized eutrophication occurs, the potential for lowered dissolved oxygen and increased turbidity and frequency of algal blooms also increases (Frankic and Hershner 2003; McLusky et al. 2004). In some circumstances, shellfish aquaculture can ameliorate poor water quality by improving light penetration for seagrasses and enhancing removal of nitrogen (Newell 2004; Dumbauld et al. 2009; Kellogg et al. 2014). However, the extent to which aquaculture combats eutrophication varies based on a number of factors, including tidal exchange conditions, proximity to phytoplankton sources, residence time, and shellfish density (Dumbauld et al. 2009; Kellogg et al. 2014; Murphy et al. 2016). Sediment deposition by bivalves may actually be higher in farmed areas if currents are not strong enough to redistribute fecal deposits (Cranford et al. 2006; Testa et al. 2015).

In addition to the effects on benthic organisms mentioned above, aquaculture can directly impact many estuarine populations. Aquaculture involves the introduction of new gear and hatchery-raised animals into the estuarine ecosystem which creates an opportunity for the introduction of potentially harmful diseases to wild conspecifics as well as the introduction of invasive species that could alter community structure and functioning (Naylor et al. 2001; Thorstad et al. 2008). Farmed species such as salmon (Salmo salar) have been known to escape cages and become established as invasive species or interbreed with local wild stocks, resulting in lowered individual fitness, reduced lifetime success, and decreased production across generations (McKinell and Thomson 1997; Thorstad et al. 2008). Non-native sturgeon (Acipenser sturio) in Western and Central Europe introduced as escapes from fish farms and the pet trade have thrived and may interfere with endemic sturgeon restoration efforts...
by competing for habitat, introducing disease, and potentially hybridizing (Arnold et al. 2002).

Aquaculture sites are seen as irresistible concentrations of prey to many aquatic predators that not only cause economic losses for the culturist, but also increase opportunities for bycatch mortality. For example, Australian fur seals (Arctocephalus pusillus) are often drawn to forage on farmed salmonids where they harass and eat fish and damage nets in which they sometimes become entangled, injured, and drown (Kemper et al. 2003). Also, cownose rays (Rhinoptera bonasus) are known to ransack bivalve aquaculture sites in US estuaries; in this situation, fisheries managers must balance the interests of culturists who advocate for “harvest control” of rays with the concern that this species has extremely low reproductive rates (one pup per year), making high catches unsustainable (Fisher et al. 2011).

Box 17.4  Aquaculture of an estuarine-dependent species: a case study of milkfish (Chanos chanos) in Southeast Asia.

Milkfish, known as bangus in the Philippines and bandeng in Indonesia, is a euryhaline fish native to tropical and subtropical waters of the Pacific and Indian Oceans that relies on estuaries as a nursery ground (Froese and Pauly 2018). Adult milkfish school in marine waters above 20°C near coasts and around islands. Spawning occurs in marine waters on sand or coral reefs. Larvae remain at sea for 2–3 weeks before migrating en masse into estuaries, mangroves, and, occasionally, freshwater lakes. Subadults return to the ocean to mature and complete the life cycle.

Milkfish are an important food fish in Southeast Asia, primarily in the Philippines, Indonesia, and Taiwan. Milkfish culture began primarily in brackish water ponds and has spread to freshwater and marine sites as well given the species’ high tolerance for a wide range of salinities (Macintosh 1994).

Culture of milkfish in estuaries occurs in shallow ponds often excavated from nipa palm beds located in mangroves. To prepare ponds for culture, chicken manure and other fertilizers are commonly added (FAO 2018a). Mature breeders spawn in hatchery ponds without the use of hormones.

Traditionally, young seed fish called fry are harvested wild in estuaries and sold to culturists to be raised to harvestable size. Since the 1970s, milkfish have also been bred in hatcheries (FAO 2018a). However, the supply of wild fry, as with most fish recruitment, is often unpredictable, and the wild capture of fry cannot satisfy the demand from aquaculture. Catches of wild milkfish fry in recent years have diminished to the point that the Philippines has begun importing hatchery-raised fry from Taiwan and Indonesia (FAO 2018b).

Milkfish typically consume natural food (benthic diatoms, epiphytic algae, and detritus) in culture, but are often supplemented with artificial feed when natural productivity of the water cannot sustain optimum fish growth, more so in marine than brackish sites. Artificial feed options used include lab-lab (a mixture of cyanobacteria, diatoms, filamentous algae, and invertebrates) or rice bran mixed with fish meal or other animal byproducts (FAO 2018a). Fish meal and animal byproducts may be produced locally or imported and include a variety of sources including anchoveta-based fish meal, tuna or shrimp offals, snail meat, mussel, and poultry (FAO 2018b). The use of fish meal in milkfish aquaculture is small relative to other farmed species and is gradually being replaced with vegetable-based protein sources (Tacon and Metian 2008). However, the production of farmed milkfish is rising, resulting in a total increase in artificial feed use.

Source: Pauly et al. (2020).
Aquaculture can also have widespread effects on ecosystem and human health when pharmaceuticals and other chemicals are used. Many aquaculture operations employ the use of antibiotics, hormones, and biocides to treat disease and enhance production (Subasinghe et al. 2000; Hoga et al. 2018). In addition, pollutants such as pesticide run off from land-based agriculture can be taken up by the farmed animals from their aquatic environment and bioaccumulate (Wood and Mayer 2007). Chemicals and pollutants are later consumed by predators and humans or dispersed into sediments and the water column, having localized or broad effects depending on the size and location of the aquaculture operation (Frankic and Hershner 2003; Guardiola et al. 2012).

Finally, some forms of estuarine aquaculture can impact wild fish stock dynamics due to their reliance on wild-caught broodstock and forage fish as a source of protein in aquaculture feed. For example, many aquaculture operations that raise tropical shrimp are stocked using wild-caught juveniles and are sustained using fish-derived feeds (Klinger et al. 2013). Even low trophic level species farmed inland or in estuaries and which require very little protein in their diet such as tilapia, are being produced at such high and increasing rates that demand for fishmeal is placing growing pressures on fisheries exploiting fish to turn into fishmeal and fish oil (Chiu et al. 2013). Although the use of fishmeal in aquaculture has declined in recent years, aquaculture production and demand for omega-3 oils has grown (Naylor et al. 2009). Advances in the production and use of alternative plant- and animal-based feeds may alleviate this problem in the near future (Frankic and Hershner 2003; Hasan and Halwart 2009; Naylor et al. 2009).

### Future Challenges

Looking ahead, the major challenges facing managers of estuarine fisheries and aquaculture in the future will be rebuilding wild fish populations in the face of increasing human population size and climate change. With anticipated population growth, global demand for seafood may exceed our capacity to fish sustainably (Pauly et al. 2002). Although some regions have made improvements, overall global stock status trends are worsening, and approximately 40% of stocks are estimated to be overexploited or collapsed (Froese and Kesner-Reyes 2002; Froese et al. 2012; Kleisner et al. 2013; Pauly and Zeller 2017). To reverse this trend, significant reductions in fishing effort will be required (Pauly et al. 2002). Countries identified as being the most dependent on fisheries and vulnerable to marine production losses are also some of the same countries expected to have the highest population growth (Bradshaw and Brook 2014; Fulton et al. 2018). If truly precautionary fisheries management practices are adopted worldwide, fisheries alone will not be able to meet the current and growing global demand for seafood.

It has been suggested that aquaculture could, in some circumstances, complement, or supplant fisheries catches to help address growing demand (Kobayashi et al. 2015). However, most aquaculture production, particularly in estuaries, is currently aimed at producing specific products for export to wealthy markets in developed countries (Little et al. 2016; FAO 2018d). Many developing countries do not currently have the infrastructure to support aquaculture production at levels sufficient to meet nutritional demands, particularly in sub-Saharan Africa and the Pacific Islands where seafood production consists predominantly of subsistence and artisanal fishing (Golden et al. 2016; Blanchard et al. 2017; Tacon and Metian 2018).

Further complicating the issues of overfishing and population growth is climate change (Mohanty et al. 2010). Future plans for maintaining or enhancing the production of seafood from estuaries must take into account anticipated effects of climate change on these fragile ecosystems. Shifts in species distributions and abundances are expected which could result in lower catches for some and higher for others (Kennedy 1990; Wood et al. 2002; Roessig et al. 2004; Barange and Perry 2009; De Silva and Soto 2009). The highly seasonal nature of estuarine biological processes such as migration may be altered with unpredictable consequences for fish yields (Cochrane et al. 2009). Also, both fisheries and aquaculture will likely be challenged by higher incidence of disease caused by even a small increase in temperature (Roessig et al. 2004; Mohanty et al. 2010). The erosion of coastal margins as a result of sea level rise will likely cause increased turbidity and decreased extent of vegetative habitats upon which estuarine fishes rely (Wood et al. 2002).

Changes in freshwater flow will affect nutrient and dissolved oxygen levels, salinity, and estuarine circulation patterns that affect seasonal migrations as well as the quality and quantity of fish nursery and foraging habitats. Climate change-induced ocean acidification already threatens shellfish aquaculture in temperate regions because acidic waters can corrode shell. For example, hatcheries in the Pacific Northwest, the United States have begun buffering seawater and relocating operations to more optimal sites (Clements and Chopin 2017). Changes in precipitation patterns will also significantly affect fish habitat conditions in estuaries and require adaptive measures to minimize impacts on fisheries and aquaculture systems (Cochrane et al. 2009). If management of fisheries and aquaculture in estuaries is going to effectively rise to these challenges, novel solutions generated through interdisciplinary cooperation will be required that involves stakeholders, fisheries and aquaculture scientists, ecosystem managers, public health specialists, environmental engineers, and policymakers (Golden et al. 2016; Fulton et al. 2018).
17.5 Summary

Estuarine fisheries and aquaculture activities are an important component of global food security and nutrition. Fisheries yields are typically higher in estuaries than other types of ecosystems, and aquaculture yields are typically twice as high in estuaries as in coastal seas or freshwater systems.

Estuaries are highly productive systems that are critical to the success of many fisheries because they serve as habitat during all or certain stages in the life cycle of many fish and invertebrate populations. Also, given the migratory nature of many estuarine fish populations, estuaries have broad, regional impacts that extend far beyond their physical borders.

Assessing wild fish population dynamics primarily involves quantifying recruitment, growth, natural mortality, and fishing mortality. Fish growth in estuaries is influenced by several factors including temperature/seasonality, species, sex, estuary size, and habitat quality. Estuarine fishes display relatively high natural recruitment and natural mortality compared with their open-water counterparts. Natural mortality is strongly correlated with other aspects of fish life history such as growth, and thus can be estimated from life history information. Changes in the age composition of fishery catch and tagging data are often used to estimate fishing mortality. When proportional to biomass, CPUE can be used to monitor stock trends when absolute biomass is unknown.

Fisheries management involves controlling the current and future behavior of participants in a fishery in an attempt to ensure sustainable use of the resource. Establishment and enforcement of fishery regulations is complicated by numerous factors including seasonality, migration, jurisdictional limitations of oversight agencies, and the small-scale nature of many estuarine fisheries.

Management of aquaculture in estuaries is more similar to land-based agriculture, and involves activities such as regular stocking, broodstock maintenance, feeding, and predation control. Aquaculture management challenges in estuaries include use conflicts with other activities such as fishing and navigation, and coordination across multiple natural resources agency jurisdictions.

Ecosystem impacts of fisheries and aquaculture activities in estuaries include bycatch, habitat disturbance or destruction, and alterations in community structure and functioning of food webs. Ecosystem impacts of aquaculture may also include alteration of local water quality, introduction of harmful diseases and invasive species, the use of pharmaceuticals and other chemicals, and the reliance on wild-caught broodstock and forage fish.

The future of estuarine fisheries and aquaculture will involve tackling global problems such as overfishing, a growing demand for seafood worldwide, and the negative impacts of climate change.

Review Questions

Multiple Choice

1. Which of the following factors promote high fisheries yields in estuaries? (Select all that apply)
   a. High primary productivity
   b. High turbidity
   c. High natural recruitment
   d. Proximity to human population centers and ports
   e. Extreme temperature and salinity fluctuations

2. Which of the following factors affect the growth of fish in estuaries? (Select all that apply)
   a. Dissolved oxygen levels
   b. Size and type of estuary
   c. Water salinity
   d. Water temperature
   e. Moon phase

3. When comparing estuarine fishes with conspecifics in the coastal ocean, which of the following is generally true?
   a. Estuarine fishes have higher natural mortality rates
   b. Estuarine fishes migrate longer distances
   c. Estuarine fishes have lower incidence of disease
   d. Estuarine fishes have higher catch per unit effort
   e. None of the above

4. What are the two components of total mortality \((Z)\) in fish population dynamics modeling?
   a. Fishing mortality and bycatch mortality
   b. Natural mortality and fishing mortality
   c. Natural mortality and migration mortality
   d. Natural mortality and discard mortality
   e. None of the above

5. Which of the following are aspects of estuarine aquaculture that are often regulated by managers?
   a. Feed type
   b. Location of aquaculture site
   c. Use of pharmaceuticals
   d. Water quality impacts
   e. All of the above
6. Which of the following statements is false? (Select all that apply)
   a. Most estuarine fisheries are industrial in scale.
   b. Most fish species in estuaries are seasonal migrants.
   c. Estuarine fisheries can be affected by shoreline development and agricultural run-off.
   d. Fish recruitment in estuaries is stable from year to year.
   e. Estuarine fisheries often compete for space and market share with aquaculture.

7. Which of the following statements is true? (Select all that apply)
   a. Spawning stock size is a good predictor of recruitment.
   b. Recruitment is highly variable in estuarine fishes.
   c. Most fish species that occupy estuaries are year-round residents.
   d. Recruitment is most easily predicted for year-round estuarine resident fishes.
   e. Temperature has little effect on fish growth.

8. Fishery catch is a function of (Select all that apply)
   a. The age of the stock
   b. The size of the stock
   c. The amount of effort expended
   d. Catchability
   e. Water temperature

9. Which of the following statements is true?
   a. Globally, aquaculture production is declining.
   b. Most estuarine-dependent species spawn in freshwater.
   c. The impact of estuarine fisheries is limited in spatial scope.
   d. Fisheries yields are typically higher in estuaries than other types of ecosystems.

10. Which continent has the largest aquaculture industry?
    a. North America
    b. Europe
    c. Asia
    d. Australia

Short Answer Questions

1. What are the primary causes of catastrophic mortality in estuarine fishes?
2. Describe the four main challenges to estimating fishing mortality in estuaries.
3. In what way are the management of estuarine fisheries and aquaculture similar?
4. Describe three ecological impacts of fisheries activities on estuarine systems.
5. Describe three ecological impacts of aquaculture activities on estuarine systems.
6. Given the following catch-at-age data from a 2009 survey of white perch (Morone americana) in Chesapeake Bay, estimate the instantaneous fishing mortality rate assuming natural mortality is equal to 0.2 year⁻¹. Assume all fish ages provided are fully selected by the gear.

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Numbers caught</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2916</td>
</tr>
<tr>
<td>5</td>
<td>710</td>
</tr>
<tr>
<td>6</td>
<td>1614</td>
</tr>
<tr>
<td>7</td>
<td>884</td>
</tr>
<tr>
<td>8</td>
<td>896</td>
</tr>
<tr>
<td>9</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>153</td>
</tr>
</tbody>
</table>

   Source: Paul Piavis, Maryland Department of Natural Resources.

7. Define fisheries bycatch and describe why it is important to characterize.
8. List three ways in which climate change will likely impact estuarine aquaculture.

Spreadsheet Exercises

1. In the Northern Gulf of Mexico, a growth study of red snapper (Lutjanus campechanus) yielded the parameters \( L_\infty = 90.4 \text{ cm (total length, or TL)}, K = 0.19 \text{ year}^{-1} \) and \( t_0 = -0.48 \text{ year}. \)

   Using information available in FishBase (fishbase.de), present a von Bertalanffy growth function (VBGF) that incorporates these parameters, but with length expressed as fork length (FL).

   Convert your VBGF for length into weight.

   Plot the 10 first years of the VBGF for length (cm FL) and for weight (kg).

   Hints: Consult the FishBase glossary for an explanation of fork vs. total length measurements and the length-length and length-weight pages for additional parameters. Above each table, click on the "More Info" link for detailed explanations of each equation.

2. Using data available from SeaLifeBase (sealifebase.ca), view growth parameters for all available species. Hint: search "Information by topic".

Create a spreadsheet containing \( K \) and \( L_\infty \) growth parameters for any 5 marine mammals, seabirds, crustaceans, and cephalopods, being sure to choose a combination of both large and small species in each group. Visit FishBase (fishbase.de) and select 5 large and small fish species and add their growth parameters to your spreadsheet. In total, you should have 25 sets of parameters. Be sure to include a column containing the species group name (e.g., “fish”, “seabirds”) as well.

Plot \( \log(K) \) vs \( \log(L_\infty) \). Label your points using the species group name (e.g., seabirds). Hint: To add custom data labels, right click on any single point on your graph, select “Add Data Labels”, right click on any data label, select “Value From Cells”, and select the column containing your species group names. Unclick “Y value”.

What is the main pattern that emerges? How do fish, crustacean, and cephalopod growth rates and max compare with seabirds and marine mammals?
3. Using information obtained from the Sea Around Us (seaaroundus.org) tool and the links provided in the tool to FishBase (fishbase.de) data, Examine data queries for the Beaufort Sea and Gulf of Mexico Large Marine Ecosystems (LMEs). Scroll down to the “More Info” section and create a table of the number of fish species exploited (i.e., caught by fisheries) in each LME, both in total and on a per-area (km²) basis. Compare statistics gathered between the two LMEs and provide an ecological explanation for these differences based on what you know about fisheries in estuaries.

References


