# EASTERN OYSTER
## *Crassostrea virginica*

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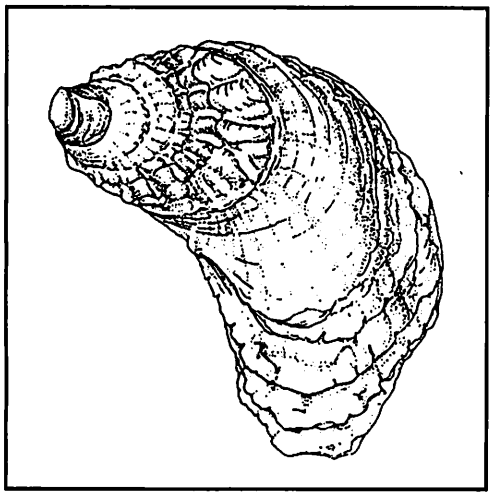

**The eastern oyster is a resilient estuarine species that is well adapted to its fluctuating environment in the Chesapeake Bay. It tolerates wide natural variation in temperature, salinity, suspended sediments, and dissolved oxygen, to the extent that environmental regulations protecting more active or more sensitive species like blue crabs and striped bass will probably protect oysters. It is fecund enough to produce billions of spat in the Bay if brood stock abundance is high, suitable hard substrate is plentiful, and climatic conditions are optimal. Predation causes high mortality of the young stages. High mortality rates also have been caused by diseases in recent years. Pollution is a local problem for oysters near industrialized regions of the Bay. Overfishing has led to depressed harvests, degraded oyster grounds, and a weakened fishery. To rehabilitate the resource, it will be necessary to understand aspects of oyster biology more completely (especially diseases), to rehabilitate the oyster grounds, to manage the resource according to scientific principles, and to encourage the growth of aquaculture.**

## INTRODUCTION

The eastern oyster is a very fecund commercial bivalve that is well-adapted to an estuarine existence. Consequently, it is very resistant to the wide swings of temperature, salinity, turbidity, and dissolved oxygen that characterize its habitat. In addition to its fecundity, the species has morphological, physiological, and behavioral adaptations that, by colonial times, allowed it to persist in immense numbers in the Chesapeake Bay. European settlers reported that cemented agglomerations of oyster shells formed navigational hazards ("rocks") thrusting up from the soft Bay bottom.

The filtering activities of these massive concentrations of oysters may have resulted in the Bay harboring a much different assemblage of phytoplankton and zooplankton than at present. This assemblage may have contained fewer sea nettles, microplankton, and bacterioplankton, and the Bay waters probably were much less turbid than now, thus allowing submerged aquatic vegetation to thrive.

Naturally, these immense beds of oysters began to be exploited by early settlers, to the extent that the Bay fishery was one of the most important in the U.S. at the turn of the 20th century.[43] However, politically directed management of the Bay's oyster resources at the behest of oyster harvesters resulted in virtually unregulated overharvesting and subsequent decline in the abundance of the species over the past century. In some heavily populated regions of the Bay, pollution and high sediment loads have also contributed to the decline. Oyster beds in unpolluted or relatively unpolluted regions (roughly from Eastern Bay south on the Eastern Shore, and in the Patuxent and Potomac River mouths on the Western Shore, with scattered populations elsewhere) are in danger of being overwhelmed by sediment because overfishing has led to excessive scraping of the substrate, leaving the surface of the beds projecting just above the sediment where it can be covered during storms.

The repeated warnings of numerous scientists and commissions of inquiry and their recommendations for conservation of the resource have generally been ignored by the Maryland and Virginia legislatures.[43,44] Oyster farming (aquaculture) in Maryland has been discouraged for most of the 20th Century by passage of various laws. The potential for rehabilitation of the fishery has been greatly hindered by episodic incidences of lethal diseases over the past 30 years.

With over-exploitation and disease having depleted oyster stocks, the Bay fishery is a fraction of what it once was. Over 15 recent years (1971-1986), oysters have represented 21% of Maryland's total commercial fishery catch and 48% of dockside value. However, from 1983 to 1986, these proportions declined to 8% and 30%, respectively.[8] Catches have declined dramatically from 14 million bushels in 1890 shortly after overfishing began to less than 0.5 million bushels per year since 1987. The market for Bay oysters has declined along with the harvest, so that an increasing market share has been captured by aquaculture industries on the Pacific coast of the United States and elsewhere.

Because it is highly adapted for an estuarine existence, and because the central Chesapeake Bay is so conducive to sustained reproduction, settlement, and growth of oysters, the eastern oyster could once again become a major natural resource in the Bay if aquaculture were encouraged and if resources were available to rebuild oyster beds in formerly highly productive habitat. The oyster is immobile for much of its life, and therefore does not have a high metabolic demand. As will be described later, it is resistant to all but the most extreme environmental fluctuations. Consequently, except perhaps for anthropogenic chemicals found near industrial population centers, water quality criteria established for more metabolically active and sensitive species such as the blue crab and the striped bass will undoubtedly protect the oyster as well.

## BACKGROUND

The eastern oyster, also known as the American oyster or Virginia oyster, is a bivalve mollusk in the family Ostreidae, a family that is worldwide in distribution, and that supports numerous commercial fisheries in many nations. The eastern oyster ranges along the coast of North America from the Gulf of St. Lawrence to the Gulf of Mexico. It has been introduced to Hawaii, the west coast of North America, and other locations worldwide. Its typical habitats are estuaries, sounds, and bays, from brackish water to hypersaline lagoons. It is found in the shallows of the Chesapeake Bay from salinities above about 5 ppt in the upper Bay and its tributaries to the near-oceanic salinities of the Bay mouth.

Four recent reviews of oysters in general and the eastern oyster in particular are the authority for statements in this text, unless otherwise noted.[2,33,44,48]

## LIFE HISTORY

### Reproduction

Adult oysters are immobile, but release eggs and sperm into the water where external fertilization occurs. Production of spawn (gametogenesis) depends on storage of glycogen, which begins after spawning in summer or autumn with the accumulation of nutrients and which slows or stops under winter conditions. Ripening (development of gametes) is rapid (over a few weeks in the Chesapeake Bay) as water temperatures warm above 10°C in spring. Temperature increase stimulates natural spawning, and spawning in the Bay may occur at 18°C (limited spawning) to 20°C and above.[45] The presence of sperm or eggs also stimulates release of gametes, as may the presence of some chemical (perhaps food-related) in the water pumped by adults.[45,93] Where temperatures permit, females may spawn more than once in a season, with up to 20 million eggs (sometimes more) released at any one time by an individual female, depending upon her size and condition.

### Larval Development and Settlement

Fertilized eggs develop into ciliated veliger (D-stage, straight-hinge) larvae in 24 hours or less, depending upon temperature. During the next two to three weeks the free-swimming larva grows until ready to settle. Before settlement occurs at about 260-300 µm, a foot develops (pediveliger stage). The foot is used to crawl and "explore" substrate before settlement and metamorphosis occurs. When a suitable substrate is found, liquid cement is extruded from a pore in the foot and the left valve becomes fixed in place. Subsequently the ciliated velum that allowed the larva to swim is discarded, the foot is reabsorbed rapidly, and gills and a digestive tract are elaborated. The attached juvenile oyster is called a spat.

Metamorphosis will be delayed if suitable substrate is unavailable (e.g., as a result of siltation, presence of noxious chemicals, etc.). The length of delay that can occur in nature is unknown, but Coon *et al.*[18] have been able to keep competent-to-settle Pacific oyster (*Crassostrea gigas*) larvae in the laboratory for 30 days without settlement occurring. Settlement and metamorphosis in the eastern oyster are mediated by neuroactive compounds such as L-3,4-dihydroxyphenylalanine (L-DOPA), epinephrine, and norepinephrine.[16,17] Anthropogenic substances in the water column that mimic or inhibit such compounds might stimulate settlement prematurely or inhibit it, but this possibility has not been explored at all.

The planktonic larval stage is the only mobile stage. Larvae can swim up or down in the water column, but are

carried more-or-less passively by horizontal water movements.

### Growth

Fastest relative growth occurs in the early months of an oyster's life. Annual growth rate is affected by temperature (the rate increases from north to south), by food quality and quantity, by salinity, and by parasitic infection. Shell growth may be greatest in spring as water warms. Growth of the soft body tissues is greatest after spawning ends, as glycolytic reserves are built up in preparation for gametogenesis during the subsequent winter. Growth slows in the spawning season as energy is allocated to production of eggs and sperm.

## ECOLOGICAL ROLE

### Substrate

Because estuaries are areas of high sediment deposition, their basins are predominantly soft-sediment in nature, subject to continual sediment influx from the surrounding watersheds. As a result of its production of shell, the eastern oyster provides the greatest volume of hard substrate found in estuaries. In pristine or carefully managed habitats, oyster reefs can be massive, thus affording extensive attachment area for oyster larvae, as well as numerous associated species that, like oysters, require solid substrate. As a result of overfishing in the Chesapeake Bay, oyster shell substrate is usually limited to a relatively thin layer of dead shell and live oysters spread widely over Bay bottom. These damaged habitats are more readily covered by sediment because currents are slower near the bottom. In addition, reefs with many live oysters seem to remain freer of sediment for reasons that are not clear but may include the effects of water pumping and vigorous shell clapping by the resident oysters. Ultimately, over-exploited reefs disappear, overwhelmed by sediment, leaving less habitat available for oysters and other species that require hard substrate, such as hooked mussels, tunicates, bryozoans, and barnacles.

### Principal Foods

As is characteristic of a species with planktotrophic larvae that depend on phytoplankton for food, oyster eggs are supplied with the minimum lipid reserves to support energy requirements until feeding and digestive systems develop and function. For the 2-3 weeks of larval existence before settlement, suitable planktonic food is necessary for survival and metamorphosis. Young spat grow rapidly after settlement and have low food reserves; an adequate quantity and quality of phytoplankton is required for the buildup of nutrient reserves to meet metabolic needs over winter. The adult also requires suitable food to support gametogenesis. Preliminary data on studies in the Choptank River indicate that Broad Creek and the Tred Avon River have sufficient food to support the presumed food requirements of any life history stage of the eastern oyster (personal communication: R. Newell, Horn Point Environmental Laboratory).

Larvae, spat, and adults ingest predominantly living plankton. Oyster larvae can ingest food particles ranging in size from 0.2 to 30 μm, selectively ingesting 20-30 μm organisms.[4] Adults are less efficient in retaining particles below 3 μm in diameter than in retaining larger particles.[50] The biochemical composition of algal cells as well as cell size is important. The detrital complex in the seston appears to supply very little of an adult oyster's carbon requirements in Maryland's Chesapeake Bay.[19,74]

### Role as a Filter Feeder

Recently, it has been proposed that over-exploitation of oysters in the Chesapeake Bay has reduced the important filtering role oysters play in the ecosystem, resulting in major biotic changes.[73] Oyster populations in the Bay are calculated to have declined since the late 19th century from a standing stock biomass of 188 million kg dry tissue to a present biomass of 1.9 million kg dry tissue. Where once the population in summer was capable of filtering the Bay's entire water column from surface to bottom in an estimated 3 to 6 days, present stocks require an estimated 325 days. The pre-1870 oyster population is estimated to have been capable of filtering 42-77% of the 1982 daily carbon production in Bay waters shallower than 9 m, compared with less than 1% filtered by the 1988 population.[73]

Newell[73] hypothesized that the loss of such a major filtering assemblage may have been an important factor in the apparent shift to microbial food webs in the Bay and to an increase in zooplankton, including gelatinous zooplankton (ctenophores and jellyfish). Restoration of oyster populations by aquaculture and the careful management of public beds would improve water quality through the enhanced removal of particulate carbon by oysters. Oyster biomass would then be harvested, permanently removing the carbon from the system. Note also that many of the organisms commonly found attached to oyster shells (e.g., hooked mussels, tunicates) are also filter feeders whose numbers may also have declined as a consequence of the decline in oyster populations.

### Predation

The oyster, like all bivalves that broadcast sperm and eggs into the water column, suffers over 99% loss of gametes, fertilized eggs, and larval stages before settlement occurs. Much of that loss is undoubtedly due to predation by ctenophores and other planktivores. Benthic carnivores that consume oyster larvae include sea anemones, the scyphistoma stage of sea nettles, and probably a variety of filter feeding invertebrates. Newly settled spat are consumed by the carnivorous flatworm *Stylochus ellipticus*, and by small crabs. Older spat and first year oysters may be eaten by larger blue crabs and some fish. In higher

salinity waters (>20 ppt), predatory snails and starfish feed on oysters, including the largest individuals. Finally, disease kills many oysters, usually those older than one year; salinities below about 12 ppt seem to protect oysters from disease. Water saltier than about 5 ppt is excellent habitat for oyster production because predatory snails and starfish are generally absent, with disease limited in low salinity years.

## HABITAT REQUIREMENTS

A number of "physiological races" of the eastern oyster apparently exist along the western Atlantic coast.[54,55,56,94] These races appear to differ in timing of gametogenesis and spawning as a function of geographic location and temperature regime. Studies are currently being conducted on these differences. Relatively few data on environmental requirements of the eastern oyster have been collected from Chesapeake Bay populations. Existing data have been collected as the result of experiments in Long Island Sound, Delaware Bay, and the Gulf of Mexico, so they may not be entirely accurate for Bay oysters. But these data do provide general insights into tolerances and adaptations of the eastern oyster. Table 1 summarizes habitat requirements for temperature, salinity, sediment, pH, and dissolved oxygen. These requirements are "best estimates" rather than exact values, but can serve as guides for managers.

### Water Quality

#### *Temperature*

Temperature influences growth, development, reproduction, and feeding activity. It has not been reported to jeopardize oyster populations, except where industrial discharges release much warmer water than occurs naturally. Oysters cannot control their body temperature, and are subject to a temperature range of about -1°C to about 36°C throughout their geographic range. Oysters exposed to air at low tide in southern regions have briefly attained body temperatures of 46-49°C.[33] However, temperatures much above about 32°C would be stressful over a period of many hours or days and could be lethal in winter when oysters are acclimatized to cold temperatures.

The eastern oyster has a maximum rate of ciliary activity (responsible for pumping water for respiration and feeding) at about 24-26°C. Ciliary activity is usually disrupted above 32°C and feeding may cease below 6-7°C.[33,52,70]

Efforts to determine lethal temperatures by Henderson[37] and Fingerman and Fairbanks[30] were environmentally unrealistic and did not produce data that are ecologically useful. No other studies on lethal temperatures of adults or spat have been reported. However, to simulate conditions of passage through power plant cooling condensers, Hidu *et al.*[40] subjected fertilized eggs, ciliated gastrulae, and 2-day-old veliger larvae to temperature increases for periods from 10 seconds to 16 hours. Mortality increased with increasing temperature and exposure time. Fertilized eggs were least resistant to higher temperatures, followed by ciliated gastrulae, then veliger larvae. Maryland law governing temperature addition to estuaries should protect oysters from lethally high temperatures, and heated effluents are not allowed near oyster beds.

Temperature affects rate of larval development. In the Bideford River, Canada, oyster larvae required 30 days to reach 365 µm in length at 19°C, 26 days at 20°C, and 24 days at 21°C.[67] Maximum larval growth in the laboratory occurred between 30.0 and 32.5 °C at Long Island Sound salinities between 10.0 and 27.5 ppt[22], and larvae reached setting stage in 10-12 days at 30-32.5°C and 36-40 days at 20°C. Diaz[26] noted that a five-second exposure to a 20°C increase above 25°C (but not increases of 10 or 15°C) permanently impaired larval growth; his results would be applicable to larvae exposed to industrially heated water.

Increased temperatures (below lethal levels) influence setting success of pediveligers. In the Delaware Bay, an increase in temperature from 24 to 29°C for four hours increased the percentage of larvae that set.[59] Such temperature increases occur when water floods over tidal flats heated by exposure during ebb tide. Setting in Virginia was also found to be influenced by the age of larvae and degree of temperature increase above 25°C.[40]

#### *Salinity*

Like temperature, salinity influences growth, development, reproduction, and feeding activity. Oysters tolerate a wide range of salinities and thrive in the mesohaline waters of Chesapeake Bay; they become less abundant toward the head of the Bay and in the upper regions of Bay tributaries where salinity falls below about 5 ppt. The most deleterious salinities are low salinities associated with freshwater flooding over a number of weeks.

Low salinity can be fatal, and can inhibit feeding, growth, and spawning. In an extensive study by Loosanoff,[51] there were no differences in salinity tolerance among oysters of different ages, including spat. Oysters could feed at levels as low as 5 ppt if temperatures were cool, but no feeding was ever observed at 3 ppt or below. The crystalline style disappeared in oysters held in low salinities (a sign that feeding was not occurring) but regeneration occurred soon after the oysters were returned to normal salinities. Growth was limited or nonexistent at 5 ppt or less, retarded at 7 ppt, and unaffected at 12 ppt and above.

Salinities of 0 and 3 ppt totally inhibited gametogenesis in Loosanoff's experiments.[51] At 5 ppt, gametogenesis was arrested in about 50% of an experimental sample, and depressed in the remainder of the sample. At 10 ppt, 12 ppt, and 27 ppt (control), oysters were ripe, with some

starting to spawn. If oysters were held in ambient conditions and allowed to grow until the gonads began enlarging (about three weeks before the normal onset of spawning) and were then placed in lower salinities, 0 to 5 ppt inhibited further gonad development. Normal gametogenesis proceeded at 7.5 ppt and above, with some oysters spawning at 7.5 ppt and with more intense spawning in higher salinities. Salinities of 7.5 ppt or above are necessary for gametogensis and spawning to be even moderately successful.

Pumping rate (method of assessment not stated by Loosanoff)[51] was strongly affected by sharp reductions of salinity from 27 ppt (control) but began to increase somewhat after additional exposure (acclimation) to the lower salinities. Rapid changes from low to high salinities had little effect. Oysters accustomed to living in lower salinities were more tolerant of the effects of even lower salinity (as measured by shell-closing behavior or by pumping behavior) than were oysters used to living in higher salinities.[51]

Optimum salinity and the salinity range for the development of oyster eggs into straight-hinge larvae is influenced by the salinity experienced by the parents during gametogenesis.[21] Thus, adults acclimated at 26.0-27.9 ppt produced zygotes that developed over a salinity range of 12.5-35 ppt, with an optimal development at about 22.5 ppt. Parents acclimated to about 9 ppt produced zygotes that developed within a range of 7.5-22.5 ppt with optimal development between 10.0-15.0 ppt. Optimal larval growth occurred at 17.5 ppt for larvae whose parents were held at 26.0-27.9 ppt. Thus, optimal salinity conditions for larval development will differ with location in the Chesapeake Bay.

For older larvae (165 µm long) from parents acclimated to 26.0-27.0 ppt, Davis[21] found good growth between 12.5 and 17.5 ppt and in the controls (26.0-27.0 ppt), and limited growth at 7.5 ppt (25% of control value). Setting was good between 12.5 and 17.5 ppt but non-existent at 7.5 ppt. No experiments were made with larvae from parents held in low salinity conditions.

Davis[21] speculated that oyster populations in low salinity areas (< 10 ppt) may depend on the influx and settlement of nearly full-grown larvae from higher salinity areas. In upper Chesapeake Bay, Eastern Bay and the lower Choptank River are the northernmost regions with consistently good spat settlement success. Both these areas have salinities generally above 10 ppt during the spat settlement period, in contrast with the less saline Chester River further up the Bay which is not usually self-supporting in terms of spat settlement. Setting of oyster spat in the Bay varies directly with the cumulative high salinity during the spawning season in the central Bay.[97]

When Chanley[15] placed recently set spat (0.3-0.5 mm long) directly into salinities ranging from 2.5 ppt to "full salinity" (not specified) at 21-24°C, 100% died within two weeks at 2.5 ppt and 50% died at 5 ppt. Growth at 7.5 and 10.0 ppt was slow compared to growth in higher salinities. In a second experiment, spat (1.0-1.4 mm) that were transferred gradually to experimental conditions over a week experienced poor growth at 10.0 and 12.5 ppt and least growth at 7.5 and 5.0 ppt. At 2.5 ppt, only 19% survived, compared with 66% at 5 ppt and 80-100% at the remaining salinities.

Based on these studies[15,21,51] one can expect larvae to grow well at about 12.5 ppt and higher whereas spat and adults should grow slowly from about 7 to 12 ppt and normally from 12-27 ppt.

Responses of different life history stages of oysters to salinity vary with temperature. For example, mortality in oysters subjected to fresh water and low salinities increases as temperature increases.[51] Salinity also affects temperature tolerance of oyster larvae.[22] At salinities from 10.0 to 27.5 ppt, the optimum temperature for larval growth was between 30.0 and 32.5°C, but was 27.5°C at 7.5 ppt. No well-defined optimum growth salinity was delineated; growth depended upon the experimental temperature. Reduced salinities reduced the temperature range that eggs and larvae could tolerate for development and growth.

Managers should understand that there is a synergism between temperature and salinity in relation to their effects on oysters. However, temperature regulations in Maryland seem adequate to protect oysters, and no salinity regulations seem to be required.

### *Suspended Sediments*

The eastern oyster is well adapted to withstand erratic environmental increases in turbidity and sedimentation resulting from the effects of wind, currents, runoff from land, etc.[68] Most studies of sediment effects on the eastern oyster have involved sediment concentrations that are higher than usually encountered in nature.

Nelson[69] found the oyster to be capable of feeding rapidly in waters containing up to 0.4 g (dry weight) of suspended matter per liter. He described the efficient gill filtration system that allows for this, including the promyal chamber which is characteristic of oviparous oysters (genus *Crassostrea*), and concluded that the oyster (at least from turbid Delaware Bay) is able to feed in the presence of heavy loads of suspended sediment.[71,72] However, oysters from less turbid Long Island Sound are more sensitive to high sediment concentrations.[53,58]

Loosanoff and Tommers[58] provided quantitative estimates of pumping rates by oysters from Long Island Sound in

the presence of various concentrations of turbidity-creating substances. Feeding was most efficient when the water contained little suspended material. Additional studies reported by Loosanof[53] showed that even for short exposures (3-6 hours), oysters demonstrated sensitivity to a variety of particulate materials. As particle concentration increased, the rate of water pumping dropped, reaching zero in high concentrations of suspended material. Upon return to clean sea water, oysters exposed for longer periods took longer to recover than oysters held in the same sediment concentrations for shorter periods. Loosanoff[53] assumed that the longer exposure period resulted in tissue damage to the filtering apparatus.

Oyster eggs and larvae can be killed by suspended sediment.[23] Concentrations of 0.25 $gL^{-1}$ resulted in 27% mortality, with 69% mortality at 0.5 $gL^{-1}$, and 97-100% mortality from 1 $gL^{-1}$ and above. Davis and Hidu[23] concluded tentatively that larger particles were primarily responsible for the mortalities. Larvae were more tolerant of sediment than were eggs. A concentration of 0.5 $gL^{-1}$ of sediment led to nearly 20% mortality in eastern oyster larvae after 12 days of exposure,[23] with 50% mortality between 1.0 and 1.5 $gL^{-1}$ and 100% mortality at 3 $gL^{-1}$. Eastern oyster larvae suffered reduction in growth in 0.75 $gL^{-1}$ of sediment, and growth stopped at 2 $gL^{-1}$. To place their results in an environmental perspective, Davis and Hidu[23] noted that eastern oyster larvae tolerated experimental turbidity levels higher than those normally encountered in nature. However, they felt that excessive turbidity caused by storms or activities such as dredging might be detrimental to oysters.

### *Dissolved Oxygen*

Although limited experiments have been performed to evaluate the effects of low dissolved oxygen on oysters (whether measured in terms of survival, physiological activity, reproduction, or spat settlement) the eastern oyster seems to be a tolerant species. It is an oxygen regulator down to a critical oxygen tension of about 30 mm Hg at 20 °C and 28 ppt.[88] Below 30 mm Hg, it becomes an oxygen conformer. Louisiana oysters (30-50 mm long) starved for 35-65 days remained resistant to anoxia, with their metabolic rate depressed to only 75% of the normoxic rate.[95] Values of $LT_{50}$ (days of exposure to anoxia causing 50% mortality) for these oysters when held at salinities of 10, 20 and 30 ppt were 28 days at 10°C, 18-20 days at 20°C, and 3-8 days at 30 °C.[95] Compared with blue crabs (29-54 mm carapace width) from the same region, oysters were much more resistent to hypoxia and anoxia, both in terms of metabolic rate and of mortality.

Elsewhere, oysters have survived for up to 5 days (no temperature data given) in water containing less than 1.0 $mgL^{-1}$ oxygen.[91] Presumably they underwent anaerobic metabolism during that time.[33] Median mortality times for anoxia-exposed larvae are 11 hours for 82 µm larvae and 150 hours for 16 mm spat.[99] Kennedy (personal observations) found that larval swimming rates after 12 hours at oxygen concentrations as low as 0.5 $mgL^{-1}$ were not significantly different from rates at saturation levels of oxygen. Also, oyster larvae avoided low oxygen water (exposure to about 1 $mgL^{-1}$ or less for one hour) by swimming upwards, an action that would bring them towards the surface where hypoxia is minimal.

Because of larval avoidance of hypoxia, and spat and adult resistance to low dissolved oxygen concentrations, short-term (days) intrusions of anoxic and hypoxic waters over shallow (<5-10 m) oyster beds are probably not deleterious. Should such intrusions kill less tolerant shell-fouling organisms, space would become available on the oyster shell for settlement by larvae. Regulations designed to protect blue crabs from low dissolved oxygen would serve to protect the oyster as well.

### *pH*

Estuaries are generally well-buffered systems, with pH in unpolluted waters ranging from 6.8 to 9.25, depending upon time of day and season. Data on pH tolerances of oysters are meager. Oysters were found to spawn at pH 7.8 to 8.2 in Long Island Sound,[79] and not below pH 6.0 or above pH 10.[13] Pumping rate in adults was normal at pH 4.4, but oysters at pH 4.25 remained open about 76% of the time and pumped about 90% less water than did controls at pH 7.75.[57] At pH 6.75 and 7.00, oysters initially pumped more than did the controls at 7.75, but the rate gradually declined to become less than in the controls.[57] Respiration is also affected by pH; at pH 6.5, oxygen consumption was 50% of normal, decreasing to 10% at pH 5.5.[33]

Normal embryonic development occurs at pH 6.75 to 8.75.[13] Survival of larvae was more than 68% in the range of 6.25 to 8.75, with pH 6.00 being the lower limit for survival. Normal larval growth occurred from pH 6.75 to 8.75, with growth dropping rapidly below pH 6.75. Abnormal development of eggs and mortality of larvae increased rapidly at pH 9.00 to 9.50. Calabrese and Davis[13] concluded that successful recruitment of oysters requires a pH above 6.75. High concentrations of sediment lower seawater pH below 6.75 to 6.40. Thus, heavy sediment loads (or any pollutant lowering pH in tidal estuaries) may lead to failure of oyster recruitment.

## Structural Habitat

### *Substrate*

Even with an efficient mechanism for tolerating the often heavy sediment load in estuaries, oysters can be overwhelmed and buried by heavy sedimentation,[72] with death by suffocation resulting. In general, oysters survive best on bottoms that are firm, such as those of shell, rock, and firm or sticky mud. Sand bottoms are subject to shifting activity, resulting in abrasion and valve injury. In

addition, shifting sand destroys young spat of the flat oyster, *Ostrea edulis*,[85] so presumably young eastern oyster spat would also be at risk in sandy environments.

Oyster shell is the most suitable substrate for spat settlement. The removal of whole oysters from the Bay and their transport to distant markets means that there is a constant drain of this cultch from the Bay. Alternatives such as buried shell are in finite supply, so if shell conservation is not practiced or if replacement material is not readily available, future spat settlement will be hindered.

### *Depth*

In years past, oysters were dredged from the deeper waters of the Bay by sailboats, but most beds now are found in the shallows along the shore and in Bay tributaries where sediments are firmer and where the supply of dissolved oxygen is more reliable.

## SPECIAL PROBLEMS

### Overfishing

For the past century, management of the Bay's oyster industry has been influenced predominantly by political concerns rather than by scientific information.[43] The result has been a steadily decreasing harvest, degraded oyster grounds, and a diminished industry. It is not clear if the brood stock of the Bay has been depleted to the point that recruitment has been influenced negatively, but it may be significant that spat settlement has been poor during recent years when salinities have been low enough to inhibit disease organisms yet high enough to allow for normal reproduction. Many oyster beds are in danger of being smothered by sediments because they have been scraped so much that they barely project above the surrounding soft sediment. Silt-covered shells are not attractive to settling larvae.

### Diseases

Mid-Atlantic Bight populations of oysters are subject to the diseases known as "MSX," "SSO," and "dermo".[3,32,92] Except for the more marine SSO which does not occur in the Chesapeake Bay, these diseases have heavily depleted Bay oyster populations over the past 40 years. In addition to causing mortality, MSX inhibits growth and gametogenesis in spring. However, temperature-associated remission of infection may occur in summer and allow for gametogenesis and spawning to proceed.[31] Similar results have been obtained for Louisiana populations infected by dermo.[62] Of the two diseases, MSX is inhibited by salinity; salinities below about 10-15 ppt and above 30-32 ppt are associated with decreased parasite activity of MSX.[35] Dermo seems to be more tolerant of low salinity[61,75] than MSX. One of the most pressing problems facing resource managers is that of understanding and combating these two disease organisms.

### Contaminants

#### *Overview*

An extensive and hard-to-manage literature exists on toxicants, pollutants, pesticides, etc. It cannot readily be condensed for easy comprehension. Contaminants affecting oysters in Chesapeake Bay include heavy metals, pesticides, PCB, PAH, chlorine-produced oxidants, and petroleum hydrocarbons.[6,36] Selected information has been compiled previously,[42,44,66] and a comparative toxicology of marine organisms is available.[77,81] Information on biological effects and body burdens of selected pollutants in the eastern oyster is summarized in Tables 2, 3 and 4.

It is difficult to generalize about the oyster's sensitivity, either to classes of contaminants, or relative to other species. However, adult and juvenile oysters appear to be somewhat more tolerant of most environmental toxicants than embryos and larvae, and more tolerant than some other estuarine species.

Judging from the diverse and inconsistent body of studies summarized in the Tables, the substances of most concern for toxicity to adult oysters in chronic exposures appear to be tributyltin (TBT), a few heavy metals, and petroleum hydrocarbons. Chlorinated pesticides and PCB (Arochlor 1016) caused acute mortality or sublethal effects in juvenile oysters at relatively low concentrations (~10 $\mu gL^{-1}$). Embryos were quite sensitive to mercury and silver, showed moderate sensitivity to copper and zinc, and were relatively insensitive to other metals and most of the pesticides tested. For the few substances tested, larval sensitivities were similar to those of embryos.

#### *Interpretation of toxicity tests*

Reisch[80] reviewed the use of laboratory tests for marine organisms. Acute toxicity tests typically measure the concentrations of a particular contaminant at which 50% of the test subjects die over a given period of time, usually 48 or 96 hours. This concentration is the $LC_{50}$ for the substance. Chronic toxicity tests measure the effect(s) of sublethal concentration on one or more attributes, such as survival, growth rate, or developmental abnormalities. Problems in the standardization of these tests often limit their comparative value. Also, laboratory studies do not simulate field conditions very well, so that a contaminant's actual effect is likely to be different from what the bioassay predicts. However, short-term toxicity tests can be a valuable diagnostic tool for ranking toxicants[80].

#### *Heavy metals and trace elements*

The physiological aspects of heavy metal contamination in oysters have been summarized in the literature[20,29]. Empirical data indicate wide variability in the toxicity of different metals to *C. virginica* embryos (Table 2). The relative toxicity of several metals is: mercury = silver > copper > zinc > nickel > lead > cadmium > arsenic >

chromium > manganese. Similar comparisons for larval or attached life stages cannot be made due to lack of data, except that mercury, silver, copper, and cadmium show acute toxicity to adults or larvae at relatively low concentrations. Comparisons between life stages reveal that embryos tend to be more susceptible than larvae for those metals which were tested on both life stages. Comparison between embryos or larvae and attached stages is not possible because acute assays were used for embryos and larvae whereas chronic tests were used for attached oysters.

Body burdens of heavy metals for oysters collected from Chesapeake Bay (Table 3) suggest that some metals (e.g., zinc) are accumulated out of proportion to their environmental concentrations. A few additional references are available for metal contamination in oysters from the Bay[7,27,36].

### *Pesticides*

Kerr and Vass[46] summarized information on the accumulation of pesticide residues in aquatic invertebrates; a comprehensive treatment of the general toxicology of pesticides was given by Matsumura[65]. Differences in biological effects and toxicological endpoints measured preclude effective comparison of the relative toxicity of different pesticides (Table 2). However, acute toxicity data suggest that *C. virginica* is less sensitive to herbicides than to insecticides. An extensive list of acute toxicity of pesticides on various life stages of oysters can be found in Table 4.

### *Polychlorinated biphenyls (PCB) and polynuclear aromatic hydrocarbons (PAH)*

Information is available on contamination of oysters and other shellfish in limited areas of Chesapeake Bay by the environmentally very persistent and ubiquitous PCB and PAH, which are both toxic and mutagenic[5,6,28,36,78] (Table 3). Several PCB, along with other selected contaminants are monitored in oyster tissue at a few sites in the Bay by the National Oceanic and Atmospheric Administration's National Status and Trends Program; generally, shellfish body burdens in Chesapeake Bay tend to be lower than in several other contaminated U.S. estuaries[25].

### *Chlorine and chlorine-produced oxidants*

These compounds (CPO) are produced by reactions of chlorine used for disinfection of water supplies and wastewater effluents with various compounds in the source water. Growth and mortality of adult oysters, chronic effects on spat, and larval responses have been measured at various concentrations of CPO[82,84,86]. High mortality of juvenile oysters was observed in chronic exposures to a fairly low concentration of sodium hypochlorite (Table 2).

### *Petroleum*

Petroleum hydrocarbons, especially the more refined products and contaminated waste oils, are very toxic to at least some bivalves (see HARD CLAM, this volume). Low concentrations of petroleum were lethal to adult oysters in chronic exposures, and to larvae in acute tests (Table 2). Additional information on oil pollution in marine environments and the effects of oil on estuarine organisms, including oysters, is available in the literature[1,49].

## RECOMMENDATIONS

The eastern oyster is a highly resilient species that appears to be reasonably protected in Maryland by laws governing thermal discharge, effluent dechlorination, use of tributlytin, and dredging. It may be at risk in areas near industrial pollution, and laws establishing limits of pollution discharge in relation to oysters may be needed. Petroleum spills, chronic discharges of petroleum wastes, and diffuse low level loadings of some very toxic heavy metals (e.g., mercury) are possible, but undocumented threats to oysters, either locally or generally in Chesapeake Bay. But because it is not mobile for most of its life, the oyster's metabolic activity is such that regulations protecting more active species (e.g., blue crabs and striped bass) for the most part will protect the oyster. Perhaps the most pressing concerns involve improving our understanding of key aspects of the species' life history, especially disease, rehabilitating depleted oyster grounds, the basing of oyster management on scientific insight rather than on political pressure, and encouraging aquaculture.

### Research

In their extensive review of the biology of the eastern oyster, Kennedy and Breisch[44] posed dozens of questions on biology and management that needed answers. Unfortunately, most of these questions remain unanswered, and it is difficult to manage what is not well understood. Particularly needed is a more thorough understanding of five major areas of oyster biology, namely larval biology, feeding and nutrition of all life history stages, genetics, disease, and the effects of pollutants. It is important that studies of disease and of genetics be pursued in order to counter the incidence of MSX and dermo in the Bay, especially if oyster farming is to be encouraged.

Improved management and rehabilitation of the oyster fishery requires thorough study of three components of oyster habitat. Here are some of the questions that need to be answered in each area:

### *Brood stock*

What is the abundance of natural brood stock now available in different areas of the Bay? Has brood stock declined as a result of mortality due to recent disease epizootics? Is there an optimal brood stock concentration that ensures adequate spawning and is population age

distribution a factor in determining this optimal concentration, i.e., does one age group contribute more gametes than another age group?

### *Seed and cultch supply*

How much cultch is now available in the Bay, and how much is optimal? What are the best concentrations on different bottom types or in different locations? Can any area of the Bay with a favorable current system and flushing rate be made into a good seed area, given suitable firm bottom and adequate cultch for settlement?

### *Growing and setting areas*

The best areas still available for settlement and growth need to be determined and protected from loss of cultch and from pollution. It is not clear why some areas are historically conducive to setting (are they "larvae traps"?), but are not suitable for rapid growth and fattening, and vice versa, but the reasons must be clearly understood in order to utilize different areas effectively.

## Management

As noted earlier, overfishing (and now disease) has reduced oyster populations to such a level that there are no more reefs. Rather, small mounds or relatively thin layers of shell are scattered over Bay bottom, with unproductive beds often becoming silted over. The supply of seed oysters is a limiting and critical factor in rehabilitation and management. Those areas of the Bay consistently producing adequate quantities of seed should be protected and expanded. A private oyster farming industry would encourage growth of a seed industry, as it has elsewhere in North America. Fresh shell should not be exported or used for anything other than as cultch for replenishment of the bottom because fossil shell used in Maryland's repletion program is a finite resource.

The present practice in Maryland of prohibiting dredging near oyster beds during the summer larval period helps protect oysters from excessive turbidity, as does the effort to prevent sediment from running off cleared land. Bagless dredging or the use of special boards towed just above the bottom can help to remove sediment from depleted oyster beds in the Bay. These techniques can reduce the potential for smothering spat and can clear substrate for settlement in summer.

Oyster beds must be re-established in formerly productive locations by building up a base of firm substrate into the water column, and covering that base with oyster shell and broodstock. Recent incidences of anoxia and severe hypoxia mean that attempts should not be made to rehabilitate oyster beds in deep water (below about 10 m), but rather should concentrate in the shallows where low dissolved oxygen is relatively rare or short-lived. Also, off-bottom culture should be undertaken.

Because these immense tasks will have to be supplemented by private enterprise rather than being left to public agencies, oyster farming should be encouraged. Aquaculture will enable the private sector to distribute the tasks of cleaning, shelling, and harvesting the beds among numerous individuals and entities, rather than leaving those tasks to public agencies and a heavily subsidized industry.

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Table 1. Habitat requirements for eastern oyster eggs, larvae, spat, and adults. The critical life period is the larval period (June-August). Many ranges are broad estimates, even those based on laboratory-derived determinations, and may vary with geographic location.

| Life stage | Life zone | Temperature[a] °C | Salinity[a] ppt | Sediment[b] $gL^{-1}$ | pH | Dissolved oxygen $mgL^{-1}$ |
|---|---|---|---|---|---|---|
| Eggs | water column | 19-32 | 12.5-35[c]<br>7.5-22.5[d] | <0.25 | 6.75-8.75 | ? |
| Larvae | water column | 19-32 | 12.5-27.0[c] | <0.5 | 6.75-8.75 | e |
| Spat | hard substrate (benthos) | 0-32+ | 15.0-22.5[f] | ? | ? | g |
| Young (30-50 mm) | benthos | | | | | < 0 at 10°C[h]<br>0.8-1.49 at 20°C[h]<br>2.75-4.98 at 30°C[h] |
| Adults | benthos | | | | | |
| survival | | 0-32+ | 0-36+ | ? | ? | ~1 (5 days) |
| feeding | | 6-32;<br>(15-25 "optimum") | 5+ | <0.4 | ? | ? |
| growth | | 6-32;<br>(15-25 "optimum") | 12+ | ? | ? | ? |
| gametogenesis | 10+ | 7.5-30+ | ? | ? | ? | |
| spawning | | 20± | 10+ | ? | 6-10 | ? |

[a] Salinity can affect temperature tolerances, and vice versa. Tolerance to temperature is roughly adult = spat > veliger larvae > zygotes.

[b] Effects depend upon type and size of particle; experimental values have been higher than values normally encountered in nature except during intense storms.

[c] Adults acclimated to 26.0-27.9 ppt; optimal egg development at 22.5 ppt and optimal larval growth at 17.5 ppt.

[d] Adults acclimated to 9 ppt; optimal egg development at 10-15 ppt.

[e] Median mortality times in anoxia: 11 hours for 82 µm larvae; larval swimming rates unaffected at 0.5 $mgL^{-1}$ for up to 12 hours.

[f] Spat had been set at near marine salinities.

[g] Median mortality times in anoxia: 150 hours for 16 mm spat.

[h] $LC_{50}$-$P0_2$ ($mgL^{-1}$) causing 50% mortality after 28 days of exposure at 10, 20, and 30°C, with oysters held at 10 ppt, 20 ppt, and 30 ppt at each temperature.

Table 2. Toxicity of selected compounds to the eastern oyster. Life stages: E = embryos; L = larvae; J = juveniles; A = adults. Flow conditions: S = static; F = flow-through. Effect: M = percent mortality; G = percent reduction in shell growth.

| Compound | Life stage | Temperature °C | Salinity ppt | Flow | Duration | Effect | Concentration $mgL^{-1}$ | Strength of effect % | Reference |
|---|---|---|---|---|---|---|---|---|---|
| METAL SALTS | | | | | | | | | |
| cadmium chloride | E | 26 | 25 | S | 48 h | $LC_{50}$ | 3.80 | | 11 |
| | A | 20 | 31 | F | 20 wk | M | 0.10 | 84 | 89 |
| chromium chloride | E | 26 | 25 | | 48 h | $LC_{50}$ | 10.3 | | 11 |
| | A | 20 | 31 | F | 20 wk | M | 0.10 | 14 | 89 |
| cupric chloride | E | 26 | 25 | S | 48 h | $LC_{50}$ | 0.103 | | 11 |
| | L | 25 | 24 | S | 48 h | $LC_{50}$ | 0.046 | | 14 |
| | A | 20 | 31 | F | 20 wk | M | 0.050 | 15 | 89 |
| lead nitrate | E | 26 | 25 | S | 48 h | $LC_{50}$ | 2.45 | | 11 |
| manganese chloride | E | 26 | 25 | S | 48 h | LC50 | 16.0 | | 11 |
| mercuric chloride | E | 26 | 25 | S | 48 h | $LC_{50}$ | 0.006 | | 11 |
| | L | 25 | 24 | S | 48 h | $LC_{50}$ | 0.012 | | 14 |
| | A | 25-35 | | F | 74 d | M | 0.001 | <10 | 47 |
| nickel chloride | E | 26 | 25 | S | 48 h | $LC_{50}$ | 1.18 | | 11 |
| | L | 25 | 24 | S | 48 h | $LC_{50}$ | 1.21 | | 14 |
| silver nitrate | E | 26 | 25 | S | 48 h | $LC_{50}$ | 0.006 | | 11 |
| | L | 25 | 24 | S | 48 h | $LC_{50}$ | 0.028 | | 14 |
| sodium arsenate | E | 26 | 25 | S | 48 h | $LC_{50}$ | 7.50 | | 11 |
| zinc chloride | E | 26 | 25 | S | 48 h | $LC_{50}$ | 0.31 | | 11 |
| | E | 25 | 26 | S | 48 h | M | 0.200 | 12.2 | 60 |
| PESTICIDES | | | | | | | | | |
| atrazine | L | 20 | 16 | S | 48 h | $LC_{50}$ | >30 | | 98 |
| abate | A | 21 | 20-30 | S | 99 d | M | 10 | 0 | 96 |
| chlordane | J | | | F | 24 h | G | 0.01 | 35-100[a] | 10 |
| cypermethrin | J | | | | 96 h | $EC_{50}$ | 0.370 | | 41 |
| dibrom | A | 21 | 20-30 | S | 99 d | M | 0 | 96 | |
| dieldrin | E | 24 | 30 | S | 48 h | $LC_{50}$ | 0.64 | | 24 |
| | J | 17 | 31 | F | | G | ? | 50 | 76 |
| endrin | E | 24 | 30 | S | 48 h | $LC_{50}$ | 0.79 | | 24 |
| | A | 23 | 16 | S | 109 h | M | 0.05 | 50 | 64 |
| 2,4-D | E | 24 | 30 | S | 48 h | LC50 | 8.00 | | 24 |
| heptachlor | J | | | F | 24 h | G | 0.01 | 35-100 | 10 |
| kepone | L | | | | 96 h | $LC_{50}$ | 0.066 | | 34 |
| toxaphene | A | 28 | 23 | F | 96 h | $EC_{50}$ | 0.016 | | 83 |
| TBT (tributyl tin) | A | 25-28 | 35 | F | 30 d | M | 0.0025 | 50 | 38 |
| PCBs | | | | | | | | | |
| arochlor 1016 | J | 30 | 29 | | | $LC_{50}$ | 0.010 | | 34 |
| CHLORINE (CPOs) | | | | | | | | | |
| sodium hypochlorite | J | 21-33 | 22-35 | F | 12 wk | M | 0.25 | 66 | 86 |
| PETROLEUM | | | | | | | | | |
| Nigerian crude oil | A | 25 (avg.) | 21 (avg.) | F | 14 wk | M | 0.50 | 45 | 63 |
| | L | 22.5 | 21 | S | 48h | $LC_{50}$ | 1.7 | | 90 |
| No. 2 fuel oil | A | 13-25 | 21 (avg.) | F | 8 wk | M | 0.50 | 85 | 63 |

Table 3. Representative residues (body burdens) of selected contaminants in eastern oysters. All residues are on a wet tissue weight basis. ND = no data.

| Substance | Mean Residue | Range | Remarks |
|---|---|---|---|
| TRACE ELEMENTS (mg $kg^{-1}$) = μg/g | | | |
| *means of 6 sites in Chesapeake Bay*[87] | | | |
| aluminum | 31.4 | 16.1-53.1 | |
| arsenic | 10.6 | 6.5-16.7 | |
| cadmium | 4.62 | 1.8-10.4 | |
| chromium | 0.3 | 0.1-0.9 | |
| copper | 137 | 31.8-340 | |
| iron | 194 | 170-224 | |
| lead | 0.28 | 0.17-0.34 | |
| mercury | 5.5 | 0.01-15.1 | |
| manganese | 8.3 | 6.8-9.1 | 3 sites |
| nickel | 4.0 | 1.6-6.6 | |
| selenium | 2.9 | 1.8-3.8 | |
| silver | 2.9 | 0.4-6.9 | |
| tin | 0.11 | 0.02-0.26 | |
| zinc | 3513 | 1120-5480 | |
| PESTICIDES[46] (μg $kg^{-1}$) | | | |
| DDT (total) | 60 | <30-710 | median, 2.5 y, 6 states |
| | 15 | <10-30 | mean, 2 sites, Canada |
| | 51 | ND-150 | representative estimate, 8 sites, Texas |
| aldrin | 3 | ND-30 | mean, 10 samples |
| | <10 | <10-30 | median, 2.5 y, 6 states |
| BHC-lindane | 4 | ND-10 | representative estimate, 10 samples |
| | 10 | <10-500 | median, 2.5 y, 6 states |
| camphechlor | 80 | <10-1000 | median, 2.5 y, 6 states |
| chlordane | <10 | <10-10 | median, 2.5 y, 6 states |
| dieldrin | 4 | ND-10 | representative estimate, 10 samples |
| | 10 | <10-30 | median, 2.5 y, 6 states |
| endrin | 5 | ND-20 | median, 1 y, 2 sites |
| heptachlor | 1 | ND-<10 | representative estimate, 10 samples |
| | <10 | ND | median, 2.5 y, 6 states |
| heptachlor epoxide | <10 | ND | median, 2.5 y, 6 states |
| methoxychlor | <10 | ND | median, 2.5 y, 6 states |
| PAH (mg $kg^{-1}$) | | | |
| Elizabeth River, Va.[5] | | | |
| total PAH | 60 (max.) | 15-50 | 17 km transect |
| PCB (mg $kg^{-1}$) | | | |
| Maryland shellfish survey, 1979[28] | | | |
| PCB 1254 | 0.02 (mean) | 0-0.07 | |

Table 4. Acute toxicity ($EC_{50}$) of pesticides and other chemicals to the eastern oyster.[66] Flow: S = static; F = flow-through. Life stage: E = embryos; L = larvae; J = juvenile; A = adult. Measured concentrations are indicated by *. All other concentrations are nominal.

| Compound | Use | Life stage | Temperature °C | Salinity ppt | Duration h | Flow | Concentration $\mu gL^{-1}$ | 95% Confidence Interval |
|---|---|---|---|---|---|---|---|---|
| acephate | insecticide | E | 25 | 20 | 48 | S | 150000 | 800-300000 |
| acroleia | herbicide | J | 21 | 30 | 96 | F | 55 | |
| acrylamide | polymer | L | 20 | 20 | 48 | S | >100000 | |
| aldicarb | insecticide | E | 25 | 20 | 48 | S | 8800 | 1400-56000 |
| aldrin | insecticide | J | 30 | 27 | 96 | F | 15 | |
| aminocarb | insecticide | J | 27 | 27 | 96 | F | >1000 | |
| amobam | fungicide | J | 23 | 26 | 96 | F | >1000 | |
| anilazine | fungicide | J | 10 | 24 | 96 | F | 40 | |
| antimycin A | piscicide | J | 26 | 28 | 96 | F | 62 | |
| arochlor 1016 | industrial (PCB) | A | 28 | 28 | 96 | F | 10 | |
| arsenic trioxide | rodenticide | J | 15 | 22 | 96 | F | >1000 | |
| aspon | insecticide | J | 23 | 28 | 48 | F | 32 | |
| atrazine | herbicide | J | 28 | 28 | 96 | F | >1000 | |
| azinphos-methyl | insecticide | J | 29 | 28 | 96 | F | >1000 | |
| bensulide | herbicide | A | 24 | 15 | 96 | F | 450 | |
| benzene hexachloride | insecticide | J | 27 | 27 | 96 | F | 190 | |
| bromacil | herbicide | J | 23 | 25 | 96 | F | >1000 | |
| bromopropylate | acaracide | J | 14 | 30 | 96 | F | 150 | |
| butylbenzyl phthalate | industrial | L | 20 | 20 | 48 | S | 780 | 560-1000 |
| cacodylic acid | herbicide | J | 19 | 28 | 90 | F | >1000 | |
| calcium arsenate | insecticide, herbicide | J | 13 | 31 | 96 | F | >1000 | |
| captafol | fungicide | J | 20 | 26 | 96 | F | 34 | |
| carbaryl | insecticide | J | 29 | 27 | 96 | F | >2000 | |
| carbofuran | insecticide, nematicide, miticide | J | 30 | 29 | 96 | F | >1000 | |
| carbophenothion | insecticide, acaracide | E | 20 | 20 | 48 | S | 99 | 96-102 |
| chlordane | insecticide | J | 29 | 27 | 96 | F | 10 | |
| chlordecone | insecticide | A | 20 | 21 | 48 | S | 66 | 60-74 |
| chlorobenzilate | acaricide | J | 28 | 25 | 96 | F | 180 | |
| chloropropylate | acaricide | J | 19 | 26 | 96 | F | 280 | |
| chlorothalonil | fungicide | J | 29 | 27 | 96 | F | 26 | |
| chloropyrifos | insecticide | E | 25 | 20 | 48 | S | 2000 | 1500-2800 |
| clonitralide | molluscicide | J | 11 | 22 | 96 | F | >1000 | |
| coumaphos | insecticide | J | 9 | 21 | 96 | F | 290 | |
| | | J | 30 | 23 | 96 | F | 880 | |
| creosote | wood preservative | A | 21 | 21 | 96 | F | 710 | 410-1000 |
| crotoxyphos | insecticide | J | 10 | 28 | 96 | F | 1000 | |
| | | J | 28 | 28 | 96 | F | >1000 | |
| 2,4-D butoxy-ethanol ester | herbicide | J | 18 | 29 | 96 | F | 2600 | |
| | | A | 18 | 29 | 96 | F | 3800 | |
| 2,4-D isooctyl ester/EPTC | herbicide | A | 29 | 25 | 96 | F | 1000 | |
| 2,4-D propylene glycol ether ester | herbicide | A | 28 | 25 | 96 | F | 55 | |
| dalapon sodium salt | herbicide | J | 31 | 28 | 96 | F | >1000 | |
| DCPA | herbicide | J | 27 | 30 | 96 | F | 620 | |
| DDD | insecticide | J | 20 | 30 | 96 | F | 25 | |
| DDE | DDT residue | J | 12 | 25 | 96 | F | 14 | |
| DDT | insecticide | J | 30 | 23 | 96 | F | 9 | |

| Compound | Use | Life stage | Temperature °C | Salinity ppt | Duration h | Flow | Concentration $\mu gL^{-1}$ | 95% Confidence Interval |
|---|---|---|---|---|---|---|---|---|
| DEF | herbicide | E | 25 | 20 | 48 | S | 700 | |
| | | J | 10 | 27 | 96 | F | 100 | |
| | | J | 27 | 27 | 96 | F | 200 | |
| demeton | insecticide, acaricide | J | 24 | 13 | 96 | F | >2000 | |
| diamidfos | nematicide | J | 19 | 22 | 96 | F | >1000 | |
| diazinon | insecticide, nematicide | J | 25 | 28 | 96 | F | >1000 | |
| dicamba | herbicide | J | 28 | 28 | 86 | F | >1000 | |
| dichlobenil | herbicide | J | 24 | 24 | 96 | F | 2500 | |
| dicholfluanid | fungicide | J | 29 | 25 | 96 | F | 35 | |
| dichlorvos | insecticide | J | 30 | 25 | 96 | F | >1000 | |
| dicofol | acaricide | J | 24 | 25 | 96 | F | 21 | |
| dicrotophos | insecticide | J | 29 | 28 | 96 | F | >1000 | |
| dieldrin | insecticide | J | 22 | 25 | 96 | F | 15 | |
| | | A | 17 | 31 | 96 | f | 31* | 6-62 |
| diquat | herbicide | J | 20 | 29 | 96 | F | 720 | |
| dithianon | fungicide | J | 28 | 32 | 96 | F | 9.0 | |
| diuron | herbicide | J | 22 | 25 | 96 | F | 1800 | |
| DMSA | herbicide | J | 15 | 29 | 96 | F | >1000 | |
| endosulfan | insecticide | L | 20 | 20 | 48 | S | 460 | |
| endothall aquathol plus | herbicide | J | 26 | 28 | 96 | F | >1000 | |
| endrin | insecticide | J | 24 | 22 | 96 | F | 33 | |
| | | J | 12 | 21 | 96 | F | 400 | |
| | | A | 22 | 29 | 96 | F | 14* | 4.0-50 |
| EPN | acaricide, insecticide | E | 25 | 20 | 48 | S | 2200 | |
| | | J | 21 | 29 | 96 | F | 130 | |
| EPTC | herbicide | J | 29 | 29 | 96 | F | >5000 | |
| ethion | insecticide, acaricide | J | 10 | 29 | 96 | F | 46 | |
| | | J | 30 | 23 | 96 | F | 40 | |
| ethoprop | nematicide | E | 25 | 20 | 48 | S | 16000 | 7000-38000 |
| ethylan | insecticide | J | 16 | 28 | 48 | F | 120 | |
| fenac sodium salt | herbicide | J | 13 | 23 | 96 | F | >1000 | |
| | | J | 29 | 29 | 96 | F | >1000 | |
| fenamiphos | nematicide | J | 11 | 29 | 96 | F | >1000 | |
| fenitrothion | insecticide | J | 27 | 29 | 96 | F | 450 | |
| fenthion | insecticide | J | 22 | 16 | 96 | F | 360 | |
| | | J | 15 | 23 | 96 | F | 340 | |
| fenuron | herbicide | J | 22 | 26 | 96 | F | >2000 | |
| fenvalerate | insecticide | E | 20 | 20 | 48 | S | >1000 | |
| ferbam | fungicide | J | 25 | 27 | 96 | F | 52 | |
| fonofos | insecticide | J | 25 | 20 | 96 | F | 330 | |
| heptachlor technical 74% | insecticide | J | 12 | 21 | 96 | F | 21 | |
| | | J | 29 | 23 | 96 | F | 17 | |
| heptachlor technical 89% | insecticide | A | 31 | 36 | 96 | F | 1.5* | |
| hexachloro-benzene | fungicide, industrial | L | 20 | 20 | 48 | S | >1000 | |
| isobenzan | insecticide | J | 18 | 33 | 96 | F | 32 | |
| landrin | insecticide | J | 26 | 30 | 96 | F | >1000 | |
| lethane 384 | insecticide | J | 26 | 30 | 96 | F | 760 | |
| lindane | insecticide | J | 30 | 25 | 96 | F | 240 | |
| malathion | insecticide | J | 30 | 24 | 96 | F | >1000 | |
| | | J | 16 | 14 | 96 | F | >1000 | |

| Compound | Use | Life stage | Temperature °C | Salinity ppt | Duration h | Flow | Concentration $\mu gL^{-1}$ | 95% Confidence Interval |
|---|---|---|---|---|---|---|---|---|
| maneb | fungicide | J | 13 | 16 | 96 | F | >1000 | |
| metam-sodium | fungicide, nematicide | J | 15 | 30 | 96 | F | >1000 | |
| methidathion | insecticide, acaricide | J | 13 | 22 | 96 | F | >1000 | |
| | | J | 29 | 25 | 96 | F | >1000 | |
| methiocarb | insecticide | J | 23 | 28 | 96 | F | >1000 | |
| methoxychlor | insecticide | J | 19 | 21 | 96 | F | 90 | |
| methyl parathion | insecticide | E | 25 | 20 | 48 | S | 12000 | 1000-160000 |
| | | J | 24 | 29 | 96 | F | >800 | |
| methyl trithion | insecticide, acaricide | J | 30 | 25 | 96 | F | 140 | |
| mevinphos | insecticide, acaricide | J | 22 | 30 | 96 | F | >1000 | |
| mexacarbate | insecticide, acaricide | J | 24 | 26 | 96 | F | >1000 | |
| mirex | insecticide | J | 25 | 17 | 96 | F | >2000 | |
| molinate | herbicide | J | 24 | 28 | 86 | F | >1000 | |
| monuron | herbicide | J | 22 | 25 | 96 | F | 2000 | |
| naled | insecticide, acaricide | J | 30 | 27 | 96 | F | 590 | |
| neburon | herbicide | J | 21 | 28 | 96 | F | 280 | |
| niacide-Z | fungicide | J | 21 | 28 | 96 | F | 280 | |
| nitrapyrin | nitrification inhibitor | J | 10 | 29 | 96 | F | 280 | |
| paraquat L | herbicide | J | 20 | 26 | 96 | F | >1000 | |
| parathion | insecticide | J | 24 | 31 | 96 | F | >1000 | |
| pentachloro-phenol | wood preservative, defoliant, molluscicide | L | 20 | 20 | 48 | S | >180 | |
| pentachloro-phenol sodium salt | | E | 25 | 17 | 96 | S | 40 | 36-44 |
| | | A | 8 | 20 | 96 | F | 76* | 37-120 |
| permethrin | insecticide | E | 25 | 20 | 48 | S | >1000 | |
| phenol | disinfectant, industrial | J | 20 | 30 | 96 | F | >2000 | |
| phorate | insecticide | E | 25 | 20 | 48 | S | 900 | |
| phosmet | insecticide | J | 30 | 27 | 96 | F | >1000 | |
| phosphamidon | insecticide | J | 25 | 25 | 96 | F | >1000 | |
| phoxim | insecticide | J | 30 | 29 | 96 | F | 320 | |
| prometrin | herbicide | J | 27 | 31 | 96 | F | >1000 | |
| propoxur | insecticide | J | 25 | 27 | 96 | F | >1000 | |
| Ronnel | insecticide | J | 24 | 24 | 96 | F | 270 | |
| rotenone | insecticide, piscicide | J | 30 | 29 | 96 | F | 220 | |
| silver nitrate | industrial | L | 20 | 20 | 48 | S | 3.3 | 2.4-5.4 |
| sodium lauryl sulfate | detergent | E | 20 | 25 | 48 | S | 1700 | 1600-2000 |
| sulphenone | acaricide | J | 18 | 20 | 96 | F | 1200 | |
| 2,4,5-T | herbicide | J | 16 | 20 | 96 | F | >2000 | |
| 2,4,5-T propylene glycol butyl ether ester | herbicide | A | 13 | 25 | 96 | F | 140 | |
| TCA sodium salt | herbicide | J | 13 | 23 | 96 | F | >1000 | |
| temephos | insecticide | J | 24 | 27 | 96 | F | 220 | |
| temephos EC | insecticide | J | 14 | 26 | 96 | F | 320 | |
| | | J | 26 | 29 | 96 | F | 170 | |
| terbutryn | herbicide | J | 14 | 29 | 96 | F | >1000 | |
| terpene poly-chlorinates | insecticide | J | 25 | 29 | 96 | F | 35 | |
| tetravinchlorphos | insecticide | J | 17 | 24 | 96 | F | >1000 | |
| tetradifon | acaricide | J | 27 | 27 | 96 | F | 310 | |
| tetrasul | acaricide | J | 22 | 25 | 96 | F | 94 | |
| thanite | insecticide | J | 11 | 25 | 96 | F | 25 | |

| Compound | Use | Life stage | Temperature °C | Salinity ppt | Duration h | Flow | Concentration $\mu gL^{-1}$ | 95% Confidence Interval |
|---|---|---|---|---|---|---|---|---|
| toxaphene | insecticide | J | 31 | 24 | 96 | F | 34 | |
| | | A | 28 | 23 | 96 | F | 16* | |
| trichlorofon | insecticide | J | 30 | 22 | 96 | F | >1000 | |
| trichloronate | insecticide | J | 28 | 28 | 96 | F | 46 | |
| triphenyltin | fungicide | J | 29 | 28 | 96 | F | 1.5* | |
| hydroxide | | J | 16 | 28 | 96 | F | 2.4 | |
| vernolate | herbicide | J | 29 | 28 | 96 | F | >1000 | |
| ziram | fungicide | J | 15 | 22 | 96 | F | 1000 | |
| zytron | insecticide | J | 27 | 24 | 96 | F | 330 | |