UNIT ONE

INTRODUCTION TO TAXONOMY OF FISHES

1.1 Introduction to fish

The study of fishes is known as Ichthyology. The term "fish" most precisely describes any non-tetrapod craniate (i.e. an animal with a skull & in most cases a backbone) that has gills throughout life & whose limbs, if any, are in the form of fins. Unlike groupings such as birds or mammals, fish are not a single clade (*monophyletic*) but a *paraphyletic* collection of taxa. For instance, some e.g., lungfish & coelacanths are closer relatives of tetrapods (e.g. mammals, birds, amphibians, etc.) than of other fish such as ray-finned fish or sharks, so the last common ancestor of all fish is also an ancestor to tetrapods.

Many types of aquatic animals commonly referred to as "fish" are not fish in the sense given above; e.g. include shellfish, cuttlefish, starfish, crayfish & jellyfish. In some contexts, especially in aquaculture, the true fish are referred to as *finfish* (or *fin fish*) to distinguish them from these other animals. Fishes differ from each other in size, shape, habits & habitats. Despite the thousands of different species with various adaptations, all fish share some common evolutionary adaptations that help them thrive in the water environment. A list of the traits common across typical fishes include;

- they are ectothermic,
- they have streamlined bodies for rapid swimming,
- they extracts oxygen from water using gills,
- they have two sets of paired fins,
- they usually have one or two (rarely 3) dorsal fins,
- they have an anal fin,
- they have a tail fin,
- they have jaws,
- their skin is usually covered with scales, &
- they lay eggs

Each criterion has exceptions but these exceptions do not negate them but instead provide clues to adaptations arising from particularly powerful selection pressures. For e.g., *homeothermy* (warm-blooded adaptations) in tunas, swordfish, & some species of sharks indicate the metabolic requirements of fast-moving predators in the open sea. Through this adaptations, they can heat their bodies significantly above ambient water temperature.

Streamlining & swimming performance varies from fish such as tuna, salmon, & jacks that can cover 10–20 body-lengths per second to species such as eels & rays that swim no more than 0.5 body-lengths per second.

Many groups of freshwater fish *extract O_2* from water using a variety of different structures. Unusual adaptations include lungfish with paired lungs similar to those of tetrapods – the African lungfish can survive in dry mud for up to 4 years; gouramis with a structure called the labyrinth organ that performs a similar function; while many catfishes, such as *Corydoras* extract O_2 via the intestine or stomach, etc. The lungs & other accessory breathing structures indicate environmental conditions where gills are inefficient for transferring water-dissolved O_2 to the blood.

Body shape & the arrangement of the *fins* is highly variable, covering such seemingly un-fishlike forms as seahorses, pufferfish, anglerfish, & gulpers, etc.

Similarly, the surface of the skin may be naked (as in moray eels), or covered with scales of a variety of different types usually defined as *placoid* (typical of sharks & rays), cosmoid (fossil lungfish & coelacanths), *ganoid* (various fossil fish but also living gars & bichirs), *cycloid*, & *ctenoid* (these last 2 are found on most bony fish).

Fish live in virtually every watery habitat found on earth. There are even fish that live mostly on land or lay their eggs on land near water. Some mudskippers (Periophthalmidae) & the species *Alticus kirki* of the Red sea are truly amphibious, emerging from water to graze on algal films on mud or rocks. The mudskipper species *Phreatobius*, has been called a true "land fish" as this worm-like catfish strictly lives among waterlogged leaf litter.

The deepest living fish in the ocean is *Abyssobrotula galaltheae* found at depths of 8372 m in the Peurto Rican Trench. On the other hand, the Tebetan stoneloach (brook loaches), *Triplophysa stoliczkae* (ray-finned fish, family Nemacheilidae), lives in a hot spring at an altitude of over 5200 m in the Himalayas.

Many species live in underground lakes, underground rivers or aquifers & are popularly known as cavefish. They are usually blind e.g. the Northern Cavefish (*Amblyopsis spelaea*), *Lucifuga* sp, etc. Included in the diversity of fishes is a tremendous diversity of sizes from the smallest - the Philippine goby, *Paedocypris progenitica* which measures about 7.9 mm to the largest - the whale shark, *Rhinodon* which can grows to 20+ m. One unusual size adaptation is the existence of some deep sea fishes that can swallow prey larger than themselves.

It might be expected that most of this diversity of fishes would be contained in the oceans, because it covers more than 70% of earth’s surface. By volume, 97% of all water is in the oceans, & 0.0093% is in freshwater lakes & streams (the remainder is in ice, atmospheric water, salt lakes, etc.). But, only 58% of modern fish species are marine, whereas 41% are freshwater inhabitants & 1% move on a regular basis between the 2 environments. Fresh water consists largely of thousands of distinct "islands" of water in a sea of land which helps to promote speciation. In contrast, most of the saltwater habitat consists of Open Ocean, which is rather unproductive & lighted only in the surface layer. Only 13% of all fish species are associated with the open ocean: 1% in the surface layer (*epipelagic fishes*), 5% in the unlighted sections of the water column (*deepwater pelagic fishes*), & 7% on the bottom (*deepwater benthic fishes*). A majority (78%) of marine fish species (making up 44% of all fishes) live in the narrow band of water less than 200 m deep along the margins of land masses. Thus, a majority of fishes live in close association with land & with humans. An additional factor affecting the number of fish species is the annual temperature regime. In both fresh & salt water, a majority of the species are found in warmer environments where annual temperature fluctuations are comparatively small. Thus, the greatest diversity of fishes is found in the tropics, particularly, the coral reefs in Indo-West Pacific region for marine fishes, & the tropical South

America, Africa, & Southeast Asia for freshwater species especially in large river basins of tropical rainforests, such as the Amazon, Congo, & Mekong basins.

Fishes are economically a very important group of animals. They are valuable food resources because they have high feed conversion value requiring just 1.9 units of feed to produce 1 unit fish compared to 2, 4 & 8.5 respectively for poultry, pork & beef respectively. Fish liver is the main source of liver oil containing vitamin A & D. Body oils of fishes are externally used in soap industry & tanneries. Beautiful coloured fishes are the present craze to have in aquariums. They also provide economic sustenance to many nations.

The gradual erosion of commercial fish stocks due to over-exploitation & alteration of the habitat is one reason why the science of fish biology came into existence.

1.2 Introduction to Fish Taxonomy

Taxonomy is the science & practice of classification. It is composed of 2 Greek words, *taxis* (order, arrangement) & *nomos* (law of science). Hence, the word literally means "science of arrangement." It deals with the description of biodiversity, its arrangement into a system of classification, & the devising of identification keys. Over the years there has been several changes in classification systems for living organisms & for fishes. Current systems are based on classifying living organisms into separate systematic categories or ranks called "taxon or taxa (plural)." Hence, the term taxonomy. All fishes fall into one of these ranks. Taxonomic ranks from the most to the least inclusive are: Kingdoms, Divisions, Orders, Families, Genera & Species. Within these major groups, many sub-groups are also known. Many more divisions like tribe are also known but it is sufficient to use the broadly accepted classification. The aim is to highlight their individuality & identity for easy recognition. Thus, this system of classification in a graded fashion broadly called taxonomy is sometimes also called systematics – though this concept focuses more on the relationships among species.

Classification of Fishes

To understand the significance of the ecological, physiological, behavioural, & morphological adaptations of fish, scientists must also understand the evolutionary relationships among fishes. Modern classification schemes are generally presumed to reflect evolutionary relationships, because common structural features (on which most schemes are based) generally reflect common ancestry (Fig. 1.1).

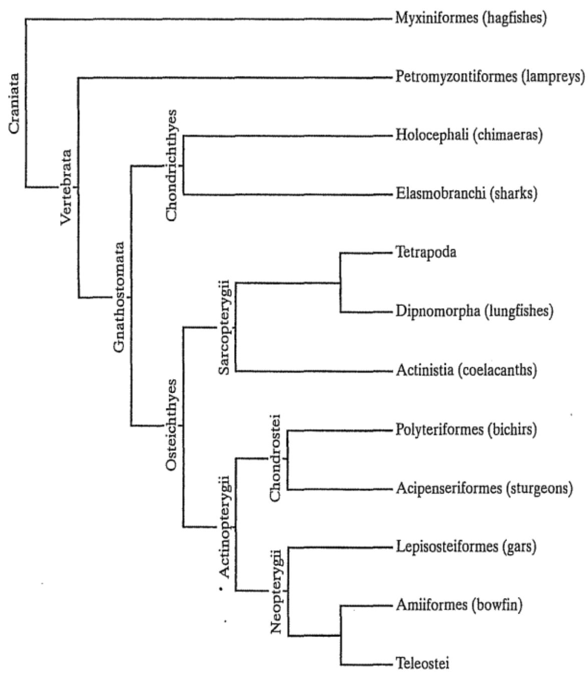

Fig 1.1 The interrelationships of the major groups of modern fishes, lampreys, & hagfishes

Because our knowledge of most fishes is far from complete, refinements & changes to accepted classification systems are continually being proposed.

Systematics is a dynamic field, so continuous changes are likely as new studies provide a better understanding of the interrelationships among fishes. Thus, the classification system (Fig 1.1) used in this course should be viewed only as a guide to fish diversity.

Taxonomic characters

Whichever system of classification is employed, characters are needed to differentiate taxa & assess their interrelationships. To be useful, they must show some variation in the taxon under study.

Characters can be divided, somewhat arbitrarily, into different categories.

i) *Meristic characters* originally referred to characters that correspond to body segments (myomeres), such as numbers of vertebrae & fin rays. Now, it is used for almost any countable structure, including numbers of scales, gill rakers, etc (Fig. 1.2).

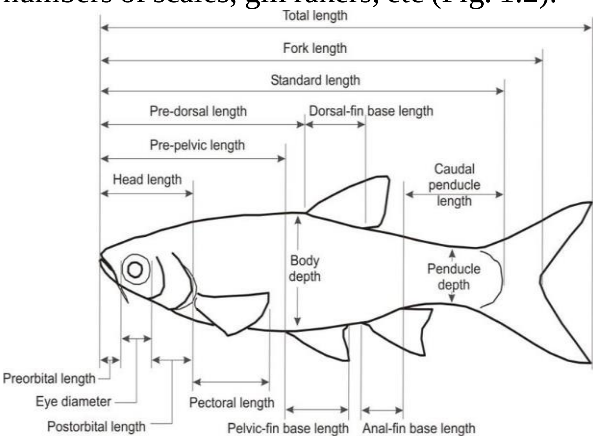

Fig 1.2 Some meristic & morphometric characters on a fish

These characters are useful because they are clearly definable, & usually other investigators will produce the same counts. In most cases, they are stable over a wide range of body size. Also, meristic characters are easier to treat statistically, so comparisons can be made between populations or species with a minimum of computational effort.

ii) *Morphometric characters* are measurable structures such as fin lengths, head length, eye diameter, or ratios between such measurements. Some morphometric characters are harder to define exactly, & being continuous variables, they can be measured to different levels of precision and so are less easily repeated. Furthermore, there is the problem of *allometry*, whereby lengths of different body parts change at different rates with growth. Thus analysis of differences is more complex than with meristic characters. Widely used features of most meristic & morphometric characters were presented in Fig. 1.2.

iii) *Anatomical characters* include characters of the skeleton (osteology) & soft anatomy, such as position of the viscera, divisions of muscles, and branches of blood vessels, etc. Some investigators favour osteological characters because such characters have been thought to vary less than other characters.

Other anatomical characters can include almost any fixed, describable differences among taxa. For example, colour can include such characters as the presence of stripes, bars, spots, or specific colours. Photophores - light-producing structures that vary in number & position among different taxa, are also anatomical characters.

Cytological (including karyological), electrophoretic, serological, behavioural, and physiological characters are useful in some groups.

iv) *Molecular characters*, especially nuclear DNA & mitochondrial DNA (mtDNA) have become increasingly useful at all levels of classification. All organisms contain DNA, RNA, & proteins. Closely related organisms show a high degree of similarity in molecular structures. Molecular systematics uses such data to build trees showing relationships. It is becoming easier & cheaper to sequence longer sequences of nucleotides. Molecular data can be used to test hypotheses of relationships based on morphological data.

Traditional classification divides fish into two superclasses:

1. Superclass Agnatha (Cyclostomata or the jawless fishes)

- Class Myxini (hagfishes) &
- Class Cephalaspidomorphi (lampreys –Petromyzontiformes)
- Class Ostracodermi (armoured jawless fish - extinct)

2. Superclass Gnathostomata (jawed fishes)

- Class Chondrichthyes (cartilaginous fish)
  - Subclass Elasmobranchii
    - Order Cladoselachiformes
    - Order Xenacanthiformes
    - Order Selachi (sharks & dogfish)
    - Order Batoidea (skates & rays)
  - Subclass Holocephali (chimaeras & extinct relatives)
    - Order Chimaeriformes

3. Class Placodermi (armoured fish - extinct)

- Order Arthrodiniformes
- Order Antiarchiformes

4. Class Acanthodii ("spiny sharks", sometimes classified under bony fishes - extinct)

5. Class Osteichthyes (bony fish)

- Subclass Actinopterygii (spinyray-finned fishes)
  - Infraclass Chondrostei
  - Infraclass Holostei
  - Infraclass Teleostei (spiny-finned fishes)
- Subclass Sarcopterygii (fleshy-finned fishes)
  - Order Crossopterygii (stalked fins. Most species are extinct)
    - Suborder Rhipidistia
    - Suborder Coelacanthini
  - Order Dipnoi (lung fishes)

The above scheme is the one most commonly encountered in non-specialist & general works. Many of the above groups are paraphyletic, in that they have given rise to successive groups: Agnathans are ancestral to Chondrichthyes, who have given rise to the Acanthodiians, the ancestors of Osteichthyes. With the arrival of phylogenetic nomenclature, the fishes has been split up into a more detailed scheme.

The various fish groups account for more than half of all living vertebrate species. Numerically, there are over 28,000 known extant species of fish in 515 families & 62 orders, of which over 26,000 are bony fish, about a 1000 are cartilaginous (sharks & rays = 534, sharks = 403, & chimeras = 33) & about 108 are jawless hagfishes (70) & lampreys (38). A 3rd of these species fall within the 9 largest families. From largest to smallest, these are Cyprinidae, Gobiidae, Cichlidae, Characidae, Loricariidae, Balitoridae, Serranidae, Labridae, & Scorpaenidae. About 64 families are monotypic, containing only one species.

Hierarchical Classifications of Fishes

In most classification systems, the components are arranged in an organized ranking manner. This gradation is according to their status in the evolutionary ladder.

All groups of anyone kind are supposed to differ from its related group by a roughly equal & the same degree of difference.

Closely related organisms have more features in common. The various taxa are defined below.

Phylum**:** It is a principal taxonomic category that ranks above class & below kingdom, equivalent to a division in botany.

Class**:** A major taxonomic rank below the phylum & above order consisting of one or more similar taxonomic orders. e.g. Class Osteichthyes (bony fishes) different from Class Chondrichthyes (Cartilaginous fishes), etc.

Order**:** It consists of one or more groups of similar families. Sometimes it may be even one family such as order Gonorhynchiformes with one family Chanidae. All fish orders end with the suffix '*formes'* & mostly the prefixes are the most common fish generic name e.g. Cypriniformes, Siluriformes (after genera *Cyprinus*, *Silurus*).

Family**:** It consists of a number of genera similar in most characters. Even a single genus may constitute a family because of its peculiarities e.g. Horaichthyidae for the genus *Horaichthys* Kulkarni. All fish family names end with the word '*idae*.**'**

Genus: This consists of a group of species presumably of common phylogenetic origin separated from other similar units by a decided gap e.g. Genus *Puntius* has an assemblage of 55 species but *Chanos* has only one species (*Chanos chanos*).

Species**:** These are actually (or potentially) interbreeding groups of populations which are reproductively isolated from similar such groups e.g. *Mystus cavasius* can interbreed among themselves but cannot do so with any other species of *Mystus*. This is the normal pattern though hybrids are known & are cultured artificially now. The species is the keystone of any taxonomic study because it is the only objective category which one can actually observe, collected, & tested in any investigations.

An example of a hierarchy for a fish group is depicted as below:

Phylum: Chordata
Class: Osteichthyes
Order: Cypriniformes
Family: Cyprinidae
Genus: *Puntius*
Species: *Puntius sophore* (Hamilton-Buchanan)

It will be seen that all categories above species have only a single word. Only species is always cited by 2 names followed by the name of the author or scientist who first gave the specific name.

There are several kinds of names used in taxonomy such as descriptive names, ecological names, geographical names, patronymic names, & names without any definite meaning e.g.:

(i) The specific name indicate prominent features or the common local name e.g. *Channa punctatus* is a species of the genus *Channa* with punctuated marks on the body, *Salmostoma longicauda* meaning long caudal fin, etc.

(ii) Sometimes the name of the locality, the collector, or an eminent person is adopted as the specific name e.g. *Glyptothorax anamalaiensis* Silas after Anamalai hills, S. India (Geographical name); *Euchiloglanis hodgarti* (Hora) after the name of the collector (Patronymic name), etc.

(iii) Descriptive name describing some character of the species e.g. *Monopterus albus* (Zuiew) indicating white colour.

(iv) Ecological name - according to the habitat in which it lives e.g. *Siksika* Lund, 1989 (Carboniferous fish) named after the Siksika nation in Alberta, Canada; *Akawaio* sp (knifefish) is named after the Akawaio people who populate the upper Mazaruni River, Guyana, where the fish was discovered.

However no taxon should be given an offending or seditious name.

Author names: These are names of persons or scientists who first proposed the taxa, be it a new species or genus. Names of genera

& species & below must be cited with the name of the first author who proposed, found or described it for the first time. For instance genus *Rasbora* Bleeker means that the genus was first proposed by the author Dr. P. Bleeker, though only his surname is cited & not the initials etc.
In similar manner the author or the one who first proposed the specific name is mentioned immediately often the taxon name & not anywhere else e.g. *Barilius bakeri* Day means that Day proposed the name *bakeri* for this species & described it under the genus *Barilius* of Bleeker.

<u>NB</u>*:* *Type Specimens* - Species & subspecies are described on the basis of specimens which are called **type specimens**. These specimens are stored carefully so that they can be studied by future generations. Specimens are of 2 types, primary & secondary specimen.

Primary specimens can be further divided into several categories:

- <u>Holotypes</u>: When a species is described on the basis of single specimen it is called holotype.
- <u>Neotype</u>: Sometimes a replacement of primary specimen is permitted if there is strong evidence that the original primary type specimen was lost or destroyed & when a complex nomenclature problem exists that can only be solved by the selection of a neotype.

Secondary types are additional specimens which are used in the description of a new species.

1.3 Features of Major Groups of Fishes

a). Superclass Agnatha

These are the jawless fishes. They consist of both present (cyclostomes) & extinct (conodonts & ostracoderms) species. The group is sister to all vertebrates with jaws, known as Gnathostomes.

1. **Class Myxini** (Hagfishes)
Typical characteristics of this Class Myxini include:

- Body is slender, eel-like, rounded with naked skin containing slime gland;
- Jaws are absent;
- Have biting mouth with 2 rows of eversible teeth;
- Paired fins are generally absent;
- Early species had heavy bony *scales* & plates in their skin, but these are not present in living species;
- In most cases the skeleton is fibrous & cartilaginous with the embryonic *notochord* persisting in the adult;
- Five to 16 pairs of gill pouches are present;
- The heart has one atrium & one ventricle; there is an accessory heart in the caudal region & aortic arches in gill region;
- Pronepheric kidney is positioned anteriorly & an independent mesonepheric kidney posteriorly;
- They are entirely marine & their body fluids are isosmotic with seawater;
- The digestive system is without a stomach & there is no spiral valve or cilia in the intestine; they are scavengers;
- There is a dorsal nerve cord with differentiated brain; there is no cerebellum; there are 10 pairs of cranial nerves & the dorsal & ventral nerve roots are united;
- Have well-developed sense organs for taste, smell, & hearing but the eyes are degenerate i.e. are almost blind;
- Sexes are separate (ovaries & testes in one individual but only one is functional); fertilization is external; there is no larval stage & the eggs are large & yolky.

2. **Class Cephalaspidomorphi** (Lampreys)
Typical characteristics of this Class include:

- Body is slender, eel-like, rounded with naked skin;
- Jaws are absent;
- One or 2 median fins, no paired appendages
- Fibrous & cartilaginous skeleton with a persistent notochord;
- There is a sucker-like oral disc & tongue with well-developed teeth;
- Heart has one atrium & one ventricle; aortic arches in the gill region;
- Seven pairs of gills each with an external gill opening are present;
- Mesonepheric kidneys are present; they are freshwater & marine forms are anadromous; & body fluids are osmotically & ionically regulated;
- There is a dorsal nerve cord with differentiated brain; a small cerebellum is present; 10 pairs of cranial nerves are present; & the dorsal & ventral nerve cords are separated;
- The digestive system lacks a stomach but the intestine has a spiral fold & cilia;
- There are well-developed sense organs for taste, smell, & hearing; eyes are well-developed in adults; 2 pairs of semicircular canals;
- Sexes are separate; there is a single gonad without duct; fertilization is external & there is a long larval stage (ammocoete)

b). Superclass Gnathostomata
3. Class Placodermi
Typical characteristics of this Class include:

- They are an extinct class only known from fossil remains which reveal that they lived in Silurian, Devonian & Carboniferous periods of Paleozoic era.
- They evolved from the Agnathans or jawless fishes;
- They were abundant in the freshwaters of the Devonian era
- They are the first to evolve true jaws though these jaws are primitive;
- They the first animals to exhibit internalized egg fertilization;
- They are all armoured fishes with endo- & exoskeletons made of bony plates or shields;
- The hyoidean gill slits are complete & not reduced.
- E.g. *Climatius, Palaeospondylus.*

4. Class Chondricthyes
(Gr. *Chondros* = Cartilage; *icthyos* =fish)
Typical characteristics of this Class include:

- Mouth is ventral & jaws are present;
- Body is fusiform, with a heterocercal caudal fin (diphycercal in chimaeras); there are paired pectoral & pelvic fins, 2 dorsal median fins; pelvic fins in males are modified as claspers;
- Almost all are marine animals with very few freshwater forms;
- Endoskeleton is entirely cartilaginous; notochord is persistent; vertebrae is complete & separate in elasmobranchs; vertebrae is absent in chimaeras; appendicular, girdle, & visceral skeleton present;
- The digestive systems has a J-shaped stomach (stomach is absent in chimaeras) & intestine has a spiral valve & a cloaca; liver, gall bladder, & pancreas are present;
- The circulatory system consists of several pairs of aortic arches; dorsal & ventral aorta, capillary & venous systems, hepatic portal & renal portal systems; they possess a 2-chambered heart; in the heart, sinus venosus, auricle, ventricle & conus arteriosus with valves are present;

- Respiration is by means of 5-7 pairs of gills; there are separate & exposed gill slits in elasmobranchs; the operculum covers over 4 gill openings in chimaeras; paired nostrils are present at the ventral side of rostrum; first gill slit is a spiracle;
- Skin with minute placoid scales & mucous glands in elasmobranchs; skin is naked in chimaeras; there are modified placoid scales for teeth in elasmobranchs; teeth are modified as grinding plates in chimaeras;
- A mesonepheric kidney & rectal gland are present; blood is isosmotic or slightly hyperosmotic to seawater; are ureotelic & store high levels of urea & trimethylamine oxide (TMO) in their blood & body fluids;
- The brain consists of 2 olfactory lobes, 2 cerebral hemispheres, 2 optic lobes, cerebellum, medulla oblongata; there are 10 pairs of cranial nerves & 3 pairs of semicircular canals;
- The senses of smell, vibration reception (lateral line system), & electroreception are well-developed;
- Sexes are separate; gonads are paired; reproductive ducts open into cloaca (separate urinogenital & anal openings in chimaeras); they are oviparous, ovoviviparous, or viviparous; development is direct & fertilization is internal; a pair of claspers, used in copulation, are present in males on either side of cloaca; eggs are macrolecithal (high amount of yolk) & cleavage is meroblastic;
- Air bladder & lungs are absent.
- E.g. *Scoliodon*, *Torpido*

5. Class Osteichthyes (Bony fishes)
(Gr. *Osteos* = bone; *ichthiyes* fish)
Typical characteristics of this Class include:

- Endoskeleton is made up of bone;
- Inhabits both freshwater as well as marine.
- Skin has mucous glands & is covered with embedded dermal scales of 3 types – ganoid, cycloid, or ctenoid; some are without scales; there is absence of placoid scales;
- Fins are both median & paired, with fin rays of cartilage or bone;
- Mouth is usually terminal or sub-terminal (with many teeth), some are toothless; jaws are present; olfactory sacs are paired & may or may not open into the mouth;
- Respiration is through gills; four pairs of gills are present on either side of the pharynx & their openings are covered by operculum or gill cover;
- Swim bladder often present with or without duct connected to the pharynx; air bladder is present in many species
- Tail is usually homocercal, but diphycercal or heterocercal forms exists;
- Claspers, cloaca & nasobuccal grooves are absent.
- Separate oval & urinogenital apertures are present.
- Circulation consists of a 2-chambered heart with an auricle & a ventricle; conus arteriosus is absent; lung fishes have an incompletely divided auricle & a ventricle; pulmonary artery & pulmonary vein are present in lung fishes;
- The nervous system consists of a brain with small olfactory lobes & cerebrum; large optic lobes & cerebellum; 10 pairs of cranial nerves; 3 pairs of semicircular canals
- Sexes are separate (sex reversal in some) gonads are paired & fertilization is external; larval forms may differ greatly from adults
- They are ammonotelic;

- They are usually oviparous; few are viviparous. (e.g. *Gambusia*, *Labestis*).

Class Osteichthyes is divided into two sub-classes:
1. Actinopterygii (Ray-finned fishes)
2. Sarcopterygii (Lobe-finned fishes)

a). Subclass Actinopterygii (ray-finned fishes)
1. Internal nostrils are absent.
2. Paired fins are supported by fin-rays arranged in a palmate fashion.

3. Caudal fin is homocercal.
4. Lungs are absent.
5. An air bladder or swim bladder or gas bladder is present which is hydrostatic in function.

Sub class Actinopterygii is divided into 3 super orders:
i) Superoder Chonrostei
ii) Superoder Holostei
iii) Superoder Teleostei

i. Infraclass Chondrostei
1. These are fresh water fishes.
2. Weak jaws without teeth.
3. Endoskeleton is cartilaginous.
4. Exoskeleton consists of bony plates covering the body.

5. Tail is heterocercal.
6. Spiral valve is present in the intestine
7. Air bladder with duct is present e.g. *Acipenser* (Sturgeon), *Polyodon*.

ii. Infraclass Holostei
(Gr. Holo- complete; osteo=bone)
1. These are known as bow fins.
2. They are found in fresh water of North & Central America America & Cuba.
3. Endoskeleton is bony.
4. An air bladder is present above the oesophagus.
5. Spiral valve is present in the intestine
6. Air bladder is present with a duct E.g. *Amia*, *Lepidosteus*.

iii. Infraclass Teleostei
(Gr. Teleo = entire, osteo=bone)
1. Includes a large number of modern bony fishes in which the skeleton is fully ossified.
2. Occur in fresh water as well as in oceans.

Infraclass Teleostei is commonly known as advanced ray finned fishes. They are modern fishes. Teleostei is divided in to 40 orders. Some important orders & examples of species are listed below.
1. Anguilliformes: eg. *Anguilla* (Eel)
2. Siluriformes: eg. *Wallago attu* (cat fish)
3. Cypriniformes: eg. *Labeo rohita* (Ruhu)
4. Syngnathiformes: eg. *Hippocampus* (Sea horse)
5. Beloniformes: eg. *Exocoetus* (Flying fish)
6. Perciformes: eg. *Anabas* (Climbing perch)
7. Tetradontiformes: eg. *Diodon* (Porcupine fish)
8. Lophiiformes: eg. *Lophius* (Angler or fishing frog)
9. Pleuronectiformes: eg. *Solea* (Flat fish)
10. Channiformes: eg. *Channa* (Murrel)
11. Clupeiformis: eg. *Chanos* (Milk fish)

b). Subclass Sarcopterygii (fleshy-finned fishes)
i) Infraclass Crossopterygii (ancestors of land vertebrates)
ii) Infraclass Dipnoi

i). Infraclass Crossopterygii (stalked-fin)
1. First vertebrate animals in which nasal passage connects the mouth cavity to the outside e.g. *Osteolepis* (extinct) & lung fishes.
2. Each paired fin is provided with large median lobe & dermal fin rays arising on either side of an axis in a pinnate fashion.
3. Caudal fin is diphycercal. Fins are paired & have a scale covered lobe.
4. Lungs are formed by the ventral evaginations of the pharynx.

Order Crossopterygii is divided into 2 suborders:

ii. Infraclass Dipnoi (Lung Fishes)

1. These are fresh water fishes.
2. Body is long & slender.
3. Jaws are short, teeth form a pair of plates.
4. Pectoral & pelvic fins are slender.
5. Skin is covered by cycloid scales.
6. Spiral valve in intestine in present.
7. Internal nostrils & one or two lungs & pulmonary arteries & veins are present e.g. *Protopterus*, *Lepidosiren*, *Neoceratodus*.

UNIT TWO

INTRODUCTION TO FUNCTIONAL ANATOMY OF FISH

2.1 Form and Movement

The great ecological diversity of fishes is reflected in the astonishing variety of body shapes & means of locomotion they possess. Indeed, much can be learned about the ecology of a fish simply by examining its anatomical features or by watching it move through the water. These features also form the basis for most schemes of classification & identification.

External Anatomy

Although life in water puts many severe constraints on the "design" of fish, the 1000s of species living in a wide variety of habitats means that these constraints are pushed to their limits. This results in many unlikely forms, such as seahorses & lumpfishes, etc.

Understanding the significance of the peculiar external anatomy of such forms is important. Fish species that are more recognizably fish-like can usually be placed in some sort of functional category through an examination of *body shape*, *scales*, *fins*, *mouth*, *gill openings*, *sense organs*, etc (Fig. 1.1 & 2.2).

Body Shape

Most fishes fall into one of 6 broad categories based on body configuration:

(1) rover predator,
(2) lie-in-wait predator,
(3) surface-oriented fish,
(4) bottom fish,
(5) deep-bodied fish, &
(6) eel-like fish (Fig. 2.1).

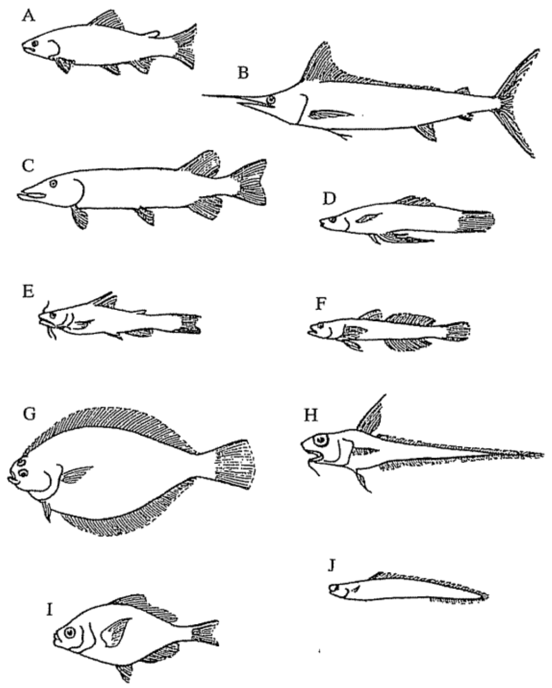

Fig 2.1 Typical fish body shapes: **(A)** and **(B)** rover-predator; (**C**) lie-in-wait predator; **(D)** surface-oriented fish; (E) bottom rover; (**F**) bottom clinger; (**G**) flatfish; **(H)** rattail; (**I**) deep-bodied fish; **(J)** eel-like fish.

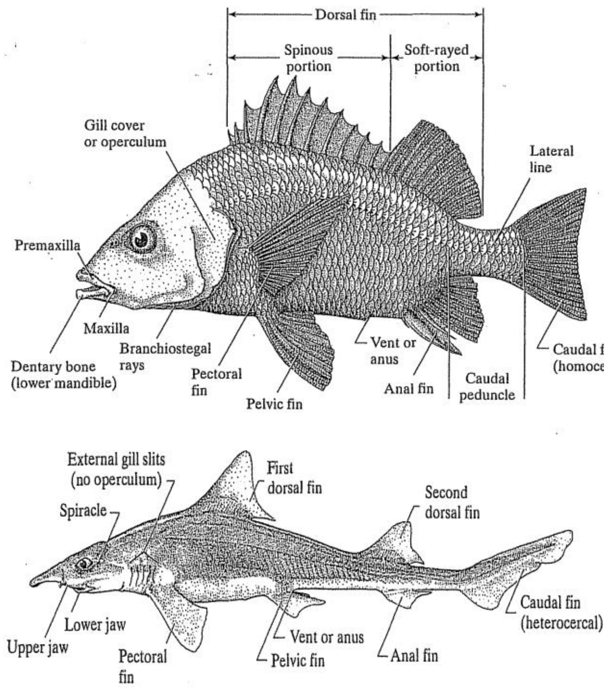

Fig 2.2 External features of a bony fish (snapper, top) & cartilaginous fish (smoothhound shark, bottom).

i) *Rover-predators* (Fig 2.1A & B) have the body shape that comes to mind when most people think of fish: streamlined ***(fusiform)*,** with a pointed head ending in a terminal mouth & a narrow caudal peduncle tipped with a forked tail. The fins are more or less evenly distributed about the body, providing stability & manoeuvrability. Such fish typically are constantly moving & searching out prey, which they capture through pursuit. E.g. many species of minnows bass, tuna, mackerel, swordfish, etc.

Their body shape is also characteristic of stream fish, such as trout, which spend much of their time foraging in fast water.

ii) *Lie-in-wait predators* (fig. 2.1C) are mainly *piscivores* (fish eaters) that have a morphology well suited for the ambushing of fast-swimming prey. The body is *fusiform*, but it is also elongate, often torpedo-like. The head is flattened & equipped with a large mouth filled with pointed teeth. In many species, the mouth is largely contained in a long, pointed snout. The caudal fin tends to be large, & the dorsal & anal fins are placed far back on the body, often in line with each other. This arrangement of the fins gives a fish the large amount of thrust it needs to launch itself at high speed toward passing fish. The narrow frontal profile that these fish present, coupled with their cryptic coloration & secretive behaviour, also makes them less visible to their prey. Members of this group include the freshwater pikes (Esocidae), barracuda (Sphyraenidae), gars (Lepisosteidae), needlefish (Belonidae), & snook (Centropomidae).

iii) *Surface-oriented fish* (fig. 2.1D) are typically small in size, with an upward-pointing mouth, a dorsoventrally flattened head with large eyes, a fusiform to deep body, & a dorsal fin placed toward the rear of the body. The morphology is well suited for capturing plankton & small fishes that live near the water's surface or insects that land on the surface. In stagnant water, the surface-oriented morphology is particularly suitable for taking advantage of the thin layer of oxygen-rich water that exists at the air-water interface.

The mouth of the fish can be placed in the layer & the water then pumped across the gills. Most surface-oriented fish are stocky-bodied fresh or brackish water forms, such as mosquitofish *(Gambusia),* many killifish (Fundulidae), etc.

iv) *Bottomfish* (**fig. 2.1E-H**) possess a wide variety of body shapes, all of them adapted for a life in nearly continuous contact with the bottom. In most such fish, the swim-bladder is reduced or absent, & most are flattened in one direction or another. Bottom fish can be divided into 5 overlapping types:
(1) bottom rovers,
(2) bottom clingers,
(3) bottom hiders,
(4) flatfish, &
(5) rattails

Bottom rovers (fig. 2.1E) have a rover-predator-like body, except that the head tends to be flattened, the back humped, & the pectoral fins enlarged.
Many bottom rovers among the bony fishes have small eyes & well-developed ***barbels*** ("whiskers" equipped with tastebuds) around the mouth, indicating their ability to find prey at night or in murky water. Many sharks, with their inferior mouths, flattened heads, & large pectoral fins, can also be classified as bottom rovers.

Bottom clingers (fig. 2.1F) are mainly small fish with flattened heads, large pectoral fins, & structures (usually modified pelvic fins) that allow them to adhere to the bottom. Such structures are handy in swift streams or intertidal areas with strong currents.

Bottom hiders are similar in many respects to the bottom clingers (fig. 2.1F), but they lack the clinging devices & tend to have more elongate bodies & smaller heads. These forms usually live under rocks or in crevices or líe quietly on the bottom in still water.

Flatfish (fig. 2.1G) have the most extreme morphologies of the bottom fish. Flounders (Pleuronectiformes) are essentially deep-bodied fish that live with one side on the bottom. In these fish, the eye on the downward side migrates during development to the upward side, & the mouth often assumes a peculiar twist to enable bottom feeding. In contrast, skates & rays are flattened dorsoventrally ***(depressiform)*** *&* mostly move about by flapping or undulating their extremely large pectoral fins. Not only is the mouth completely ventral on these fish, the main water intakes for respiration (the spiracles) are located on the top of the head.

The *rattail shape* (fig. 2.1H) is another type of body shape that has independently evolved in both the Osteichthyes & Chondrichthyes. They have bodies that begin with large, pointy-snouted heads & large pectoral fins & end in long, pointed, rat-like tails. These fish are almost all bottom-dwelling ***(benthic)*** inhabitants of the deep sea, but exactly why this peculiar morphology is so popular among them is poorly understood.
The fishes live by scavenging & by preying on benthic invertebrates. ·

v) *Deep-bodied-fish* (fig. 2.1I) are laterally flattened ***(compressiform)*** fish, with a body depth usually at least one-third that of the standard length (distance from snout to structural base of caudal fin). The dorsal & anal fins are typically long, and the pectoral fins are located high on the body, with the pelvic fins immediately below. The mouth is usually small and protrusible, the eyes large, & the snout short. Deep-bodied fish are well adapted for manoeuvring in tight quarters, such as the catacombs of a coral reef, dense beds of aquatic plants, or tight schools of their own species. They are also well adapted for picking small invertebrates off the bottom or out of the water column. A majority of deep-bodied fish possess stout spines in the fins, presumably because during the course of their evolution they sacrificed speed for manoeuvrability and developed spines for protection from predators. Although most deep-bodied fish are closely associated with the bottom, many open-water plankton feeders (*planktivores;* e.g., herring) are also moderately deep-bodied.

vi) *Eel-like fish* (fig. 2.1J) have elongate bodies, blunt or wedge-shaped heads, & tapering or rounded tails. If paired fins are present, they are small, whereas the dorsal & anal fins are typically quite long. Scales are small & embedded or absent. In cross-section, their bodies can range from compressed to round. Eel-like fishes are particularly well adapted for entering small crevices & holes in reefs & rocky areas, for making their way through beds of aquatic plants, & for burrowing into soft bottoms. However, a surprising number are also found swimming about in the open ocean, so this body shape is useful for other purposes as well. Examples of this group include the many eels (Anguilliformes), loaches (Cobitidae), & gunnels (Pholididae).

Fish Skin & Scales

The *epidermis* of fish skin consists entirely of live cells, with only minimal quantities of keratin in the cells of the superficial layer (**Fig** 2.3).

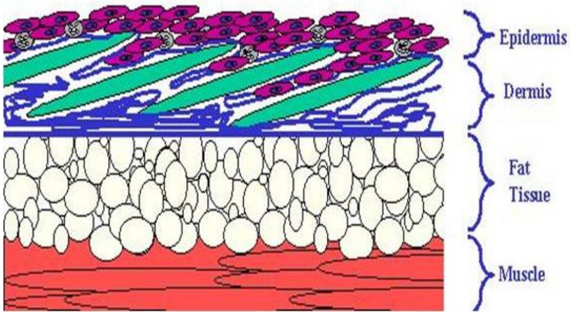

Fig. 2.3 Structure of Fish Skin
Image Credit: Wikipedia

It is generally permeable. The *dermis* of bony fish typically contains relatively little of the connective tissue found in tetrapods. Instead, in most species, it is largely replaced by solid, protective bony **scales**. Others have no outer covering on the skin.

The type, size, & number of scales can reveal much about how a fish makes its living.

The scales of bony fish range from a heavy coating of mail-like armour to a few large bony plates on the back to a dense covering of thin, flexible scales to no scales at all (Fig. 2.4).

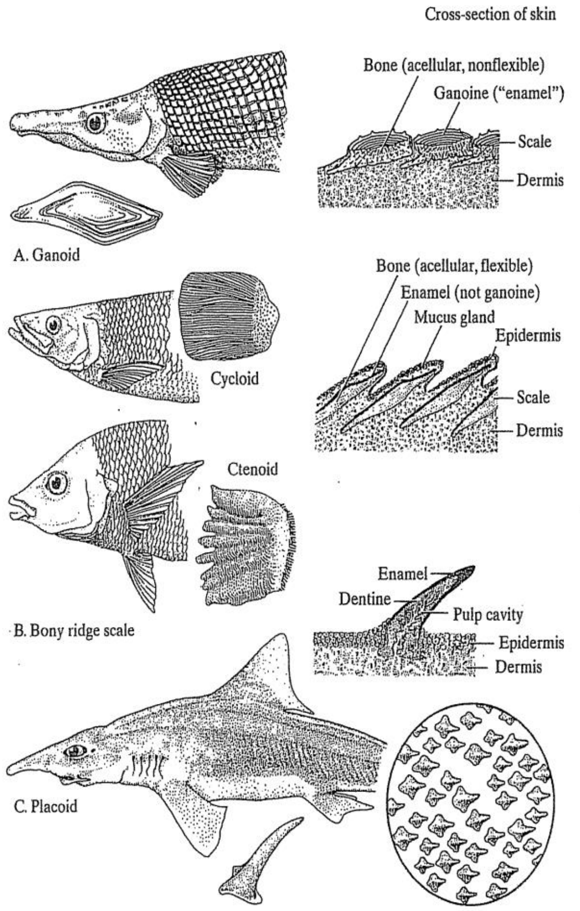

Fig 2.4 Examples of ganoid scales on gar, cycloid scales on sardine, ctenoid scales on snapper, & placoid scales on a shark.

Bony plates are large, modified scales that serve as armor on a number of bottom-oriented fishes. Most of such fishes are rather slow in their movements. In contrast, typical scales usually cover the bodies of most free-swimming fish, apparently providing some degree of protection from predators while not excessively weighing down the fish. Fish that are fast swimmers or regularly move through the fast water of streams typically have many fine scales (e.g., trout), whereas those that live in quiet water and do not swim continuously at high speeds tend to have rather coarse scales.

Scales evolved independently in cartilaginous & bony fish as indicated by their fundamentally different structure. The *placoid scales* of sharks are tiny, tooth-like structures, whereas the scales of bony fish are layered plates, with bone as one of the layers. The ancestral condition for bony fish is represented by the heavy *ganoid scales* of gars (Lepisosteidae; Fig. 2.4) & the more derived condition by the *bony ridge (elasmoid) scales* of teleosts (Fig. 2.4). The latter are of 2 basic types: cycloid, & ctenoid. *Cycloid scales* are the round, flat, thin scales. *Ctenoid scales* are similar to cycloid scales except for the tiny, comb-like projections *(ctenii)* on the exposed (posterior) edge of the scales. The ctenii apparently improve the hydrodynamic efficiency of swimming. Some kinds of fish possess both types of scales.

Curiously, the tiny placoid scales of sharks may be an independently evolved solution to the same "problem," because these scales, like ctenoid scales, make the exterior of the fish rough to the touch.

Although scales are usually considered to be an integral part of any físh, a surprising number of species lack them altogether or have just a few that are modified for other purposes. Such fish are by & large bottom dwellers in moving water; fish that frequently hide in caves, crevices, & other tight places; or fast-swimming pelagic fish. However, many fish that appear to be scaleless in fact have a complete coating of deeply embedded scales (most tunas & anguillid eels). Many of the bottom-dwelling skates & rays also do not have placoid scales, except as patches of bony armour or as spines (in stingrays).

Fins

In both bony & cartilaginous groups, the fins are supported internally by sturdy fin rays. In sharks & rays, the fin rays are called *ceratotrichia* & are fairly stiff, unbranched, & unsegmented. In contrast, the *lepidotrichia* of bony fish are flexible, segmented, & branched. Lepidotrichia seem to start as embryonic spines ***(actinotrichia)*** that become covered with embryonic scales, which then replace the actinotrichia completely before emerging as fin rays. When this developmental process does not occur, *true spines* emerge, which are stiff, round in cross-section, & unsegmented. In all fish, the various combinations of location, size, & shape of the fins are closely associated with the different body shapes. The paired fins (pectorals & pelvics) & the unpaired fins (dorsal, anal, caudal, & adipose) evolved together as a system that simultaneously propels, stabilizes, & manoeuvers each fish.

Pelvic fins are the most variable of the fins in terms of position. In more ancestral bony fishes & in sharks, the fins are located ventrally, toward the rear of the fish ***(****abdominal position****).*** Most of these fish have rover-predator body shapes, & the fins assist in steering & braking. In more derived teleosts, many of which are deep-bodied, the pelvics are more anterior, below the pectoral fins ***(****thoracic position* Fig. 2.2); occasionally, they are even in front of the pectorals *jugular position*). In eels & eel-like fish, the pelvic fins are absent or greatly reduced in size, in part for ease of squeezing through tight places. In bottom-dwelling fish, the pelvics are frequently modified into organs for holding on to the substrate.

Pectoral fins are generally located high up on the sides of deep-bodied fish, which depend on precise movements for picking prey from the bottom or the water column. In rover-predators, these fins tend to be more toward or below the midline of the fish. In very fast-swimming fish & in very deep-bodied fish that picks prey from the substrate, these fins tend to be long & pointed. In slower-moving rover-predators or other fish that need more surface area for stability while swimming, the fins tend to

be more rounded. The pectoral fins of bony fish that rest on the bottom, are usually broad, rounded, ventral in position, & spread out laterally. Other fish use enlarged pectoral fins for gliding (flying fish) or, in the case of many ray fishes (eagle rays), "flying" in the water. In some fish, enlarged pectoral fins are apparently used mainly for display, either to startle predators when suddenly opened or to signal predators (& conspecifics) to stay away from poisonous spines.
In contrast, the pectoral fins of sharks are rather like rigid wings that can be moved but not collapsed. These fins operate as stabilizers.

Dorsal & ***anal fins*** are generally long on rover-predators deep-bodied fish to provide stability while swimming. In fast-swimming pelagic fish e.g. tuna & mackerel, the rearmost portions of both fins are frequently broken up into numerous finlets. When such fish are swimming at high speed, the forward portion of the dorsal fin may fold into a dorsal slot to reduce the resistance. Bony fish that lack these specializations will collapse the dorsal & anal fins & fold back the pectoral & pelvic fins when putting on a burst of speed. Though this method of reducing drag is not available to sharks, a number of the mackerel sharks are capable of swimming at quite high speeds.
Another group of fish with long dorsal & anal fins are the eel-like fish. Their fins frequently run most of the length of the body & may unite with the caudal fin; such a configuration is necessary for the anguilliform locomotion.

The ***caudal fin (tail fin)*** has a shape that is strongly related to the normal swimming speed of a fish. The tails of most bony fish are *homocercal* (Fig. 2.5A)**,** with upper & lower lobes being about the same size. The fastest-swimming fish e.g. tuna & marlin, have a stiff, quarter-moon-shaped ***(lunate)*** fin attached to a narrow caudal peduncle.

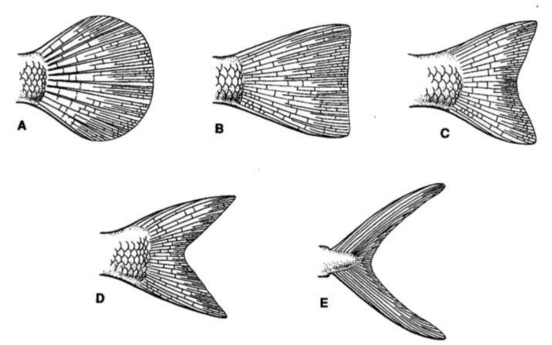

Fig 2.5A Types of homocercal tails (A=round, B=truncate, C=emarginate, D=forked, E=lunate)

Fish whose survival depends on frequent, sustained swimming have forked tails, with the deepest forks occurring on the most active fish. Deep-bodied fish & most surface & bottom fish have tails that are square, rounded, or only slightly forked. When a homocercal tail lacks well-defined lobes, it is referred to as *isocercal***.** In the Chondrichthyes, the tail is usually *heterocercal***,** with the upper lobe being longer than the lower lobe (Fig. 2.5B).

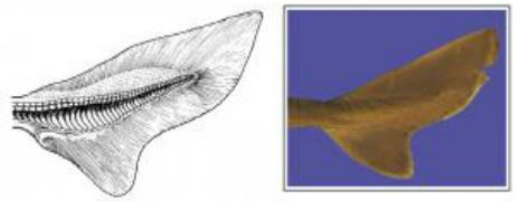

Fig 2.5B Heterocercal tails of fish

In the homocercal tail, the vertebral column ends in modified vertebrae that support the fan-like tail structure; in the heterocercal tail, the vertebral column actually extends into the upper lobe of the tail.

The ***adipose fin*** is a fleshy, dorsal appendage that is found in some fishes. Although located between the dorsal & caudal fins toward the caudal peduncle, the small size & lack of stiffening rays make the function of this fin a mystery. It may have an important function in the swimming of fish during the post-larval stage of development, when other fins are poorly developed.
One of the most important attributes of the fins of fish is the presence or absence of

spines on the dorsal, anal, & pectoral fins. The importance of spines is indicated by the fact that they have developed independently in several different groups of fish. In the dominant group of spiny-finned teleosts (Acanthopterygii), spines are solid bony structures without any segmentation & are round in cross-section. Others have spines that are just stiffened, thickened rays, which are segmented, dumbbell-shaped in cross-section, & often branched.

Regardless of their structure & origin, spines are an effective & lightweight means of protection against predators. Dorsal, pectoral, & opercular spines are often located at the fish's centre of mass, the usual target point of piscivorous fish. Besides being uncomfortable for a predator to bite down on, spines greatly increase the effective size of a small fish, because once the dorsal, anal, & pectoral spines are locked into place, the fish can be grabbed only by a predator that can get its mouth around the spines. By increasing its effective size through the use of spines, a small fish reduces the number of predators that can prey on it, because large predators are almost always fewer in number than small predators. As a consequence, well-developed spines are found mainly in small to medium-sized fishes that actively forage for their food. As an additional disincentive to predators, many spines have poison glands associated with them, such as those found on scorpionfish (Scorpaenidae), some catfish, & stingrays.

Muscular System

In almost all fish, the large muscles of the body & tail comprise the majority of the body mass. The body muscles are divided vertically along the body length into sections called the *myomeres* or *myotomes* **(**fig. 2.6**)**, which are separated by sheets of connective tissue. The myomeres are shaped like a *W* on its side, so that they fit into one another like a series of cones. The myomeres on the right & left halves of the body are separated by a vertical *septum.* A horizontal septum separates the muscle masses on the upper & lower halves of the body. The upper muscles are called the *epaxial muscles* & the lower muscles the *hypaxial muscles* (Fig. 2.7).

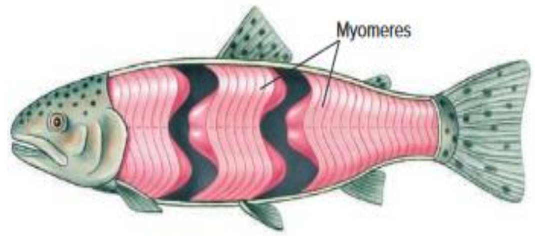

Fig. 2.6 Trunk musculature of a teleost fish, partly dissected to show internal arrangement of the muscle bands (myomeres). The myomeres are folded into a complex, nested grouping, an arrangement that favours stronger and more controlled swimming.

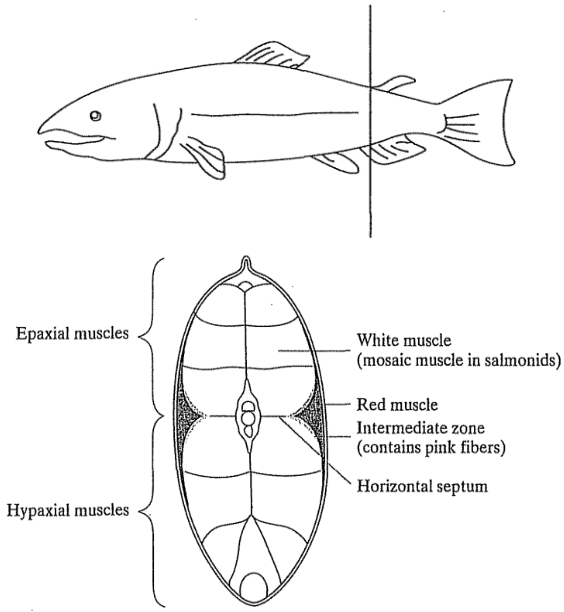

Fig. 2.7 Cross-section of salmon posterior to vent, indicated by line in top drawing, showing position of locomotory muscles (bottom).

Fish muscles can often be divided into red (slow), white (fast), & pink (intermediate) muscle (Fig. 2.7).

Red muscle (Fig. 2.7) is infused with capillaries & appears red in colour because of the high concentrations of red, oxygen-binding pigments in the blood ***(****haemoglobin****)*** & in the muscle tissue itself ***(****myoglobin****).*** The high capillary density & presence of the pigments ensure that the red muscle receives adequate oxygen for its abundant mitochondria to metabolize fat (lipids) to sustain high levels of continuous (aerobic) swimming.

Therefore, in continuously active fish, a large proportion of their muscle mass is red muscle. Fish of "intermediate" activity levels often have the lateral band of muscles, which is always red in colour & well developed. These fishes may also have red muscle fibres scattered in the white muscle that makes up most of the body mass. In some cases, the position of the red bands within the body also reflects swimming ability. Thus, the fastest-swimming tunas (e.g., *Thunnus)* carry their red muscle bands deep in the body core. This arrangement aids the stiff-body (thunniform) swimming mode & permits the conservation of metabolic heat, which in turn allows faster muscular contractions & higher swimming velocities.

At the opposite end of the spectrum of temperatures at which red muscle operates (i.e., at low temperatures), red muscle shows increased:

(1) capillary densities (enhancing blood flow through muscle tissues),

(2) cellular mitochondrial densities (increasing aerobic potential), &

(3) lipid droplet densities (which may accelerate O_2 flux via increased O_2 solubility)

These adaptations presumably maintain swimming performance in the face of slowed metabolic & chemical processes at cold temperatures.

White muscle fibres (Fig. 2.7) are thicker than those of red muscle, have a poorer blood supply, & lack red, oxygen-carrying pigments such as myoglobin. Not surprisingly, white muscle contraction is not as dependent on oxygen supply. White muscle usually converts glycogen to lactate via anaerobic pathways. Thus, white muscle is most useful for short bursts of swimming & dominates the muscle mass of moderately active to "sluggish" swimmers.

Pink muscle (Fig. 2.7)**,** containing fibres intermediate in character between those of white & red muscle, is typically used at swimming velocities too high for red muscle to sustain but too low for the effective use of white muscle. But, in some fish, pink muscle is used similar to red muscle at slow velocities whereas in other fish, it is used for swimming at fairly high velocities.

Not surprisingly, the powering of fish swimming rarely is strictly a matter of red & white-or even pink. The different kinds of muscle fibres are typically used in concert as fish change swimming speed.

Locomotion

Fish move by a variety of means. The simplest is the passive drift of many larval forms, but such drifters quickly metamorphose into forms capable of active, directed movement (Fig. 2.8).

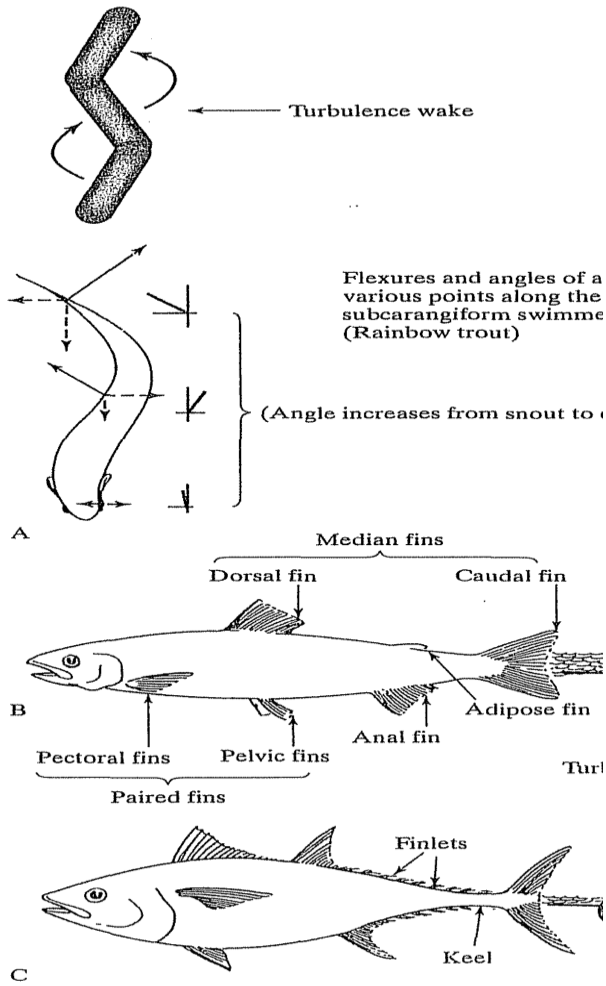

Fig. 2.8 Generalized swimming features of fishes.

Although various fishes have evolved the abilities to burrow, walk, crawl, glide, & even fly, swimming is by far the most important means of locomotion. To swim forward (or backward!), most fish utilize rhythmic undulations of part or all of their bodies or fins. The sides of the body & the fins exert force on the relatively incompressible surrounding water through the sequential contraction of myomeres. The relatively stiff vertebral column provides compression resistance, so the body bends from side to side rather than shortening.

Sideways or lateral flexures of the body muscles at the appropriate angle of attack propel fish forward. These flexures typically move backward along the body with increasing amplitude & at a speed somewhat greater than the forward progress of the fish. As this propulsive wave moves posteriorly, the water adjacent to the fish is accelerated backward until it is shed at the posterior margin of the caudal fin, producing thrust.

The more undulatory waves a fish can exert against the surrounding water, & the faster & more exaggerated the waves are, the more power the fish can generate. If other factors such as *drag* (resistance to movement) from body features & shape are held constant, fish that generate more power can accelerate more quickly & swim faster.

It should be obvious from the wide variety of body shapes of fish that, despite the basic approach to swimming just discussed, considerable variation exists in how fish swim. A general classification of swimming modes or types has been developed & the chief characteristics of the different types are how much of & which parts of the body are involved in propulsion & whether the body or the fins undulate or oscillate. Undulation involves sinusoidal waves passing down the body or a fin or fins while oscillation involves a structure that moves back & forth. Several swimming methods are recognized e.g. anguilliform, subcarangiform, carangiform, modified carangiform (= thunniform), ostraciform, tetradontiform, balistiform, rajiform, amiiform, gymnotiform, & labriform (Fig. 2.9)

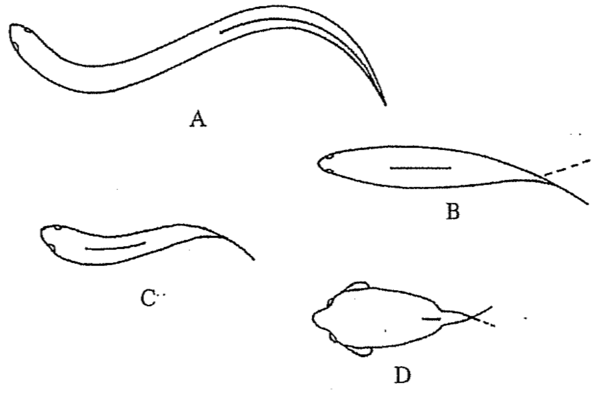

Fig. 2.9 Swirnming rnodes of fishes: (A) anguilliforrn;**(B)** carangiforrn; (C) subcarangiform; **(D)** ostracifonn.

The first 4 types involve sinusoidal undulations of the body. ***Anguiliform swimming*** (fig. 2.9A) is characteristic of flexible, elongate fish e.g. eels (Anguilliformes). The whole body of such fish is flexed into lateral waves for propulsion except the head. Typical eel median "fins" consist of a continuous dorsal-caudal-anal fin extending around the posterior half of the fish. A similar fin configuration & swimming style is also found in such diverse groups as marine gunnels (Pholididae), anadromous lampreys (Petromyzontidae), & lungfish (Dipnomorpha). Anguilliform swimmers without a strict eel-like shape include certain elasmobranches (e.g., nurse sharks, Ginglymostomatidae) & some teleosts, e.g. cods (Gadidae), when swimming slowly. These swimmers are comparatively slow because of their relatively long bodies & the involvement of the anterior regions in propulsion. But it also has its compensating advantages, including a greater ability to move through dense vegetation & sediments & to swim backwards.

To overcome the slow swimming of the slow anguilliform swimmers, faster swimming fishes involve only posterior segments of the body in wave generation, using ligaments to transfer force from anterior body musculature to the caudal region. The progression of types from the subcarangiform (trout & cod) through carangiform (jacks, herrings) to modified carangiform (thunniform) (mackerel, sharks, billfishes, tunas) entail increasing involvement of the tail & decreasing involvement of the anterior body in swimming.

Carangiform swimming (fig. 2.9B) is intermediate between the anguilliform & ostraciform extremes & is named after the jakes (Carangidae). Carangiform swimming is a type of swimming in which undulations are limited to the caudal or tail regions instead of the whole body as in anguiliform swimming. The body shape of carangiform swimmers is typically fusiform, tapering to a narrow caudal peduncle & then broadening to a large, forked caudal fin. Species normally thought of as carangiform types are swift swimmers.
Slower fish that swim at speeds greater than one body length per second) are often placed in a separate movement category: ***subcarangiform swimming*** (fig. 2.9C). They have low aspect ratio with broad, flexible tails which are better suited for rapid acceleration from a dead start & also aid during hovering by passing undulations down the posterior edge.
At the other extreme, the fastest-cruising fish (tunas, billfish, & lamnid sharks) are often placed in a separate ***thunniform swimming*** category. These fish have a low-drag fusiform shape & undulate a narrow caudal peduncle stiffened by a keel & a large, slim, lunate (moon-shaped) caudal fin for propulsion. With its "swept-back," tapered tips", the lunate tail provides efficient power for fast underwater movement & frictional drag is minimized by the design of the tail. This maximizes propulsive force, & energy wasted on lateral displacement of water. The vertically large tail allows a greater mass of water to be accelerated to the rear, thus increasing forward thrust. The thunniform mode of propulsion, involving a streamlined shape, narrow necked & keeled peduncle, & high aspect ratio tail (high height:width ratio) has evolved convergently in several fast swimming, pelagic predators e.g. mackerel sharks, tunas, billfishes, porpoises, & dolphins.

Ostraciform swimming (fig. 2.9D)**,** named after the boxfish family (Ostraciidae), also involves flexing the caudal peduncle, but not to generate high velocities. By contracting the entire muscle mass on one side of their bodies & then the other, these swimmers oscillate the caudal fin to produce a sculling type of locomotion. Thus, only the tail is moved back & forth while the rest of the body is held rigid. The side to side movement of the tail is more an oscillation than an undulation. Fish with this type of locomotion, rely on armour (plus spines & toxins) rather than on speed to protect them from predators. The small isocercal caudal fin also is in keeping with their low swimming velocities.

Swimming with fins alone is characteristic of a surprising number of teleosts, including forms that use their body musculature for swimming when high-speed or sustained swimming is necessary. The ray-&-membrane fin design allows these fishes to undulate individual fins or fin pairs rather than their bodies to achieve precise movements. Examples are found among, but are not limited to, fish inhabiting areas of dense vegetation or coral or rock reefs. ***Tetraodontiform*** & ***balistiform*** swimmers flap their dorsal & anal fins synchronously e.g. triggerfishes, ocean sunfishes). They have narrow-based, long, pointed fins which function like wings & generate lift (forward thrust) continuously. Many species can utilize a rowing/flapping action of the pectoral fins for forward propulsion. This is termed ***labriform swimming*** e.g. chimeras, surfperches, wrasses, parrotfishes, surgeonfishes, etc. If rapid acceleration or sustained swimming is needed, labriform swimmers & many fin-based locomotors shift to carangiform locomotion. ***Rajiform*** locomotion involves hovering & slow movement through multiple undulations that pass backwards or forwards along the pectoral fins as found in skates & rays. Here, thrust is generated by undulatory waves passing down the enlarged, muscular pectoral fins. These fishes increase pectoral fin undulatory wave frequency to increase swimming velocity. Rajiform & related swimming modes are slow but allow for precise hovering, manoeuvring, & backing. In contrast to the pectoral fin movements, ***gymnotiform*** fishes use anal fin undulations for propulsion (e.g. South American & African knifefishes or featherfins). In ***amiiform*** swimmers, undulations pass along the dorsal fin e.g. seahorses, Bowfin, etc).

It is believed that most fishes are locomotor generalists rather than locomotor specialists. This implies that few fishes use only one type of swimming mode. Many fishes switch between modes depending on whether fast or slow swimming or hovering is needed.

2.2 Respiration & Ventilation in Fishes

Water as a respiratory environment

Fishes like all eukaryotic life forms, require oxygen to produce sufficient energy to support their metabolic needs. But acquiring oxygen from water is challenging due to oxygen's low solubility in water. Hence, fishes have evolved a number of morphological & physiological adaptations that increase the efficiency of oxygen uptake & delivery to help them succeed in a wide range of aquatic environments. Fishes must extract oxygen from water fast enough to meets the demands of metabolism.

Gas solubility in liquids diminishes with increasing temperature. Hence, warm water contains less oxygen than cold water, making the challenges of meeting metabolic needs far greater for warm water fishes. Oxygen levels also reduces with increasing salinity of water. Hence, freshwater can hold about 25% more oxygen than seawater. This is referred to as the *salting out effect*. Thus, the combined effects of temperature & salinity make oxygen availability especially low in warm, marine environments.

Aquatic breathing

The *gills* are the main site of oxygen exchange in almost all fishes & oxygen's low solubility has contributed to their evolutionary development, which is characterized by large surface area, thin epithelial membranes of its secondary lamellae, extremely efficient gas exchange, & to the many - & often bizarre mechanisms that some fishes use to extract oxygen from air. The diffusion of gases across the gills is also enhanced by blood in the secondary lamellae flowing in opposite direction to the water passing over the gills, thereby maximizing the diffusion gradient across the entire lamellar surface. This *countercurrent flow* ensures that as blood picks up oxygen from the water, it moves along the exchange surface to an area where the adjacent water has an even higher oxygen concentration.

The gills located in the pharyngeal cavity or branchial chamber & covered by a moveable flap called the operculum (fig. 2.10A) are the main respiratory organ for O_2 extraction & CO_2 excretion. The gills are the most effective respiratory devices in the animal kingdom for extracting oxygen from a water medium that contains less than $1/20^{th}$ as much oxygen as in air.

Instead of opercula flaps as in bony fishes, cartilaginous fishes usually have a series of gill slits out of which water flows. They are not usually visible but can be seen in some cartilaginous fishes. Five to 7 gills are found in cartilaginous fishes & 3-5 gills are found in teleosts or bony fishes. Fish gills are supported by a cartilaginous or bony structure called the *gill arch* (Fig 2.10C).

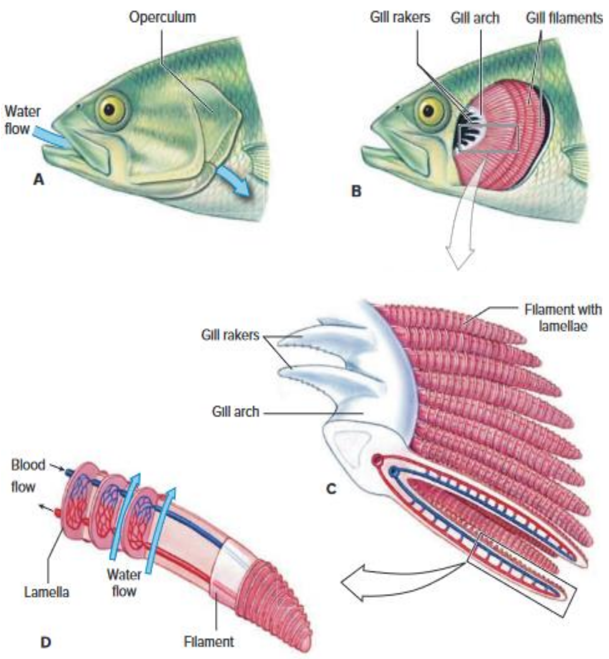

Figure 2.10 Gills of fish. Muscles attached to the operculum (A) pump water over gills & out the gill slit. The bony, protective flap covering the gills (operculum) has been removed (B) to reveal branchial chamber containing the gills. There are 4 gill arches on each side, each bearing numerous filaments. A portion of a gill arch (C) shows gill rakers that project forward to strain out food & debris, & gill filaments that project to the rear. A single gill filament (D) is dissected to show the blood capillaries within the platelike lamellae. Direction of water flow is opposite the direction of blood flow.

Each gill arch bears 2 rows of slender fleshy projections called *gill filaments* (Fig 2.10B). *Gill rakers* project along the inner surface of the gill arch (Fig 2.10B). They prevent food particles from entering the gill slits or may be specialized for filtering water in filter-feeding fishes. The gill filaments have a rich supply of capillaries, the blood of which gives them a bright red colour (Fig 2.10C). Each gill filament contains many rows of thin plates or discs called *lamellae* that largely increase the surface area through which gas exchange takes place (Fig 2.10C & D). The number of lamellae is higher in active swimmers, who need large supplies of blood.

Gills function efficiently only if water is kept moving across it in the same direction, from anterior to posterior. This is accomplished in two ways especially in bony & cartilaginous fishes. First, the great majority of fishes pump water across their gills by increasing & decreasing the volume of the *buccal* (mouth) *chamber* in front of the gills & the *opercular chamber* behind them. The expansion & contraction of these 2 chambers is timed so that the pressure in the buccal chamber is greater than that in the opercular chamber, thereby ensuring that the water flows in the anterior to posterior direction throughout the breathing cycle. This mechanism is called *gill pumping mechanism*.

The 2nd method of gill ventilation, called *ram ventilation*, consists simply of keeping the mouth slightly open while swimming. The forward movement of the fish keeps the water flowing over the gills.

Many larger fishes use ram ventilation while swimming at moderate to high speeds, but rely on the gill pumping mechanism while still or moving slowly. As speed increases, they can switch from gill pumping to ram ventilation.

Agnathans have a different gill structure & rely on different means of ventilation. For example, hagfishes have a muscular, scroll-like flap called *velum* which moves water in through the single median nostril & over the gills. Lampreys on the other hand expand & contract the branchial area causing water to flow in & out through the multiple gill openings.

Air-breathing fishes

Most air-breathing fishes remain in water all the time (aquatic air breathers). Almost all air-breathing fishes retain the ability to breathe water & are categorized as *bimodal air breathers*. Among these, some only supplement gill respiration when necessary (*facultative air breathers*), whereas others must have access to air or swim to the surface to inspire the oxygen-rich water next to the atmosphere or they will drown (*obligate air breathers*, also called *aquatic surface respiration*). Many of these tropical air-breathing fishes live in freshwaters in which high rates of decomposition further decrease the amount of dissolved oxygen available & a thick forest canopy inhibits aquatic photosynthesis.

Some fishes also have the ability to survive & even remain active while out of the water due to their ability to breathe air (*amphibious air breathers*) during seasonal aestivation, occasional strandings, or intentional excursions into land. These include some tropical freshwater species in habitats that may become dry seasonally & marine intertidal species that leave the water to forage.

Air-breathing organs of fishes fall into three broad categories:

i). those that are derived from the *gut* e.g. lungs, gas bladder, stomach, or intestine;

ii). Structures of the *head* & *pharynx* e.g. modifications of the gills, mouth, pharynx, or opercles; &

iii) *skin*, which can be very effective for gas exchange if it is well vascularized & kept moist

Freshwater air-breathing fishes show a wide array of adaptations for aerial gas exchange. Gills are not suited for aerial respiration because they collapse & stick together when not supported by the buoyancy of water.

Modified gills

Some fishes have modified gill structures that assist with aerial respiration. For example, the modified treelike branches found above gill arches of the walking catfish, *Clarias batrachus,* called *respiratory tress* traps air bubbles & ensure adequate support in air. There is also the complex platelike or much-folded suprabranchial outgrowths of gill arches of anabantoids or labyrinth fishes such as the Giant Guorami & several other perciformes called the *labyrinth organ* which also serve as an accessory breathing organ.

Buccal respiration

Some fishes have well-vascularized area in the buccal cavity, where most of its required O_2 is taken up. Whereas this region has a large surface area, resulting from surface convolutions & papillae, the gills have degenerated over evolutionary time. Example is the electric eel (*Electrophorus electricus*). The electric eel comes out of water at intervals of approximately 1 minute to replenish the O_2 supply in its mouth, & it will drown if it is forcibly kept immersed. Other examples are the Asian climbing perch (*Anabas testudineus*) & the North American mudsucker (*Gillichthys mirabilis*).

Gut respiration

Some fishes notably, tropical catfishes e.g. *Hoplosternum, Ancistrus,* & *Plecostomus* have parts of their gut specialized for O_2 uptake by actually swallowing air.

Lungs & swim-bladder

The South American (*Lepidosiren paradoxa*) & African (*Propterus*) lungfishes are obligate air breathers. The latter forms are adapted to extensive drought conditions, which may completely dry up their environments. By breathing through a small vent to the atmosphere, these fishes have survive extensive dry periods in the mud of dried lakes & rivers in aestivated state. When their habitats refill with water, they surface to inspire air into well-sacculated & heavily vascularized lungs. On the other hand, most of the CO_2 is eliminated directly into the water through vestigial gills. The Australian lungfish (*Neoceratodus forsteri*) is not subjected to such lengthy drought conditions in its natural environment, & will die if denied access to water for extensive periods.

Other facultative air breathers that use a modified swim-bladder for some gas-exchange include bichirs (*Polypterus* spp.), the bowfin (*Amia calva*), gars (*Lepisosteus* spp), & the Pacific Tarpon (*Megalops cyprinoides*).

Aquatic Cutaneous respiration

Though gills typically are identified as the respiratory organ of most fishes, any thin surface in contact with the respiratory medium is a potential site of gas exchange.

For e.g., gas exchange across the skin (cutaneous respiration) can be important to some fishes, particularly in young fish whose gills have not yet developed fully. Thus, whereas most juvenile & adult fishes use the skin for some aquatic gas exchange, early life-history stages such as larvae, may use it almost exclusively for respiration. Significant cutaneous respiration have also been found in some adult fishes.

Gas Transport

The red blood cells of most fishes & other vertebrates contain *haemoglobin*, an oxygen-carrying protein that increases the overall capacity of the blood to transport oxygen. Haemoglobins of different fishes have different affinities for O_2. Fishes with higher affinities for haemoglobin are better adapted to low O_2 environments & vice versa. Different haemoglobins also show different sensitivities to temperature & pH.
In addition to transporting O_2, the blood must pick up the CO_2 that is produced in cellular metabolism & transport it back to the gills for release to the environment.

Metabolic rate

Metabolism is the sum total of all biochemical processes taking place within an organism. In fishes, the rate of oxygen consumption is frequently used as an indicator of aerobic metabolic rate by assuming that no significant anaerobic metabolism takes place during such measurements.
Metabolic rates can be influenced by a variety of factors e.g. age (life stage), body weight, sex, reproductive status, food in the gut, physiological stress, level of activity, season, & environmental temperature. The *standard metabolic rate* is the metabolic rate of a fish while it is at rest & has no food in its gut. However, because almost always have some food in their gut & also rarely remain still while metabolic rates are been measured, the term *routine metabolic rate* is usually used in place of the standard metabolic rate. Measuring this rate at various velocities is commonly used to estimate the standard metabolic rate by extrapolating back to a swimming speed of 0 body lengths per second.
Metabolic rate increases with activity until a fish reaches the point at which it is using oxygen as rapidly as its uptake & delivery system can supply it. This is its *maximum* (active) *metabolic rate*. The difference between the standard metabolic rate & the maximum metabolic rate at any given time is known as the *metabolic scope*, which is a useful index for determining the relative amounts of non-maintenance energy reserves. Fish with better reserves are better able to move, grow, reproduce, resist diseases & parasitism, etc.
In general, fishes tend to have higher metabolic rates at higher temperatures, so as temperature increases, a fish's need for O_2 also increases. Because the availability of O_2 in water decreases with increasing temperature, warm conditions stress most fishes. This stress probably was an important selection factors favouring the evolution of air breathing in many tropical fishes.
Oxygen consumption also increases exponentially with swimming velocity. But it is believed that even this exponential increase may underestimate the true metabolic cost of swimming at high speeds because of the increased use of anaerobic metabolism by swimming muscles at higher velocities.

2.3 Blood Circulation in Fishes

Closed type of circulatory system is found in fishes that typically consists of a single heart as a pump in line with the *branchial* (gill) & *systemic* (body) capillary beds connected by arteries & veins.
The main role of the circulatory system is to transport:

- respiratory gases
- nutrients
- metabolic waste products
- endocrine factors
- heat

All fishes have a 2-chambered *heart* located below the gills consisting of one *atrium* to receive blood & one ventricle to pump it. But fish heart has entry & exit compartments that may also be called chambers so the atrium & ventricle are often described as the *true chambers* while the others called *accessory chambers* (fig. 2.11).

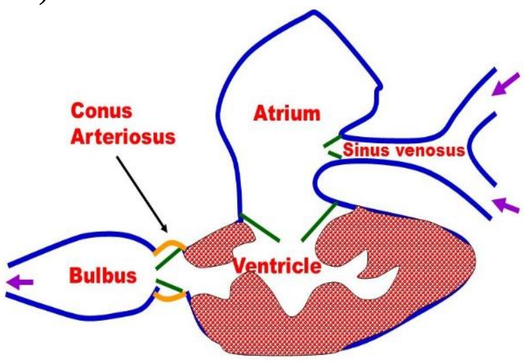

Fig. 2.11 Structure of a fish's heart

The 4 compartments are arranged sequentially:

a). ***sinus venosus*** - is a thin-walled sac with some cardiac muscle that collects deoxygenated blood from the body through the incoming hepatic & cardinal veins. From here, the blood is directed to the atrium in many species through the sinoatrial valve.

b). ***atrium*** is a thick-walled, muscular chamber that sends blood to the more thicker-walled ventricle. Whereas the sinus venosus provides the initial transition from smooth to pulsed flow, the atrium provides the first significant acceleration of blood. The atrium empties its blood ventrally to the ventricle, via the atrioventicular valve.

c). ***ventricle*** is a thick-walled, muscular chamber that pumps blood to the 4^{th} part or outflow tract (OFT). The heavy muscle & efficient geometry of the ventricle provide the main propulsive force for circulatory flow. The ventricular walls may be composed of two layers of muscle: the cortex, & the spongy myocardium. The cortex is relatively dense cardiac muscle (*compact myocardium*) that generally receives oxygen & nutrients from the *coronary artery*. The *cortex* is well-developed in active species & those that lack them are usually sluggish swimmers. The *spongy myocardium* (the more universal inner layer of the ventricular myocardium), consists of a spongy mesh that is supplied with O_2 & nutrients only by the venous blood that it pumps.

d). outflow tract (OFT) – goes to the ventral aorta & consists of the tubular ***conus artiosus*** (elasmobranchs, lampreys, hagfishes, & holosteans), ***bulbus arteriosus*** (teleosts) or both. In contrast to the atrium or ventricle, this part of the heart does not increase the acceleration of blood. It functions as an elastic chamber to dampen the pulses of pressure & intermittent flow from the ventricle into a more continuous flow to the ventral aorta & the gills. The bulbus wall consist only of elastic tissue & layers of smooth muscle & have no valves. But the conus can have many valves (up to 72 in gars).

2.4 Feeding and Digestion in Fishes

Feeding habits - Fishes have different feeding habits. Throughout the long evolution of fishes, there has been unrelenting selective pressure for those adaptations that enable a fish to win the eat-or-be-eaten contest. Certainly the most far-reaching single event was the evolution of jaws. Jaws freed fishes from a largely passive filter-feeding existence, enabling them to adopt a predatory mode of life. Improved means of capturing larger prey demanded stronger muscles, more agile movement, better balance, & improved special senses. More than any other aspect of its life habit, feeding behaviour shapes a fish.

The vast majority of living fishes are predatory (piscivorous) or *carnivorous* fishes & prey on a myriad of animal foods, from zooplankton & insect larvae to large vertebrates. Some deep-sea fishes are capable of eating victims nearly twice their own size—an adaptation for life in a world where meals are infrequent. These typically have large terminal or sub-terminal mouths

& well-developed grasping & biting teeth for handling the prey. Gill rakers if present are typically short or blunt. They have well-developed stomachs with a pyloric caeca. Their intestine is typically short & straight. Many are fast swimmers or sit-&-wait ambushers in which case they may possess camouflage, lures, etc. Predators mainly use vision to hunt for prey, although sharks, eels, & others that feed at night may also rely on smell, taste, & lateral line sense organs to locate their prey.

A 2nd group of fishes, the *herbivores,* eat plants & macroalgae. They feed exclusively on plant matter. They are relatively uncommon among fishes, but are crucial intermediates in the food chain in some habitats. Plant eaters are most common in coral reefs (parrotfishes, damselfishes, & surgeonfishes) & in tropical freshwater habitats (some minnows, characins, & catfishes). They usually have small, often inferior mouths equipped with rasping or nipping teeth. Stomachs are generally absent & if present are thin-walled & elastic. Since plant materials are hard to digest, they may use cellulase & other enzymes produced by the gut microflora, hind gut fermentation by bacteria & protozoans of carbohydrates to short chain fatty acids that can be directly absorbed with the help of bile salts or mechanical processing (trituration) by a muscular gizzard/stomach or mastication by pharyngeal teeth. Generally, herbivorous fish food digestion has the following characteristics:

- diet has low nutritional value
- high fibre content
- involves ingestion & processing of high volumes of food
- requires retention of food in gut for extended period of time

Overall, herbivorous fishes are in the minority in the oceans & temperate freshwaters but common in tropical freshwaters. Most marine herbivorous fishes belong to the order Perciformes. They spend more time eating than carnivorous ones with some feeding continuously. As in phytoplankton feeders, herbivorous fishes normally have longer guts with greater surface area for absorption compared to carnivorous or omnivorous fishes. In other words, fishes that eat hard to digest plant materials, tend to have coiled intestines, which may be much longer than the fish itself. As a rule, the ratio of gut length to body length is greater than 3 in herbivorous fishes, from 1-3 in omnivorous one, & less than 1 in carnivorous ones.

Planktivores crop the abundant microbes of the sea & other water bodies & form a 3rd & diverse group of fishes ranging from fish larvae to basking sharks. But, the most characteristic group of plankton feeders are herring-like fishes (menhaden, herring, anchovies, etc), mostly pelagic (open-sea dwellers) fishes that travel in large schools. Both phytoplankton & smaller zooplankton are strained from the water with sieve-like gill rakers (fig. 2.10C).
Because plankton feeders or filterers are the most abundant of all marine fishes, they are important food for numerous larger but less abundant carnivores. Many freshwater fishes also depend on plankton for food. Feeder typically strain food by swimming with their large mouths open. Phytoplankton filter-feeders just like herbivorous fishes, have exceedingly long guts & many have numerous pyloric caeca compared to the carnivorous fishes. Others feed on large zooplankters (e.g. sharks & rays) &/or passive particle pickers (e.g. deep-sea tripod fishes).
In addition, some fishes are *bottom-feeders* & consume fine, particulate organic matter. Many bottom feeders are *detritivores* & feed on decaying organic matter. Some are also bottom vacuumers or *suckers* (which suck in mud or food-containing material to strain food). They possess small inferior mouths equipped with sucktorial lips, barbels, & sensory pits etc positioned to help detect buried prey. Some detritivores feed on phytoplankton & mud particles

which are triturated by a gizzard. They have either a 1- or 2-part stomach. Those with 2-part stomachs have short intestines & those with 1-part stomachs have longer intestines. Other groups of fishes include *scavengers* e.g. hagfishes that consume dead & dying animals. Some fishes use a *parasitic* mode of feeding in which they consume parts of other live fishes e.g., lampreys, etc.

Within these major categories, fishes can further be categorize as:

1. *euryphagous* – having a mixed diet;

2. *stenophagous* – eating limited assortment of food types; &

3. *monophagous* – consuming only one sort of food

Digestion - Fishes have a complete alimentary canal or gut like other vertebrates (Fig. 2.12).

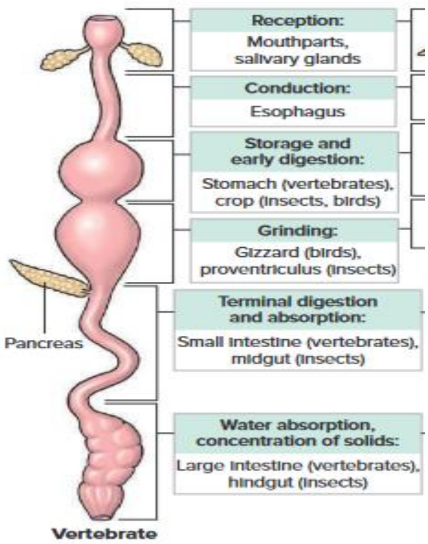

Fig. 2.12 Generalized digestive tract of a vertebrate showing major functional regions of digestive systems.

It consists of:

a) The headgut

- mouth & buccal cavity
- gills (branchial or pharyngeal cavity)

b) The foregut

- oesophagus
- stomach

c) The midgut (the longest portion & may be coiled into complicated loops)

- small intestine with pyloric caeca & related organs such as liver, gall bladder, pancreas

d) Hindgut

- large intestine
- rectum
- anus

<u>Headgut</u> – the first stage involves *ingestion* of food into the mouth which has a variety of adaptations for capturing, handling, & sorting food before entry into the stomach. Fish mouths may be terminal (many fishes), upturned (*Catla* - Cyprinidae), sub-terminal (*Labeo* - Cyprinidae) & ventral (cartilaginous fishes). Fish teeth serve to catch & hold prey & its arrangement & structure are related to the kind of food a fish normally eats. Generally, more active feeders such as carnivore have well-developed sharp teeth & strong jaws. Those that feed on mollusks & crustaceans have short heavy teeth that is strong enough to crush their shells. Planktivores have practically no teeth. Shredding of food is done in the thorax or pharynx where another set of specialized pharyngeal teeth may be found.

<u>Foregut</u> – most fish have a short, wide *oesophagus* that serve as a transition area between the mouth & the rest of the gut (Fig. 2.12). Fishes with long slim body forms e.g. eels have a long oesophagus. Osmoregulation may take place if mucus is present as well as passive & active transport of ions into the blood. The *stomachs* of fishes vary greatly in their anatomical structure due to adaptations to specific foods (Fig. 2.12 & 2.13).

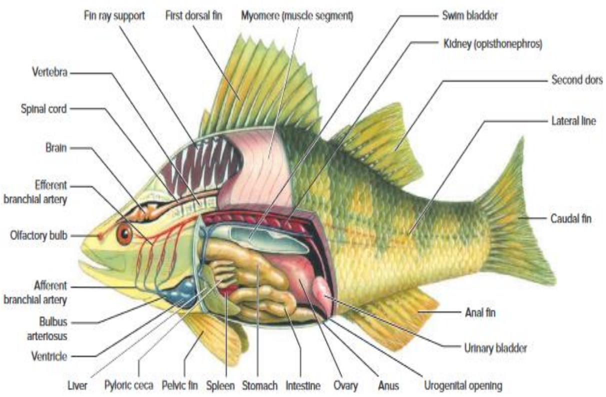

Fig. 2.13 Anatomy of a freshwater teleost.

There are 4 general configurations or shapes of fish stomachs;

- a straight stomach with an enlarged portion;
- a U- or J-shaped stomach;
- a stomach shaped like Y on its side where the stem faces the caudal portion;
- stomachless fish e.g. carps & other cyprinids

Food is stored for a while in the stomach & is gradually processed through other parts of the digestive tract. The stomach is where chemical digestion usually begins. Generally fish that eat relatively small, soft particles have small stomachs whereas fish that eat large food particles or eat at infrequent intervals have larger stomachs. The absence of stomach has been suggested to benefit freshwater (with low salinity or chloride concentration) fish where stomach acids impose added osmoregulation pressure. This is to avoid acidifying large amounts of alkaline food, as in omnivorous fish that eats plant sources, corals, shells, etc.

<u>Midgut</u> – except in several fishes that lack distinct stomachs (fig. 2.13), food proceeds from stomach to tubular intestines.

In the intestines, the digestion process actively continues after initial digestion in the stomach. All fishes have intestines. The length of the intestines vary from as low as 1/5 to as high as 20 times the body length. In general, it tends to be short & straight in carnivores but may be extremely long & coiled in herbivorous & detritivorous. Gut length is directly related to the amount of indigestible material in the food rather than whether the food is of plant or animal origin. Hence, fish that ingest large amounts of detritus have gut lengths similar to those of herbivores. Some fishes possess the *pyloric caeca* (Fig. 2.13). Several functions of the pyloric caeca has been postulated. They include increasing the effective surface area for digestion & absorption; serving as an accessory food reservoir; surfaces for uptake of amino acids & sugars; & is believed to be principally involved in lipid absorption. The intestine of cartilaginous fishes also contains a spiralling portion called the *spiral* or *scroll valve* (fig. 2.14).

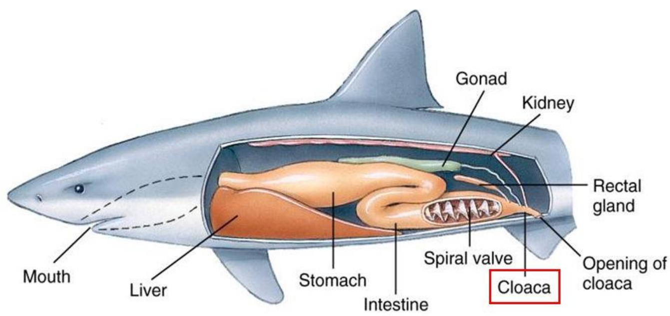

Fig. 2.14 Anatomy of a cartilaginous fish showing a spiral valve in the intestine.

This increases the internal surface area of the intestine & it facilitates efficient food nutrient absorption. These nutrients pass through the circulatory system to be distributed through the body. A *cloaca* is also present in cartilaginous fishes (Fig. 2.14). The pyloric caeca together with the inner walls of the *intestine* & *pancreas*, secrete insulin & other digestive enzymes. The *liver* secretes bile needed for the breakdown of fats. The liver is particularly large & oil-rich in sharks sometimes constituting as much as 20 % of their body weight & may be important in buoyancy.

The liver is also a storage organ for lipids & glycogen.

<u>Hindgut</u> – is an extension of the midgut where digestion has been shown to continue but with a gradually diminishing digestive or absorptive function, an increase mucus secretion, & with a pH near neutral. Undigested material exits through the **anus**.

2.5 Reproduction in Fishes

In a group as diverse as fishes, it is no surprise to find extraordinary variations on the basic theme of sexual reproduction. Most fishes favour a simple theme: they are dioecious, with external fertilization & external development of their eggs & embryos (*oviparity*). However, *ovoviviparous* species & several other teleosts, develop in the ovarian cavity of the mother, then are born. Some *viviparous* sharks develop a kind of placental attachment through which the young are nourished during gestation. Oviparity is the most common mode of reproduction in fishes.

Many marine fishes are extraordinarily profligate egg producers. Most have *megalecithal eggs* with *meroblastic cleavage*. Males & females come together in great schools & release vast numbers of gametes into the water to drift with currents. Unlike the minute, buoyant, transparent eggs of pelagic marine teleosts, those of many near-shore & bottom-dwelling (benthic) species are larger, typically yolky, non-buoyant, & adhesive. Some bury their eggs, many attach them to vegetation, some deposit them in nests, & some even incubate them in their mouths. Many benthic spawners guard their eggs. Intruders expecting an easy meal of eggs may be met with a vivid & often belligerent display by the guard, which is almost always male. Freshwater fishes usually produce non-buoyant eggs. Some provide no parental care & simply scatter their myriads of eggs among weeds or along the sediment. Freshwater fishes that do provide egg care, produce fewer, larger eggs that have a better chance for survival. *Sequential hermaphrodites* are species that initially mature as one sex, & then change to the other sex. In some species, individuals begin as females, but then become males & vice versa. Some species are *synchronous hermaphrodites*, which have both functional testes & ovaries at the same time (but only cross-fertilize). A few fish species consist only of females. Many of these e.g. the Amazon molly, *Poecillia formosa*, exhibit a form of *ameiotic parthenogenesis* called *gynogenesis*, in which a sperm of a different species initiates egg development, but does not contribute genetic material (p. 136). Most fishes undergo ***direct*** development except in *Anguilla* (Anguillidae, a family of ray-finned fish that contains the freshwater eels) in which development is *indirect* & consists of elver (young eels) or *leptocephalus* larval form. *Indirect development* is typical for *fish* with numerous small eggs, little yolk & in most cases, no parental care & it is especially common in pelagic marine species. With increasing parental care — from egg scatterers to brood hiders to external & internal bearers — the eggs become yolkier & less numerous*; parental care* is found in some fishes e.g. *Oreochromis* (Cichlidae).

Most fishes hatch as larvae, carrying a semi-transparent sac of yolk, which provides their food supply until the mouth & digestive tract have developed & the larvae can feed on their own. After a period of growth a larva undergoes a metamorphosis, especially dramatic in many marine species, including eels. Body shape is refashioned, fin & colour patterns change, & the animal becomes a juvenile bearing the unmistakable definitive body form of its species.

Growth is temperature-dependent. Consequently, fishes living in temperate regions grow rapidly in summer when temperatures are high & food is abundant but nearly stop growing in winter. Annual rings in scales, otoliths, & other bony parts reflect this seasonal growth (Fig. 2.15), a distinctive record of convenience to fishery biologists who wish to determine a fish's age.

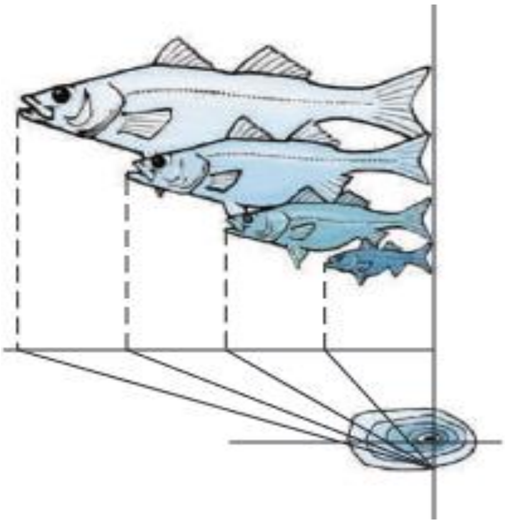

Fig. 2.15 Fish scales disclose seasonal changes in growth rate. Growth is interrupted during winter, producing year marks (annuli). Each year's increment in scale growth is a ratio to the annual increase in body length. Otoliths (ear stones) & certain bones can also be used in some species to determine age and growth rate.

Unlike birds & mammals, which stop growing after reaching maturity, most reproductively mature fishes continue to grow, though more slowly, for as long as they live.

Lifespan in fishes may vary from a little over 1 year to over 150 years. A few die relatively soon after a single spawning (a phenomenon termed *semelparity*), but individuals of most species normally produce for more than one season (*iteroparity*). Fewer than 1 % of fishes are semelparous, & these tend to be diadromous species.

2.6 Nervous & Sensory Systems in Fishes

Though vertebrates have the most complex & advanced nervous system of any animal group, fish typically has small brains compared to a similar sized bird or mammal. But, some have relatively large brains, most notably mormyrids & sharks, which have brains about as massive relative to body weight. At the heart of the system is the central nervous system (CNS), consisting of the *brain* & the *spinal cord* – which coordinates & integrates all bodily activities & stores information. It is protected by a cartilaginous or bony skull. Nerves connect the CNS with various organs of the body & with sense organs that receive information from the surroundings. Information received by the CNS is sent to the brain in the form of nerve impulses.

The brain is divided into several regions known to serve as centres for particular functions such as olfaction, vision, etc (Fig. 2.16).

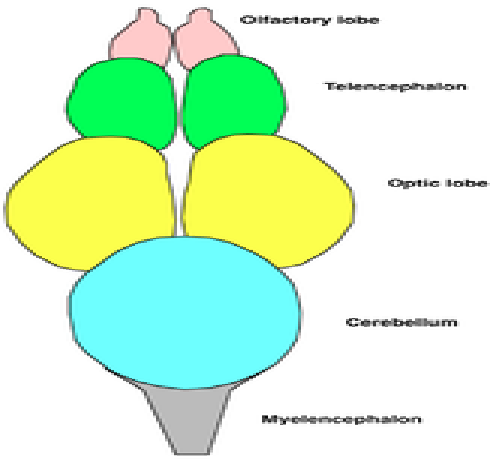

Fig. 2.16 Dorsal view of a fish's brain of the

At the front are the *olfactory lobes*, a pair of structures that receive & process signals from the nostrils via the 2 olfactory nerves. Similar to the way humans smell chemicals in the air, fish smell chemicals in the water by tasting them. The olfactory lobes are very large in fish that hunt primarily by smell, such as hagfish, sharks, & catfish. Behind the olfactory lobes is the 2-lobed *telencephalon*, the structural equivalent to the cerebrum in higher vertebrates. In fish the telencephalon is concerned mostly with olfaction. Together these structures form the ***forebrain***. The forebrain is connected to the ***midbrain*** via the *diencephalon* (below the optic lobes). The diencephalon performs functions associated with hormones & homeostasis. The *pineal body* lies just above the diencephalon & it functions in detecting light, maintaining circadian rhythms, & controlling colour changes. The midbrain or *mesencephalon* contains the 2 optic lobes which are very large in species that hunt by sight, e.g. rainbow trout & cichlids.

The ***hindbrain*** (*metencephalon*) is particularly involved in swimming & balance. The *cerebellum* is a single-lobed structure that is typically the biggest part of the brain. Hagfish & lampreys have relatively small cerebella, while the mormyrid cerebellum is massive & apparently involved in their electrical sense.

The ***brain stem*** (*myelencephalon*) is the brain's posterior. As well as controlling some muscles & body organs, in bony fish at least, the brain stem governs respiration & osmoregulation.

Most fishes have a highly developed sense of ***smell***, which they use to detect food, mates, & predators, & sometimes to find their way home. For instance, Salmon (*Onchorhynchus*) which lives as adults at sea but reproduce in freshwater, use olfaction to find the stream where they were born years earlier. Evidence suggest that they "memorize" the sequence of smells on their way out to the sea. The *olfactory lobes* or sacs are the sense organs involved in these activities. Each sac opens to the outside through one or two openings or *nostrils*. The sense of smell is particularly well-developed in sharks which are able to detect blood & other substances in very low concentrations in water.

Fish detect other chemical stimuli with ***taste*** buds located in the mouth & on lips, fins, & skin. Taste buds are also found on *barbels* which are the whisker-like organs near the mouth of many bottom feeders such as the goat fish (*Pseudopeneus*).

Vision is an important sensory system for most species of fish. Fish eyes are similar to terrestrial vertebrates, but have a more spherical lens. Unlike land vertebrate which change focus by changing the shape of the lens, fish normally adjust focus by moving the lens closer to or further from the retina. Their retinas generally have both rod cells & cone cells (for *scotopic* & *photopic* vision), & most species bony fishes have *colour vision* but most cartilaginous forms have little or none. Some sharks have a distinct nictitating membrane that can be drawn across the eye to reduce brightness. Some fish can see ultraviolet & some can see polarized light. Fish vision shows adaptation to their visual environment, for e.g. deep sea fishes have eyes suited to the dark environment.

Fishes have specialized ***hearing*** or sound-detecting apparatus that is effective underwater called *lateral lines.* It consists of a system of small canals lined with sensory cells which are sensitive to sound vibrations. The lateral line system picks up vibrations resulting from the swimming of other animals, & water displacement caused by sound waves. It allows fish to avoid obstacles, orient to currents, & keep their position in a school. Fishes can also perceive sound waves with their inner ears with calcareous ear stones or *otoliths* which are paired hearing organs located to the sides of the brain just behind the eyes. Changes in the position of many fishes are detected by shifts in the position of the otoliths. Some fishes also have the *Weberian organ* (3 specialized vertebral processes, Weberian ossicles) that transfer vibrations in the swim bladder to the inner ear. Sharks may have a sharp sense of hearing & can possibly hear prey many miles away. Cartilaginous fishes also have a sense organ called the *Ampullae of Lorenzini* that can detect weak electrical currents. This system has been shown to help them detect prey – a kind of electrical sensing device. It may also assist in navigation as a sort of electromagnetic compass or as a current detector. This helps sharks find prey. The shark has the greatest electrical sensitivity of any animal. Sharks find prey hidden in sand by detecting the electric fields they produce. Ocean currents moving in the magnetic field of the Earth also generate electric fields that sharks can use for orientation & possibly navigation. Electric fish can produce weak electric currents which they use in navigation & social communication.

2.7 Hydromineral Balance in Fishes

Osmoregulation is the active regulation of the osmotic pressure of an organism's body fluids, detected by osmoreceptors, to maintain the homeostasis of the organism's water content. Two major types of osmoregulation involve osmoconformers & osmoregulators.

Osmoconformers match their body osmolarity to their environment actively or passively. *Osmoregulators* on the other hand, tightly regulate their body osmolarity, which always stays constant, & are more common in the animal kingdom. They also actively control salt concentrations despite the salt concentrations in the environment. An example is freshwater fish.

Freshwater is an extremely dilute medium with a salt concentration much below that of the blood of freshwater fishes. Water therefore tends to enter their bodies osmotically, & salt is lost by diffusion outward. Although the scales and mucous-covered body surface is almost totally impermeable to water, water gain & salt loss do occur across thin membranes of the gills. Freshwater fishes are hyperosmotic regulators with several defenses against these problems (Fig. 2.17).

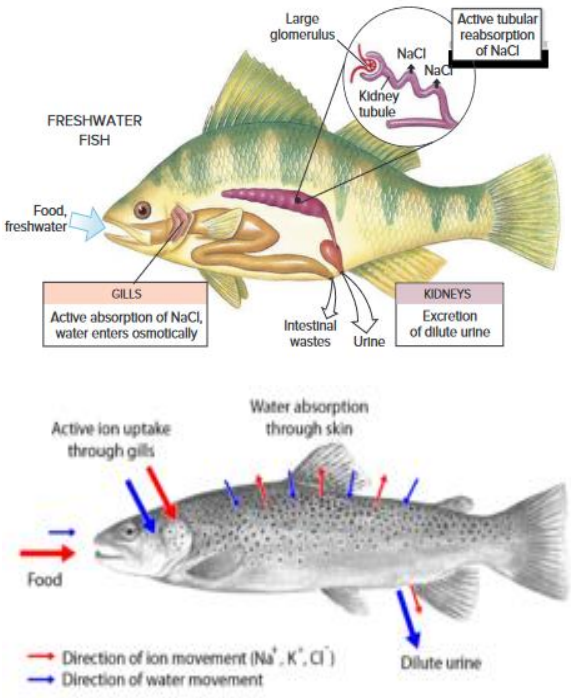

Fig. 2.17 Osmotic regulation in freshwater bony fishes. A freshwater fish maintains osmotic & ionic balance in its dilute environment by actively absorbing NaCl across the gills (some salt is gained with food). To flush out excess water that constantly enters the body, the glomerular kidney produces a dilute urine by reabsorbing NaCl.

First, excess water is pumped out by the kidneys, which are capable of forming very dilute urine. Second, special salt-absorbing cells located in the gill epithelium actively move salt ions, principally sodium and chloride, from water to the blood.

This absorption, together with salt present in the fish's food, replaces diffusive salt loss. These mechanisms are so efficient that a freshwater fish spends only a small part of its total energy maintaining itself in osmotic balance.

Marine bony fishes are hypoosmotic regulators that encounter a completely different problem. Having a much lower blood salt concentration than seawater around them, they lose water and gain salt. A marine teleost fish quite literally risks drying out, much like a desert mammal deprived of water. To compensate for water loss, a marine teleost drinks seawater (Fig. 2.18).

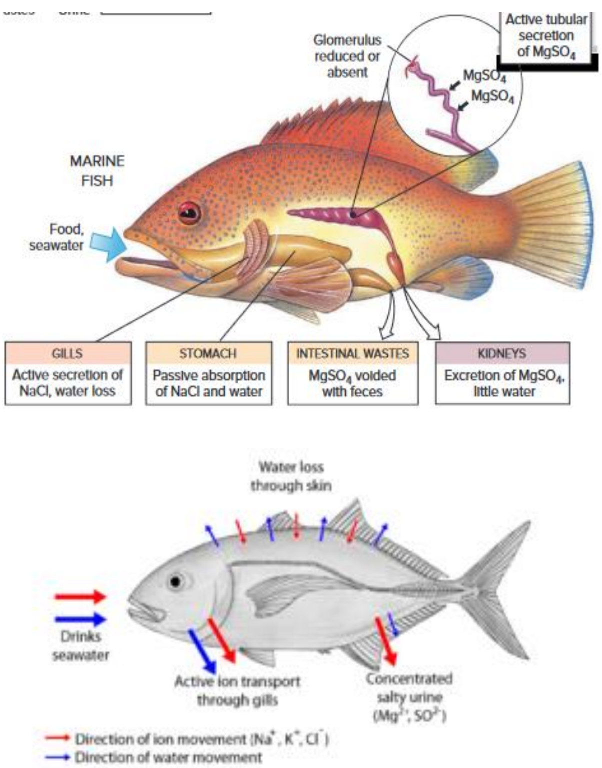

Fig. 2.18 Osmotic regulation in marine bony fishes. A marine fish must drink seawater to replace water lost osmotically to its salty environment. NaCl & water are absorbed from the stomach. Excess NaCl is actively transported outward by the gills. Divalent sea salts, mostly MgSO4, are eliminated with faeces & secreted by the tubular kidney.

Excess salt accompanying the seawater is disposed of in multiple ways. Major sea salt ions (Na^+, Cl^-, & K^+) are carried by the blood to the gills, where they are secreted outward by special salt-secretory cells. The remaining sea salt ions, mostly Mg, sulfate, & Ca, are voided with faeces or excreted by the kidneys.

Unlike a freshwater fish's kidneys, which form urine by the usual filtration-resorption sequence typical of most vertebrate kidneys, a marine fish's kidneys excrete divalent ions by tubular secretion. Because very little if any filtrate is formed, the glomeruli have lost their importance & disappeared in some marine teleosts. Pipefishes and frogfishes are examples of "aglomerular" marine fishes.

NB: Perhaps 90% of all bony fishes are restricted to either a freshwater or a seawater habitat because they are incapable of osmotic regulation in the "wrong" habitat i.e. they are *stenohaline*. Most freshwater fishes quickly die if placed in seawater, as do marine fishes placed in freshwater. But, some 10% of all teleosts can pass back & forth with ease between both habitats showing tremendous ability to effectively osmoregulate across a broad range of salinities. These *euryhaline* fishes (Gr. eurys, broad, + hals, salt) are of 2 types: those such as many flounders, sculpins, & killifish that live in estuaries or certain intertidal areas where salinity fluctuates throughout the day; & those such as salmon, shad, & eels, that spend part of their life cycle in freshwater & part in seawater.

In contrast to bony fish, & with the exception of the coelacanth, the blood & other tissue of sharks & Chondrichthyes is generally isotonic to their marine environments because of the high concentration of urea & trimethylamine N-oxide (TMAO), allowing them to be in osmotic balance with the seawater. This adaptation prevents most sharks from surviving in freshwater, & they are therefore confined to marine environments. A few exceptions exist, such as the bull shark, which has developed a way to change its kidney function to excrete large amounts of urea.

2.8 Behavioural Adaptations in Fishes

Fish have several anatomical & physiological adaptations. But they also exhibit *behavioural* adaptations such as territoriality, schooling, migrations, etc which is basically due to their well-developed nervous system which enables them to respond to their environment in complex ways.

Fish use behaviour to adapt to such physical factors as light, currents, finding food, shelter, & avoiding enemies, etc. They also display a variety of behaviours related to courtship & reproduction.

Territoriality – some fishes are known to establish territories (home areas they defend against intruders). Some defend such territories during reproduction but others have more or less permanent territories that they use for feeding & resting or as shelter. It is thought that fishes often guard territories to ensure that they have enough food & other resources. Thus, territoriality is common in crowded environments where resources are most likely to be in short supply. For e.g. coral reef damselfishes are famous for fiercely defending their territories, often attacking fishes many times their size or even divers. Fishes often use aggressive behaviour in the form of bluffing instead of actual fights e.g. raised fins, open mouth, rapid dartings, sound productions, etc.

Shoaling & schooling – A *shoal* is a group of fish swimming together. *Schooling* is a behaviour within the shoal where fish can be seen performing various manoeuvers in a synchronized manner. Some e.g. herrings, sardines, mullets, & some mackerels, school throughout their lives. Others are part-time schoolers especially as juveniles or during feeding. Most cartilaginous fishes are solitary but some such as hammerhead sharks, mantas, & other rays sometimes travel in schools. It is estimated that over 4000 species of marine & freshwater species school as adults. Members of schools are typically all about the same size. Stationary schools common around coral reefs, kelp beds, rocks, & shipwrecks, however, may include members of different sizes or even different species. Several reasons have been suggested for schooling in fishes. These include protection against predators, increase the swimming efficiency, feeding, mating, etc.

Migration is the regular mass movement from one place to another. Fishes in all aquatic environments may migrate phenomenal distances & use various homing mechanisms. It can be once a day, once a year, or once in a life time. Some migrations are between on & offshore areas or up & down the vertical column of the open water. But the most spectacular migrations are the *transoceanic* journeys made by tunas, salmon, & other fishes. Most migrations seem to be related to feeding &/or reproduction. Even more dramatic are the migrations between the oceans & freshwater undertaken by some fishes that are dependent on freshwater for reproduction. *Anadromous* fishes spend most of their time at sea but migrate to freshwaters to breed e.g. sturgeons, some lampreys, smelts, etc. But the best known anadromous fishes are the salmons. The mechanism of such migrations have been severally hypothesized & include the use of:

- currents
- salinity
- temperature
- orientation to polarized light
- the sun
- earth's magnetic field
- other water features

Salmons are known to find their stream home with remarkable accuracy, the result of a king of chemical memory. The ability of an animal to find its way back to a home area is known as *homing behaviour*. *Catadromous* fishes feature a migratory pattern opposite to that of *anadromous* ones i.e. they breed at sea & migrate into rivers to grow & mature e.g. freshwater eel (*Anguilla*). Before & during the period of the migration, they make anticipatory changes in serum ion content, body colour, & visual pigments. Fishes which migrate between freshwater & the oceans are referred to as *diadromous* fishes. A 3rd category of diadromous fishes called amphidromous fishes migrate between the oceans & the freshwaters but do not do so for breeding purposes.

Colouration: Different colours are found in fishes & can be used as *camouflage*. Some fishes are very brightly coloured especially those living in the tropics. The coloured pigments in fishes are found in special cells called *chromatophores*. Fishes also have *structural colours* that result when a special surface reflects only certain colours of light. Most structural colours of fish are the results of crystals contained in special chromatophores called *iridophores* that act like tiny mirrors. The iridescent shiny quality of many fishes is produced by structural colours in combination with chromatophores.

Colours can tell a lot about fishes e.g. some change colour with their mood or reproductive condition. They may also use colour to advertise themselves in what is known as *warning colouration* e.g. the colourful bar-tailed lionfish advertises spines that contain a powerful venom capable of killing a human. *Cryptic colouration* (camouflage), i.e. blending with the environment to deceive predators or prey is a common adaptation e.g. the stonefish (*Syananceia verrucosa*). Others such us some flatfishes, blennies, sculpins, & rockfishes can change colour to match their surroundings. Another use of colour is *disruptive colouration* – the presence of stripes, bars, or spots that help break up the outline of a fish e.g. the butterfly fish, *Chaetodon trifasciatus* that lives among coral reefs. Thus, fishes use disruptive colouration to prevent detection or recognition by potential predators or prey.

But, open water fishes & many shallow-water predators are rarely colourful. Most of them have silver or white bellies in shape contrast to dark backs. This distinctive colour pattern, known as *countershading*, is a form of disguise in open water. When viewed from below, the white belly blends with the bright light coming from the surface. The dark back blends into the water's colour as seen from above. Deep-water fishes also use colour for concealment. They tend to be black or red – colours which are hard to see in deeper waters.

Bioluminescence - Deep sea fishes exhibit this phenomenon e.g. *Blepherodon*, etc. It is the process by which energy from a chemical reaction is transformed into light energy. In deeper parts of the ocean, light is absent & vision is not useful for locating prey. There is however, a major exception to this rule. Many marine animals including some species of fish emit light. The light is usually a product of a chemical reaction that takes place in specialized cells (*photocytes*) or organs (*photophores*). When a substance known as luciferin reacts with O_2 in the presence of the enzyme luciferase, the chemical product gives off blue-green light. Bioluminescence is a widely distributed property among marine organisms is produced by specialized structures (*intracellular luminescence*) as noted already or by symbiotic bacteria (*intercellular luminescence*). Note that bioluminescence is difference from *phosphorescence* or *fluorescence* in which light involves energy received from other sources causing emission. Bioluminescence is mainly a marine phenomenon. Reasons attributed to bioluminescence include:

- confusing predators
- finding mates
- camouflage

UNIT THREE

FISH POPULATION DYNAMICS, EXPLOITATION, & THREATS

3.1 Introduction

A ***fishery*** is an area with an associated fish or aquatic population which is harvested for its commercial or recreational value. Fisheries can be wild or farmed.

Population dynamics describes the ways in which a given population grows & shrinks over time, as controlled by birth, death, & migration. Fish population dynamics may be defined as the fluctuation in number of fish in a population & the factors responsible for these changes including the rate of loss & replacement of individual in the population & any other regulatory forces tending to keep the number in population steady at least to prevent excessive changes. It is the basis for understanding changing fishery patterns & issues such as habitat destruction, predation and optimal harvesting rates. The population dynamics of fisheries is used by fisheries scientists to determine sustainable yields.

The basic accounting relation for population dynamics is the birth, immigration, death, emigration (**BIDE**) model, shown as:

$$N_1 = N_0 + B - D + I - E$$

where N_1 is the number of individuals at time 1, N_0 is the number of individuals at time 0, B is the number of individuals born, D the number that died, I the number that immigrated, & E the number that emigrated between time 0 & time 1. While immigration & emigration can be present in wild fisheries, they are usually not measured. Thus, a fishery population is affected by 3 key dynamic rate functions, viz:

a) Birth rate
b) Growth rate
c) Mortality rate

If these rates are measured over different time intervals, the *harvestable surplus* (i.e. number of individuals that can be harvested from the population without affecting long term stability or average population size) of a fishery can be determined. The harvest within the harvestable surplus is called *compensatory mortality*, where the harvest deaths are substituting for the deaths that would otherwise occur naturally. Harvest beyond that is *additive mortality*, harvest in addition to all the animals that would have died naturally.

Life history of a fish is the descriptive the complete life cycle of a fish. The life history of fisheries species & the size of the stock must be understood before sensible planning can be done regarding fisheries management. The population contains unique & dynamic features e.g. birth rates, death rates, age structure, phenotypic plasticity, & gene pool. These attributes, which are shaped by the environment can be collectively summarised under the term *life-history traits* & their configuration determines the resistance of the population to external disturbance & stress.

The concept "life history" of a stock comprises optimally a comprehensive description of the various phases through which individuals of the population pass, i.e. from birth to maturity. This includes *survival*, *mortality rate*, *fecundity* & expectation of *life span duration* linked to the general environmental conditions. The full set of this information will provide not only a complete description of the population ecology but will, in theory, also enable one to deduce the controlling factors that determine its population dynamics.

3.2 Population dynamics & fisheries terms and concepts

a) Birth rate or ***recruitment*** usually refers to the age a fish can be caught & counted in nets. It is the amount of young fish of a year-class added to the exploitable stock each year due to growth &/or migration into the fishing area. Simply put, it is the number of new young fish that enter a population in a given year. The size of fish populations can fluctuate by orders of magnitude over time, & 5 to 10-fold variations in abundance are usual. This suggests that fluctuations in reproductive & recruitment success are prime factors behind fluctuations in abundance. Annual fluctuations often seem random, & recruitment success often has a poor relationship to adult stock levels and fishing effort.

The recruitment problem is the problem of predicting the number of fish larvae in one season that will survive & become juvenile fish in the next season. It has been called "the central problem of fish population dynamics" & "the major problem in fisheries science". Fish produce huge volumes of larvae, but the volumes are very variable and mortality is high. This makes good predictions difficult.

b) ***Growth rate*** measures the growth of individuals in size & length. This is important in fisheries where the population is often measured in terms of *biomass*. *Growth* in its broadest sense, i.e. a change in biomass due to both change in numbers from recruitment & mortality & increment in weight. There are 2 types of growth to consider:

1. Population growth in numbers or weight
2. Individual growth in length or weight

Population growth depends on the combination of natality (birth rate), mortality rate & immigrations/emigrations, & when weight is considered, also on the sum of individual growth increments.
Individual growth is within wide limits determined genetically, but is influenced by several factors:
• Food availability (quality/quantity)
• Temperature (fish are poikilotherms)
• Variable allocation of surplus energy (somatic or gonadal tissue growth &/or for locomotion & maintenance)
• Sexual differences
• Density & size distribution (hierarchical behaviour and/or competition)

Approaches to growth estimation
• Direct observations from experiments of either confined or tagged/recaptured fish.
• Length-at-age data. With precise and valid age determination & a large unbiased random sample, this is the most satisfactory method.
• Back calculations from analysis of hard parts, using the ratios between the lengths of fish & the spacing between the growth zones of the otoliths, scales etc.
• Estimating average length at arbitrary age from length frequency analysis with known or assumed periodicity. This is often the only alternative when dealing with tropical or other stocks not exhibiting a regular zone pattern in their hard parts.

Growth parameters
There are several different definitions of growth expressed as rates. The simplest assumes a linear growth rate within the time interval of concern [t_1, t_2]. These include the following:
i) Absolute growth rate is the change in weight/length per unit time, usually per year.

$$g(t) = \frac{W_2 - W_1}{t_2 - t_1} = \frac{\Delta W}{\Delta t}$$

ii) Relative growth rate is the change in weight/length per unit time relative to start value in percent.

$$g(t) = \frac{\frac{W_2 - W_1}{t_2 - t_1}}{W_1} \cdot 100$$

iii) Instantaneous growth rate:
When studying growth over shorter time intervals (less than one year), & when studying juveniles, one usually finds that the growth rate is exponential & can be

expressed as an instantaneous rate as follows:

$$G = \frac{\ln(W_2) - \ln(W_1)}{t_2 - t_1}$$

When this rate is multiplied by 100, it is called the specific growth rate & it is given in %.

Regulation of Fish Recruitment & Growth

A number of hypotheses have been formulated to explain fluctuations in adult abundance due to differences in the recruitment & growth of young fish, & none are mutually exclusive. Some of these include:

1. Starvation hypothesis**.** If there is not enough planktonic food in the sea, larval fish mortality will increase & few, if any, will survive to become adults (Fig 3.1).

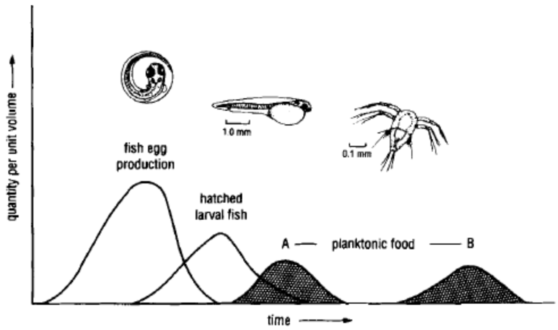

Fig. 3.1 The critical phase of larval fish survival requires that planktonic food must be present in the water at the time of hatching (time A). If the food organism occur later (time B) all the fish larvae from one particular spawning will die from starvation

This is concerned with what is called the *critical phase* in the life of fish. This phase begins immediately after hatching when the young larvae still have the remnants of the yolk sac on which to subsist. In order to survive, the larvae must begin to eat sufficient planktonic food before the yolk is exhausted. This means that the larvae must hatch at a time in phase with abundant plankton concentrations. If a larval fish hatches too early, or too late, relative to its food supply, it will die (Fig. 3.1).

2. Predation hypothesis**.** Predators, including larger fish & some carnivorous zooplankton, may consume large numbers of both larval & juvenile fish. Heavy predation results in few young surviving to become adults (Fig 3.2a & b).

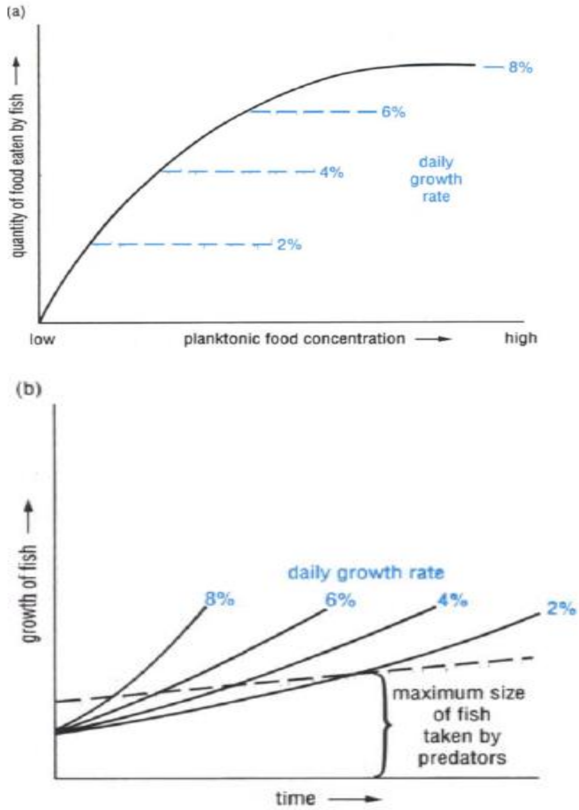

Fig 3.2 (a) A hypothetical relationship showing how the availability of plankton food affects food intake of fish & resultant growth rate of fish (b) The growth rates from (a) are shown over time together with the size at which maximum predation of fish occurs. Juvenile fish that grow slowly (2 % day-1) are exposed to predation over a longer period of time & hence have lower survival than faster-growing (e.g. 8% day-1) fish.

The hypothesis assumes that larger organisms have fewer predators & are also better able to escape from predatory attacks. Thus, if larval or juvenile fish can grow fast enough, mortality will be lessened & more fish will survive. This is illustrated in Figure 3.2 (a &b) which also shows that this hypothesis is partly dependent on the planktonic food supply, although here food concentrations are not restricted to the critical phase as in Figure 3.1.

3. <u>Advection hypothesis</u>**.** Physical oceanographic processes may transport the young fish away from their nursery areas to unfavourable environments where they will not survive. This hypothesis can be illustrated in a number of different ways depending on the type of fish species e.g. plaice (*Pleuronectes platessa*) tend to spawn on specific sites that are associated with favourable nursery areas to which the larvae are carried by currents. This is shown in Fig. 3.3 for a population that spawns in the southern North Sea. In some years, however, strong storm activity may disrupt the current system that carries larval fish to their nursery area, & plaice larvae may then be transported to areas unfavourable for survival.

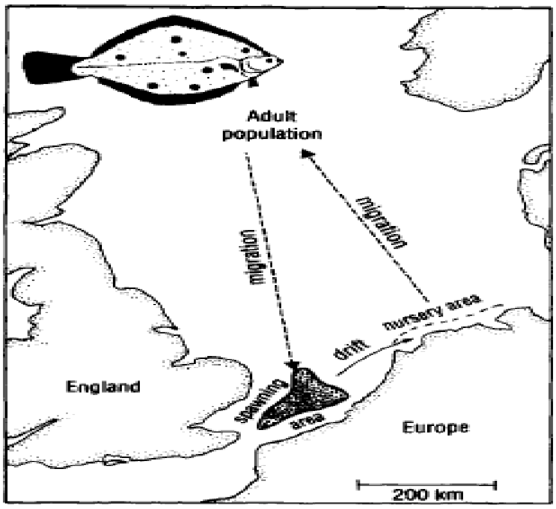

Fig 3.3 The larval drift & migrations of plaice in the North Sea. Larvae hatch in the spawning area, then drift northeast to the food-rich nursery area. They remain in the nursery area for their first year of life, growing from 1.5 cm to 20 cm in length before migrating to the northwest

4. <u>Growth hypothesis</u>**.** The growth hypothesis is based on the consequences of fish growth being inhibited by either biotic (e.g. food, etc) or abiotic (e.g. temperature, etc) factors. Note that, the maximum size attained by fish at the time of harvest, multiplied by the number of fish captured, gives the biomass yield to the fishery. Size & numbers of fish are also used to establish fish quotas in terms of allowable tonnage. Numbers are determined by survival (see hypotheses 1-3 above), & size is determined by growth. This hypothesis is derived from the growth curve shown in Fig. 3.4.

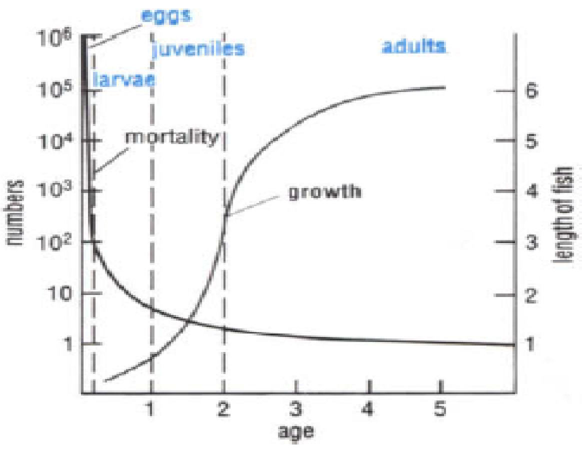

Fig 3.4 Idealized population mortality & individual growth curves for a species of teleost fish during its life cycle from egg to adult. Arbitrary units of age & length & variable time intervals (indicated by dash lines) for life stages

Growth is dependent on a variety of parameters affecting the rate of growth & the length (size) at maturity. For instance, growth rate is directly proportional to temperature, but size at maturity is inversely proportional to temperature. Thus, an increase in temperature, which is governed by the physical climate of the water body, can have the dual effect of producing more rapidly growing fish, but ones that are smaller at maturity.

In addition, the growth efficiency of fish varies with the type of food consumed. Prey with high protein content (e.g. copepods) produce faster growth than foods with very high water content & low protein (e.g. small ctenophores).

Growth is further influenced by the metabolic costs associated with particular types of prey; e.g., a predator that has to chase its prey would have a higher metabolic cost than one that filters its food. Thus, as prey type changes (due to changes in the ecosystem), the growth efficiency of fish will also change, & this will affect the growth curve (Fig. 3.4).

In summary, each of the 4 hypotheses discussed above can be shown to have some experimental support. But, none can be shown at present to be the only mechanism determining the fluctuations in the abundance of fish, & it is likely that more than one mechanism is operable. It is also possible that some other factors, such as *fish disease*, may at times be important in regulating recruitment of young to adult stocks. In order to improve the management of fisheries, these mechanisms need further research through experimentation, field data, & ecosystem computer models.

c) ***Mortality*** includes harvest mortality & natural mortality. Natural mortality includes non-human predation, disease & old age. In contrast to growth & reproduction, which can be looked upon as individually based processes, the concept of mortality applies to the population level in stock assessment.

The key parameters used when describing death are called the *mortality rates* i.e. the chance of dying as a function of time is, other things being equal, closely correlated to the predictability of the environment, i.e. the frequency of random fluctuations that somehow endangers the survival of the population. The first thing to recognise is that the events that cause variation in the year-class strength in fish occur during the first year of life, because it is the youngest stage that suffers most of the mortality. Mortality rates tend to be size specific, with rates being highest during the egg and yolk-sac stages & declining thereafter. In stock assessment, mortality rates are normally considered only for the adult stages of the population, where the variation tends to be much less. Of particular importance in fisheries stock assessment - as a key input for management measures - is the level of fishing mortality that affects the stock in relation to the natural mortality.

The factors contributing to mortality can be divided into 2 main categories, although it must be stressed that this subdivision is purely for simplification:

• Abiotic factors **(**physical environment)
- temperature
- salinity
- oxygen
- light
- stability & disturbances
- pollution

• Biotic factors (other organisms)
- predation
- cannibalism
- density
- starvation
- competition
- diseases

Each of these factors has a different importance at various stages in the life cycle (Fig 3.5).

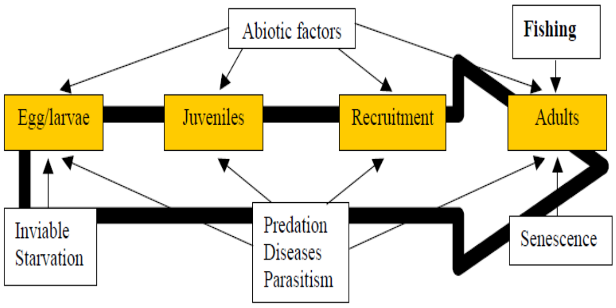

Fig. 3.5 Impact of different factors on different stages of fish life history

In general, predation is considered the most naturally important factor, at least at the larvae stage & older. For the adult stages, the fishing mortality is often the most important factor, often surpassing predation for heavily fished stocks.

Quantitative measures of mortality

Over a given time interval, a proportion of the fish alive (N_1) at the beginning of the time interval (t_1) will die by various natural causes or by fishing pressures, while the rest will survive (N_2) until the end of the time interval (t_2). Mathematically, one has

$$N_1 = P + D + O + C + N_2$$

where P,D,O = numbers dying from predation, diseases, and other causes, & C = numbers caught by fishing.

There are 2 ways of expressing the above-mentioned mortality:

i) Relative mortality -The most obvious & easily understood expression is represents the mortality as a fraction or a percentage of the initial number; for example, the total death rate over time interval [t_1, t_2] is defined as

$$Z(t_1,t_2)=\frac{N(t_1)-N(t_2)}{N(t_1)}$$

Thus, the ratio between the numbers of individuals that have left the cohort & the initial number.

The closely related quantity, *survival*, is defined as:

$$S(t_1,t_2)=1-Z(t_1,t_2)=\frac{N(t_2)}{N(t_1)}$$

i.e. the ratio between the numbers of individuals that were present at time t_2 and the initial number at time t_1. The possible values of mortality & survival are from 0 to 1, or if expressed in percentages, from 0 to 100.

ii) Instantaneous mortality (F) - is simply defined as the fraction of the average population taken by fishing. F is also called the instantaneous rate of fishing mortality, i.e. the rate at which fish are dying due to fishing, and therefore expressed per time unit, usually per year.

It applies to mortality rates applied over a very short period of time (*dt*), where the numbers in the population do not change significantly. In that case, the numbers dying from any one cause are not affected by the numbers dying from any other cause & the deaths will be proportional to the instantaneous rates. A decrease in the population numbers can then be considered as proportional to the total mortality coefficient *Z* & written as:

$$\frac{dN}{dt}=-Z\cdot N_t$$

Integrating the above equation, one obtains:

$$\ln(N_t)=-Z_t+\textbf{constant}$$

$$N_t=N_0\cdot e^{-Zt}$$

where N_0 = numbers alive at time t = 0.

This is the traditional model for describing mortality in a fish stock (fishing or natural causes), the so-called *exponential decay model*.

In this form, the total mortality Z, is then the sum of all the other coefficients, so that

$$Z=F+M$$

F = instantaneous rate of fishing mortality
M = natural mortality

Fishing Effort (f): It is the total time spent for fishing or the total number of gears used for specific period of time in a particular place. This can be expressed in number of boats deployed, the number of fishermen working, the number of boat-days or time spent at fishing, the number of meters of gill-net set, the number of hooks set, the number of pulls or shots made, etc. A good measure of the fishing effort will be approximately proportional to the amount of fish captured. Different measures are appropriate for different kinds of fisheries e.g., the fishing effort exerted by a fishing fleet in a trawl fishery might be measured by summing the products of the engine power for each boat & time it spent at sea (KW × days). For a gill-net fishery the effort might be measured by summing the products of the length of each set net & the time it was set in the water (Km × soak time). In fisheries where boats spend a lot of time looking for fish, a measure based on search time may be used.

Fishing Intensity **(**nominal fishing effort) is the fishing effort per unit area.
Fishing Intensity=f/A, where A is the area.

Fish population size (N) refers to a group of fish of the same species that are alive in a defined area at a given time. *Overpopulation* may indicate any case in which the population of any species of fish may exceed the *carrying capacity* (K) of its *ecological niche*. The carrying capacity is the maximum fish population that can be sustained by the resources of the aquatic system under consideration. In the case of fisheries, it is the maximum fish population that would exist in the absence of commercial fishing.

How can the population size of a fishery be estimated? Since it is impossible to count every single fish in a population, the population size is often estimated by sampling. One common way to sample a population is to count all individuals within a few representative areas, & then extrapolate to the total number of individuals that are likely to be in the entire range. Of course, this method only works well if the samples are representative of the overall density of the population; if one happen to sample areas of exceptionally high density, one would overestimate population size & vice versa.

Another common method to estimate population size for mobile animals like fish is the mark-recapture method. In this method, a certain number of individual fishes are captured & tagged or marked, then released back & allowed to mingle with the rest of the population. After a certain period, a 2nd sample is taken. As long as the marked individuals are dispersed well within the population & have not suffered increased mortality from the 1st capture, the ratio of marked:unmarked individuals in the 2nd capture should reflect the ratio of marked:unmarked individuals in the entire population. Hence, we can estimate population size with the following formula:

$$M/N = m/R$$

$$N = \frac{m/R}{M}$$

where: N = Population size; M = Number of fish captured & marked in 1st sample; R= Number of fish captured in resampling event; m= Number of "R" that were already marked

For these equations to provide reasonable estimates of N, the following assumptions among others, must be met:

1) The natural mortality & vulnerability to fishing gears of tagged & untagged animals are the same.

2) The tagged fish should be randomly distributed in the population.

3) Tags are not lost.

4) There is no immigration nor emigration of fish into or out of the stock.

5) All tagged fish are reported.

Minimum viable population (MVP) is the smallest possible size at which a biological population can exist without facing extinction from natural disasters or demographic, environmental, or genetically random events.

Fish stock - is a subset of one particular species having the same demographic parameters (growth, natality, & mortality) & inhabiting a defined geographical area. Practically, a unit stock is an arbitrary definition of a fish population that is large enough to be essentially self-reproducing, where abundance changes are not dominated by immigration or emigration, & where members of the population show similar patterns of growth, mortality, migration & dispersal. Hence, a sub group of species can be treated as a stock if possible differences within the group & interchange with other groups can be ignored.
In practical terms, the size of the stock is mainly assessed by quantity of landings, which is principally a function of the

population size, the spatial variability of the fish, & the amount of fishing effort.

Age is the number of years completed or attained by an individual. It is expressed by Roman or Arabic letter. It can be determined by counting growth rings in fish *scales*, *otoliths*, cross-sections of fin *spines* for species with thick spines or *teeth* for a few species, *operculum*. The pattern of ridges (circuli) denotes changes in growth rate resulting from changes in environmental conditions or spawning. Each method has its merits & drawbacks. Fish scales are easiest to obtain, but may be unreliable if scales have fallen off of the fish & new ones grown in their places. Fin spines may be unreliable for the same reason, & most fish do not have spines of sufficient thickness for clear rings to be visible. Otoliths will have stayed with the fish throughout its life history, but obtaining them requires killing the fish. Also, otoliths often require more preparation before ageing can be done. The rings of the *cleithrum*, a membrane bone that extends upwards from the base of the pectoral fin & anchors to the cranium above the gills, can also be used to determine fish age. It forms the posterior edge of the gill chamber.

Age group (***cohort***) refers to the group of fish at given age. In other words, it refers to the actual age in years & contains fish of the same age, regardless of the year in which they were born. For instance,

- A fish in its first growing season belongs to age-group 0
- A fish in its second growing season belongs to age-group 1 or simply age 1 and so on.

Year Class: In a stock, a group of fish spawned during a year; also known as age-class. In other words, it refers to the group of fish produced in a particular year e.g. the 1987 year class would refer to fish that are age 0 in 1987, age 1 in 1988, etc. Hence, 2 fishes belonging to the same age group also belong to the same year-class. As they grow older, they will belong to progressively older age groups, but remain in the same year-class.

Catch per Unit Effort **(CPUE)**: The amount of catch that is taken per unit of fishing effort. In other words, it is the number or weight (biomass) of fish caught by an amount of effort. As noted, effort is a combination of gear type, gear size, & length of time a gear is used. CPUE may be influenced by changes in abundance. The basic assumption in fisheries theory is that catch (*C*) and stock abundance, or standing biomass (*B*) are related by:

$$C = q \cdot f \cdot \overline{B}$$

where *f* is a measurement of the nominal fishing effort or intensity, & *q* is the so-called catchability coefficient

$$CPUE = \frac{C}{f} = q \cdot \overline{B}$$

For scientific research surveys, or experimental fishing, effort is standardised & fishing gears kept constant in order to keep a simple relationship between catch rates & population abundance (*B*), i.e. to minimise the inherent measurement errors &/or variations in *f* & *q*.

Catchability/gear efficiency/fishing power (*q*) is the relationship between the catch rate (*CPUE*) & the true population size (*B*). It is the average proportion of a stock that is taken by each unit of fishing effort expressed mathematically as:

$$q = C/f{*}B$$

where C = catch; Biomass; f = effort

Catchability is strongly related to gear selectivity because it is species & size dependent. Sometimes, gear selection is simply defined as the relative change in *q* (ranges from 0 to 1) where 0 = no catch; 1

= entire stock; typically it is very small e.g. 0.000001.

But, the probability of a fish being caught at any time depends on several factors, not only man-made, & can broadly be grouped into biological & technological factors:

1) Biological factors include:

- fish availability on the fishing ground
- fish behaviour towards the fishing gear
- the size, shape, and external features of the fish where some of these factors again are dependent on season, age, environment & other species

2) Technological factors include:

A number of technological innovations have enabled fishers to greatly increase fish catch. These include;

- new engines to power larger fishing vessels
- refrigeration
- factory trawlers
- fish-locating equipment, &
- GPS technology,
- gear type, design, size, colour, & material
- gear position, duration, & handling

Selectivity - A generally important technical measure for fishing gears is the size selectivity, which is defined as the probability of fish being retained in a fishing gear as a function of the length of the fish Important selectivity measures are L_{50}, defined as the fish length, where the fish have a 50% probability of being retained by the gear on encounter, & the *selection factor,* defined as L_{50} divided by mesh size in cm. In addition to the *selection range* which is defined as $L_{75} – L_{25}$ (L_{75} is fish length where 75 % of the fish is retained, and L_{25} is fish length where 25 % of the fish is retained), these parameters describe the size selection characteristics of fishing gears.

This means that all fishing gears are only able to catch a certain portion of the total (multi-species) fish community present.

The use of the catch rate as an index of abundance of a fish stock is therefore complicated by the selectivity of a fishing gear. Catch rates only reflect the abundance of the *fishable stock* or that portion of a fish population or fish community that can be caught by a specific gear.

The area of operation of a gear, the inconstant behaviour of the fish relative to the gear, & the size of the fish determine the part of a stock that can be caught by a gear.

3.3 Fisheries Theories

Early studies on the population dynamics of fish stocks management in traditional fishing, led to the development of what are generally called ***stock/recruitment theories*** where ***'stock'*** refers to population numbers of adult fish, and ***'recruitment'*** to the numbers of juvenile fish entering the adult population.

These fisheries theories were based upon a central premise that reproduction, survival, & productivity of fish populations were largely independent of changes in the physical environment of the fish, or of changes in biological components (i.e. interacting species) within the community under consideration. The basic argument put forward was that the recruitment of new fish stock was a function of the numbers of eggs produced & subsequent survival of young. Because total egg production is a function of the size of the adult population & survival was considered constant, it was maintained that the size of the adult stock could be controlled by manipulating fishing pressure through regulating the number of boats, the size of nets, & the total allowable catch. This basic premise, with later variations, became the basis for the management of fisheries for a long period.

3.4 Exploitation of Fisheries Resources

Concept of Maximum Sustainable Yield (MSY) of Fisheries

In population ecology, the **MSY** is, theoretically, the largest catch that can be taken from a fishery stock over an indefinite period. In fisheries terms, it is the largest average catch that can be taken or captured from a stock over time under existing environmental conditions without negatively impacting the reproductive capacity of the stock.

The MSY concept is based on a model, referred to as a ***surplus production*** or ***biomass dynamic model*** (Fig 3.6).

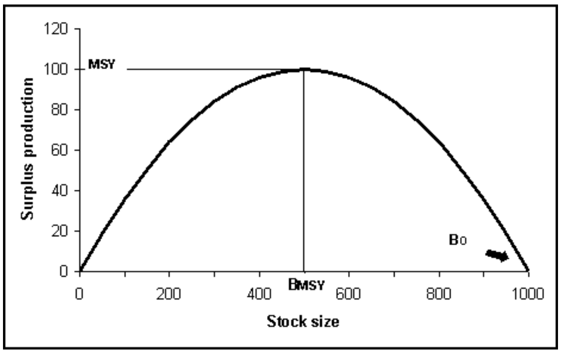

Fig. 3.6 Surplus production model

The model assumes that the annual net growth (production) in abundance & biomass of a stock increases as the biomass of the stock increases, until a certain biomass is reached at which this net growth, or surplus production, reaches a maximum called MSY. This biomass is referred to as $\boldsymbol{B_{MSY}}$. The fishing mortality rate which will achieve MSY is similarly referred to as $\boldsymbol{F_{MSY}}$. As the biomass increases above B_{MSY}, density dependent factors such as competition for food & cannibalism on smaller individuals start to reduce the net population growth which therefore decreases until at some point, the average carrying capacity (K) of the stock, net population growth reaches zero.

In reality, an unexploited stock will tend to fluctuate about this biomass (B_{MSY}) because of environmental variability.

Very basically MSY works like this:

- At low population size the rate of population growth will increase because the environmental resistance factors are low.
- At low population size, the rate of population growth will increase until environmental resistance factors begin to limit population size. This point is MSY.
- As the population size becomes larger than the MSY, the rate of population growth decreases & the number of individuals that can be fished does not increase.
- MSY is the point where the highest rate of recruitment can occur. The highest rate of harvesting can occur at the point where the highest recruitment occurs.

MSY aims at a balance between too much & too little harvest to keep the population at some intermediate abundance with a maximum replacement rate. It seeks to decrease population density to the point of highest growth rate possible. This changes the number of the population, but the new number can be maintained indefinitely, ideally. It is based on the logistic growth model in which a population introduced to a new habitat (with plenty of resources & less competition) or with very poor numbers goes through a lag phase of slow growth at first (Fig. 3.7).

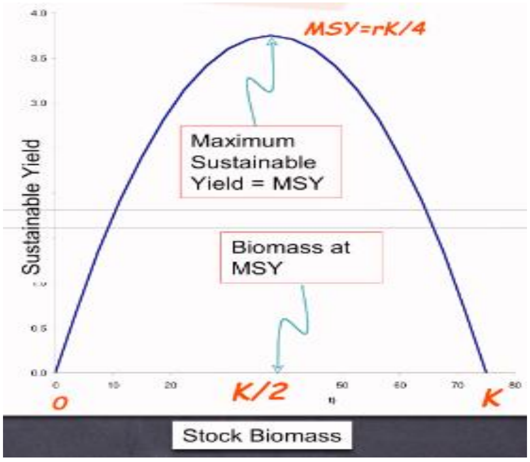

Fig. 3.7 Concept of MSY

Once it reaches a foothold population it will go through a rapid growth rate (log phase) that will start to level off once the species approaches carrying capacity (stationary phase).

Under the assumption of logistic growth, the MSY will be exactly at half the carrying capacity (K) of a species, as this is the stage at which population growth is highest. But the MSY estimates are typically based on limited data with considerable uncertainty attached to them & overestimates are common, allowing unsustainable harvesting & making subsequent recovery difficult. To reduce this risk, an ***optimum sustainable yield*** (OSY) has been proposed & is usually set at 10 – 20% below the MSY. It is considered the harvest level for a particular fish species that achieves the greatest overall benefits taking into account economic, social, & biological factors. MSY considers only the biology of the species.

What are MSY's Shortcomings?

MSY is extensively used for fisheries management. But, it has been widely criticized as ignoring several key factors involved in fisheries management & has led to the devastating collapse of many fisheries by focusing solely on the species in question. As a simple calculation, it ignores;

- ignore the size of fish being taken
- ignores the age of the fish being taken,
- ignores the reproductive status,
- ignores the damage to the ecosystem caused by the designated level of exploitation &
- puts fish populations at too much risk;
- considers only the benefits, not the costs, of harvest;
- is too sensitive to political pressure
- does not account for species other than the target species;
- ignore the issue of bycatch

Note:
Bycatch – refer to fish & other marine organisms taken in addition to the target fish. They are unwanted aquatic species caught incidentally. It constitutes a major threat to endangered species in aquatic systems. They are discarded after catching either dead or almost dead because they are either undersized or unwanted species & usually cannot be sold.

Hence, among conservation biologists, MSY is widely regarded as dangerous & misused & it is not always easy to apply in practice. Estimation problems arise due to poor assumptions in some models & lack of reliability of the data. Biologists, for example, do not always have enough data to make a clear determination of the population's size & growth rate. The concept also tends to treat all individuals in the population as identical, thereby ignoring all aspects of population structure e.g. size, age classes, & their differential rates of growth, survival, & reproduction.

As a management goal, the static interpretation of MSY (i.e.as a fixed catch that can be taken year after year) is generally not appropriate since it ignores the fact that fish populations undergo natural fluctuations (i.e., treats the environment as unvarying) in abundance & will usually ultimately become severely depleted under a constant-catch strategy.

The traditional goal in fisheries management has been to obtain continuing yields from a living 'resource'. Hence, concerns are raised when populations fall below levels that provide adequate yields or which fail to meet other specified concerns. Top predatory fishes e.g. sharks with relatively low reproductive capacities are often overexploited. As increasing fishing pressure cause populations of top predators to decline, organisms at progressively lower trophic levels begin to dominate the foodwebs of aquatic ecosystems. Fishers in turn must target fish populations at these lower trophic levels. This shift in targeted fishes is described as "fishing down the foodwebs."

As has been noted, to prevent overfishing of a fish stock, managers typically set quotas with the goal of adhering to the *maximum sustainable yield* (MSY) of the fish stock i.e. limits are set on fish catches (*total allowable catch*) so that stocks are maintained at a level that will preserve the long-term viability of the target species or the *carrying capacity* (i.e. the maximum population that can be sustained by the resources of the aquatic ecosystem).

Quotas for targeted species usually take into consideration;

- the lifespan of the target fish;
- its population growth rate;
- allowable catch size; &
- its reproductive capacity

Concept Ecologically Sustainable Yield (ESY) of Fisheries

A fishery is sustainable if it can be fished indefinitely at reasonable levels while maintaining the ecosystem (structure, function, & diversity) on which the fishery depends, & the integrity of the habitat essential to the fish species.

Hence, protection of fisheries requires a thorough understanding of the entire ecosystem involving multiple species, not just the targeted commercial or recreational fish. This understanding is the basis for achieving an ***ecologically sustainable yield*** (ESY) i.e. the yield that an aquatic ecosystem can sustain without undergoing an undesirable change in state. Thus, fisheries managers are reassessing the traditional approach to sustaining the populations of exploited fish species (i.e. MSY). This is because these targeted fish species are components of the aquatic ecosystem in which they interact with other organisms (e.g. as food sources, competitors, etc) & with their physical & chemical environment (e.g. suitable breeding & feeding habitats, etc). Hence, a decline in the population of a particular species of fish (e.g. targeted specie in MSY), may have a ripple or cascading effect on the entire ecosystem & may result in a change in its biotic composition & a reduction in its stability. This is especially the case when fishers decimate the populations of commercially attractive fish such as cod, tuna, swordfish, etc & other species at the top of the foodwebs as top predators. Hence, ESY advocates for a more holistic approach to fisheries management.

ESY is based on an *ecosystem-based management approach* which has several key challenges in its implementation such as;

- improving & creating processes for public participation in objective setting & in prioritizing those objectives;
- developing operational protocols for taking into account foodweb complexity (recognizing that only a crude level of predictability is likely, at best) & climate change; &
- determining the functional value of habitat-related ecosystem goods (e.g. food, etc) & services (e.g. CO_2 absorption, etc) that benefit humanity

For instance, the ecosystem-based management approach requires protection of floor habitats (e.g. by phasing out destructive trawling practices) & expanding the areas of the water bodies designated as protected areas e.g. *marine reserves* where fishing is prohibited designed to protect crucial marine communities & to provide reproductive reserves for fisheries that will hopefully disperse over wider areas.

The establishment of such protected areas or reserves are usually justified from 2 points of view:

- protection of areas crucial to the maintenance & even population expansion of fishery species; &
- protection of very diverse structural habitats e.g. coral reefs or other communities that are deemed to be

of importance for economic, educational, or aesthetic reasons

3.5 Overfishing

This is the removal of a species of fish from a body of water at a rate that the species cannot replenish, resulting in those species becoming underpopulated in that area.

Overfishing can occur in water bodies of any sizes, e.g. ponds, rivers, lakes or oceans, & can result in stock depletion, reduced biological growth rates & low biomass levels. Sustained overfishing can lead to critical depensation, where the fish population is no longer able to sustain itself. Some forms of overfishing, such as the overfishing of sharks, has led to the upset of entire marine ecosystems.

The ability of a fishery to recover from overfishing depends on whether the ecosystem's conditions are suitable for the recovery. Dramatic changes in fish species composition can result in an ecosystem shift, where other equilibrium energy flows involve species compositions different from those that had been present before the depletion of the original fish stock. For example, once trout have been overfished, carp might take over in a way that makes it impossible for the trout to re-establish a breeding population.

Acceptable levels - The notion of overfishing hinges on what is meant by an "acceptable level" of fishing. More precise biological & bioeconomic terms define acceptable level as follows:

- Biological overfishing occurs when fishing mortality has reached a level where the stock biomass has negative marginal growth (reduced rate of biomass growth). Fish are being taken out of the water so quickly that the replenishment of stock by breeding slows down. If the replenishment continues to diminish for long enough, the population will decrease.
- Economic or bioeconomic overfishing considers the cost of fishing when determining acceptable catches. Under this framework, a fishery is considered to be overfished when catches exceed maximum economic yield where resource rent is at its maximum. Fish are being removed from the fishery so quickly that the profitability of the fishery is sub-optimal.

Harvest control rule **(HCR)** is a model for predicting acceptable levels of fishing - a set of tools & protocols with which management has some direct control of harvest rates & strategies in relation to predicting stock status, & long-term sustainability.

Types of overfishing - There are 3 recognized types of biological overfishing: growth overfishing, recruit overfishing, & ecosystem overfishing.

a) Growth overfishing - occurs when fish are harvested at an average size that is smaller than the size that would produce the maximum yield per recruit. In other words, it refers to the excessive removal of smaller-sized fish that inhibits the fishery's ability to produce its maximum yield. Growth overfishing does not affect the ability of a fish population to replace itself. A *recruit* is an individual fish that makes it to maturity, or into the limits specified by a fishery, which are usually size or age. This makes the total yield less than it would be if the fish were allowed to grow to an appropriate size. It can be countered by reducing fishing mortality to lower levels & increasing the average size of harvested fish to a size that will allow maximum yield per recruit.

b) Recruitment overfishing - happens when the mature adult population (spawning biomass) is depleted to a level where it no longer has the reproductive capacity to replenish itself—there are not enough adults to produce offspring. In other words, it refers to levels of fishing mortality in which removals are so high the production of new recruits to the fishery is compromised. The number of fish removed is greater than the number gained from fish remaining & reproducing in the population. Increasing the spawning stock biomass to a target level is the approach taken by managers to restore an overfished population to sustainable levels. This is generally accomplished by placing moratoriums, quotas, & minimum size limits on a fish population.

c) Ecosystem overfishing - Ecosystem overfishing occurs when the balance of the ecosystem is altered by overfishing. With declines in the abundance of large predatory species, the abundance of small forage type increases causing a shift in the balance of the ecosystem towards smaller fish species.

It is a concept based on *trophic cascade* which occurs when predators in a food chain suppress the abundance of their prey, thereby releasing the next lower trophic level from predation (or herbivory if the intermediate trophic level is an herbivore). For example, if the abundance of large piscivorous fish is increased in a lake, the abundance of their prey, zooplanktivorous fish, should decrease, large zooplankton abundance should increase, & phytoplankton biomass should decrease. Trophic cascades is important for understanding the effects of removing top predators from food webs, as humans have done in many places through overfishing activities. For e.g., in lakes, piscivorous fish can dramatically reduce populations of zooplanktivorous fish, zooplanktivorous fish can dramatically alter freshwater zooplankton communities, and zooplankton grazing can in turn have large impacts on phytoplankton communities. Removal of piscivorous fish can change lake water from clear to green by allowing phytoplankton to flourish.

What Renders Species Susceptible to Overfishing?

There are about five key features of the biology of fishes & the motivations of fishermen that render fish populations susceptible to overfishing.

Fish stocks that are most vulnerable to overfishing usually have;

- Catchability remains high as population size decreases
- Fish are highly valuable
- Fish are susceptible to capture as non-target species
- Life histories result in low productivity
- Per capita recruitment decreases as population size decreases

a) Catchability remains high as population size decreases

Species that form shoals can be targeted profitably by fishers even as the total population sizes decline. This continuing efficiency works against the old concept that as fish became rare, they would become unprofitable & therefore subject to lower mortality. Species that migrate through physical bottlenecks or points of congestion, such as diadromous salmonids, shads & sturgeons, are susceptible to high mortality due to focused fishing effort & pollution outputs associated with the dense human populations of river mouths. Damming & the introduction of dikes also contributed to the decline of some species. Thus, conservation of anadromous fishes remain a serious concern, as their freshwater spawning habitats remain subject to a variety of threats, including forestry and damming. Species with limited physiogeographic ranges, living in small catchments, with specific breeding & feeding habitats appear to be particularly vulnerable to extinction in freshwater habitats due to overfishing. In the sea critical habitats such as locations where fishes aggregate to spawn are vulnerable.

b) Fish are highly valuable

Some fish derive their value not only as a source of protein, but also from cultural or social values leading to premium prices. Buyers capable of paying for rare species may advertise their wealth & social status. The reservation of caviar & sturgeon for English & French nobility in the 14th century is testament to the deep-rooted existence of this behaviour, which continues today in fine restaurants. Raw tuna or *sashimi* is highly coveted by rich restaurant-goers in Japan. The most prized species is the southern bluefin tuna. It set a new price record in 2001, when US$178000 was paid for one individual. Western Atlantic bluefin tuna (*Thunnus thynnus*) has been sold for up to US$83500 for a single individual. Another expensive fish is the giant yellow croaker (*Bahaba taipingensis*), which has been exploited for its swim-bladder in the South & East China seas. In recent years the swim-bladder has been called 'soft gold' due to market prices of US$20000–64000 per kg. It is highly valued for its medicinal properties, & as a health tonic, & is typically boiled & drunk as a soup. Despite the near extinction of this species, many boats still target its historical spawning sites in the hope of netting a windfall.

Unfortunately for conservation efforts the high prestige & price of rare species often widen the geographical net to meet demand, thereby threatening even those species that have large ranges. This increasing price associated with biological & market rarity has meant that it is economically viable to fly fish to markets from such distant sources.

c) Fish are susceptible to capture as non-target species

If fish are caught as a by-product of other activities, they again defy the hope that unprofitability at low population sizes might protect their populations. For example, roughly 50 % of elasmobranchs are taken as bycatch without any regulations, & these species rarely appear in catch statistics. Non-target species thus inhabit the poorly known underworld of fisheries conservation. They are either discarded at sea or, if landed, they often fetch a lower price than the species being targeted. Therefore they do not attract much attention from assessment biologists or managers.

d) Life histories result in low productivity

Species with long generation times, low natural mortality rates & slow body growth are expected to be less able to withstand elevated mortality. Such species e.g. sharks & rays feature prominently in the *Red List of Threatened Animals*, on the basis of severe population declines under exploitation. Other examples of species with life histories that are incompatible with elevated mortality include sturgeons, rockfishes (*Sebastes*) & orange roughy (*Hoplostethus atlanticus*), which reaches maturity in its 20s to thirties & may live to a maximum age of 150 years. The coelacanth (*Latimeria chalumnae*) also fits this category. While most details of its life history remain unknown, this species has the lowest metabolic rate known for any fish. This suggests a very slow life history, which would render the species susceptible to the mortality that individuals suffer as a result of bycatches in deep-water artisanal fisheries.

e) Per capita recruitment decreases as population size decreases

Depensation, called the 'Allee effect' in terrestrial systems, occurs when there is a positive relationship between individual productivity & population size. In fisheries, depensation can occur due to a reduced ability to aggregate & find mates, reduced fertilization success, or increased predation rates. The concern here is that as fish stocks are pushed downwards, they may fall over a cliff of recruitment from which they cannot climb back.

What is needed to safeguard fish biodiversity or mitigate overfishing? Overfishing is a serious problem. The situation especially for freshwater fishes is serious in many parts of the world. Direct & indirect effects of exploitation, habitat destruction & degradation loom large among the drivers of decline. As demand for freshwater increases, & technologies for catching fish have improved, so the areas free from exploitation & habitat loss have diminished. Inland water bodies are used as sources of irrigation & hydroelectric power, at the expense of aquatic biodiversity.

The United Nations Convention on the Law of the Sea treaty deals with aspects of overfishing in articles 61, 62, and 65.

- Article 61 requires all coastal states to ensure that the maintenance of living resources in their exclusive economic zones is not endangered by over-exploitation. The same article addresses the maintenance or restoration of populations of species above levels at which their reproduction may become seriously threatened.
- Article 62 provides that coastal states: "shall promote the objective of optimum utilization of the living resources in the exclusive economic zone without prejudice to Article 61"
- Article 65 provides generally for the rights of, inter alia, coastal states to prohibit, limit, or regulate the exploitation of marine mammals.

There is also the use of *government regulation* - Many regulatory measures are available for controlling overfishing. These measures include fishing quotas, bag limits, licensing, closed seasons, size limits & the creation of marine reserves & other marine protected areas.

A model of the interaction between fish & fishers showed that when an area is closed to fishermen (*closed season*), but there are no *catch regulations*, fish catches are temporarily increased but overall fish biomass is reduced, resulting in the opposite outcome from the one desired for fisheries. Thus, a displacement of the fleet from one locality to another will generally have little effect if the same quota is taken. As a result, management measures such as temporary closures or establishing a marine protected area of fishing areas are ineffective when not combined with individual fishing quotas. An inherent problem with quotas is that fish populations vary from year to year. For instance, fish populations rise dramatically after stormy years due to more nutrients reaching the surface & therefore greater primary production. To fish sustainably, quotas need to be changed each year to account for fish population variability.

Another important measure is the adoption of the *precautionary principle* & *reference points*. This is now being implemented in fisheries management in many parts of the world. The elements of this principle are simple, such as taking account of uncertainty, being cautious with new fisheries, not using lack of information as an excuse for inaction, and using reference points. Reference points include benchmark population sizes or mortality rates that are not to be exceeded (‘limit reference points’) or which are desirable (‘target reference points’).

The use of *targeted management at key points in the life history* is also another tool for safeguarding fish biodiversity. Identifying key points in the life history of organisms could prove to be a fruitful approach for focusing often-limited management efforts. But, identification of critically important ages, stages, habitats or even sexes is still in its infancy. Guesses can be made based on experience e.g. salmon are more vulnerable in estuaries than in the open sea, & females usually limit populations more strongly than do males.

Additionally, *individual transferable quotas* (ITQs) are fishery rationalization instruments defined as limited access permits to harvest quantities of fish. Fisheries scientists decide the optimal amount of fish (total allowable catch) to be harvested in a certain fishery. The decision considers carrying capacity, regeneration rates, & future values. Under ITQs, members of a fishery are granted rights to a percentage of the total allowable catch that can be harvested each year. These quotas can be fished, bought, sold, or leased allowing for the least-cost vessels to be used. Studies indicate that ITQs can help to prevent collapses & restore fisheries that appear to be in decline.

A further measure is the *removal of subsidies* - Because government provided financial subsidies can make it economically viable to fish beyond biologically sustainable levels, several scientists have called for an end to subsidies.

Moreover, measures can be put in place aimed at *minimizing fishing impact* - Fishing techniques may be altered to minimize bycatch & reduce impacts on marine habitats. These techniques include using varied gear types depending on target species and habitat type. For example, a net with larger holes will allow undersized fish to avoid capture. Avoiding fishing in spawning grounds may allow fish stocks to rebuild by giving adults a chance to reproduce.

Also, *aquaculture* has also been prescribed as an effective mitigating factor. It involves the farming of fish in captivity. This approach effectively privatizes fish stocks & creates incentives for farmers to conserve their stocks. It also reduces environmental impact. But, farming carnivorous fish, e.g. salmon, does not always reduce pressure on wild fisheries, since carnivorous farmed fish are usually fed fishmeal & fish oil extracted from wild forage fish. Aquaculture now provides approximately half of all harvested aquatic organisms.

Fish farming can enclose the entire breeding cycle of the fish, with fish being bred in captivity. Some fish prove difficult to breed in captivity & can be caught in the wild as juveniles & brought into captivity to increase their weight. With scientific progress, more species are being made to breed in captivity.

3.6 A Brief on Aquaculture

Aquaculture is defined as the farming of aquatic organisms. It includes the culture of freshwater & marine species.

Types of Aquaculture
Aquaculture can be divided into 4 types that are easy to separate conceptually but overlap in practice.

1. Extensive culture involves raising organisms under relatively natural conditions, traditionally based on stocking selected species from the wild into ponds, reservoirs, sections of rivers, or flooded rice fields. Supplementary feed is normally not provided, but habitat improvement may be undertaken.
2. Semi-intensive culture entails rearing fish under more controlled conditions, usually in ponds. Their diet is supplemented; stocking densities are well above natural densities; & the eggs or young are usually obtained from hatcheries. It is usually done in conjunction with other aquatic species (invertebrates, ducks), combining relatively high yields (Fig. 3.8) with small capital costs & low economic risks.

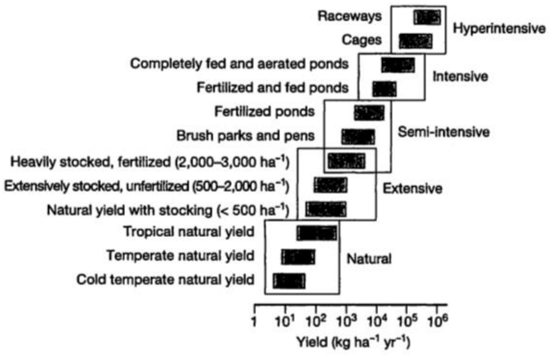

Fig. 3.8 Fish yield from world capture & culture systems

3. Intensive culture systems are characterized by more intensive management & additional feeding &/or fertilizer application. Many of the intensive culture systems are *monocultures* (one species), but *polycultures in* which several fish species are raised together are increasingly common. The use of 2 or more species utilizing different food resources (plankton vs bottom feeders) make it possible to increase stocking densities without exceeding the carrying capacity of the system as a whole. Selective breeding is used to increase growth rates. Hybridization of closely related tilapia species is widely practiced in order to gain hybrid vigour, more rapid growth, a more desirable meat colour, & to produce unisex offspring that prevent the production of a large number of poorly growing (stunted) individuals.

4. Hyperintensive culture involves raising high value species with high stocking densities in cages, raceways (artificial stream channels) in which the water is replaced within hours, or enclosed tanks with water circulating systems. Diet, habitat, & water quality are controlled, & active disease prevention & control done. Fish yields are exceptionally high (Fig. 3.8), but so is the initial investment & continuing operating cost. There are major financial risks from bad weather, floods, vandalism & theft, bird & mammal predation, disease, parasites, & market conditions. The key concern is the effluent that is produced, especially when it is released into oligotrophic waters.

Desirable features of Aquaculture species

Successful aquaculture requires proper choice of species for rearing. The following characteristics are considered desirable;

1. *desirability as food* – the species should already be a desirable food item or should be salable with some publicity;
2. *uncomplicated reproduction* – the organism should be relatively easy to propagate, or young organisms should be easy to obtain;
3. *hardiness* – the species should be resistance to handling & changes in environmental conditions, & should be adaptable to different substrata;
4. *disease resistance* – diseases & parasites should be controllable to minimize mortality;
5. *high growth rate per unit area* – they organism should be able to grow rapidly in limited culture areas;
6. *readily met food requirements* – feeding the organism should be easy & cheap. Animals that are high on the food chain are liable to require higher cost protein foods;
7. *readily met habitat requirements* – the physical habitat should be easy to duplicate in the mariculture system. Preferably, the organisms should be able to grow in relatively high-density systems. There should be relatively low aggressive behaviour, & the organisms should be resistant to poisoning by waste products;
8. *monoculture or polyculture* – it should be considered whether one species is to be grown alone (monoculture) or whether several species will grow most efficiently when placed in the same system (polyculture). For instance, some mariculture habitats may be innately complex, & a polyculture, permitting several marketable species to grow in the assemblage of micro-habitats, would be more efficient;
9. *marketability* – the chosen species should be easy to market, accessible to markets, & of presentable growth form to consumers;

10. *minimal ecological effects* – the mariculture system should have few detrimental effects on the surrounding environment

Another mitigating factor, *consumer awareness* is also been used. As global citizens become more aware of overfishing & the ecological destruction of the oceans, movements have sprung up to encourage abstinence—not eating any seafood—or eating only "sustainable seafood". Sustainable seafood is a movement that has gained momentum as more people become aware of overfishing and environmentally destructive fishing methods. It is seafood from either fished or farmed sources that can maintain or increase production in the future without jeopardizing the ecosystems from which it was acquired. In general, slow-growing fish that reproduce late in life, are vulnerable to overfishing. Seafood species that grow quickly & breed young, such as anchovies & sardines, are much more resistant to overfishing.

Barriers to Effective Management

The fishing industry has a strong financial incentive to oppose some measures aimed at improving the sustainability of fish stocks. Recreational fisherman also has an interest in maintaining access to fish stocks. This leads to extensive lobbying that can block or weaken government policies intended to prevent overfishing.

Outside of countries' exclusive economic zones, fishing is difficult to control. Large oceangoing fishing boats are free to exploit fish stocks at will.

In waters that are the subject of territorial disputes, countries may actively encourage overfishing. Fish are highly transitory. Many species will freely move through different jurisdictions. The conservation efforts of one country can then be exploited by another.

While governments can create regulations to control people's behaviours this can be undermined by illegal fishing activity. Illegal fishing can take many forms. In some developing countries, large numbers of poor people are dependent on fishing. It can prove difficult to regulate this kind of overfishing, especially for weak governments. Even in regulated environments, illegal fishing may occur. While industrial fishing is often effectively controlled, smaller scale & recreational fishermen can often break regulations such as bag limits & seasonal closures. Fisherman can also easily fish illegally by doing things such as underreporting the amount of fish they caught or reporting that they caught one type of fish while actually catching another. There is also a large problem with the surveillance of illegal fishing activity. Some illegal fishing takes place on an industrial scale with financed commercial operations.

Resistance from fishermen

There is always disagreement between fishermen & government scientists. Imagine an overfished area of the sea in the shape of a hockey field with nets at either end. The few fish left therein would gather around the goals because fish like structured habitats. Scientists would survey the entire field, make lots of unsuccessful hauls, and conclude that it contains few fish. The fishermen would make a beeline to the goals, catch the fish around them, and say the scientists do not know what they are talking about. The subjective impression the fishermen get is always that there's lots of fish - because they only go to places that still have them. Fisheries scientists survey and compare entire areas, not only the productive fishing spots.