Chapter 10
Water related environmental concerns

Þröstur Þorsteinsson
Jarðvisindastofnun Háskólans
Sturlugata 7, 101 Reykjavík
research.turdus.net | ThrosturTh@gmail.com

Natural changes in the hydrological cycle, climate change, and last, but by no means least, human induced changes, are creating pressures on freshwater systems all over the globe.

10.1 Vulnerability of freshwater ecosystems

There are many threats facing freshwater ecosystems on Earth. Below are a few of the main pressures facing the freshwater ecosystems according to the United Nations Water Development project [24].

Population and consumption growth

The world population is growing, and may reach 9 000 000 000 (9×10^9, or nine billion) people by the year 2050, see Figure 10.1.

Increased water abstraction and acquisition of cultivated land through wetland drainage is neccessary to sustain increasing populations; increases requirement for all other activities with consequent risks. Virtually all ecosystem functions are at risk due to this, including habitat, production and regulation functions.

Infrastructure development

Infrastructure development include dams, dikes, levees, and diversions. The effect of those is the loss of integrity, which alters the timing and quantity of river flows, water temperature, nutrient and sediment transport and thus delta replenishment, and, in some cases, blocks fish migrations. At risk is water quantity and quality,

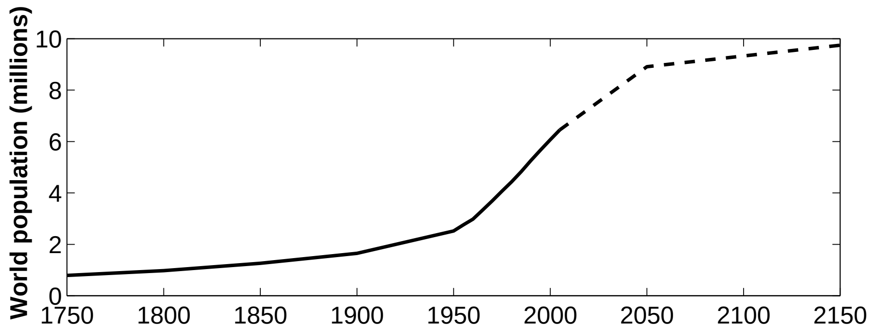

Fig. 10.1 World population and prediction of population increase till the year 2150.

habitats, floodplain fertility, fisheries, and delta economies. Figure 10.2 shows the dikes, canals and dams in the Netherlands.

Land conversion

Eliminates key components of aquatic environment; loss of functions; integrity; habitat and biodiversity; alters runoff patterns; inhibits natural recharge, fills water bodies with silt. At risk is natural flood control, habitats for fisheries and waterfowl (Fig. 10.3), recreation, water supply, water quantity and quality.

Overharvesting and exploitation

Depletes living resources, ecosystem functions and biodiversity (groundwater depletion, collapse of fisheries). *Food production, water supply, water quality and water quantity*.

Introduction of exotic species

Competition from introduced species; alters production and nutrient cycling; and causes loss of biodiversity among native species. *Food production, wildlife habitat, recreation*.

Fig. 10.2 Along the southwest coast of the Netherlands, sediment-carrying rivers have created a massive delta of islands and waterways in the gaps between coastal dunes. After unusually severe spring tides devastated this region in 1953, the Dutch built an elaborate system of dikes, canals, dams bridges and locks to hold back the North Sea. This simulated natural color image was acquired on September 24, 2002, covers an area of about 50.6 $\times$ 52.4 km, and is centered near 51.7 degrees north latitude, 4 degrees east longitude. Image from NASA/GSFC/METI/ERSDAC/JAROS.

Fig. 10.3 Swans (*Cygnus olor*, in Iceland we have *Cygnus cygnus*, or álft), and many other species of water fowl, are at risk due to land changes and increasing demands on water systems.

Release of pollutants to land, air or water

Pollution of water bodies alters chemistry and ecology of rivers, lakes and wetlands; greenhouse gas emissions produce dramatic changes in runoff and rainfall patterns. *Water supply, habitat, water quality, food production; climate change may also impact hydropower, dilution capacity, transport, flood control* .

10.2 Sea water intrusion

Under natural condition fresh groundwater is discharged to the ocean seaward of the coastline. But, increased demands for ground water has in some cases reversed this seaward flow, causing sea water to enter inland aquifers. This phenomenon is sea water intrusion [20].

By lowering the water table in an unconfined aquifer, or the potentiometric surface in a confined aquifer, the natural gradient sloping towards the ocean is reduced, or even reversed. Because of the different densities of freshwater and seawater, a boundary surface (interface), is formed where the two fluids are in contact.

Ghyben-Herzberg relation

The Ghyben-Herzberg relation describes the boundary between fresh and saline waters. For an unconfined aquifer in a coastal region, we have that the hydrostatic pressure in the ocean at point A is,

$$p_A = \rho_s g h_s, \tag{10.1}$$

where subscript s refers to sea water. At another point B, inland, at the same depth,

$$p_B = \rho_f g h_f + \rho_f g h_s, \tag{10.2}$$

where subscript f refers to fresh water, and h_f is height of the water table above sea level, see Figure 10.4.

Equating these yields the Ghyben-Herzberg relation, named after two investigators who studied sea water intrusion along the European coast [20],

$$h_s = \frac{\rho_f}{\rho_s - \rho_f} h_f. \tag{10.3}$$

It is convenient to define a density ratio,

$$\tilde{\rho} = \frac{\rho_f}{\rho_s - \rho_f}. \tag{10.4}$$

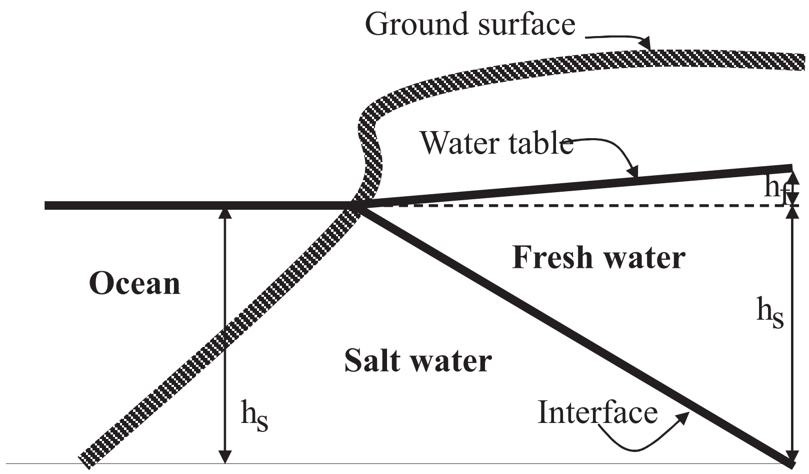

Fig. 10.4 Idealized sketch of fresh- and salt-water distributions in an unconfined coastal aquifer.

Taking typical values for the density of freshwater, $\rho_f = 1000$ kg m^{-3}, and salinewater $\rho_s = 1025$ kg m^{-3}, we get $\tilde{\rho} = 40$, and

$$h_s = 40h_f.$$

For confined aquifers we can replace the water table with the potentiometric surface.

If only flow in the fresh water zone, then from Darcy's law, we can relate the slope of the water table δ,

$$\sin\delta = \frac{dh}{ds} = \frac{v}{K}, \qquad (10.5)$$

where v is velocity and K is hydraulic conductivity (permeability), to the slope of the fresh-salt water boundary ξ,

$$\sin\xi = \tilde{\rho}\frac{v}{K}. \qquad (10.6)$$

Length of the Intruded Sea Water Wedge

If there is a fresh-water flow towards the ocean from a confined aquifer, then the approximate relation below can be used,

$$q = \frac{1}{2\tilde{\rho}}\frac{Kb^2}{L}, \qquad (10.7)$$

where b is the thickness and L the length to which sea-water reaches into the confined aquifer. Equation 10.7 implies that the length of the wedge is inversely proportional to the fresh water flow, see Figure 10.5.

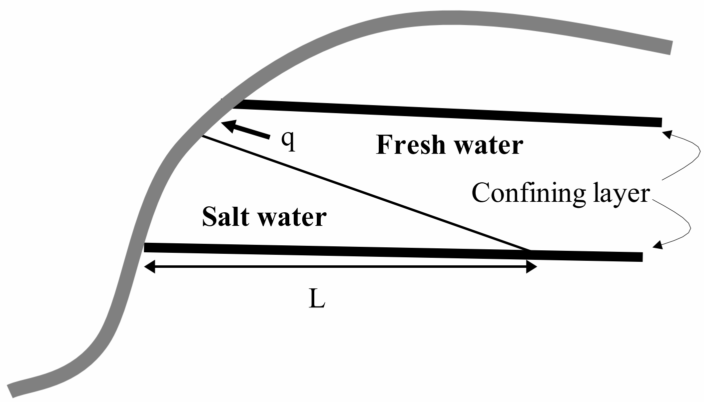

Fig. 10.5 Sketch of an confined coastal aquifer with fresh-water flux to the ocean.

Solution Glover's 1964

In reality the fresh water drains into the ocean over a certain area, rather than at a point [1]. The shape of the interface can be approximated by [5] (note, missing ρ_f in [1]),

$$z^2 - \frac{2q\tilde{\rho}x}{K} - \frac{q^2\tilde{\rho}^2}{K^2} = 0, \tag{10.8}$$

where q is flow in aquifer per unit length of shoreline, K is hydraulic conductivity of aquifer, x, z are coordinate distances, and $\tilde{\rho}$ is given by (10.4).

We call the distance from the shore out to sea where fresh water enters the sea w, and the depth to the fresh-salt water interface at the shore z_0. Substituting $z = 0$ in Equation 10.8 gives,

$$w = \frac{q\tilde{\rho}}{2K},$$

for the width w of the bottom zone through wich fresh water seeps into the ocean, and substituting $x = 0$ gives

$$z_0 = \frac{q\tilde{\rho}}{K},$$

for the depth of the freshwater-saltwater interface beneath the shoreline. The height of the water table at any distance x from the coast is given by

$$h = \sqrt{\frac{2qx}{\tilde{\rho}K}}.$$

Figure 10.6 shows the water-table h, and interface z given by Equation 10.8.

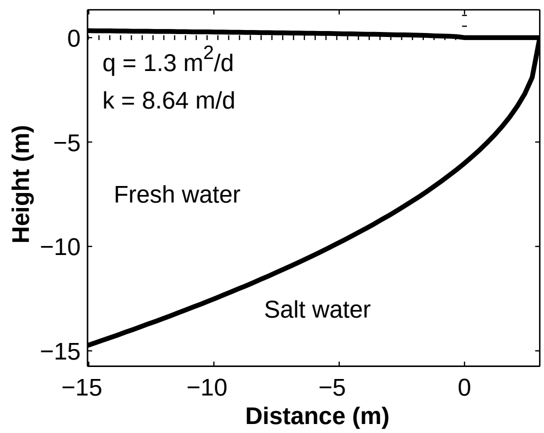

Fig. 10.6 The interface according to Equation 10.8.

Control of Sea Water Intrusion

There are a few methods that can be used to limit or prevent sea water intrusion.

- Modification pumping. Move well further inland or reduce pumping rate.
- Artificial recharging. Pump fresh (or nearly fresh) water into the well, as illustrated in Figure 10.7.
- Pumping through. If many wells are placed parallel and along a coastline, the through generated by the drawdown will limit the intrusion of sea water (potentiometric surface driving flow against the salt water), as illustrated in Figure 10.8.
- Pressure ridge. Many wells along the coastline as above, but now pumping water into the wells.
- Subsurface barrier. Put in some barrier to salt water intrusion.

Oceanic Islands

The depth d (measured from sea level) to the fresh/salt water boundary, assuming a circular island, is given by [20, modified from p. 259],

$$d^2 = \frac{W}{2K}\left(\frac{\tilde{\rho}}{1+1/\tilde{\rho}}\right)(R^2 - r^2), \tag{10.9}$$

where K is hydraulic conductivity, R is the radius of the island, $\tilde{\rho}$ is given by Eq. 10.4, and W the recharge rate.

The head above sea level, for a circular island, is given by,

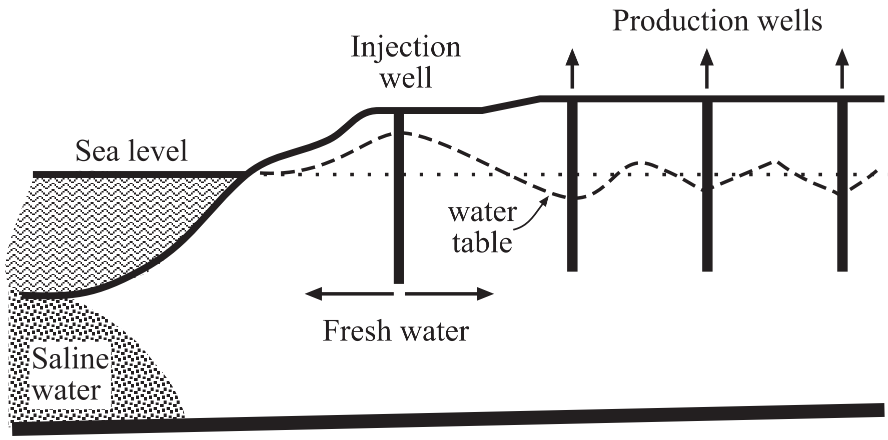

Fig. 10.7 Artificial recharging is used to raise the water table closest to the shore such that the fresh water flow is towards the shore.

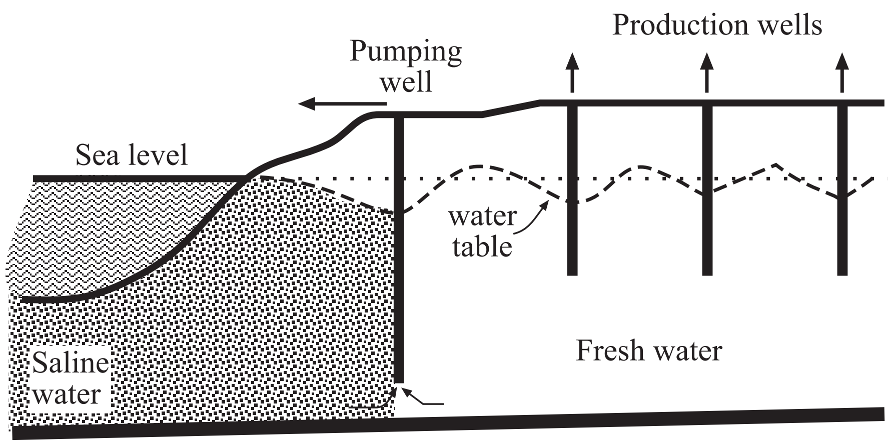

Fig. 10.8 Many well are lined up in parallel along the coastline, generating a drawdown that will limit the intrusion of sea water.

$$h^2 = \frac{W}{2K}\frac{1}{1+\tilde{\rho}}(R^2 - r^2), \tag{10.10}$$

and if the island is an infinite-strip, like a long peninsula, with a width 2 a [5],

$$h^2 = \frac{W}{K}\frac{1}{1+\tilde{\rho}}[a^2 - (a-x)^2].$$

Figure 10.9 shows the water table and interface for a circular oceanic island according to (10.9) and (10.10).

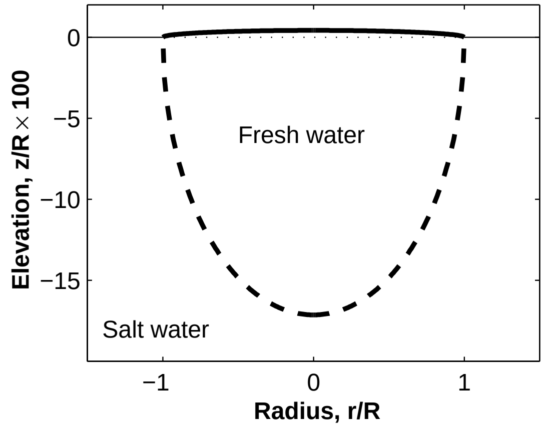

Fig. 10.9 Water table and interface of an circular island, with recharge $W = 13$ mm d^{-1}, $K = 10^{-2}$ cm s^{-1} = 8.64 m d^{-1}.

Figure 10.10 shows a sketch of the situation on an island with a pumping well where the pumping rate exceeds the natural recharge. If pumping continues at this rate, the well may start pumping up sea water in the near future.

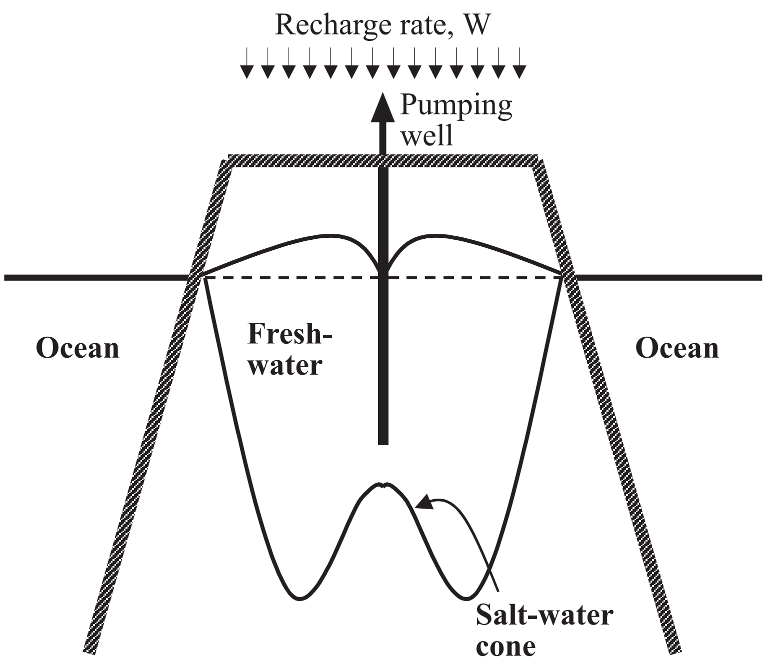

Fig. 10.10 Sketch of an oceanic island with a pumping well.

10.3 Climate change

In most studied catchments (in Europe), forecasted climate change will lead to an increase in flood frequencies [13].

It is forecasted that climate change will account for 20% of the increase in global water scarcity [24]. Along with temperatur rise the pattern of precipitation is expected to change, see Figure 10.11.

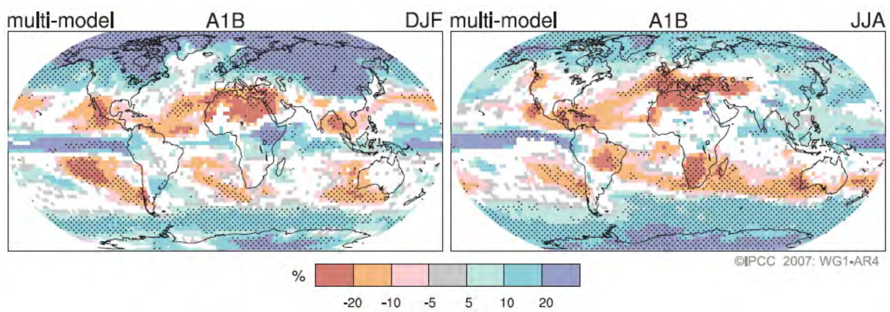

Fig. 10.11 Relative changes in precipitation (in percent) for the period 2090 - 2099, relative to 1980 - 1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change.

Sea level rise is a clear indicator of changing climate. Over the last 100 years, the global sea level has risen by about 10 to 25 cm. Melting of ice, especially mountain glaciers, and thermal expansion have contributed to the sea level rise so far. With warming temperature, it is expected that the large ice sheets, Greenland and Antarctica, will contribution increasingly more. Table 10.1 shows the estimated contribution to sea level rise 1993 – 2003 (based on data from IPCC press releases).

Table 10.1 Observed rate of sea level rise 1993 – 2003.

Source of sea level rise	**Rate (mm per year)**
Thermal expansion	1.6 ± 0.5
Glaciers and ice caps	0.77 ± 0.22
Greenland ice sheet	0.21 ± 0.07
Antarctic ice sheet	0.21 ± 0.35
Sum	$\mathbf{2.8 \pm 0.7}$
Observed total sea level rise	3.1 ± 0.7

10.4 Lake Chad

Lake Chad, located at the intersection of four countries in West Africa (Chad, Niger, Nigeria and Cameroon), was once one of the African continent's largest bodies of fresh water. About 20 million people live in the four countries surrounding the lake. Lake Chad is very shallow, average depth of only a few meters, and only 10.5 m where it is deepest. It has dramatically decreased in size possibly due to climate change, and certainly due to human demand for water; been the source of water for massive irrigation projects. The region has suffered from an increasingly dry climate, experiencing a significant decline in rainfall since the early 1960's. According to studies, the lake is now about $\sim 1/10^{th}$ of the size it was 35 years ago, as can be seen in Figure 10.12. In 2002 the surface area was about 1 350 km^2, while in 1963 it was 25 000 km^2.

10.5 Problems

Sea infilteration problems

10.1. Fresh water lens for an oceanic island (circular). Given that $W = 80$ mm/d, $K = 5$ m/d (rather low), $R = 50$ km, $\rho_f = 1000\,\mathrm{kg\,m^{-3}}$, $\rho_s = 1025\,\mathrm{kg\,m^{-3}}$. Calculate the maximum depth of the fresh-water lens (10.9), and plot the interface for $r = 0$ to 20 km.

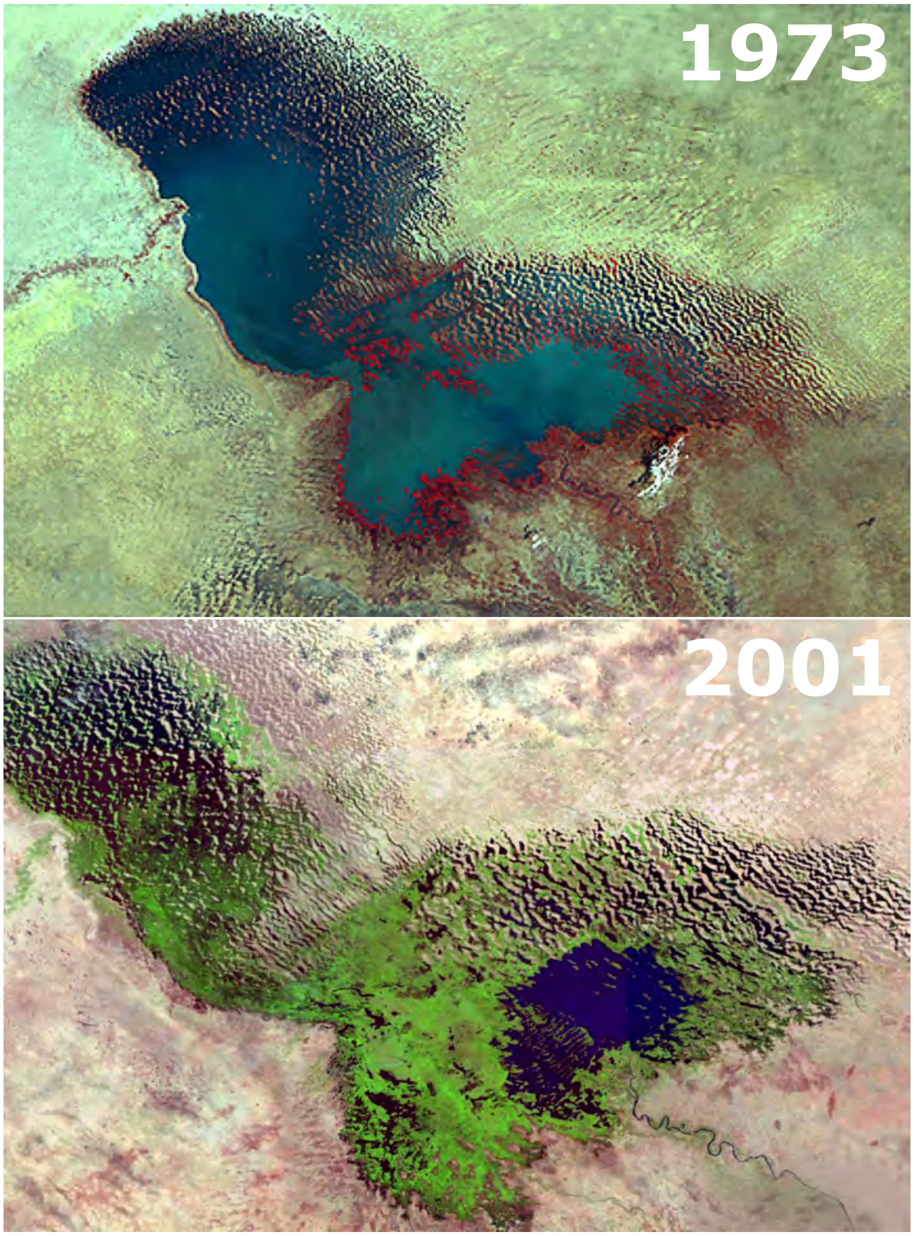

Fig. 10.12 Changes in Lake Chad, West Africa. NASA images courtesy the MODIS Rapid Response Team at NASA GSFC.

Chapter 11
Environmental hazards

Water is, in one way or another, be it floods or droughts, responsible for 90% of all natural disasters.

11.1 Floods

Flooding is a major concern for many areas of the world. Fertile river deltas are quite often densly populated, and thus prone to disaster when the rivers grow.

Flooding is an annual occurrence in many parts of the world. In Mozambique (Figure 11.1), and southern Africa, summer floods are a way of life along the rivers. The rainy season begins in October, builds to a climax during December through March, and then tapers off in April, delivering much of the region's annual rainfall.

11.2 Mud flows and lahars

A mudflow, or mudslide, is the fastest (up to 80 km per hour) and most fluid of downhill mass wasting. Debris flow is used for similar processes, usually in high mountains. Mud slides, lahars and mud streams are less liquid.

Definition 11.1. *Lahars* are mud and debris flows, usually used for mudflows related to volcanic activity.

Lahars, or mud-and debris flows, occur when large volumes of water and mud are released. Possible sources include a glacier covered volcano that erupts (Figure 11.2), intense rainfall, and breakout of crater lakes. In all cases large volumes of water and debris are created, and this deadly mixture races down the slopes of the volcano, at speeds up to 64 km per hour.

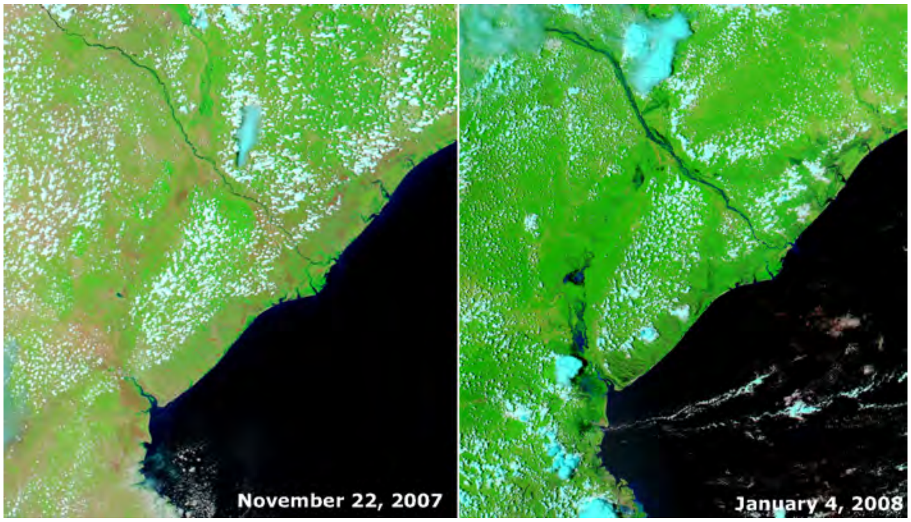

Fig. 11.1 Flooding in Mozambique 2008. Both images were made with a combination of infrared and visible light to increase the contrast between earth and mud-laden flood water; water is black, or dark blue when tainted with sediment, bare or sparsely vegetated land is tan, and plant-covered land is bright green, clouds are light blue and white. The field of view is approximately 500 km north to south (up-down). NASA images courtesy the MODIS Rapid Response Team at NASA GSFC.

11.3 Pollution

In a still lake a pollutant with strength c will disperse with time from the source due to diffusion, which is described with the equation,

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2}, \tag{11.1}$$

where D is the diffusivity of the material. A more general form of the equation is $\partial_t = D\nabla^2 c$. Figure 11.3 shows the diffusion of a point source, a drop spilled at time $t = 0$, at three later times.

Definition 11.2. Diffusion is the process by which fluids and solids mix intimately with one another due to the kinetic motions of the particles [7].

In groundwater the pollution can also be advected, due to water movement (flow). The velocity of the water is given by Darcy's equation,

$$v_x = \frac{K}{n_e}\frac{d\phi}{dx}.$$

In the soil, water doesn't move along straight lines, particles in the soil force the water to move to the sides. This causes mechanical dispersion, which is the product

Fig. 11.2 Mount St. Helens erupted explosively on March 19, 1982, which resulted in a lahar flowing from the crater into the North Fork Toutle River valley. Part of the lahar entered Spirit Lake (lower left corner) but most of the flow went west down the Toutle River, eventually reaching the Cowlitz River, 80 kilometers downstream. USGS Photograph taken on March 21, 1982, by Tom Casadevall.

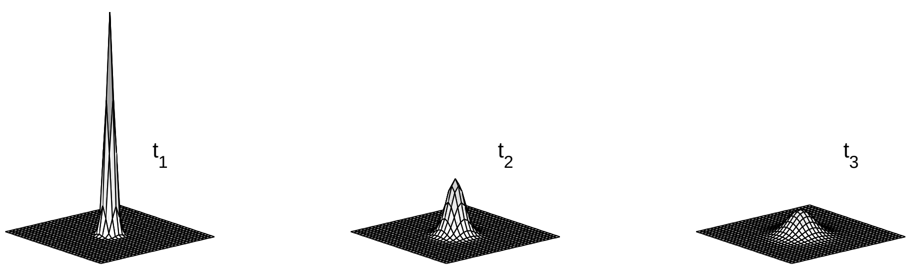

Fig. 11.3 Diffusion of a point source of pollution. Shown is concentration at three different times $0 < t_1 < t_2 < t_3$.

of velocity and a constant called dynamic dispersivity, a_L,

$$a_L = 0.0175 \cdot L^{1.46}, \tag{11.2}$$

where L is the distance from the source.

In groundwater the distribution is therefore the combined effect of molecular diffusion D and the dynamic dispersivity,

$$D_L = a_L \cdot v_x + D. \tag{11.3}$$

The equation for the pollutant strength, with combined diffusion and advection, is then,

$$\frac{\partial c}{\partial t} = D_L \frac{\partial^2 c}{\partial x^2} - v_x \frac{\partial c}{\partial x}. \tag{11.4}$$

The solution to Eq. 11.4 is,

$$c = \frac{c_0}{2}\left[erfc\left(\frac{L - v_x t}{2\sqrt{D_L t}}\right) + \exp\left(\frac{v_x L}{D_L}\right) erfc\left(\frac{L + v_x t}{2\sqrt{D_L t}}\right)\right], \tag{11.5}$$

where c_0 is the source strength and t is time.

Figure 11.4 shows the effect of combined diffusion and advection of a continous point source of pollution.

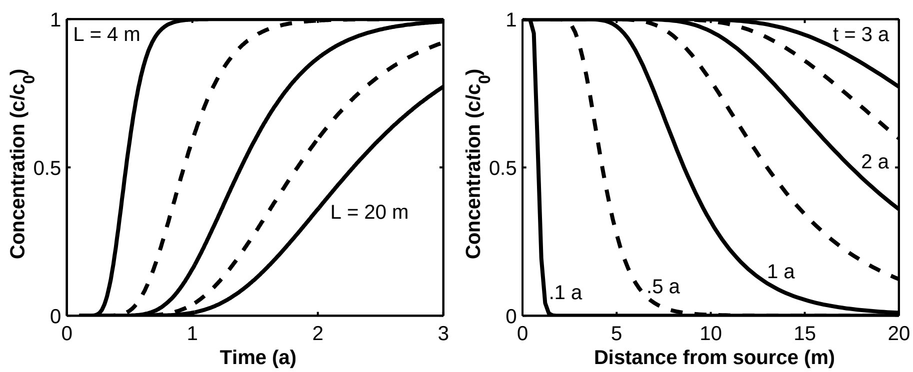

Fig. 11.4 The effect of combined diffusion and advection of a continous point source of pollution. Shown are concentration profiles at five different locations from the soure, $L = 4, 8, 12, 16, 20$ m (left) and as a function of distance from the source for times $t = 0.1, .5, 1, 1.5, 2, 2.5, 3$ a (right). Here we used $D = 10^{-9}$ m^2 s^{-1}, $v_x = 2.6 \times 10^{-7}$ m s^{-1}, and c is normalized by c_0.

Oil spills

Every year large amounts of oil reach the ocean. Contrary to common belief, large oil spills are not neccessarily the main source, see Figure 11.5. The category “Drain” accounts for 1374 million liters, and that figure includes for instance used engine oil, which can end up in waterways. On average a oil change uses five quarts; one change can contaminate a million gallons of fresh water. Much oil in runoff from land, municipal and industrial wastes ends up in the oceans. “Road runoff” adds up to 19 million liters every year, as oily road runoff from a city of 5 million could contain as much oil as one large tanker spill. “Maintenance” adds 518 million liters to the ocean worldwide every year. Bilge cleaning and other ship operations release millions of liters of oil into navigable waters, in thousands of discharges of just a few liters each. “Smoke” adds 348 million liters. Air pollution, mainly from cars and industry, places hundreds of tons of hydrocarbons into the oceans each year. Particles settle, and rain washes hydrocarbons from the air into the oceans. “Spills” add 140 million liters. Only about 5% of oil pollution in oceans is due to major tanker accidents, but one big spill can disrupt sea and shore life for kilometers. “Drilling” adds 57 million liters. Offshore oil production can cause ocean oil pollution, from spills and operational discharges. Natural “seeps” account for 235 million liters.

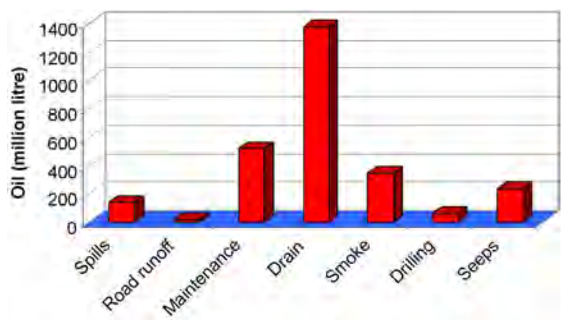

Fig. 11.5 Sources of oil (in millions of liters) to the oceans worldwide each year.