NATURAL RESOURCE SYSTEM CHALLENGE: OCEANS AND AQUATIC

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Summary

Water is vital for all life on earth. It is also vital for humanity's food security and health.

At present at least one billion people lack access to an adequate supply of safe water, and 1.7 billion people do not have adequate sanitation. Freshwater is vital, not only for drinking but also for food security; agriculture is responsible for 93 percent of total water consumed by all economic sectors. Many countries have increasing problems in providing clean water to sustain human activities. The oceans are used extensively to provide fish for human consumption, and there are already indications that this extraction of seafood is unsustainable, yet human populations are growing by 90 million per year and the demand for seafood is growing. The food security requirements of an increasing human population will exacerbate current problems with water availability and quality. Human health and economic development are threatened, or restricted, by water quality issues that limit human welfare and water uses. These include salinization of rivers and lakes, microbiological and organic pollution, and pollution by wastes from human activities (for example, heavy metals, toxic organic compounds, nutrients, and eroded soils). Human activities also exacerbate water-related diseases, especially in the tropical world where economic development is still greatly limited by illnesses such as river blindness (onchocerciasis), malaria, bacterial diarrhea, and bilharziasis (schistosomiasis). These problems may become worse in the future.

The aim of this essay is to guide the reader through the various pathways followed by surface water on earth. It will describe the dominant processes that govern how organisms interact with water and with each other, and how they in turn can modify water properties. This knowledge is important for humanity. Indeed, only by understanding our actions' impacts upon water, and the animals and plants living in it, can we learn to exploit water, marine and fresh-water habitats and the living organisms, without destroying the resources on which our livelihood and very survival depend.

1. Introduction: Water on Earth

Ninety-seven percent of the liquid water available on earth is found in the oceans. Only about 3 percent is freshwater (see Table 1); most of this is locked in sea ice, and, in practice, is unavailable to humans for drinking and other uses. Only 0.016 percent of the water on earth is in lakes and rivers, while 0.6 percent is groundwater.

The oceans cover 360×10^6 km^2, or 70 percent of the earth's surface. Their volume is about 1.5×109 km^3, and they extend to an average depth of 3.8 km. They hold about 300 times more water than the atmosphere.

2. The Oceans

The oceans' socio-economic importance to humanity is enormous. At least 90 percent of international freight (or more than 3,000 million metric tonnes per year) is transported upon them; more than 50 percent of the world's population lives within 200 km of the seashore; 129 of the UN's *c*. 160 nations have a coastline. The world's fisheries produce more than 80 million tonnes of fish each year, representing 2 percent of the food (and 20 percent of the proteins) consumed by humans. Crude oil accounts for 50 percent of goods transported by sea; 25 percent of petroleum products are extracted offshore.

Seawater contains about 35 gl^{-1} of dissolved minerals, mainly NaCl (salt). Ten dominant ions or inorganic compounds dominate the chemistry of seawater, providing a relatively stable osmotic pressure within the medium in which life develops.

2.1. Water circulation

Water circulates continuously between the oceans, the atmosphere, the land, and the rivers through the hydrologic cycle. This cycle is controlled by evaporation from the sea, lakes, and rivers, as well as evapotranspiration, rainfall, and runoff. The annual volumes of water which evaporate from the sea and from the land are, respectively, 0.35 $\times 10^6$ km^3 per year and 0.06 $\times 10^6$ km^3 per year. In other words, only a tiny amount (0.26 percent of 1 percent) of all sea-water passes annually through the hydrologic cycle. However, a large amount (27 percent) of freshwater in river and lakes is renewed annually. Freshwater is renewed on average every 3.8 years, while seawater is renewed on average every 4,000 years.

The salinity of the sea has not changed during the last 200 million years, although minerals are continuously injected into the sea by volcanic activity and freshwater influx. Its stable salinity is explained by precipitation and sedimentation of minerals.

The ocean is not static; indeed major oceanic currents are generated by a number of forces, principally wind and solar heating. A dominant factor dictating the width and depth of these currents is relative water density, which is controlled mainly by temperature and salinity. Water density varies spatially, both vertically and horizontally. Water absorbs infrared solar radiation, hence the heating rays from the sun do not penetrate directly to any great depth. This leads to the water becoming thermally stratified, with a warm layer on the surface and a colder layer below. Warmer water, being less dense, usually floats above colder water. The waters below are warmed only by mixing from currents or wind action. The boundary zone between water masses of differing temperature is called a thermocline. In equatorial regions of the oceans, this is usually quite thick (typically 100 m); at higher latitudes, the thickness of the warm surface layer seldom exceeds a few tens of meters.

Ocean currents are driven mainly by wind, heating, and the effects of the sun and the moon, combined with a rotational force (the Coriolis force) caused by the earth's rotation on its axis. The Coriolis force causes surface currents to deflect to the right of wind direction in the Northern Hemisphere, and to the left of wind direction in the Southern Hemisphere. The currents vary from ocean to ocean, because of variations in the shape of the ocean basins and the surrounding landmasses. They often form gyres (eddies). Easterly winds at the equatorial zone, and westerlies at medium latitude, induce current systems that form distinct loops separated by the equator.

The tides are generated by the gravitational forces of the moon and the sun. The moon's gravitational force effectively pulls the ocean water toward it, generating a bulge on the water surface. A high tide may also occur simultaneously on the opposite side of the earth. This is due to the centrifugal force generated because the earth and moon spin around each other, as though they were joined as a unit. Their rotation about a common imaginary axis, about 4,800 km from the earth's center, generates a centrifugal force opposite in direction to the gravitational force of the moon. This force not only overcomes the gravitational pull of the moon, but also actually causes a water bulge on the *opposite* side of the earth. Since the moon revolves around the earth once every twenty-eight days, each day it moves 1/28 further around the earth. High tides therefore occur fifty minutes later each day, or twenty-five minutes from tide-to-tide. The sun also influences the tides. When there is a full moon, the sun is on the side of the earth opposite the moon. When the moon is new, the sun and the moon are on the same side of the earth. At these times the sun and the moon reinforce each other's gravitational effects, producing the highest tide-range (spring tides). In general the tides generate only very small net currents, when averaged over one tidal cycle (in other words, the water often returns more-or-less to where it started after one tidal cycle), while the wind can cause strong net currents (when water does not return to its starting-point).

2.2. Plankton, nekton, and benthos

Plankton are pelagic organisms entrained by currents. Within plankton one can usually distinguish phytoplankton, which is vegetal (plant matter), from zooplankton (which feeds on the existing biomass, often phytoplankton). It differs from nekton, which are pelagic organisms able to swim and capable of autonomous displacement. Benthos are the organisms living in or on the sediment and in its vicinity. Phytoplankton grow in abundance in surface waters where there is enough light for photosynthesis, the process whereby plants store energy from sunlight as chemical energy in sugar. The phytoplankton is the major primary producer in the oceans, and is considered to be the basis of the food chain. Zooplankton are microscopic animals, with many different species in several different classes. Some (such as protozoans) are single cells; others (such as copepods and krill) are multicellular, and large enough to be visible to the human eye. Copepods are zooplankton, feeding mainly, but not necessarily exclusively, on phytoplankton; they provide food for fish and even for some filter-feeding whales. Most fish feed on zooplankton during some phase at least of their life-cycles, commonly as juveniles.

Permanent members of the zooplankton community include foraminiferans, radiolarians, and copepods. Foraminiferans ("hole-bearers") are organisms that live within small shells made of calcium carbonate. As they outgrow their shells the abandoned ones are shed, and the animal grows a new one by taking in calcium carbonate from the surrounding water. Dead animals and discarded shells sink to the deep ocean bottom, there to be dissolved into calcium and carbon available for reuse. In shallower waters, where this breakdown cannot take place, their remains accumulate in thick layers of "Globigerina ooze," named for the most common foraminiferans, the Globigerina. Radiolarians are similar to their relatives the foraminiferans, both in skeletal shape and protoplasmic food-trapping ability. Their skeletons are made of silica, however, and cover about 4.8 million km^2 of tropical ocean. Copepods are so numerous that it is estimated that they account for 70 percent of zooplankton. The Greek name copepod ("oar-footed") refers to the shape of their swimming legs. Copepods dominate the zooplankton community in the oceans and in fresh-water, and are also hugely abundant in aquatic sediments. They are parasitic on virtually every phylum from sponges up to chordates, including mammals and reptiles. Copepods spend much of their time swimming and creating flow fields in order to detect and capture food particles, such as the single-celled algae of the phytoplankton.

Plankton's average density (1.10) is greater than that of seawater (1.03). Nevertheless, planktonic organisms are adapted to stay in the water column without sedimenting away. Phytoplankton is composed mainly of unicellular organisms. It converts inorganic elements, such as nitrogen and phosphorus, into biomass by photosynthesis using light energy. Plankton biomass is high in nutrient-rich coastal waters, and the plankton is constituted of large cells (size ranging from 10–100 µm: 1 µm = 0.001 mm). In nutrient-poor ocean waters, by contrast, biomass is small and the cells also are generally small. Most of the primary production is supported by small cells, only a few microns in size; these are called picoplankton. Picoplankton comprise eukaryotes (cells with a nucleus), cyanobacteria, and prochlorphytes. The latter two belong to the group of bacteria. Protista is a taxonomic grouping that includes single-celled (mostly) eukaryotes from most of the groups, formerly classified as algae, protozoa, and flagellated fungi (slime molds). Some phytoplankton do ingest other microorganisms in addition to photosynthesizing, thus utilizing both plant and animal nutrition. The separation of plants from animals is clearly defined in superior organisms, that is, organized multicellular organisms. This separation does not properly apply to unicellular organisms, including algae, fungi, and bacteria: some may use dissolved organic matter through osmotrophy, and some of them are even able to ingest particles by phagotrophy. Bacteria and some phytoplankton assimilate compounds of very low molecular weight, such as amino acids and urea, rapidly. These low-weight compounds are generally thought to comprise 20 percent or less of the dissolved organic nitrogen (DON) transported by rivers to estuaries. Most DON consists primarily of complex compounds of high molecular weight. These compounds may be less readily available to microbial breakdown.

The primary producers within the ocean have to cope with the rapid vertical attenuation of light within a water column. Further, the vertical stratification of currents results in long residence times for water in the upper, well-lit, regions of the ocean. It also prevents replenishment of nutrients from the deeper layers. The need for organisms to balance their requirements for both light and nutrients has led to a number of algal physiological and behavioral responses for survival in the turbulent marine environment.

The two main factors regulating primary production in the ocean are light-intensity and inorganic nutrients. Key nutrients include phosphorus, nitrogen, and iron. Light-intensity depends upon solar radiation; this varies seasonally, with distance from the equator, with depth, and with turbidity. The water's turbidity depends upon the load of particles in suspension, both organic (for example, plankton and algae) and inorganic (mud), as well as dissolved organic matter (color). The layer affected by light is known as the photic layer. This is regarded as the depth at which light still supports photosynthesis. Although this threshold is arbitrarily fixed at 1 percent surface incident light, photosynthesis may, in fact, occur at greater depths. Hence the lower limit of the photic layer corresponds to the compensation depth, that is, the depth at which organisms' primary production equals their respiration rate. This depth is typically a few centimeters in grossly eutrophicated stagnant water, 0.5 m in productive coastal waters, and 100 m in the open ocean. Phytoplankton grow very fast, typically doubling their biomass (essentially their weight) in a few days; by contrast it takes land plants typically a few months, or even years, to achieve this. On a global scale, annual phytoplankton photosynthesis is roughly equivalent to that of all plants and trees on land, even though their total biomass is only 0.2 percent of that of terrestrial plants.

Oceanic ecosystems differ from terrestrial ones in that some organisms are constantly removed from surface layers by sedimentation. Plankton, while healthy, compensates for its density being higher than seawater by regulating its osmotic pressure, or by swimming (that is, by flagellar or appendage movements). Sedimentation losses can be compensated by plankton’s high growth-rate. When environmental conditions are not optimal, however, the plankton settles out rapidly. The settling plankton, in addition to fecal matter and other detritus, constitutes organic matter which is degraded by bacteria. This process, called mineralization, releases inorganic nutrients. It occurs at depth, and at different rates for various nutrients: phosphorus often mineralizes fastest.

Ten thousand kilograms of phytoplankton (primary producers) support 1,000 kg of first-order consumers, the zooplankton (for example, copepods). These in turn support 100 kg of second-order consumers, such as small fish (for example, herring or anchovies). These would support 10 kg of third-order consumers, such as the larger fish species. In turn, these may support 1 kg of fourth-order consumers, such as seabirds or seals.

Marine macroalgae have been exploited for hundreds of years as human food and animal fodder, as a source of phycocolloids and bioactive products, and recently in biofiltration. At present, microalgae provide a wide range of fine chemicals, oils, and polysaccharides. They are also used as soil conditioners, in waste treatment, and in aquaculture. Because of the usable products that they yield, natural resources of algae cannot meet present demand and are over-exploited in their natural habitats. The cultivation of macroalgae is presently one of the most productive and environmentally friendly forms of livelihood among coastal populations.

2.3. Biodiversity

Biodiversity is a measure of species diversity, including the total pool of genetic information, as well as the relationships with ecosystems and habitats. On land, humans have radically altered the biological diversity. In some cases the changes are total, so that many species have been eliminated from large areas dominated by human influences. On land, current rates of extinction are estimated to be 100–1,000 times greater than pre-human rates. At sea, the human impact on biodiversity is considered to be more indirect. In the ocean, high-level carnivores playing key roles in structuring biodiversity are exploited heavily, with often-unknown effects on biodiversity and on ecosystem functions. This contrasts with the situation on land, where the ecosystems are dominated by large herbivores and increasingly, of course, by humans, who monopolize about 40 percent of the total world primary production.

2.4. Upwelling

Upwelling is an oceanographic term that refers to a situation in which water from subsurface layers ascends into the surface layer, and is then removed from the area of upwelling by horizontal flow. Upwelling can occur wherever water is stratified, and where winds carry surface water away from the coast. It is generally most extensive along the western coasts of continents. Upwelling brings subsurface nutrients into nutrient-limited surface waters. It is a common feature along the coasts of California, Peru, and the west and east coats of southern Africa. In all cases phytoplankton are quick to take advantage of nutrients brought up by upwelling. Zooplankton feed on phytoplankton, and are themselves fed upon by larger plankton and small fishes. These, in turn, can support larger fishes, seabirds, seals, and whales.

2.5. El Niño

El Niño is an oceanographic phenomenon that occurs irregularly, typically every 4–7 years. Its start is usually signaled by anomalous warming of the waters of the eastern Pacific Ocean off Peru. It involves major changes in both the atmospheric and oceanic circulation across the equatorial Pacific, and offers a clear example of large-scale air-sea coupling and short-term climatic variation. The first observations of this unusual warming were usually made around Christmas, hence the name, which means "Christ child."

The warming diminishes the usual upwelling of cold and nutrient-rich waters to the ocean surface; this, in turn, leads to a disastrous decrease in numbers of anchovies and other fish, with severe economic consequences for the coastal fishing communities. Furthermore, a number of teleconnections (due to atmospheric and oceanic influences over long dis tances) result in increased rainfall in some areas of the earth (for example, the Peru coast), and decreased rainfall in others (Indonesia).

2.6. Nutrient cycling and eutrophication

Eutrophication is a situation of ecological degradation, caused by an excess of nutrients (inorganic or organic) relative to the rate at which they are flushed away. The waters, as a result, become highly fertilized. Usually this occurs as a result of human activities leading to land runoff or direct waste discharge. Eutrophication also sometimes results from natural causes, however. Increasing the amount of nutrients, such as phosphorus or nitrogen, leads typically to increases in primary production and increased plant growth. Organic nitrogen inputs may contribute more to estuarine eutrophication than has been previously suspected. Iron has been shown to limit marine production in the eastern equatorial Pacific Ocean. Nitrogen (N) inputs are especially important in marine ecosystems, because N is the nutrient that limits primary production in many estuarine and coastal waters most significantly. Large amounts of plankton and algae can lead to low oxygen concentrations (hypoxia) and to subsequent death of marine fauna, changes in species composition, and the occurrence of harmful, or even toxic, algae. Eutrophication is most commonly observed in lakes and poorly flushed coastal waters, where rivers provide important influxes of nutrients. Eutrophic waters would rapidly become impoverished without renewed inputs of nutrients, either from rivers or from internal currents uplifting deeper, nutrient-rich waters to the surface (upwelling). Areas where upwelling occurs are usually very highly productive. Primary production entails formation of new biomass from inorganic matter such as CO_2. This is measured in grams of carbon per square meter of surface area per year (g C m^{-2} y^{-1}). Primary production is typically four times larger in upwelling areas than elsewhere in the ocean, but fish production can be twenty-five times larger. The ocean's phytoplankton actually produces about half of the world's oxygen through photosynthesis. The ocean is the largest planetary reservoir for inorganic carbon. There is about fifty times more CO_2 in the ocean than in the air. Therefore even a small change in the balance of the amount of carbon in the water compared to that in the air has a huge impact on the atmosphere, and thus on climate.

When phytoplankton die they decompose, and their carbon is returned to the surrounding environment. If this occurs at sufficient depth, this carbon is effectively removed from circulation. This may happen in the Southern Ocean: one of the few places in the world where deep, oceanic water circulates back to the surface, and where surface water sinks to near-bottom depth, this may be a key area for storing CO_2 in the ocean. The Southern Ocean may thus behave like a biological pump, exporting excess carbon to the bottom of the sea in response to the higher CO_2 concentrations in the surface waters of the ocean.

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Biographical Sketch

Eric Wolanski is a Fellow of the Australian Academy of Technology Sciences and Engineering, and a Corresponding Member of the Académie Royale Belge des Sciences d'Outre-Mer. He is a member of the Sigma Xi Research Society of North America, and of the Australian Institution of Engineers. He is an editor of the scientific journal *Estuarine, Coastal and Shelf Science*, and a member of the editorial advisory board of the scientific journals *Continental Shelf Research*, *Journal of Coastal Research*, *Wetlands Ecology and Management*, *Journal of Marine Systems*, and *Oceanographic Literature Review*. For the last twenty-two years he has been a senior principal research scientist at the Australian Institute of Marine Science, where he has been studying tropical coastal oceanography and its biological implications for mangroves and coral reefs.