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Surface and Groundwater Quality and Health, with a Focus on the United Kingdom

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Introduction

Freshwater environments are of major importance to health issues in both direct (e.g., drinking water and sanitation) and indirect (e.g., industry, agriculture, and amenity/recreation) ways. However, water resources are finite, and, though renewable, demands have multiplied over the last 100 years due to escalating human populations and the growing requirements of industry and agriculture (Fig. 14.1). Hence, there are increasing global concerns over the extent of present and future good quality water resources. As Gleick (1998) emphasizes:

- Per-capita water demands are increasing, but per-capita water availability is decreasing due to population growth and economic development.
- Half the world's population lacks basic sanitation and more than a billion people lack potable drinking water; these numbers are rising.
- Incidences of some water-related diseases are rising.
- The per-capita amount of irrigated land is falling and competition for agricultural water is growing.
- Political and military tensions/conflicts over shared water resources are growing.
- A groundwater overdraft exists, the size of which is accelerating; groundwater supplies occur on every continent except Antarctica.
- Global climate change is evident, and the hydrological cycle will be seriously affected in ways that are only beginning to be understood.

The chemical composition of surface and groundwaters is influenced by a wide range of processes, some of which are outside the influence of humans while others are a direct consequence of anthropogenic pollution or changing of the environment. Starting with the range and nature of the processes involved, the changing nature of surface and groundwater quality is illustrated here, based on the evolution of the United Kingdom from a rural to an industrial and to a post-

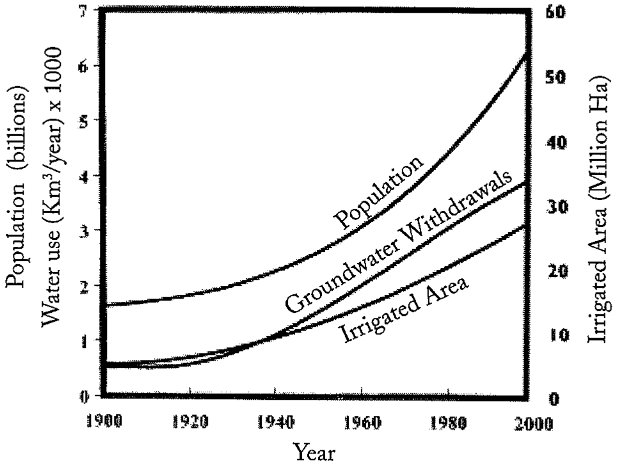

Figure 14.1: Change in the global population, water use and irrigated area over the past 100 years (data from Gleick 1998).

industrial society. The issue of what constitutes a health risk is outlined in relation to the pragmatic approaches required for environmental management.

Chemical and Hydrological Processes That Determine Surface and Ground Water Quality

Surface and groundwater exhibit a wide range of chemical compositions, and, in ecosystems uninfluenced by humans, the range of compositions can vary considerably. For example, highly concentrated $CaCl_2$ solutions (to the level of saturation, for one of the most soluble minerals known) occur at sub-zero temperatures in Antarctic lakes while brines and evaporites are associated with marine incursions and arid areas. Wide variations in pH also occur. For example, hyperalkaline spring waters of pH greater than 11 occur in ultrabasic rock terrains, whereas acidic environments associated with the oxidation of iron sulphides in soils and bedrock can produce waters of pH<3 that may be aluminum (Al) and Fe-rich. However, average compositions globally are:

- pH around neutral to slightly alkaline.
- Major ion/element concentrations greater than 1 mg/l — These comprise bicarbonate, sulphate, silica, nitrate, chloride, Ca, Mg, and Na as well as dissolved organic carbon (C).
- Minor to trace element levels in the range of 1 mg/l to 1 μg/l — K, F, P, boron (B), bromide, Sr, barium (Ba), Fe, Mn, Zn, Cu, lithium (Li), Al, and uranium (U).
- Trace element levels of less than 1μg/l — transition metals not listed above and components such as cesium (Cs), rubidium (Rb), Se, As, bismuth (Bi), and I.
- Organic components including algae and bacteria at sub μg/l levels.

Pollutants from urbanization, industry, and agriculture can change the net balance of the components. For example, mining activity can increase the concentrations of As, Fe, Cu, and others. Nonetheless, the natural geologic environment may also introduce harmful substances to groundwaters used for drinking purposes, as in the case of arsenic (As) mentioned below. Typical water chemistries for U.K. catchments affected by acid deposition and for rural, agricultural and urban/industrial rivers are presented in Table 14.1.

The chemical compositions of surface and groundwaters are linked to the bedrock sources within the catchment or aquifer, and are controlled by hydrological mixing processes (Drever 1997, Neal et al. 2000a). Wet, mist, and dry particulate deposition can be particularly important for environments where components such as sea-salt and acidic oxides from industrial emissions are supplied. Most elements in freshwaters reflect lithogenic components from "diffuse sources." They are linked to soil and bedrock type and chemical reactivity between the minerals (solids) and solution phases and the speciation in solution. Pollutant inputs come from point and diffuse sources. Point sources arise at specific locations, commonly from industry and urbanization linked to sewage works or to direct discharges, (e.g., transition metals and B). Diffuse sources are derived across a broad area and include N, P, or K fertilizers or pesticides from agriculture; and heavy metals produced by contaminated land from industrial processing and dumping.

A wide range of chemical processes determines the biogeochemical evolution of the waters within the catchment and the aquifer. These include acid-base

Table 14.1: Concentrations for water quality in four environments

Mean baseflow (left), stormflow (right) and mean (bold)
The acidic and acid sensitive catchments in mid-Wales (Afon Hafren)
The rural basins (River Tweed on the borders between England and Scotland)
The agricultural basins (River Thames in south-eastern England)
The urban/industrial complexes (River Aire, north-eastern England)

The data for the Hafren cover weekly sampling for the period 1983 to 1997 (Neal et al. 1997). Other sites cover weekly information collected from 1992 onwards (Neal and Robson 2000). Levels of micro-organic pollutants in the environment are not presented because the information is far more fragmentary (House et al. 1997, Long et al. 1998, Meharg et al. 2000a,b, and Neal et al. 2000b,c) .

	Hafren	*Tweed*	*Thames*	*Aire*
Majors (mg/l)	Acidic/Acid Sensitive	Rural	Agricultural	Urban/Industrial
Na	4 **4** 4	16 **10** 7	52 **30** 18	164 **116** 49
K	0.1 **0.2** 0.2	2.1 **1.4** 1.3	9.5 **5.9** 4.5	19.4 **15.2** 5.9
Ca	0.9 **0.7** 0.7	41 **37** 20	122 **121** 116	74 **65** 36
Mg	0.8 **0.7** 0.7	17.0 **10.2** 4.9	6.4 **5.8** 5.1	16.6 **13.8** 7.1
NH_4	0.0 **0.0** 0.0	0.0 **0.0** 0.0	0.0 **0.0** 0.1	1.0 **1.3** 1.0
Cl	7 **7** 7	26 **19** 14	65 **45** 35	179 **120** 72
SO_4	4 **4** 4	16 **12** 8	110 **74** 54	212 **157** 59
NO_3	1 **1** 1	1.2 **1.5** 1.5	6.1 **8.2** 9.5	9.1 **6.2** 3.7
Trace (µg/l)				
Al	174 **311** 416	7 **24** 199	3 **6** 51	27 **17** 45
Be	0.02 **0.05** 0.09	0.01 **0.01** 0.03	2.33 **0.02** 0.02	2.30 **0.02** 0.02
B	5 **5** 6	46 **21** 11	333 **164** 80	575 **342** 94
Cr	02.4 **2.4** 2.4	0.3 **0.4** 0.8	0.5 **0.4** 0.4	3.7 **3.7** 1.7
Fe	76 **109** 127	10 **32** 167	11 **18** 75	102 **124** 204
Mn	36 **40** 43	6 **6** 6	5 **6** 6	128 **143** 112
Mo	0 **0** 0	0 **0** 0	4 **2** 1	42 **21** 4
Ni	1.3 **2.0** 2.4	1.4 **1.3** 2.6	3.8 **2.7** 2.8	12.8 **8.8** 6.1
P	0 **0** 0	33 **28** 29	1700 **818** 257	1812 **1134** 260
Zn	14 **18** 20	6 **4** 4	8 **5** 4	32 **27** 20
pH	5.4 **5.1** 4.5	8.3 **8.3** 8.3	8.0 **8.1** 8.0	7.5 **7.4** 7.5
Alk (µEq/l)	0 **−21** −34	2888 **2412** 1264	4393 **4422** 4267	2583 **2252** 1351

reactions, acidity generation with mobilization of hydrolysable elements, alkalinity generation associated with biogenic CO_2 production and mineral weathering, photosynthesis/respiration, mineral solution and precipitation, partial solution/co-precipitation, complexation, oxidation and reduction, kinetic controls, ion exchange, and evaporation.

The chemical reactivity is linked to the hydrological cycle. Fluctuation in hydrological factors such as the frequency and duration of rainfall (and, in some cases, snow and mist), antecedent conditions, evaporation, and storage are commonplace. The storage term is particularly important as increased residence times allow for a greater degree of reactivity. For igneous and metamorphic rock terrains, transport of rainfall to the river occurs rapidly (minutes to days). For the more permeable sedimentary rock terrains, aquifer drainage results in a delayed rainfall response (days to months, to millennia and even longer).

For surface waters, the water quality often changes as a function of flow. Within rivers, attenuating mechanisms are linked to the volume and type of aquatic species, such as the effects of photosynthesis and respiration on pH. However, there will be a delayed response to rainfall (days to years) for lakes and reservoirs with their increased storage time. In soil waters, there will also be differences. For example, under acidic high flow conditions, these waters may contain aluminum or other metal ions, whereas groundwaters, probably richer in weathering components, would prevail under low flow conditions. For waters derived mainly from aquifers, the element concentrations vary less with flow except when there is point source pollution that dilutes with increasing flow, or when diffuse pollutants from agriculture are leached under high flow conditions.

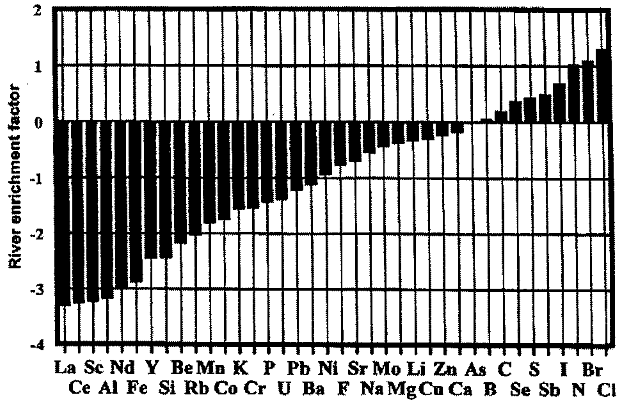

Figure 14.2: River enrichment factor (REF) for the chemical elements in global average river water (Neal 2001a).

To illustrate the net effect of the various processes, Figure 14.2 shows the relative attenuation of the chemical elements in river water relative to the earths crust based on a study by Neal (2001a). The diagram plots the logarithm of the river enrichment factor (REF), the ratio of the concentration of each element in average surface water to the average crustal abundance. For the plot, the elements are organized in sequence from the lowest to the highest REF. For C, S, and N, the predominant species in solution are HCO_3^{-}, SO_4^{2-}, and NO_3^{-}, respectively. Note that

- The highest REFs occur for sea-salt elements (Na and Cl), soluble anions (Br and I, Se, As, and Sb) and elements related to life (C, N, and S).
- The lowest REFS occur for elements of high charge and prone to solubility controls associated with the precipitation of oxide, hydroxide (lanthanides, actinides, Si, Fe, and Mn) and layer silicate weathering products (e.g., clay minerals for Al, Si, and Fe).
- The intermediate REFS occur for components with moderate solubilities but where ion exchange (e.g. K and F) and carbonate solubility/weathering (Ca and Mg) come into play.

Water Quality in the United Kingdom: An Historical Perspective

Before 1700, Britain was a rural society with a relatively clean riverine and groundwater environment. An evolving landscape/soil/sedimentation pattern over the previous few millennia had been linked to wetter and warmer conditions, historic deforestation of much of the uplands for sheep grazing and, later, to land enclosures for farming. This produced acidic organic soil in the uplands and increased erosion in both the uplands and the lowlands.

Thereafter, Britain experienced a move from cottage to mechanized production in the Industrial Revolution, a change that eventually affected other countries through developments in agriculture, physics, chemistry, and engineering, a fundamental restructuring of society and politics, and a changing aquatic environment (Neal 2001b). Throughout the eighteenth and much of the nineteenth century, population escalated, and major cities developed on navigable rivers. The rivers acted as a focus for trade, a source of water for drinking and industry, and a conduit for industrial and sewage wastes. Britain became the workshop of the world, and in much of the country a filthy riverine and urban environment resulted. This pattern has been repeated in some urban and industrial districts of the developing world. During the latter half of the nineteenth century and the early twentieth century, the industrial base peaked and then declined. At this time, environmental controls were progressively introduced with sewage and pollutant discharge controls and more enlightened health regulation. By the start of the twentieth century, waterborne epidemics such as cholera and typhoid became a scourge of the past.

After the 1920s, a great industrial clean-up began. This accelerated after the Second World War with the development of groups such water and purification boards and a national rivers association, expanded environmental management legislation and a reduction of industrial discharges. Over the past decade, these groups amalgamated into the Environment Agency of England and Wales and the Scottish Environment Protection Agency, major forces for environmental improvement.

Measurements of the extent of the pollution and the degree of clean-up are sparse as environmental monitoring has been undertaken only for the past 10 to 30 years. However, a numerical illustration of more recent improvements in the River Aire (Yorkshire), associated with discharge controls is shown in Figure 14.3 for the organic pollutant, dieldrin. Parallel reductions are found for many industrial chemicals as well as for trace metals such as mercury (from about 2µg/l to less than 0.1µg/l during the same period).

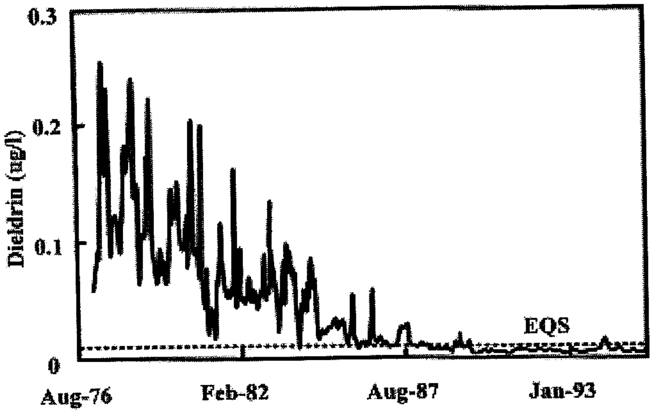

Figure 14.3: Changes in dieldrin concentrations in the River Aire: 1976 to 1994 (data from Edwards et al. 1997). EQS = environmental (water) quality standard

The broad progressive changes based on straightforward, pragmatic engineering and management measures underpinned by the developing environmental sciences, mark the actions in the U.K. as one of the worlds greatest clean-ups. However, many environmental issues remain. Groundwaters contaminated by nutrients applied as fertilizers between 1940 and 1970 are still important and contaminate lowland surface waters. Atmospheric pollution still occurs due to acidic oxides from industry (SO$_x$) and agriculture (NH$_3$), and emissions from vehicles (NO$_x$) are of growing importance. There also remains the legacy of the past in the form of land and river flood plain contamination by metals and micro-organic substances and drainage from derelict mines. There are the introduction of new micro-organic substances that are potentially highly harmful to the aquatic environment and the food chain. The biological quality of river and groundwater systems is of growing concern in relation to ecology and health risks from bacteria and viruses. There are issues of climate instability as changing extremes and long-term change have a major influence on how the aquatic environment functions.

Water Quality and Health

The impact of water quality on human health is highly complex. The factors involved include the environmental sources and pathways, the nature and rate of ingestion by humans, chemical concentrations, dose, and chronic and acute exposures to specific components. These factors need further consideration before approaching the issue of environmental controls in relation to health. There are three main areas to consider: inorganic components, man-made compounds or micro-organics, and biologic species that cause disease.

Inorganic Components

Most naturally occurring elements are utilized by plants and animals and some are essential for human health and metabolism (e.g., C, S, N, P, Se, Br, I, Fe, and many of the transition metals). The issue of essential versus harmful levels is associated with the amount and the species of each element imbibed and in some cases the relationships between different elements consumed (Edmunds and Smedley 1996). In a few cases, such as for Se, F, and I, health risks have been documented resulting from deficiencies, while in other geographic areas excess ingestion is the problem. Excess imbibition of As from contaminated groundwaters in Bangladesh and China where concentration levels can exceed 600 μg/l (sixty times the new drinking water standard) has produced a major environmental problem affecting tens of millions of people. Correspondingly, in acidic, environments mobilization of Al and heavy metals within catchments and aquifers may increase Al in drinking water to 1 mg/l when the drinking water standard is 0.05mg-Al/l. In other places excess trace metals such as Fe, Hg, and Cr are the problem. Salinization of waters and influx of brines by over-abstraction of groundwaters can also lead to excess concentrations of various salts.

The impact of toxic and harmful elements on health does not relate simply to elemental composition or the bulk amount, but also to the speciation of the component. For example, Al toxicity is reduced when the element occurs complexed with humic acids or F. Correspondingly, C in the form of bicarbonate does not usually constitute a health risk, whereas cyanide (CN) clearly does even at very low concentrations, and organo-mercury compounds may be extremely toxic. In addition, the issue of biogeochemical cycling may be of central concern as toxic and other harmful components are transferred upwards through the food chain from accumulator bacterial or plant species to farm products and livestock.

Man-made Organic Compounds or Micro-organics

The sub-microgram levels per litre of micro-organics in surface and groundwaters are of growing ecological and health concern. Despite the low levels permitted by present environmental water quality standards, the wide range of industrial contaminants from point sources, and the distinct possibility that there will be both regular and intermittent discharges, present a monitoring problem and knowledge gap.

For the United Kingdom, the industrial rivers comprise a "dilute chemical soup" that is evolving over time (Neal et al. 2000a). Some substances such as DDT are banned, while others are in the process of either being tested or being banned. However, currently banned substances may still be extensively retained in flood plain sediments, and little is known about the concentrations within biological components of freshwater ecosystems. In addition, new substances are now entering river courses. At present, perhaps 100 micro-organics are being measured, although analytical scans indicate that the total number will exceed 1000. Herbicides, pesticides, and endocrine disrupters from point and diffuse sources can occur both regularly and intermittently in sewage and can, or are being, monitored. The latter include the "natural" steroid hormones (oestrone and oestradiol), "artificial" steroid hormones (ethinyl oestradiol) (**Plant and Davis**), and mimic substances (e.g., alkyl phenols and some pesticides).

Biologic Species That Cause Disease

The most serious water quality and health issues are associated with bacteria, parasites, viruses, and rotaviruses (Gleick 1998). These species proliferate in waters where there is inadequate sanitation or contact with contaminated water and from hosts that either live in water or require water. Examples are the diseases spread by insects that breed or feed near contaminated water. Globally, about six million deaths annually can be attributed to: diarrhoeal diseases — 3,300,000; intestinal helminth — 100,000; schistosomiasis — 200,000; malaria — 1,500,000; dengue fever — 20,000; trypanosomiasis — 130,000 (Gleick 1998). The disabling effects of these and other water-related diseases affect a far greater proportion of the population; the actual extent of such morbidity is unknown.

Environmental controls in Relation to Health

The United Kingdom has developed a series of environmental and health regulations over the past century. Current pollutant control strategies for river and groundwaters are based on a clear demarcation between "regulatory bodies," those responsible for maintaining/improving the water quality of the aquatic environment, and "water industry bodies" responsible for the treatment of effluents and the supplies of potable and other waters (Edwards 2001). Atmospheric emission controls, based on the concept of a critical loading to both the soil and aquatic environment, limit acidic oxide and transition metal inputs to catchments. Correspondingly, for rivers and groundwaters, targets for maximum permissible levels are set with increasing stringency in relation to ecological vitality (maintaining or improving biological diversity) in light of riverine, groundwater and estuarine fluxes, recreational activity, and water potability.

Environmental controls are largely based on water quality standards (Gardner and Zabel 1991), which specify the concentration of a substance appropriate to a specified use. These standards may be guide values, imperative values, percentile compliance, or maximum allowable concentrations in the cases where there is knowledge about the various pollutants. New substances must be registered and permission obtained for given levels of exposure. This involves setting consent levels below a "no effect level." A threshold is determined by toxicological examination employing test organisms, plus an additional safety factor (typically a factor of 10). "Trigger conditions" (the concentration at which there is a probable health impact) are required to be stipulated for each substance before registration for use. Regulations cover potable supplies, agriculture, aquatic freshwater and salt-water life, bathing, drinking water, irrigation, and livestock watering. The regulations are often complex, and even a standard table of environmental quality standards can be misleading for two reasons. First, the standards change over time. Second, the complex conditions and caveats attached to some of the water quality standards may require some discretion given to national or local authorities. The directives and circulars produced are treated as providing the optimum conditions (Gardner and Zabel 1991).

Environmental Modeling and Future Issues for Surface and Groundwater Quality Management

Management of surface and groundwater quality in relation to ecological and human health is linked to a wide range of interacting hydrological, biological and chemical interactions influenced by climate, social and industrial change there has been a move towards mathematically based simulations. To better understand how environmental systems function and change, researchers have had been benefited by the increase in computational power, new and highly sophisticated software, and the expansion of environmental databases. Within the aquatic sciences, there is now a plethora of approaches (Hauhs et al. 1996), including empirical statistically based (black box), process-orientated (lumped), process-based (deterministic/distributed), and ecosystem approaches. As the measuring capability increases, the complexity of the environmental systems becomes apparent. Generic models utilizing functional unit networks are needed for better understanding of structural uncertainty, fractal processing, and emergent properties. The simple patterns occurring at the large/catchment-outlet scale are matched by complex relationships at the local/macropore scale (Neal 1997).

Despite major advances in science and management, maintaining and improving the environment will require better understanding of the processes. Any pragmatic approach will be underpinned by environmental modeling, and the imperative to ensure "sustainable development."Two critical issues must be recognized. First, the environment is not in steady state. The contributions of climate, industry, and urban change influence hydrological, chemical, and biological environments and the extremes are probably not yet encountered. Second, dealing with and characterizing pollution and health involves many disciplines, and there are often no numeric data on which to make judgments. Environmental policy will continue to evolve (e.g., Naiman et al. 1995).

We must use innovation to solve the emerging problems, while we work to monitor the actual, and decipher the critical pollutant levels in our physical and biological environments. We need a framework for assessing the changing extremes, the relative merits of toxicological and ecotoxicological approaches, the relationship between deterministic and ecosystem approaches, and the continued development of hydrobio-geochemical models as well as how to evaluate measurements of fluxes and structural/fractal uncertainty. Environmental quality and health issues must be tackled within an integrated framework of environmental science and management, economics, politics, law, and history.

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