Osmoregulation

Definitions:

Osmoregulation- The process by which fish maintain the balance of salts and water in their bodies as they move between freshwater and saltwater environments.

Chloride Cells- Specialized cells in fish gills that help regulate salt levels by actively transporting ions in or out of the body during osmoregulation.

Salt Wedge- Is a bottom layer of dense saltwater that intrudes landward beneath freshwater in an estuary, with mixing concentrated at the interface and the upstream limit defined by the extent of salt intrusion.

Stress- a physiological response to a challenge or disturbance that disrupts the fish's internal balance, or homeostasis.

Description of Process:

Osmoregulation is the physiological process fish use to maintain internal salt and water balance as they move between freshwater and saltwater. Anadromous fish must cope with rapid and frequent changes in salinity, especially in estuarine transition zones. This process relies on chloride cells that are grown or reabsorbed depending on external salinity levels.

Species differ in their osmoregulatory capabilities. Some are better at tolerating rapid changes or wider salinity ranges, while others may become stressed more quickly. Younger fish or those with less energy may take longer to acclimate, increasing risk. Energy is required to grow new chloride cells, maintain existing ones, or remove unneeded cells. When salinity changes rapidly, fish must expend more energy to stay in balance. This process is further influenced by acclimation rate, internal energy reserves, and environmental variability.

Salinity stress can lead to delayed migration, reduced foraging efficiency, or increased vulnerability to predation as a result of increased energy demand. In modeling, osmoregulation should account for individual acclimation, energy cost, and spatiotemporal variability in estuarine salinity. Outputs like stress hotspots or osmoregulation-related energy loss can help guide restoration priorities or evaluate the model.

Little Facts:

- Stress increases respiration and the frequency of water coming in contact with the gills of a fish.
- Water volume across gills is directly correlated to salt balance (more salt across gills leads to increased uptake of salt, or vice versa).
- Chloride cells come in two forms freshwater and saltwater chloride cells depending on a fish's need to excrete extra salt or extra water.
  - You could expect fish use freshwater chloride cells when they move into an estuary, and use saltwater chloride cells when exiting the estuary.

Discussion Objectives:

- Is function accurate and realistic to your knowledge?
- Do all species in the model perform this function?
- What accounts for species specific differences (i.e., acclimation, size, age)?
- Should different types of stress impact risk differently?
  - Salinity stress vs Thermal stress
- Where in the system would you expect the most energy expended for Osmoregulation and why?
- What type of information would we like to know from this function or process?
  - Where fish experience salinity stress?
  - Does this stress impede migration success or other functions & behaviors?
  - Does salinity stress increase mercury exposure or bioaccumulation risk?

Thermoregulation

Definitions:

Thermoregulation- The process by which fish maintain a stable internal temperature or manage physiological functions in response to changes in external water temperature.

Thermal Tolerance- The range of temperatures a fish can survive and function within without experiencing stress or mortality.

Optimal Temperature- The temperature range where a fish performs best in terms of growth, movement, metabolism, and survival.

Ectotherm- An organism that relies on external environmental temperatures to regulate its body temperature. Fish are ectotherms, meaning their internal temperature changes with the surrounding water.

Stress- a physiological response to a challenge or disturbance that disrupts the fish's internal balance, or homeostasis.

Description of Process:

Thermoregulation refers to how fish respond to changes in environmental temperature. Because fish are ectotherms (cold-blooded), their internal temperature matches that of the water. However, they can regulate their behavior to avoid thermal stress by moving out of areas that are too hot or too cold.

Anadromous fish may experience sharp temperature changes during migration, especially in shallow estuarine and riverine habitats. Each species has a thermal tolerance range and an optimal temperature window for activities like spawning, feeding, and migration. When temperatures fall outside this range, fish may become stressed, delay movement, or experience reduced survival.

Thermal stress raises metabolic rates, meaning fish use more energy for basic survival. Prolonged exposure outside optimal temperature can also weaken immune systems, reduce reproductive success, or increase mortality. Younger fish or those with low energy reserves are especially vulnerable.

In modeling, thermoregulation should reflect species-specific thresholds, size- and age-based sensitivity, and the energetic costs of moving to or remaining in thermally suitable areas. It can also interact with other functions, such as foraging or spawning, when temperature becomes a limiting factor.

Little Facts:

- Water temperature affects metabolic rate: warmer water speeds it up, colder water slows it down.
- Fish often shift depth or location to maintain suitable temperatures.
- Thermal stress increases oxygen demand, but warmer water holds less oxygen.
- Prolonged thermal stress can reduce spawning success or lead to mortality.
- Some fish can acclimate gradually, while others are more sensitive to short-term temperature spikes.

Discussion Objectives:

- Is this function accurate and realistic to your knowledge?
- Do all species in the model respond the same way to temperature changes?
- What accounts for species-specific differences (i.e., life stage, physiology, habitat use)?
- Where in the system would you expect the greatest thermal stress, and for which species?
- What kind of outputs should the model include from this function?
    - What physical environmental conditions are more likely to induce thermal stress?
    - Does temperature stress delay migration or alter behavior?
    - Whether higher temperatures increase contaminant uptake or decrease migration success?

Bioaccumulation

Definitions:

Bioaccumulation- The gradual buildup of contaminants, such as mercury, in a fish's body over time through water, sediment, or food.

Biomagnification- The increase in contaminant concentration as it moves up the food chain, causing predators to accumulate higher levels than their prey.

Contaminant Uptake- The process by which fish absorb pollutants through gills, skin, or diet.

Duration of Exposure- The length of time a fish spends in contact with contaminated water, sediment, or prey, which strongly influences the amount of contaminant accumulated.

Stress- a physiological response to a challenge or disturbance that disrupts the fish's internal balance, or homeostasis.

Description of Process:

Bioaccumulation occurs when a fish takes in more contaminants than it eliminates. In estuarine environments, this often involves mercury or methylmercury that binds to suspended particles or enters the food web. As fish move through contaminated areas or consume contaminated prey, these toxic substances build up in their tissues.

Anadromous fish are at high risk during migration and staging, especially in areas where sediment traps contaminants or where foraging and predation occurs in mercury-impacted habitats. Younger fish or smaller-bodied individuals can accumulate contaminants more rapidly due to faster growth rates or higher food intake per body mass.

The rate of bioaccumulation is influenced by environmental factors (e.g., temperature, salinity, sediment loads), physiological traits (e.g., metabolism, lipid content), and behavior (e.g., habitat use, foraging depth, migration timing). Duration of exposure is a key determinant of how much contaminant is absorbed where longer time in contaminated areas increases toxicity risk.

In modeling, bioaccumulation should consider individual-level exposure over time, including the spatial and temporal overlap with contaminated sediments or prey. Metabolic consumption, trophic level, and habitat use patterns can help estimate risk. Model outputs may inform toxicity risk to fish and identify remediation for target species.

Little Facts:

- Methylmercury is the most toxic and bioavailable form of mercury, especially harmful to fish and their predators.
- Both mercury and methylmercury bioaccumulate, but methylmercury is more dangerous because it is biologically active, binding to proteins and accumulating in tissues, especially the brain and muscles.
- Contaminants can accumulate faster in colder water, where metabolic excretion is slower.
- Bottom-feeding and filter-feeding species are often more exposed to sediment-bound contaminants.
- Fish in high-energy-demand life stages (e.g., spawning) may mobilize contaminants stored in fat.
- Exposure risk depends on both contaminant concentration and duration of exposure to affected areas.

Discussion Objectives:

- Is this function accurate and realistic to your knowledge?
- Do all species in the model accumulate contaminants at the same rate or through the same pathways?
- What accounts for species-specific differences (e.g., trophic level, diet, movement, age, behaviors, stress)?
- Where in the estuary would you expect the highest bioaccumulation risk for each model species?
- What kind of model outputs should reflect this process?
    - Are there areas or times when fish are most vulnerable to contaminant exposure?
    - Can bioaccumulation affect spawning, migration success, or behavior response?
    - How might contaminant exposure interact with other stressors like temperature or salinity?

Migration

Definitions:

Migration- The seasonal movement of fish between habitats to complete specific life stages, such as spawning, feeding, or overwintering.

Landward Migration- Movement from marine or estuarine waters into freshwater, often for spawning or juvenile development.

Seaward Migration- Movement from freshwater or estuarine habitats out toward marine environments, often for growth or oceanic life stages.

Flood Tide- The incoming tide that raises water levels and often aids landward movement of fish.

Ebb Tide- The outgoing tide that lowers water levels and can assist with seaward movement or dispersal.

Migration Timing- The seasonal or environmentally triggered window during which fish initiate and complete migration.

Description of Process:

Migration is a critical behavioral function for anadromous fish that move between freshwater and saltwater habitats to complete their life cycles. These annual migrations often follow environmental cues such as water temperature, salinity, flow direction, day length, and tidal phase.

In estuaries, fish use both landward and seaward migration strategies depending on their life stage. Adults may migrate landward on flood tides to spawn, while post-spawning adults, or adults who have completed their migration objective, may ride ebb tides seaward to reach sea or offshore habitats. These movements are often synchronized with selective tidal stream transport, behavioral staging, or energy conservation strategies (next round of break-outs).

Successful migration requires balancing internal conditions (e.g., energy, stress, readiness) with external forces (e.g., current velocity, tidal timing, salinity shifts). Barriers to movement, unfavorable hydrodynamics, or poor timing can result in delayed arrival, missed spawning, higher predation risk, or increased contaminant exposure. Juveniles are especially sensitive to energy costs and environmental mismatch.

In modeling, migration should capture directionality (landward vs. seaward), timing (seasonal and tidal), energetic cost, and behavioral decision-making. Individual migration paths and durations can influence exposure risk, spawning success, and survival, making this a key integrative process in estuarine models.

Little Facts:

- Anadromous fish often migrate during high-discharge spring events, using flow to reach spawning habitat faster.
- Some species only move during specific tidal phases (e.g., flood tide for landward migration).
- Migration success depends on both physical conditions and internal cues like maturity and energy levels.
- Delayed migration can reduce reproductive success or lead to spawning in suboptimal habitats.
- Energetic cost of migration increases with distance, poor hydrodynamic conditions, or environmental stressors (e.g., salinity, contaminants).
- Younger and small-bodied fish may be more vulnerable during migration due to lower swimming capacity or navigation ability.

Discussion Objectives:

- Is this function accurate and realistic to your knowledge?
- What are the migration objectives of each species in the model (e.g., spawning, foraging, predation, sheltering).?
- Do all species in the model migrate using similar strategies, or are there key differences?
- What accounts for species-specific migration differences (e.g., timing, migration cues, destination, behavior, energy needs)?
- Where in the estuary would you expect the most challenging or high-risk migration zones?
- What kind of model outputs should reflect this process?
    - Are fish successfully reaching intended habitats (e.g., spawning grounds, nursery zones)?
    - Do tides and flow direction facilitate or hinder movement at different stages?
    - Are there hotspots of delayed migration or increased exposure due to timing mismatches or habitat fragmentation?

Predation

Definitions:

Predation- The ecological interaction where a predator hunts, captures, and consumes a prey organism for energy and survival.

Predator- An organism that hunts and feeds on other organisms.

Prey- An organism that is consumed by a predator and often exhibits behavioral responses to avoid being eaten.

Fleeing Behavior- A reactive movement or evasion tactic by prey in response to predator presence or cues.

Pursuit Behavior- A targeted movement by predators toward potential prey using visual, chemical, or flow cues.

Trophic Transfer- The movement of energy and contaminants through food webs when one organism consumes another.

Description of Process:

Predation is a key driver of fish movement, energy use, and survival in estuarine systems. Both predators and prey use behavioral strategies to maximize fitness. Prey seek to avoid detection or escape encounters, while predators seek to optimize foraging success by locating and capturing vulnerable individuals.

Predators in estuarine systems (e.g., striped bass, larger fish, or birds) may follow prey migrations, patrol high-quality habitats, or use tidal flow to aid pursuit. Prey species respond through fleeing behaviors, habitat shifts, and schooling. These interactions create spatial and temporal “predation pressure” zones that shape fish behavior, habitat use, and exposure risk.

Importantly, predation can increase bioaccumulation risk if predators consume prey that have accumulated contaminants like methylmercury. This process, known as trophic transfer, means predators often exhibit the highest contaminant concentrations in the food web.

In modeling, predation should reflect species roles (predator vs. prey), size-based interactions, behavior rules (fleeing vs. pursuit), and spatial overlap. It may also factor into mortality, bioaccumulation, or altered movement behaviors under high risk.

Little Facts:

- Prey often change depth, speed, or habitat use in response to predators, increasing energy use.
- Schooling behavior can reduce individual predation risk but may also limit foraging opportunities.
- Predators often target slow, injured, or thermally stressed individuals.
- Contaminants like methylmercury bio-magnify through predation.
- Predators accumulate higher levels than prey.
- Estuarine predators may use flow features like eddies or slack tides to trap prey.
- Predation pressure can delay migration, shift habitat use, or reduce reproductive success.

Discussion Objectives:

- Is this function accurate and realistic to your knowledge?
- What species in the model serve as predators and which as prey?
- How does prey detect and respond to predator presence (e.g., fleeing, schooling, shifting depth)?
- What factors influence predator success (e.g., visibility, current speed, prey density)?
- Where and when in the estuary is predation risk likely highest?
- What kind of model outputs should reflect this process?
    - Are there zones where predation strongly influences movement or mortality?
    - Can predation affect contaminant transfer and exposure patterns?
    - Do certain conditions amplify predation pressure (e.g., low turbidity, slow current, low energy reserves)?

Foraging

Definitions:

Foraging- The behavior of searching for, selecting, and consuming food to meet energy needs.

Optimal Foraging Theory- A concept in ecology that predicts animals will maximize energy gained per unit of effort, balancing food quality, risk, and search or handling time.

Benthic- Associated with the bottom of a body of water; benthic foragers feed along or within sediments.

Pelagic- Associated with the open water column; pelagic foragers feed in midwater or near the surface.

Filter Feeding- A feeding strategy where organisms strain suspended particles or plankton from the water.

Bottom Feeding- Feeding on or near the substrate, often on invertebrates, detritus, or organic-rich sediment.

Intraspecific Competition- Competition for food or space among individuals of the same species.

Interspecific Competition- Competition between individuals of different species for similar food resources or habitat.

Description of Process:

Foraging is a vital behavior that allows fish to acquire energy needed for growth, movement, reproduction, and recovery. Fish use a variety of feeding strategies, such as; benthic, pelagic, filter, or bottom feeding, depending on their species, life stage, and local habitat conditions.

Optimal Foraging Theory suggests that fish will select feeding strategies and locations that maximize their net energy gain, considering not just food abundance but also the effort, risk, and time required to locate, capture, and consume prey. For example, a fish may choose a lower-quality but safer or easier-to-access food source if predation risk is high.

Foraging behavior is influenced by turbidity, current speed, prey visibility, and salinity. Fish must also avoid contaminated food sources. Bottom feeders may ingest mercuryladen sediment, and filter feeders may take in contaminated particles from the water column.

Intraspecific and interspecific competition emerge when multiple individuals or species rely on overlapping food sources. This can drive habitat partitioning, shifts in foraging depth, or even changes in diet, especially during migration or high-density periods.

In modeling, foraging should reflect species-specific strategies, energy optimization, spatial variability in food resources, and trade-offs with risk or energy cost. This behavior directly influences bioaccumulation risk, growth, and survival.

Little Facts:

- Optimal foraging does not always mean "eating the most", it balances risk, energy cost, and food value.
- Filter feeders are more likely to take in suspended contaminants along with plankton.
- Benthic foragers face higher risk of mercury exposure from contaminated bottom sediment.
- Schooling fish may reduce predation risk while foraging, but face more intraspecific competition.
- Foraging activity can increase during specific tides or times of day depending on prey availability.
- Fish may switch strategies as they grow, change habitats, or encounter competition.
- Poor foraging success can lead to energy deficits that reduce growth, delay migration, or increase mortality.

Discussion Objectives:

- Is this function accurate and realistic to your knowledge?
- What foraging strategies do different species in the model use, and how can we account for the difference in contamination exposure associated with these feeding strategies?
- What are the consequences of intraspecific or interspecific competition when it comes to foraging?
- What kind of model outputs should reflect foraging processes?
    - Are there zones or periods of high foraging activity or resource depletion?
    - Are fish able to meet their energetic needs, or falling into deficit?
    - Do foraging strategies increase exposure to mercury or other stressors in certain areas or conditions?

Spawning

Definitions:

Spawning- The process by which fish release eggs and sperm to reproduce, often in specific habitats under particular environmental conditions.

Pairwise Spawning- A reproductive strategy where one male and one female coordinate to release sperm and eggs simultaneously.

Broadcast Spawning- A reproductive strategy where multiple individuals release eggs and sperm freely into the water column, often with little direct coordination.

Homing- The behavior of returning to a specific spawning location, often the same site where the fish was born.

Semelparous- A reproductive strategy in which a fish spawns once in its lifetime and then dies shortly after.

Iteroparous- A reproductive strategy in which a fish can spawn multiple times over its lifespan, surviving and potentially returning to spawn in future.

Stress- a physiological response to a challenge or disturbance that disrupts the fish's internal balance, or homeostasis.

Description of Process:

Spawning is a key biological function that influences seasonal migration, habitat use, and species persistence. It often follows specific timing and location patterns, with different species using different strategies. Some reproduce through pairwise spawning, while others use broadcast spawning with group-based release of gametes.

Many anadromous fish are homing species, meaning they return to the same area where they were born to spawn. This can create localized hotspots of reproductive activity, but also increases sensitivity to habitat quality and access. Spawning success depends on environmental conditions such as temperature, salinity, flow velocity, depth, and in some cases substrate. When substrate data are unavailable, depth and velocity can serve as proxies for suitable habitat.

Spawning occurs only in mature individuals. Juveniles and early life stages do not participate in reproduction. The decision to spawn depends on species-specific maturity, energy reserves, environmental cues, and timing. After spawning, some species die (semelparous), while others survive and may spawn again in future years (iteroparous).

In modeling, spawning behavior should include readiness, location selection, species-specific strategies, and outcomes such as mortality, energy depletion, or recovery. Where and when spawning occurs can shape recruitment, contaminant exposure, and long-term population dynamics.

Little Facts:

- Spawning may be triggered by a combination of temperature, salinity, photoperiod, and discharge.
- Pairwise spawners may require close proximity and behavioral coordination between sexes.
- Broadcast spawners often rely on synchronous group behavior and favorable flow conditions.
- Homing increases site fidelity but can also make populations vulnerable to habitat loss.
- Post-spawning mortality is common in some species (e.g., semelparous fish like alewives), while others may survive and spawn again (iteroparous).
- Spawning in contaminated areas can expose eggs and larvae to pollutants, affecting survival.
- Overlapping spawning areas may lead to interspecific interference or increased competition for habitat.

Discussion Objectives:

- Is this function accurate and realistic to your knowledge?
- Which species in the model are spawning (iteroparous or semelparous?), and which are not?
- What strategy does each species use to spawn (pairwise or broadcast)?
- Where in the estuary or river system do you expect spawning to occur for each species, and what environmental conditions drive that?
- How should the model represent spawning readiness or timing?
- What kind of model outputs would reflect spawning accurately?
    - Does timing or location influence spawning success or overwintering?
    - Are some species more likely to experience spawning failure due to energy limitations, poor conditions, or contaminant exposure?

Resting

Definitions:

Resting- A behavioral state during which fish reduce movement and metabolic activity to conserve or recover energy.

Staging- A temporary holding behavior in preparation for a future movement event, such as spawning or migration.

Stress- a physiological response to a challenge or disturbance that disrupts the fish's internal balance, or homeostasis.

Selective Tidal Stream Transport (STST)- A movement strategy where fish use specific tidal phases to move efficiently through the estuary while minimizing energy expenditure.

Description of Process:

Resting is a critical behavioral function that allows fish to pause, recover energy, and make decisions about when and where to move next. It may occur during periods of unfavorable environmental conditions, after energetically costly behaviors like migration or spawning, or as part of staging before an upcoming event. Resting areas are often low-velocity zones that provide shelter from currents and predators.

Environmental stressors such as salinity stress and thermal stress often trigger resting. Fish may stop or slow movement to acclimate physiologically before continuing. Resting is especially important for species using selective tidal stream transport (STST), where timing and energy conservation are key. During ebb or flood tides, fish may stage in place until the optimal flow phase occurs.

Different species use resting for different purposes. Some rest to acclimate to salinity or temperature shifts during migration. Others rest between movement phases as part of an energy management strategy. Juveniles may rest more frequently due to limited swimming capacity or sensitivity to environmental changes.

In modeling, resting behavior should incorporate environmental thresholds, species-specific recovery strategies, and spatial access to low-energy zones. Resting affects the timing of behaviors like spawning or migration and can shape cumulative exposure risk if resting overlaps with contaminated areas.

Little Facts:

- Resting often occurs near channel edges, behind structure, or in backwaters with low velocity.
- Salinity and temperature changes can slow fish movement as they pause to acclimate.
- Staging fish may stay in the same location across several tidal cycles while preparing to spawn or migrate.
- STST relies on periods of low activity between directional tidal movements.
- Fish in poor condition may rest more frequently or for longer durations.
- Resting in contaminated or hypoxic areas can increase stress or exposure risks.
- Not all resting is passive. Some fish exhibit alert but stationary behavior to conserve energy while remaining responsive.

Discussion Objectives:

- Is this function accurate and realistic to your knowledge?
- Which species in the model use staging or STST behaviors?
- What environmental conditions most often trigger resting (e.g., salinity, temperature, discharge)?
- Where in the system do you expect key resting or staging locations for different species?
- What kind of model outputs should reflect resting behavior?
    - Are fish delaying movement or migration due to stress or suboptimal conditions?
    - Are resting areas aligned with habitat refugia or zones of increased risk (e.g., contaminants)?
    - Do rest periods vary by species, energy status, or environmental exposure?