

CHAPTER 7

Watershed Management

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INTRODUCTION

Even though watershed management has become an increasingly important aspect of water resources development in recent years in both developed and developing countries, it should be noted that its importance has been realized for at least some 2500 years. For example, Plato (428–348 BC) has graphically noted the impact of land use changes on river discharges (Biswas 1970). In his book *Critias*, Plato discusses the conditions of Athens some 9000 years before his time.

Furthermore it [the land of Attica in ancient times] enjoyed the fructifying rainfall sent year by year from Zeus; and this was not lost to it by flowing off into the sea, as nowadays because of denuded nature of the land. The land [then] had great depth of soil and gathered the water into itself and stored it up in the soil we now use for pottery clay, as though it were a sort of natural water-jar; it drew down into the natural hollow the water which it had absorbed from the high ground and so afforded in all districts of the country liberal sources of springs and rivers; and surviving evidence of the truth of this statement is afforded by all the extant shrines, built in spaces where springs did formally exist.

The importance of watershed management, however, has become especially relevant in recent years because of the increasing realization that the long-term sustainability of water projects is an essential requisite for human welfare. Large- and medium-scale water development projects are invariably capital-intensive, and economically they can be considered to be efficient only if the benefits accruing from such projects can be assured over their designed life periods. There is now considerable evidence from projects from many different parts of the world that the life spans of some reservoirs are going to be less than expected owing to more than anticipated rates of sedimentation, which may occur due to changing land use patterns or serious underestimation of sedimentation rates.

WATERSHED MANAGEMENT

Watershed management, in its broadest sense, can be considered to be an attempt to ensure that hydrological, soil and biotic regimes, on the basis of which water development projects have been planned, can be maintained or even enhanced; under no circumstances must they be allowed to deteriorate.

It is now well known that changing land use patterns affect water and soil regimes of any watershed. These changes, if properly planned, could be beneficial. However, in nearly all watersheds of developing countries, the changes are caused by unplanned and ad hoc activities. Individual activities that affect land use practices are generally small and incremental. However, when all the individual activities over an entire watershed during a specific time period are considered, their overall aggregated impacts could be substantial. Based on recent experiences, such aggregated impacts, unfortunately, tend to be deleterious in terms of watershed management.

The root cause of these changes is undoubtedly continual increase in human and animal populations. With rising human and animal populations, more and more land is required for shelter, food production, forage requirements and fuelwood. Since in most areas, good agricultural and pastoral land are already being utilized, people are forced to use marginal land, often in upper catchment areas having steep slopes. Forest is cleared so that the land can be used for agricultural or pastoral purposes.

Against a background of rising human and livestock populations, and the combined effects of agricultural encroachment and deforestation, land use patterns of most watersheds have undergone serious changes in recent years and are likely to be subjected to more changes in coming decades. These changes, for the most part, are unplanned. The extent of this increased pressure can be easily demonstrated by considering the case of the Sudan, where between the 20-year period of 1957-77, the human population increased more than six-fold, the number of cattle twentyone-fold, camels sixteen-fold, sheep twelve-fold and goats eight-fold (Biswas *et al.* 1987). Given such rapid increases in populations, it may not be possible to develop and implement watershed management policies which could be sustainable over a long term.

Much international attention has been focused in recent years on the present status of environmental degradation in the upland

areas of various watersheds in countries like Nepal, India, Thailand, China or Ethiopia. What is, however, much less realized is that the environmental degradation of such areas is a main symptom of a disease but not the disease itself. The disease in this case is the economic conditions of the rural poor, who are forced to exploit the environment for their very survival. It is evident that no enduring solution to such an environmental problem is conceivable without relieving the pressures that are forcing the local population from a sustainable to an unsustainable relation to their natural environment. Until the pressing needs of the rural poor living in the watersheds are alleviated, the practice will continue, unless a very forceful policy of exclusion of humans and livestock from land can be implemented, which might satisfy the needs of sustainability of land, but certainly not of the people.

Currently, two main implications of improper or inadequate watershed management that are receiving increasing attention are sedimentation in reservoirs and changing patterns of streamflow. Reservoir sedimentation, by reducing storage capacity, is seriously damaging economic and long-term sustainability of many water projects. Streamflow patterns could change due to deforestation. While increasing sedimentation in many reservoirs all over the world is no longer a debatable fact, hydrological and environmental scientists are not unanimous in their views on the extent and nature of streamflow changes caused by changing land use patterns.

RESERVOIR SEDIMENTATION

Undoubtedly the most serious and widespread impact of watershed management, so far as water projects are concerned, is in terms of reservoir sedimentation. While the problem is global in nature, the magnitude of problem often varies from country to country, and even site to site within the same country.

All rivers carry sediments, but their concentrations vary from one river to another. Table 1 indicates the sediment yields of some of the important rivers from all over the world. The table shows magnitude of surface runoff per unit area, sediment yields in tons per km² of catchment area, and sediment concentration in ppm. It can be seen that sediment yields range from a high of 40, 500 ppm for the Haihe in China to a low of 34 ppm for the Zaire River. Table 2 shows the total suspended solid and dissolved sediment loads for three African rivers (Martins 1984). It shows that the

TABLE 1. Sediment yields of selected rivers

River	Country	Catchment area (10 ⁶ km ²)	Runoff (cm)	Sediment (t/km ²)	Yield (ppm)
Haihe	China	0.05	4	1,620	40,500
Huanghe	China	0.77	6	1,403	22,041
ChiangJiang	China	1.94	46	246	531
Mekong	Viet Nam	0.79	59	203	340
Ganges/Brahmaputra	Bangladesh	1.48	66	1,128	1,720
Indus	Pakistan	0.97	25	454	1,849
Tigris/Euphrates	Iraq	1.05	4	50	1,152
Amur	USSR	1.85	18	28	160
Niger	Nigeria	1.21	16	33	208
Nile	Egypt	2.96	1	38	3,700
Zaire	Zaire	3.82	33	11	34
Mississippi	USA	3.27	18	107	602
Amazon	Brazil	6.15	102	146	143
Orinoco	Venezuela	0.99	111	212	191

Adapted from Milliman and Meade 1983; Mahmood n.d.

TABLE 2. Sediment rates of some African rivers

River	Catchment area (10 ⁶ km ²)	Average discharge (km ³)	Dissolved solids $\frac{10^3 \text{ t/yr}}{\text{t/km}^2/\text{yr}}$	Suspended solids $\frac{10^6 \text{ t/yr}}{\text{t/km}^2/\text{yr}}$	Total land $\frac{10^6 \text{ t/yr}}{\text{t/km}^2/\text{yr}}$	Percent by solution
Niger (Mouth)	1.24	200	13.8	11.1	19.4	15.6
Zairo (Mouth)	3.70	1,330	43	11.6	44	11.9
Nile (Cairo)	2.96	89	21	7.2	122	42
					143	14.6

(Source : Martins 1984)

TABLE 3. Reservoir sedimentation in China

Reservoir	River	Catchment area (km ²)	Storage (10 ⁶ m ³)	Sedimentation	
				$\frac{10^6 \text{ m}^3}{\text{Years}}$	% of storage
Sanmenxia	Huanghe	688,421	9,700	3,391	7.5
Qingtongxia	Huanghe	285,000	627	527	5
Yanguoxia	Huanghe	182,800	220	150	4
Liujiashan	Huanghe	172,000	5,720	522	8
Danjiangkou	Hanshui	95,217	16,000	625	15
Guanting	Yongdinghe	47,600	2,270	553	24
Hongshan	Laohe	24,486	2,560	440	15
Gangnan	Hutuohe	15,900	1,558	185	17
Xingqiao	Hongliuhe	1,327	200	156	14
					71

suspended solid loads for all the three rivers exceed the dissolved solid loads, thus indicating the dominance of mechanical erosion in these watersheds. For the Nile, suspended solids carried accounts for 83.4 per cent of the total sediment load which is significantly higher than dissolved solids carried at only 14.6 per cent of the total. This is because of extensive wind erosion in the desert areas through which the Nile flows.

Three estimates are currently available on the aggregated amount of sediments carried to the oceans by the world's rivers. Strakhov (1967) estimated the total load to be 12.7 billion tons. Corresponding estimates by Milliman and Meade (1983) and Holeman (1968) are 13.5 and 18.3 billion tons respectively. In the absence of real data, it should be noted that these estimates are very rough: the real figure may be very different.

Construction of dams and reservoirs invariably changes the river regime. As the river approaches a reservoir, its velocity starts to drop. This reduces the sediment transportation capacity of water, which in turn increases the rate of sedimentation. When a river enters the reservoir, because of very low velocity, sediment deposition rates become very high. Accordingly, sedimentation is a normal process in all reservoirs. What good watershed management can do is to reduce the rate of sedimentation, and thus prolong the useful life of the reservoirs. Table 3 shows the extent of sedimentation in various reservoirs in China over specific time periods.

After the sediment loads carried by a river are deposited in a reservoir, water released from it is generally clear. Thus, the construction of the Hoover Dam has reduced the sediment discharges of the Colorado River at Yuma, Arizona, where it enters Mexico, from 135 million tons to only 0.1 million tons per year (Meade and Parker 1985). Similarly, the River Nile used to carry 100–150 million tons of suspended matter at Aswan before the construction of the High Aswan Dam (Biswas 1982), most of which is now deposited in the High Dam Lake.

Discharge of clear water from reservoirs, however, may create erosion problems downstream. For example, in the case of the Aswan Dam, bank and bed erosion downstream in the Nile has become a problem. Even more serious has been the erosion of the Nile Delta, some 1000 km from the dam. Prior to the construction of the dam, the delta used to be built up during the flood season with the sediment carried by the river to the Mediterranean. This

sedimentation compensated the erosion of the delta resulting from the ocean waves of the preceding winter. There was an equilibrium between sedimentation and erosion. With most of the sediments being trapped in the lake, enough sedimentation now does not occur in the delta, and this has resulted in serious coastal erosion in that area.

Forecasting Reservoir Sedimentation

Continued sedimentation over a period of years means that the storage capacity of any reservoir decreases with time. If the rate of sedimentation is equal to or less than the designed rate, cost-effectiveness of the project from the sedimentation point of view is not under question since the expected life of the reservoir would remain as planned or more. However, when the rate of sedimentation is higher than expected, economic life of a reservoir reduces, which means that the economic effectiveness of the project may become questionable. Unfortunately, for many reservoirs all over the world, the rate of sedimentation had been seriously underestimated for a variety of reasons.

First, sedimentation is a complex process, and the present state of knowledge for forecasting the rate of sedimentation leaves much to be desired. Much of the work is empirical in nature, and there is considerable doubt over its validity in different agro-ecological zones and under different socio-economic conditions.

While some of the early studies on sedimentation were carried out in India, many of the recent analyses are from Europe and North America. Analytical techniques developed on the basis of empirical work in the Western countries are often not applicable in various Asian and African countries for many reasons.

It should be noted that there are important differences between temperate climates where most recent erosion and sedimentation studies have been carried out and tropical climates (Biswas 1985), which makes technology and knowledge transfer from one to another a hazardous process. For example, rainfall and temperature distribution patterns in tropical climates accentuate the soil erosion problem. The yearly average rainfall between London in temperate climate and Sokoto on the southern border of the Sahel, do not differ appreciably: 568 mm and 668 mm respectively. However, when distribution of rainfall throughout the year is considered, the two cases are very dissimilar. The rainfall pattern of London, which

is a temperate climate, can be characterized by a low but reasonably uniform monthly rate over the entire year. It varies from a maximum of 61 mm in October to a minimum of 35 mm in April. Similarly, rainfall retained in the soil is reasonably uniform. The situation is very different for Sokoto, where the rainfall is intense during July to September, but virtually non-existent between October to April. The rainfall varies from a maximum of 239 mm in August to zero between November to March. Furthermore, Sokoto has a significantly lower rainfall retention rate in the soil when compared to London. Thus, even though the total average annual rainfall in Sokoto is actually 15 per cent higher than in London, its distribution throughout the year is very uneven, making Sokoto very arid.

Rainfall has a direct impact on soil erosion all over the world, but the potential ability of the tropical rainstorms to cause soil erosion is far higher than in the temperate regions. This could be attributed to the high kinetic energy of the tropical rainstorms when compared to the gentler kinetic energy of rainfall in temperate regions. Kinetic energy of rainfall depends on the size of drops, intensity and wind velocity. While long-term detailed data on tropical rainfall are not available, it appears that median drop size of well above 3 mm are not uncommon. Drop sizes as high as 4.9 mm have been observed. From these data, a preliminary observation could be that the drop-size distribution of rainstorms is much higher in the tropics than in temperate regions.

Kinetic energy of rainfall is an important consideration since kinetic energy and the impact of raindrops initiates loosening and detachment of soil particles, the first essential step for soil erosion. Once soil is loosened, the particles are washed away, thus contributing to serious soil erosion problems.

So far as intensity of rainfall is concerned, it appears that its erosive power significantly increases at about 35 mm h^{-1} , which can be considered to be a threshold for erosion. Since more rainstorms in the tropics equal or exceed the level of this erosive threshold, the erosive potential is higher in the tropics when compared to the temperate parts (Hudson 1971).

Another climatic aspect further contributes to soil erosion. The rainfall and temperature distribution patterns in tropical climates, especially in those areas having pronounced dry and wet seasons, accentuates the problem of soil erosion. During the long dry season, there is some loss of topsoil due to wind erosion. However, far

more damage is done during the onset of the rainy season. The vegetative cover, at the end of the dry season, is already reduced and often at an absolute minimum. Thus when a heavy thunder shower occurs, the water does not infiltrate into the soil as it might in light steady rain, and year after year soil erosion takes place due to surface runoff.

Another important factor in the tropics for predicting sediment yields is the instantaneous river discharge, and not discharge averaged over a period of time. It is not uncommon to find that one major flood in a river carries more sediment than the sum of all non-flood events during that year. Table 4 shows the maximum 5-day sediment loads observed in some Chinese rivers, which represent 33 to 75 per cent of the maximum annual sediment load.

TABLE 4. Sediment load at gauging stations of Huanghe and its tributaries in its middle reaches

River	Drainage area (km ²)	Maximum annual sediment load		Maximum 5-day sediment load	
		Year	Load in 10 ⁶ tons	Load in 10 ⁶ tons	% of total annual load
Huanghe	497,559	1967	2,460	814	33.2
Weihe	106,498	1964	1,060	400	37.8
Wuding	30,217	1959	440	185	42.2
Beiluo	25,154	1966	216	137	63.6
Kuye	8,645	1966	303	228	75.2
Huangfu	3,199	1959	171	97	56.8

Secondly, reliable hydrological, meteorological, geological and land use data for most watersheds in developing countries are not generally available. At best, such data may be available for limited periods and for localized areas. Under these conditions, it is a difficult task to predict accurately the rate of erosion and resulting sedimentation from the entire watershed.

Thirdly, all irrigation projects significantly change the prevailing land use patterns. Cropping intensities increase, cropping patterns are changed and fallow periods are reduced or even eliminated. These changes directly affect soil loss from the area. Table 5 indicates how the rates of runoff and soil loss change under different vegetative covers in India.

TABLE 5. Runoff and soil loss under different conditions in India

Location, soil type, slope, rainfall	Vegetative cover	Runoff as % of rainfall	Soil loss (t/ha)
Dehradun, silty clay loam, 9%, 1250 mm (3-year average)	Grass (<i>Cynodon dactylon</i>)	27.1	2.1
	Bare fallow	71.1	42.2
	Bare and ploughed fallow	59.6	155.9
	Natural grass	21.2	1.0
Vasad, alluvial soil, 2%, 791 mm	Natural fallow	2.1	2.0
	Grass (<i>D. annulatum</i>)	1.1	1.5
	Tobacco	26.0	2.3
Sholapur, medium black soil, 1.18%, 607 mm (9-year average)	Natural fallow	4.8	1.3
	Bare fallow	19.8	43.0
	Shallow cultivation	22.5	60.4
Manjri, deep black soil, 3%, 627 mm (5-year average)	Bare fallow (weeds removed by cutting)	23.9	54.3
	Cultivated fallow	25.0	87.5
	Shorghum (winter)	16.1	60.5
Dehradun, silty clay loam, 11%, 1117 mm (2-year average)	Grass (<i>Cymbopogon citratus</i>)	11.0	2.3
	Cultivated fallow	16.2	18.5
	Strawberry	26.6	23.1
	Pineapple	10.5	8.4
	Pomegranate	33.5	16.4

Adapted from Singh 1985

The magnitudes of runoff and soil loss from grasslands also depend very much on their conditions in terms of livestock grazing. Studies carried out at Deochanda, India, indicate that overgrazing not only reduces grass cover but also deteriorates topsoil by compaction and loosening of soil particles by animal hoofs. Soil losses and runoffs from overgrazed areas are significantly higher than ungrazed natural pastures. Results of the Deochanda studies are shown in Table 6.

TABLE 6. Runoff and soil loss from grasslands at different levels of grazing, Deochanda, India (Singh 1985)

Conditions	Runoff (%)	Soil loss (t/ha)
Natural pasture, no grazing	11	0.40
Proper grazing	19	0.79
Overgrazing	27	2.37

Because of the above-mentioned and other problems, forecasting reservoir sedimentation in developing countries has been a complex and difficult task under the best of circumstances. Table 7 shows the designed and observed sedimentation rates for 8 major reservoirs in India. It indicates that for these reservoirs, the average observed annual sedimentation rate is twice the designed value. It further shows that the average annual rate of loss in storage capacity due to sedimentation is 0.6 per cent of storage volume.

It should be noted that while concentrations of suspended sediments depend on river discharges, the relation between them is not necessarily one to one. Figure 1 shows the seasonal variations of discharges and total suspended solids for the Niger River for 1980-1. It shows that the peak sediment concentration was attained well before the maximum river discharge (Martins 1984). While sediment load is highest during the rainy season, it appears that large amounts of fine sediments are washed to the river as flow starts to increase during the onset of the rainy season. Peak floods may, however, carry substantially higher bed load. The second sediment peak in Fig. 1 could be due to atmospheric dust deposition from the surrounding desert.

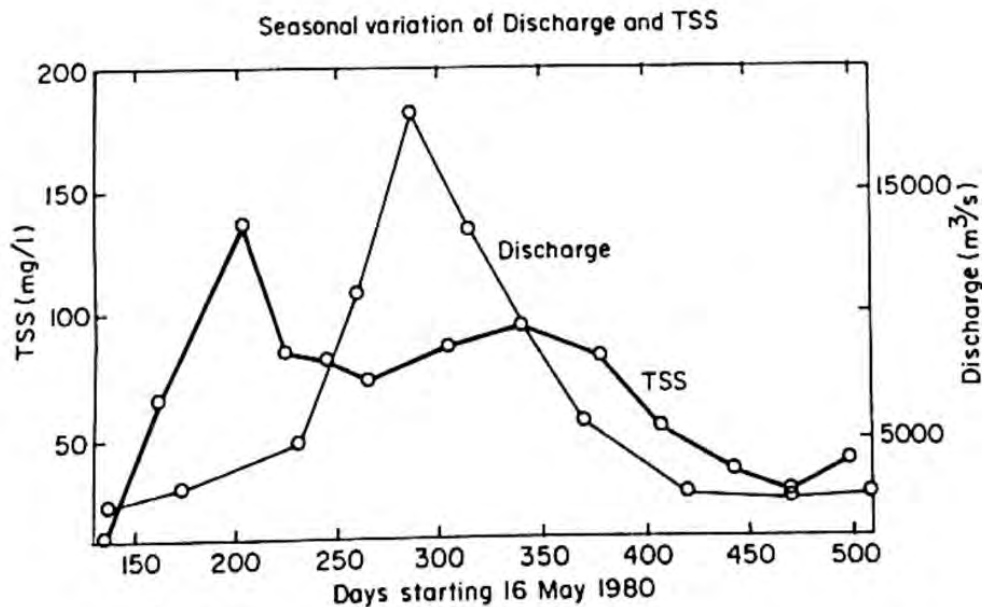


FIGURE 1. Seasonal variation of discharge and total suspended solids for the Niger River at Lokoja (source: Martins 1984)

TABLE 7. Design and observed sedimentation rates for selected Indian reservoirs

Reservoir	Year of impoundment	Storage capacity (million m ³)	Annual sedimentation rate in ha-m/100 km ²		Annual storage loss (% of volume)
			Design	Observed*	
Bhakra	1958	9870	4.29	5.93 (1979)	0.35
Gandhinagar	1960	7746	3.61	9.64 (1975-6)	0.29
Hirakud	1957	8100	2.52	6.82 (1982)	0.68
Maithon	1955	1357	9.05	12.38 (1979)	0.50
Mayurakshi	1955	616	3.75	16.48 (1969-70)	0.50
Nizamagar	1956	456	2.38	6.37 (1967)	1.40
Panchet	1956	1497	6.67	10.00 (1974)	0.65
Tungabhadra	1953	3773	4.29	6.03 (1981)	0.45
Average			4.57	9.21	0.60

* Year of survey in brackets. Observed sedimentation rate is for the period between the year of impoundment and the year of last survey for which data are available

Economic Cost of Sedimentation

The economic cost of sedimentation in rivers and reservoirs is quite substantial. While no reliable estimate is available, Mahmood (n.d.) suggests that on a global basis, reservoirs are losing storage capacity at the rate of one per cent annually. Cumulatively it would mean a total annual water storage loss of 50 km², which Mahmood (n.d.) further estimates 'modestly' at \$6 billion per year.

The one per cent estimate in annual storage capacity loss of reservoirs is likely to be an over-estimate for larger reservoirs. Analysis of 8 major Indian reservoirs shown in Table 7 indicates an average annual loss of 0.6 per cent. Similarly analysis of 19 reservoirs in central Europe, having storage capacities ranging from 1.5×10^5 m³ to 23×10^6 m³, indicated an annual storage depletion of 0.51 per cent (Cyberski 1973). According to Dendy *et al.* (1973), storage losses in the United States due to sedimentation decrease with increase in reservoir capacities, and amounts to about 0.16 per cent for capacities higher than 10^9 m³. In contrast, average annual storage loss for small reservoirs having a capacity less than 10,000 m³ is 3.5 per cent.

Sedimentation, especially in rivers, has another added economic cost in terms of dredging. It has been estimated that 376×10^6 m³ of sediments are dredged every year from the water bodies of the United States at annual costs of more than \$300 million (MR Biswas, 1979). In Bangladesh, its three major rivers—the Ganga, Brahmaputra and Meghna—carry an annual sediment load of some 2.4 billion tons, and Bangladesh Inland Water Transport Authority has to carry out every year nearly 0.8 million m³ of maintenance dredging and 2 million m³ of capital dredging at substantial cost (Biswas 1987).

CHANGES IN STREAMFLOW PATTERN

Changing land use patterns in a watershed affect streamflow. The magnitudes and durations of such variations depend on a variety of geo-hydrological, meteorological and agro-ecological factors. Because so many factors affect streamflow regimes, it is very difficult to determine the specific changes that may have occurred following alterations in land use practices in the watershed. Table 5 shows changes in runoff caused by differing vegetative covers under experimental conditions in India.

Probably the most-quoted example of changing streamflow

patterns due to alterations in upper watershed vegetations is that of Bangladesh. Writers of popular articles like Eckholm (1976) and Myers (1986) have made it a 'conventional' wisdom that deforestation and land use changes in the Himalayas in Nepal have contributed to higher flood runoffs and sediment loads during the monsoon season and lower dry-weather flow in rivers like the Ganga and Brahmaputra in Bangladesh. It has been further claimed that flooding in the Gangetic plain has systematically increased, both in terms of frequency and magnitude, during the past 50–100 years, and the devastating flood of 1988 in Bangladesh could be directly attributed to deforestations in the Nepalese Himalayas.

While this hypothesis has considerable public appeal and is quoted quite frequently in the present era of environmental consciousness, the following points are worth noting.

- There is very little reliable and replicable data which can prove or disprove the hypothesis categorically.
- Deforestation in Nepal was already well advanced by the middle of the eighteenth century, and in the Middle Mountains, which is the most densely populated region, all arable land had been converted by 1920–30. Little reduction in forest cover has occurred since 1930 (Ives 1989).
- Geologically, the Himalayas is a young mountain range, and has some of the highest erosion rates of the world.
- Preliminary studies by Gilmour *et al.* (1987) indicate that soil erosion and flooding are not necessarily due to deforestation, and are not likely to be significantly reduced by afforestation.
- High economic losses in recent years in the plains of Bangladesh can be attributed to a significant extent to rapid population growth, and consequent high level of economic activities. Thus, floods of a given magnitude will create a much higher level of damage at present than, say, 25 years ago.

It is not possible at the present state of knowledge to make cause-and-effect linkages between deforestation in the Himalayas and increased flooding and high sediment loads in rivers in Bangladesh. Urgent scientific studies are needed to determine whether flooding in the plain has actually increased in recent years, and if it has increased, to what extent deforestation in the Himalayas has contributed to this impact.

MANAGEMENT PRACTICES

The main emphasis of watershed management at present has been to reduce sediment generation in the catchment area so that storage losses of reservoirs can be kept to an acceptable level. To this extent, the main management alternatives have been to increase forest cover in the upper catchment areas, develop and implement appropriate land use policies and prevent overgrazing. In general, the results of such policies, even when they are carried out properly, take time to be visible. For example, if afforestation is practised, some improvement may be noted in about a decade or so.

One of the major difficulties of watershed management, which has not been addressed thus far, is to what should the cost of such practices be charged. The present tendency has been to charge the entire management cost to the water development project itself. This raises a fundamental question. Should afforestation costs be charged entirely to water projects, even though much of the deforestation damages may have occurred well before the project was designed? While benefits to water projects of afforestation are undeniable, society benefits from such practices in many other ways as well. If the entire cost of such afforestation is charged to a project, it may, in certain cases, no longer be economic and thus may never even be built. The real question thus is what percentage of afforestation costs are attributed to a water project and on what basis? The debate on such vital issues has not yet even started.

A second difficulty is institutional implications. Water projects are within the jurisdiction of Ministry of Water Resources, whereas forestry generally belongs to Ministry of Agriculture or Ministry of Environment. Very seldom has inter-ministerial co-ordination been effective in any developing country to ensure that rational watershed management practices are implemented in the early stages of the project. Because of the long time interval needed between the beginning of an afforestation process and some observable impacts, afforestation should be initiated during the planning phase of a project. One would, however, be hard pressed to identify even a single major water project where such practices were implemented systematically in the planning stage.

Check Dams

Even when afforestation has been practised in the upper catchment, sediments will still be generated by natural processes and by accele-

rated agricultural activities due to introduction of irrigation. One of the alternatives available for sediment and water control has been the use of check dams. Check dams are generally small. These low dams are built across gullies and streams to store flood runoff. The practice has successfully been used for many centuries in rural areas of several countries such as India, China, Sri Lanka, Mexico and the United States of America. Basically check dams provide upstream storage of flood waters, which can be used subsequently for irrigation and livestock.

Check dams could range from relatively simple structures built with stones, gravels and clay to fairly elaborate and sophisticated rockfill dams with concrete spillways. Many of the early check dams were simple structures that were built across narrow valleys, having somewhat impervious rock or soil strata. These dams required very minor changes in the local topography, and accordingly could be constructed relatively quickly with low financial investment as well as limited labour input. These dams not only controlled the flow of water, but also sediments carried by flood waters. With the reduction in flow velocities by the presence of these dams, the rates of soil erosion are also reduced. Construction of a series of check dams on a gully or stream can significantly reduce the overall rate of soil erosion. Furthermore, as the flow velocities are reduced, sediment present in flood water is deposited behind such dams.

As the silt deposited on the river bed increases every year, after a period of time a very fertile area is available for cultivation, especially when the stored water disappears. Thus, check dams are structures which can not only harvest seasonal flood waters but they also contribute to soil and moisture conservation.

While check dams have been used for centuries, their use in recent years for water and erosion control is receiving increasing attention in countries as diverse as China, Nepal, India and Ethiopia. In China, check dams have been very successfully used in many areas.

A good example of the use of check dams for water and erosion control can be found in the Jiuyuan Gully in Suide County, Shanxi Province, China. The gully is a small tributary of the Wuding River, which in turn is a tributary of the Huang-He (Yellow River). The length of the main channel of the gully is 18 km and it has a catchment area of 70.1 km², of which 2130 ha is used for agricultural production. Some 10,000 people live in this rural area and agriculture

is the main source of livelihood (United Nations Environment Programme 1983).

Water and erosion control was the most serious problem facing the Jiuyuangou Peoples' Commune in the Gully catchment area. The catchment has a high gully density of 5.34 km per km². Before a control programme was initiated, the rate of annual soil erosion from the catchment was estimated at 1.27×10^6 metric tons, which was equivalent to an average soil loss of 18,116 metric tons per km². Because of the high silt content of the water in the gully catchment, it could not be used efficiently for irrigation.

The Commune initiated a combined programme of contour farming and check dams. By 1974, 727 ha of land had been provided with contour farming. In addition, 311 small and medium check dams were constructed, which primarily acted as silt traps, and 30 small reservoirs were built to store a total of 1.18×10^6 m³ of water for irrigation. The general plan of the Jiuyuan Gully catchment is shown in Fig. 2.

The construction of this series of small- and medium-size check dams had a remarkable impact on the water use and erosion rates of the area. The irrigated area increased to 170 ha, which was eleven times the pre-construction period figure. The flood peak in the gully was 90 per cent less than before and the average annual soil loss decreased by 770,100 metric tons, which was a reduction of nearly 60 per cent. This meant that the total agricultural production in the area increased by 2.3 times within a period of only two decades.

Because check dams are small and widely dispersed over rural areas in many arid countries, it is not possible to comment on their overall efficiency. Furthermore, the check dams are often constructed by local people, based on past experience and broad rules of thumb. Thus, there are numerous types of such dams, based on different 'design' parameters, located in an immense variety of site-specific topographical and other physical conditions. Their maintenance often differs from one location to another. In addition, not even a single country has made a national survey of these dams. Under these conditions, only some general comments can be made on their advantages and limitations.

Check dams, when they are properly designed, constructed and maintained, can be considered to be a very useful small-scale alternative for water and erosion control in rural areas of arid and semi-arid countries. They are easy to design, construct and maintain.

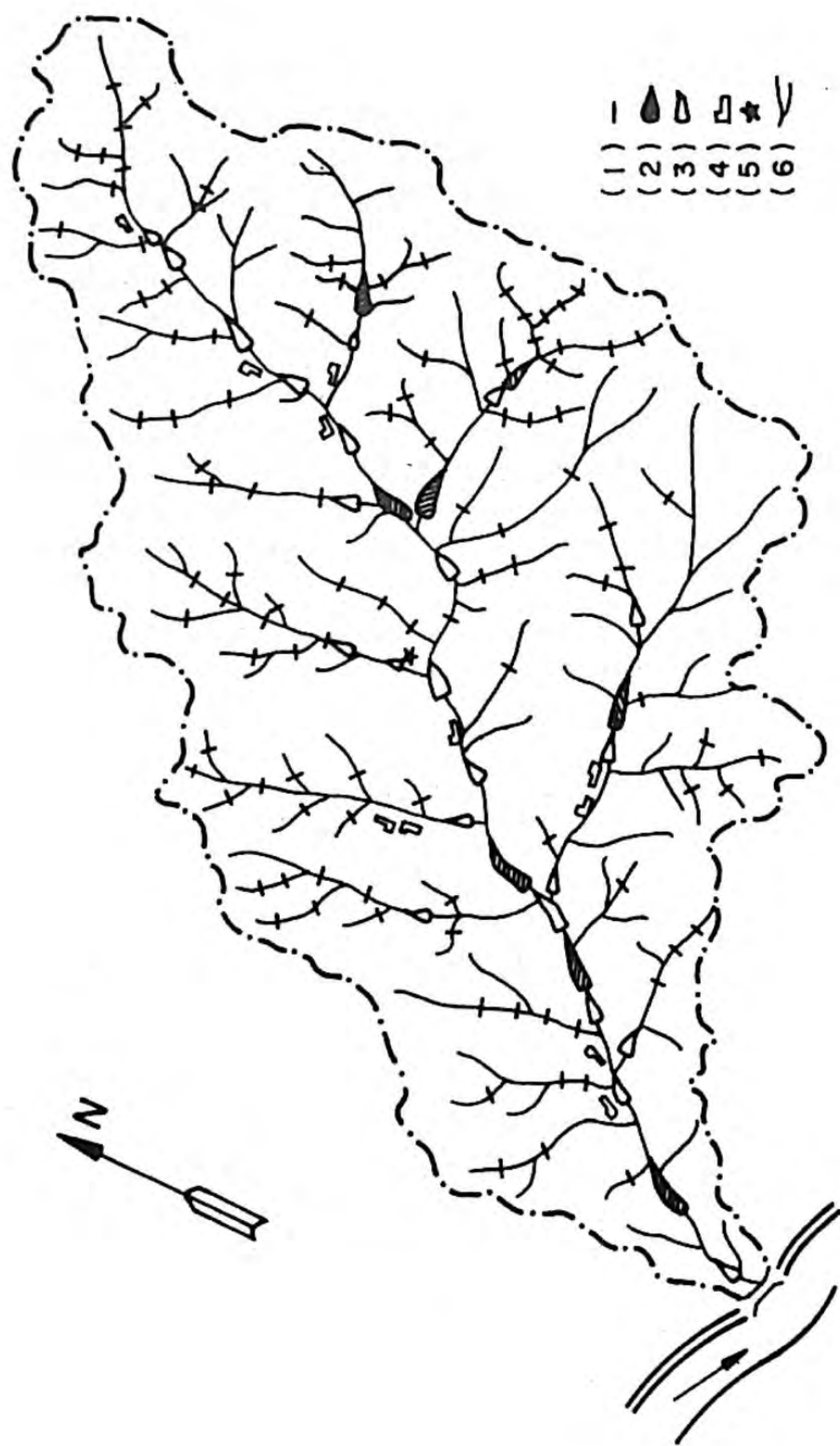


FIGURE 2. Use of check dams in the Jiuyuan Gully Catchment Area, China. Legend: (1) small check dams, (2) medium check dams, (3) small reservoirs, (4) village, (5) commune, and (6) streams

Labour and capital requirements are minimal, certainly significantly less than other sophisticated hydraulic structures. This means individual households or small communities can afford to build these dams without external assistance. Foreign exchange is generally not necessary, which could be an important consideration for many debt-laden developing countries at present. These simple structures can be constructed within a very short period of time, compared to large dams where the gestation periods are often more than a decade. Large-scale centralized institutions are not necessary for their construction, operation and maintenance. Also a series of such dams in an area can be developed incrementally.

Check dams have many limitations as well. They provide unreliable and discontinuous supplies of water, which means communities must have access to other alternative sources of water. Because of their decentralized nature, they often suffer from poor quality of design, improper construction and inadequate maintenance. Frequent repairs are necessary, but these repairs can be carried out quickly and within a limited cost. Many check dams are very vulnerable in terms of water quality contamination, and they often act as the main foci of water-borne diseases, especially those transmitted by mosquitoes.

CONCLUSION

Watershed management has become an important consideration for sustainability of water development projects. While the desirability of good watershed management is not in doubt, achieving it is not an easy task. It would require simultaneous achievement of many tasks, among which are afforestation, strict control of land use practices, and more emphasis on small-scale structures such as check dams for better soil and water conservation. Land use practices are generally very sensitive issues in most countries, at least politically, and thus to what extent it may be possible to develop and implement a rational land use policy is always difficult to predict. Furthermore, since watersheds of medium- and large-scale projects cover large areas, ensuring appropriate land use practices over entire catchment areas may not be a feasible process.

It should also be noted that afforestation of degraded lands needs substantial capital investment in early years, with no direct financial return to the investors. Thus, in most developing countries the governments would have to play the main role in afforestation,

and/or subsidize private efforts substantially. Many governments are unlikely to give it priority at present in terms of investment because of their current economic conditions as well as financial requirements for other competing activities.

However, for most countries, watershed management should not be viewed from the narrow perspective of benefits to water projects alone: it should be considered to be essential for soil and water conservation, which in the long run will enhance the prospect of self-reliance of nations in terms of food, fibre and energy. Viewed in this holistic perspective, watershed management has to be considered to be a priority activity.

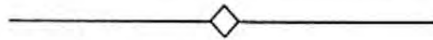
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CHAPTER 8

Water Quality Management



PART I

Surface Water Quality Management

N. C. THANH and D. M. TAM

WATER QUALITY CONSTITUENTS

Quality of water is affected by the presence of various substances. These substances can be generally classified under the following criteria.

Physical conditions, such as suspended solids which cause turbidity and prevent light penetration, sediments, and temperature;

Pathogens, including causative agents of water-borne diseases such as typhoid, paratyphoid, dysentery and viral hepatitis;

pH, and related constituents such as carbon dioxide, carbonate, bicarbonate, acidity and alkalinity;

Oxygen-consuming substances, which consist of organic compounds that are degraded by microorganisms using oxygen dissolved in the water. With large amounts of organic matter, oxygen consumption will exceed oxygen transfer from the atmosphere, and oxygen depletion in water will create profound impact;

Toxic substances, which include a variety of hazardous materials that endanger human health;

Substances of special ecological concern, like heavy metals or persistent pesticides, which are not readily biodegradable and accumulate in the food chains (the *bio-magnification* process);

Nutrients, like phosphorus or nitrogen, which promote the growth of algae and aquatic plants;

Chemicals creating aesthetic problems, such as phenol and sulphides, which have certain aesthetically objectionable properties;

Radioactive substances, which have harmful effects on the organisms in the ecosystems and consequently on human beings.

It should be noted that certain substances, at higher concentration levels, may have adverse effects on the quality while they may be beneficial at low concentrations. Thus, it may be misleading to condemn outright any constituent as a 'pollutant'. It may be preferable to consider any constituent to be suspected pollutant until its concentration is shown to be below a harmful level. Such constituents could be termed *potential pollutants* (Lamb 1985). The following sections will discuss those constituents that are the most significant potential pollutants.

Ions in Water

The major ions present in natural waters are:

- Cations (calcium, magnesium, sodium, and small amounts of potassium); and
- Anions (bicarbonate, sulphate, chloride, and small amounts of nitrate).

These ions come from the contact of the water with various mineral deposits.

Other natural ions which are less prevalent in water include:

- Cations (ammonium, arsenic, boron, copper, iron, and manganese); and
- Anions (bisulphate, bisulphite, carbonate, fluoride, hydroxide, phosphate, sulphide, and sulphite).

Most of these ions are also derived from mineral deposits.

In addition, some ions such as ammonium carbonate and sulphide are produced by bacterial and algal activities. Ions form micro-elements for nutrition of plants and animals and thus could be considered as being integral parts of the ecosystem.

The mineral deposits can also contribute to water quality in other ways. For example:

- iron and manganese could cause brown deposits and stains in water supplies;

- sulphate could be the cause of odours, corrosion of concrete sewers and, at certain levels, fish deaths;
- low levels (less than 1 mg/L) of fluoride in drinking water help prevent tooth decay, but higher levels cause tooth mottling, and very high levels may cause crippling; and
- high levels of sulphide released by decaying vegetation in a newly-formed reservoir may cause fish deaths, objectionable odours and corrosion.

Physical Conditions

Heat. Thermal and nuclear power plants use large amounts of water for cooling purposes. Where once-through cooling is used, the entire thermal load of the power plant is transferred to the receiving water body. Where closed-cycle cooling (such as cooling ponds or evaporative cooling towers) is used, the thermal load is transferred to the atmosphere on-site. The effects of thermal pollution depend on the capacity of the receiving stream, but most power plants raise the water temperature 8–11 °C in the once-through process.

Heat added to receiving water bodies as a result of cooling operations could have various impacts, both adverse and beneficial, viz.:

- (1) imbalance of the ecosystem due to increased metabolic rates of the organisms living in water, or even death due to thermal shock;
- (2) reduced solubility of oxygen in water and consequent DO reduction;
- (3) reduction of the value of downstream water used as coolant;
- (4) intensification of taste and odour problems; and
- (5) improvement of the aquatic habitat in water, especially in temperate climates.

Impact (1) leads to the most far-reaching consequences in the aquatic ecosystems. Since biochemical reactions roughly double in rate with every increase of 10 °C, the rate of exertion of biochemical oxygen demand (BOD) is increased. This, coupled with impact (2), worsens the BOD-DO profile in the water body. As the temperature of the water rises, aquatic life is profoundly affected. Fish may die from thermal shock, reproduction may be impaired, or food supply reduced. Increased temperature also enhances the

toxic effects of certain chemicals to fish. Thermal pollution may be particularly severe in the tropics and semi-tropical climates where the dry season stream flows are much lower than in the monsoon but the air temperature is at its highest.

On the other hand, increased temperature may have beneficial effects. Up to a certain level, the growth rates of fish and shellfish increase as the temperature increases, and the growing season is extended. Careful utilization of heated water for irrigation also helps increase crop yield and extend the growing season, particularly in temperate climates.

Pathogens

Water is an effective means for transporting pathogens, and in fact water-borne diseases are a major cause of deaths and sickness in developing countries. Up to 35 per cent of the potential productivity of many developing countries is lost because of these diseases.

Microbiological quality of water is often expressed by the concentration of indicator bacteria. Although total coliforms are customarily used as an indicator, especially in tropical climates, they do not possess adequate sanitary significance for several reasons. First, many types of coliform bacteria occur naturally in the soil, and very high populations of nutrient-rich natural waters may not be of sanitary significance. Secondly, under tropical conditions, coliforms tend to grow in natural waters and even during wastewater treatment before disinfection. In polluted warm waters, the numbers of coliforms can increase substantially and again may not have concomitant health implications. In temperate climates, natural bacteria have an optimum growth temperature of 15 to 20 °C which reflects the temperature of the local environment, whereas in tropical waters the temperature easily reaches 30 °C or higher. As many natural bacteria are able to grow at such temperatures, they would frequently interfere with total coliform tests which are conducted at 35 °C. Thus, relying on total coliform data under tropical conditions may lead to erroneous conclusions. Faecal coliforms serve better as an indicator of microbiological quality. Techniques of faecal coliform enumeration are similar to those for total coliforms, except that the incubation for faecal coliforms is 44.5 °C, a temperature which eliminates interference from any natural bacteria in the sample.

Besides faecal coliforms, faecal streptococci (typically *Strepto-*

coccus faecalis), clostridia (typically *Clostridium perfringens*), *Pseudomonas aeruginosa*, and some species of lactobacilli are occasionally used as indicators as they are always present in the intestinal tracts of humans. Unfortunately, all of these indicator bacteria also exist in animal faeces, so it is difficult to determine whether the faecal contamination is of human or animal origin. To solve this problem (at least partially), faecal streptococci (FS) are usually tested together with faecal coliform (FC). Since the ratio of FC/FS in human faeces is around 4.4 and in animal faeces less than 1, this ratio may be used to suggest whether faecal contamination is of human or animal origin. If the ratio is found in the range of 1 to 2, the conclusion is not clear. Knowing the source of contamination is a fundamental step in any system of water quality management. Although the ratio of FC/FS is not always reliable, in many cases it can be useful in identifying the possible source of contamination in runoffs. Geldreich (1976) and Wheater *et al.* (1979) have provided a review and evaluation of indicator systems used to distinguish sources of faecal pollution.

Toxic Agents

Trihalomethanes. Trihalomethanes (THMs) are formed when chemical elements of the halogen family (chlorine, bromine, and iodine) react with organic compounds. Main THMs of concern in water and wastewater treatment are chloroform, bromodichloromethane, chlorodibromomethane, and bromoform. THMs are suspected to cause cancer. Chlorine used in disinfecting treated water and wastewater can react with some organic compounds to form chlorinated hydrocarbons which can also cause cancer. For this reason, various alternatives to chlorine as drinking water disinfectants have been explored and applied (Drinking Water Research Division 1981).

Organic Compounds. Industrialization and technological developments have led to the increasing release into the environment of numerous organic compounds. For a large number of such compounds, very little is known about their precise effects on humans. For example, about 800 toxic compounds have been identified in the Great Lakes, the drinking source for about two-thirds of all Canadians and millions of Americans. Many of these compounds are known to cause cancer in animals. The best known chemical

at present is perhaps dioxin, whose presence has been repeatedly found in minute amounts (less than 50 parts per 10^{15}) in various water supplies in Canada. Despite the fact that the Canadian interim health guideline for dioxin in drinking water is 0.15 part per 10^9 , the very discovery of this very toxic man-made chemical has created much concern among the consumers. Recently, in Quebec province, dioxin has been found in mother's milk. However, it should be pointed out that during the last decade rapid advances in analytical methodology have substantially lowered the minimum detection limits of many compounds. This has led to increasing reports of the presence of toxic compounds in the environment, even though so little is known about their effects on human health and the environment.

Compounds of Ecological Concern

Heavy Metals. Most of the heavy metals present in water occur in ionic forms and owe their origin to human activity. They are toxic to microorganisms and ultimately to man. These heavy metal ions include arsenic, barium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, and zinc. They come from a variety of sources: plumbing and gutters (cadmium, zinc), animal wastes (copper and zinc), paints (zinc), print ink (zinc), pesticides (mercury and zinc), and wastewaters from various industries. As they cannot be broken down, heavy metals accumulate in the food chains of the ecosystem. The process begins when low concentrations of heavy metals in water and sediment build up rapidly in aquatic plants and animals. The subsequent consumption of these organisms by other organisms in the food chains produce successively higher concentrations, until the concentrations in the organisms at the top of the food chains are sufficiently high to cause toxicity. The first massive heavy metal poisoning in modern history was caused by mercury which was released from a plastics plant into the Minamata Bay, Japan, in the 1950s. Local fishermen who regularly ate fish containing high levels of mercury, died or became disabled. Because of this incident, mercury poisoning is now often known as *Minimata disease*.

Pesticides. Pesticides include insecticides, fungicides, herbicides and algicides, although the term 'pesticides' is often understood as 'insecticides'. Common pesticides include:

– *Insecticides*

Chlorinated hydrocarbons: aldrin, chlordane, DDT compounds, dieldrin, endrin, heptachlor, methoxychlor, lindane, toxaphene, hexachlorohexane (HCH)

Organophosphates: diazinon, malathion, parathion

– *Herbicides*

Carbamate: carbyl

Chlorinated hydrocarbons: 2,4-D, 1,3,5-T, silvex

– *Fungicides*: copper sulphate, ferbam, ziram

– *Algicides*: mainly copper compounds.

Shortly after the introduction of synthetic organic insecticides, problems of water quality appeared. Many of the early insecticides, such as DDT, toxaphene and dieldrin, belong to the chlorinated hydrocarbon compounds. They are stable in the environment and, like heavy metals, accumulate in the food chains of the ecosystem. Molluscs, which feed by filtering large volumes of water, have been shown to contain DDT in concentrations millions of times higher than those of surrounding water. Organophosphate pesticides degrade more rapidly, but are more expensive. In the early 1950s research began to define the nature of water quality problems caused by agricultural pesticides. Runoff from agricultural land is a major source of low-level pesticide contamination of surface waters.

For many pesticides, concentrations in the sediment are higher than those in the overlying water. DDT is the most notorious pesticide. Because of its low cost and effectiveness against a variety of pests including disease-vector insects, DDT was used widely in the 1950s to 1960s, so much so that it was found in the Arctic where it had never been used. Fish-eating birds and birds of prey, being at the top of the food chains, suffered the most. DDT reduces the thickness of the shell of bird eggs, so making them break easily. The population of birds of prey in the USA reduced sharply and several species came to the verge of extinction.

Production of DDT up to the 1960s was about 100,000 tonnes per year, and its half-life in the environment may be as long as 20 years. Hence, despite the fact that DDT has been banned in many countries, a substantial amount will persist in the environment for many years. Meanwhile, there are signs that the ecosystems are recovering where there is no more input of DDT. The populations

of various species of birds in the USA have increased significantly since DDT was banned.

Plant Nutrients

Plant nutrients elements in water exist in ionic forms. The two most important nutrients are nitrogen and phosphorus and problems caused by these are a result of human activities. The Green Revolution, with its high-yield crop varieties and intensive cultivation techniques, has led to substantial increases in the rates of fertilizer use. Consequently nutrient loads into natural waters have also increased due to the high levels in agricultural runoff.

Various forms of nitrogen exist in proteins, ammonia, nitrite, nitrate, urea, and nitrogen gas. Plants and some groups of bacteria synthesize proteins from inorganic forms of nitrogen (ammonia, nitrite and nitrate). Some bacteria (such as *Rhizobium* sp.) and plants (especially blue-green algae) are able to synthesize their protein from atmospheric nitrogen through a process known as *nitrogen fixation*. Bacteria then break down complex proteins into ammonia, nitrite and nitrate. This process is known as *nitrification*. Thus, monitoring the levels of different nitrogen forms in a water body of stream give some idea on the level of degradation of organic wastes released into the water.

Phosphorus exists at very low levels under normal natural conditions and is usually a limiting factor for bacterial and algal growth. Thus, when wastewater or agricultural runoff containing phosphorus is discharged into water bodies, algal blooms could occur. Eutrophication has occurred in water bodies receiving raw or treated household wastewaters since increased phosphorus concentrations accelerate the algal growth. Decaying algal mass decrease the dissolved oxygen (DO) in water. The eutrophication of the Great Lakes in the 1960s and of Lake Biwa, Japan, are good examples of the problems caused by phosphorus discharge into natural water bodies. In 1969, an effluent level of 1 mg/L of phosphorus, considered to be the lowest practical, was recommended in Canada. The Canadian Government adopted a two-pronged strategy using legislation and technology to reduce the amount of phosphorus in wastewater discharges (Schmidtke and Salloum 1985). Legislation was passed calling for a staged reduction in the phosphorus content of detergents to 20 per cent P_2O_5 by August 1970 and to 5 per cent by the end of 1972. The Canadian Federal Government and the Government of

the Ontario then entered into an Agreement which called for the implementation and acceleration of pollution control programmes. Sewage collection and treatment systems were upgraded, phosphorus removal equipment installed, and research on phosphorus removal technology was given top priority. This integrated strategy yielded good results. The phosphorus concentration in raw sewage had increased steadily during 1967–70 from 8.3 mg/L to around 10 mg/L. Following the introduction of the first control regulation in August 1970, the raw phosphorus content in sewage decreased to 7 mg/L, and continued the downward trend to 5.7 mg/L in 1974. Within the year of 1972–3 the influent phosphorus loadings increased by 56 per cent.

Chemicals Causing Aesthetic Problems

In the early detergents, the extensive use of ABS (alkyl-benzene-sulphonate) during the 1950s and 1960s led to the deterioration of the aquatic environment due to the appearance in many places of persistent foam and suds in wells, dams and canals. ABS is highly branched molecule that is difficult for most bacteria to break down. In developed countries ABS was replaced in the early 1960s by linear-alkyl-sulphonate (LAS), which is more easily biodegradable. Phenols are other common chemicals that impart objectional tests and odours at very low levels. Some chemicals do not themselves cause aesthetic problems, but induce secondary reactions that cause problems. For example, sugars in effluents from paper mills sometimes stimulate the growth of filamentous bacteria *Sphaerotilus* in receiving water bodies. The chemical themselves do not impart any objectionable characteristics, but the filamentous bacteria may create difficulties in downstream water supplies by diminishing recreational and aesthetic values, and clogging fishing nets.

Radioactivity

Common radioactive elements include iodine-131, strontium-90, cesium-137, and radium-226. Natural waters may contain low levels radioactivity, especially those originating from deep underground. Radioactivity of human origin comes from the nuclear power industry, the use of radioactive isotopes in medicine and industry, and nuclear weapon tests. Radioactivity is of concern in waters used for drinking and food preparation. However, widespread sensitivity and awareness to radioactivity has meant that it is being subjected to

control and monitoring perhaps more intense than for any other pollutants. There has been more justifiable concern about the accumulation of radioactivity in the food chains. Most waters contain radioactivity within WHO limits. Conventional water and wastewater treatment processes can remove radioactive elements, resulting in high levels of these elements in the sludges produced. These sludges should then be disposed of in a special way.

WATER QUALITY REQUIREMENTS FOR DIFFERENT USES

Drinking Water Supply

The quality of raw water for drinking determines the type of water treatment and its cost. For a stream under consideration, two options could be compared based on the technological feasibility and costs: (i) permitting entirely or to some degree upstream pollution, then increasing the sophistication of downstream water treatment, or (ii) reduction of upstream pollution by wastewater treatment so that downstream water treatment is made simple. Developing countries sometimes choose the first option because it is easier to increase the sophistication of water treatment (which belongs to the public sector) than to enforce pollution control (the private sector). This option also reflects the reality of water pollution in that nature's assimilative capacity is exploited to the maximum. However it could endanger the health of those people who do not have access to the public water supply and depend directly on the polluted stream as their primary water source. In large urban centres, where water supply is an important government responsibility, with few point-source polluters (making pollution control at source easier), the second option is more logical.

With regard to treated water for drinking purposes, current guidelines on quality have been laid down by the WHO (1984), and these incorporate the latest information on aesthetic, inorganic chemical, organic chemical and bacteriological aspects. The WHO *guidelines* are simply targets to aim at and not rigid rules. For instance, the guidelines determine a zero level of faecal coliforms as adequate bacteriological quality. In developing countries, this condition is difficult to fulfil throughout, and therefore it could be gradually achieved by staged improvement of the local water supplies corresponding to the available capabilities and resources.

Quality and quantity should also be considered together. Where water is scarce and/or takes effort to fetch, the convenience of having a readily available water supply is appreciated.

Water Quality for Agricultural Production

The quality of water for agricultural use is related to its effects on plant growth. Plants may be affected directly by either high osmotic conditions in the plant tissues, or the presence of a phytotoxic constituent in the water. The presence of sediment, pesticides, or pathogens in irrigation water may not affect plant growth but may affect the acceptability of the product. Various elements accumulating in plant tissues may not affect plant growth but may be toxic to human or animal consumers.

Plant growth may be indirectly affected by the influence of water quality on soil. For example, the adsorption of sodium in water on soil particles will result in a dispersion of the clay fraction. This reduces soil permeability and results in surface crust formation which, in turn, hampers germination. Soils irrigated with highly saline water tend to flocculate and have high rates of infiltration. Thus, the levels and presence of ions are important parameters, because they affect not only plant nutrition but also the physical characteristics of the soil.

Water development projects may cause problems of salinization and alkalization. The effects of salinity, often directly measured by total dissolved solids (TDS), on the osmotic pressure of the soil solution is one of the major water quality parameters for cropping. Salinity is measured by determining the electrical conductivity (EC) of a solution. This measurement relates to the ability of salts in solution to conduct electricity. General guidelines of TDS and EC for uses of saline irrigation water are given below:

TDS (mg/L)	EC (mmhos/cm)	Crop response
<500	<0.75	No harmful effects
500-1,000	0.75-1.50	Detrimental effects on sensitive crops
1,000-2,000	1.50-3.00	Adverse effects possible on many crops, careful management practices (such as good drainage and sufficient water for leaching) required
2,000-5,000	3.00-7.50	Only salt-tolerant plants can be grown on permeable soil, with careful management practices

The sodium adsorption ratio (SAR) is often used to estimate water permeability. It is based on the relationship among sodium, calcium and magnesium—the most prevalent cations in soil. Sodium causes clay soils to disperse, resulting in reduction in pore size and decreased water permeability. Thus, high values of SAR indicate less permeability as calcium and magnesium are more tightly adhered to clay surfaces. Values for SAR are often considered together with values for electrical conductivity (EC).

Water Quality for Aquatic Life

In developing countries, fish constitute an important source of low-cost and readily available protein. Any planning for water resources development projects should consider the potential impacts of water quality on aquatic life. Water quality parameter of importance for healthy aquatic life include temperature, DO, turbidity, suspended solids, pH, and toxic materials such as hydrogen sulphide, ammonia, chlorine, phenols, pesticides, and heavy metals, notably zinc, copper and cadmium. Organic discharge up to a certain level into natural waters is beneficial. In a balanced aquatic ecosystem, symbiosis exists among the organisms. Heterotrophic bacteria in water consume organic matter and release carbon dioxide and simple nutrient elements, which are taken up by algae for reproduction and to produce oxygen. All aquatic animals benefit from oxygen produced by algae. In temperate climates, low DO in water may kill fish of high economic/recreational values (game fish) while low value fish (coarse fish) can survive. Eventually the polluted water bodies may contain only undesirable fish. In tropical climates, similar situations may happen but not severely since many species of carnivorous fish such as catfish and snakehead (*Channa straita*), and herbivorous fish such as Tilapia and grass carp (*Ctenopharygodon idella*) can withstand low DO levels by breathing at the water surface.

An imbalance will occur when the algae population increases to such an extent that the carbon dioxide released by bacteria is not sufficient for their growth. When this happens, many algal species will obtain the carbon dioxide needed by splitting bicarbonate ions and releasing carbonate ions which increases pH. In organic-rich algal ponds, pH in the water could be as high as 10–12, which is toxic to most fish. Too high an algal population may lower DO during the night, when photosynthesis (which consumes carbon dioxide and produces oxygen) stops, while respiration (which is

the reverse of photosynthesis) continues as usual. This lack of dissolved oxygen can be clearly seen in the morning when fish surface to breathe from atmospheric air. Excessive algal populations may harm fish in another way. The gills of the Tilapia fish are clogged by algal cells, causing retardation in growth.

The detrimental effects of super-saturation of gases in water (such as nitrogen and carbon dioxide) to fish have only recently received attention. Super-saturation occurs when, for example, water containing a relatively high concentration of the chemical flows at a high rate (such as when flowing down a spillway). For sensitive fish, 102 to 103 per cent of saturation may start gas-bubble disease, and 115 to 125 per cent of saturation is lethal for most fish. Gas-bubble disease is characterized by the formation of fine bubbles on the fins and body surface of the fish especially the head, and the presence of gas bubbles in the vascular system. This causes blockage of the capillaries, leading to anoxia (lack of oxygen in tissues). When the bubbles break, the surrounding tissue is damaged, and becomes susceptible to bacterial infections. With too many bubbles in the blood vessels, the heart may lose suction, resulting in death.

Water Quality for Aesthetic and Recreational Uses

The common tendency in developing countries is for less stress to be laid on the aesthetic and recreational importance of water quality as other uses have a higher priority. This should not be the case in areas of high tourism, such as man-made reservoirs or river systems flowing to beach resorts. The aesthetic appearance of water bodies is perceived mainly through vision and smell. This means that the water should at least be free from floating objects or suspended solids and objectionable colours such as those given by industrial wastewaters. The water should also be odour free and have a reasonably low turbidity.

For recreational waters, the water should ideally be safe for body contact even when it is not intended for swimming. The reason is that, for many recreational uses such as fishing or boating, body contact with water is unavoidable and cannot be controlled by law. The quality constituents of concern are aesthetic (turbidity, colour, smell, floating/suspended objects), irritant chemicals, toxic compounds, and pathogens.

SOURCES OF WATER POLLUTION

Sources of water pollution include two broad categories, namely point and non-point. Point sources consist of municipal and industrial wastewaters, storm sewer outfalls, and any other sources which join water bodies through pipes and channels. Non-point sources include runoffs, atmospheric precipitations, and other diffused sources. The categorization is mostly useful in dealing with regulatory issues. Point sources can usually be quantified and controlled before discharge, whereas non-point are more difficult to manage.

Problems caused by non-point sources are:

- *Soil erosion and sediment transport.* Can result in habitat alteration and adverse effects on aquatic lives, filling of water courses and reservoirs, increase in cost and difficulty of water treatment, and reduction of recreational quality of water bodies.
- *Nutrients.* Nitrogen and phosphorus released from fertilizers and animal wastes stimulate plant bacterial growth, leading to eutrophication.
- *Heavy metals,* such as zinc, copper and mercury that are used in pesticides, paints, plumbing, and many other products.
- *Toxic chemicals,* mainly pesticides.

Irrigation-return flows may contain pollutants at concentrations higher than those in waters applied to the land because evaporation removes about 50 per cent of water, thus roughly doubling the pollutant concentrations. Runoffs from animal farms may contain high animal wastes, which contribute substantial amounts of oxygen-consuming substances and suspended solids.

Wastewaters

Municipal, agro-industrial and industrial wastewaters are important point sources of pollution. Water-borne pathogens are the main concern in municipal wastewaters, organic loads in agro-industrial wastewaters (Schaller and Bailey 1983) and organic and toxic pollutants in industrial wastewaters (Lund 1971) for industrial wastes. In developing countries, agro-industrial wastes also constitute significant pollution loads to the local environment. Examples are wastes from the processing of palm oil in Malaysia and Thailand, rubber in Malaysia, coconut oil in the Philippines and Thailand, tapioca starch in Thailand, and coffee in Kenya.

Another source of pollution that is less often recognised is urban storm runoff, which can contribute a wide variety of pollutant. In some cases, the pollution load of urban storm runoff may be even higher than that of the untreated sewage from the same community. Where sewage has been effectively treated, urban storm runoff will be a major source of pollutants and will have a strong impact on the receiving bodies.

Man-Made Reservoirs

Man-made reservoirs indirectly contribute pollutants through several mechanisms. Low turbidity due to sedimentation and high nutrients levels caused by the decay of submerged vegetation matter promote the growth of algae. This results in objectional odours, tastes, or colours. Stratification of deep reservoirs leads to anaerobic conditions which favour the dissolution of iron and manganese and production of sulphides. The discharge of impounded water in the lower layers may reduce the DO and temperature of the downstream areas far below than levels that would have been in the former free-flowing stream.

Other Sources

In developing countries, uncontrolled, open dumping sites are significant sources of organic matter (in particular refractory substances), heavy metals, and other toxic compounds, especially where hazardous materials are disposed of together with common garbage. The leachate from the dumping site will first pollute the groundwater and then surface water via ground outfalls. The residues from water treatment plants are also a threat to the environment since they contain bacteria, solids and organic material. In developed countries, correct treatment and disposal of these residues has become compulsory by law.

WATER QUALITY OBJECTIVES, CRITERIA AND STANDARDS

Water Quality Objectives

These refer to general aims or goals to be obtained usually within a fixed time frame. For example, an objective could be that within ten years no streams and rivers in a country should have anaerobic conditions as indicated by bad smells and a black colour. In most

urban centres of developing countries rivers and canals have already been rendered anaerobic through discharges of untreated municipal sewage and industrial wastewaters, so it is questionable if this objective can be achieved. However, it is an express objective of the decision-makers to achieve as much as possible. Water quality objectives usually do not specify the means by which they could be achieved. As such, they may not bear any legal enforcement power. They simply indicate the overall objective towards which the regulatory programme is directed and defined.

Water Quality Criteria

The criteria represent the characteristics of water that are necessary or desirable for specific uses. Criteria are expressed in specific numerical forms and are thus more specific than objectives. A comparison of data on the quality of water under consideration with established criteria will indicate whether the water is suitable for its intended use and, if not, what changes in quality would be necessary to make it suitable. For example, one of the criteria for irrigation water is that the boron content should be less than 0.75 mg/L for sensitive crops. This figure should not be viewed as a rigid and absolute limit, because the effects of boron vary with the type of crop and with other conditions such as temperature, water pH, and the presence of other chemicals. While boron contents lower than 0.75 mg/L indicate better quality, higher contents do not necessarily exclude the use of water in irrigation but only represents a reduction in the margin of safety.

Water Quality Guidelines

These are numerical concentrations or general statements recommended to support and maintain a designated water use. Guidelines are somewhat more detailed and forceful than criteria, meaning they indicate a strong desire for achievement and compliance. Still, guidelines are not rigid and do not have enforcement power, but they clearly express the ultimate desirable quality that should be achieved. The World Health Organization in 1984 published the *International Drinking Water Guidelines* to replace their 1970 *European Standards* and 1971 *International Standards*, apparently to better reflect this philosophy.

Water Quality Standards

These standards form the yardstick by which regulatory agencies define their requirements for water streams and water bodies. By contrast with criteria or objectives, standards are rigid reflections of laws and regulations. They are usually viewed as absolute: either they are met or violated. It should be noted that not every country by all means should try to establish their own standards. For example, even a developed country like Canada has only *criteria*, not standards, for natural waters and *guidelines*, not standards, for drinking water. Only the Province of Quebec has enforceable drinking water legislation (Tam *et al.* 1986).

There are three basic water quality standards that can be imposed and enforced.

Technology-based Standards. These are guided, in the USA for example, by the concept of Best Available Technology (BAT) or Best Practical Technology (BPT), with an assumption that the application of the best technology is adequate for environmental protection. Sometimes technology-based standards are also known as *removal standards*, when they specify the degree of removal to be attained in the treatment plant.

Effluent Standards. These refer to the minimum concentrations of potential pollutants measured at the discharge points where the wastewater stream begins its contact with the environment. Effluent standards expressed in concentrations disregard the status of the environment: whether the receiving stream is a large river or a small spring, a wastewater treatment plant still has to ensure that its effluent discharge achieve the determined concentration limits. To correct this drawback, standards based on the mass of pollutants (for example kg of BOD per day) have been established and are now commonly used in the USA.

Receiving-stream Standards. These make use of the natural purification (assimilative) capacity of the receiving stream. With the same standard, a stream which has a higher assimilative capacity can receive higher pollutants loads. An example of receiving-stream standard in developed countries is a minimum DO level of 4.0 mg/L to be obtained at all sections of the stream.

For many people, technology-based standards imply that the pollution control technology itself is a limiting factor, and standards reflect this limitation. Like effluent standards, technology-based standards disregard the capacity of the environment to absorb a certain amount of pollutants. For instance, it has been found that the COD level in palm oil wastewater can be reduced at best only to 1000 mg/L by conventional treatment processes, and there is no viable means to remove the deep brown colour in the wastewater. In other words, technology exists to bring the COD level down further or to remove the colour, but it is not practical. If this waste treatment technology is accepted as standard, the environment around palm oil factories would still be heavily loaded with refractory materials and deep brown colour. In addition to waste treatment other measures, such as waste control at source or process modification, should be explored. On the other hand, requiring the best technology in developing countries may have serious implications. New technology may require new equipment and new skills to achieve the expected performance and, if these are not available, second best or even third best technology is preferable. Equally, the cost of the best technology may be prohibitive, and marginal benefits may not justify it.

Obviously, in many cases the environment may not benefit from technology-based or effluent standards. Under different conditions environmental over-protection could result, leading to unjustifiable costs. This is the major drawback of both standards. Effluent standards based on concentrations are unfair to small-scale polluters since these people have to adopt the same sophisticated technology to produce the same level of effluent quality even though they release only small amounts of pollutants into the environment. Effluents standards based on pollutant mass may have to be 'tailor-made' for each specific water body, and so are quite complicated in terms of application. Despite these limitations, both effluent and technology-based standards still prevail since both are developed by engineers, chemists and biologists who are familiar with pollution control technology and analytical methodology. They are also easy to administer and apply, especially on a national scale.

Stream standards are the most rational and meaningful. To politicians and decision-makers, they are easier to understand. For example, 4 mg/L of oxygen means a healthy condition, and zero oxygen means a black colour and foul odours. Such a standard

should serve as an ultimate goal for any water quality management programme. Some points, however, need to be noted when receiving-stream standards are considered.

- Standards lack precision and are highly site-specific. This is especially true when standards used in the West are imposed on a developing country. Water quality standards cannot always be imported from one country to another. Rather, each country should try to develop its own standards based on specific local conditions.

The site-specific nature indicates even in the same country, there may be more than one set of standards. This concept of 'variable standards' is useful for each area of the country to deal with its own specific water quality problems.

- Standards should balance on the one hand long-term environmental impacts and on the other the economic technological and institutional capabilities of the country to monitor and implement. To do this, standards may need to be developed in stages according to the country's pace of development, but the initial level must take into account immediate costs and benefits with a clear understanding of the environmental impacts.
- Standards must be enforceable, otherwise their usefulness is limited. Unfortunately, in most developing countries this is usually the case. Any country can establish comprehensive standards, but most are not in a position to enforce them.
- Often, the common practice is to set unrealistically strict standards to provide for a large safety margin and to avoid institutional responsibility. When compliance is impossible and the standards are violated then enforcement is quietly relaxed. However, such a practice easily leads to the loss of credibility and to an atmosphere of complacency, all of which impede the seriousness of future efforts to enforce environmental regulations.

WATER QUALITY MONITORING

Water quality monitoring is a far more complex task than water quantity monitoring because there are a higher number of parameters involved, higher costs in sampling and laboratory analysis, and higher requirements for skills and equipment. Whereas the same few water quantity parameters are measured at every station of the monitoring network, a higher number of water quality parameters

must be selected specifically for each station. Equally water quality parameters to be monitored could vary with time. More equipment and skills are required to ensure that water samples are taken correctly, stored and preserved properly, analyzed reliably, and the results are interpreted properly. The site-specificity and the sophistication of water quality monitoring necessitates careful planning, appropriate implementation of the monitoring programme, and regular review.

Almost every developing country has its own water quantity monitoring programme which consists of measurements of physical parameters like rainfall and river discharge. Water quality monitoring and ecological surveillance including bioassays are less prevalent. Generally there is a missing link in these programmes, that is, what should be done next with all of these data. Commonly, large amounts of data lie on the shelves to gather dust. After substantial resources have been spent in gathering data with an elaborate station network using sophisticated equipment, developing countries often do not use the data collected. Thus, instead of collecting a lot of data, it could be more effective and efficient to focus the monitoring programme only on critical areas, where they are needed. An integrated plan with all necessary stages should be drawn up, the objectives of each stage defined clearly, and resource allocated appropriately to all the necessary stages.

Water quality monitoring must serve an explicit purpose, be it for environmental impact assessment, project planning and design, project evaluation, or for regulatory requirements. Since resource is always a constraint, only the most meaningful parameters should be selected for inclusion in the monitoring programme. For example, total coliforms need to be monitored together with faecal coliforms; or, once total nitrogen and ammonia have been determined, nitrate and nitrite could be lumped together by subtracting ammonia from total nitrogen, since determining nitrite and nitrate separately costs more but is not very useful.

WATER QUALITY INDICES

Environmental Indices

Due to the number of water quality parameters and the high variations of these parameters, a water quality index may be of help to describe the overall situation. Unfortunately, the number of water quality

indices used in different countries (or even in different states in the USA only) is as high as the number of parameters themselves. Generally there are six basic uses of environmental indices (Ott 1978).

- *Scientific research*: for reducing a large quantity of data to a form that gives better insights into the prevailing environmental conditions;
- *Public information*: providing information to the public about environmental conditions;
- *Ranking of locations*: intercomparison of environmental conditions at different locations or geographical areas;
- *Resource allocation*: assist decision-makers in allocating funds and determining priorities;
- *Enforcement of standards*: determination of the extent to which legislative standards and existing criteria are being met or exceeded;
- *Trend analysis*: identification of overall trends in environmental quality over a period.

Over the years, many water quality indices have been developed (Ott 1978, for a complete treatise of environmental indices in general, and House and Ellis 1980 for an evaluation of indices used in the UK). The US National Science Foundation Water Quality Index (NSF WQI), which is one of the best-known and most commonly used general-purpose indices, is briefly discussed here. The NSF WQI was developed using a formal procedure to combine the opinions of a large panel of water experts throughout the USA. These experts were asked (i) initially to consider 35 water constituents for possible inclusion in the index, (ii) subsequently to review his/her original ratings after being informed of the other experts' rating and then (iii) to develop a rating curve for each of the 9 constituents considered to be of the greatest importance. Each of these curves bears a distinct shape depending on the affects the constituents cause at their different levels. The rating curves for DO and faecal coliforms are shown in Figs. 1a and 1b respectively (Ott 1978) as examples. For pesticides and toxic substances, if any substance exceeds its assigned upper limit the NSF WQI is set to zero. Based on the ratings by respondents, the weights of the 9 constituents were determined as shown in Table 1.

The index is calculated by determining the subindex value from the appropriate rating curve for each water constituent. The NSF

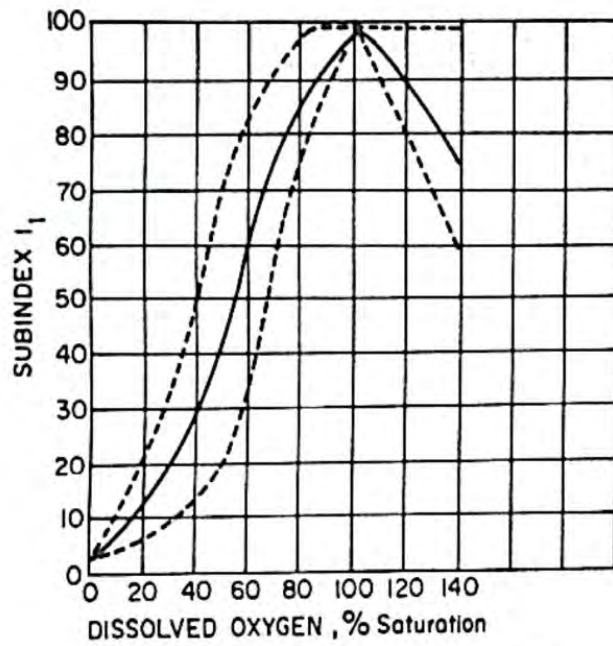


FIGURE 1a. Subindex function for DO in the NSF WQ1

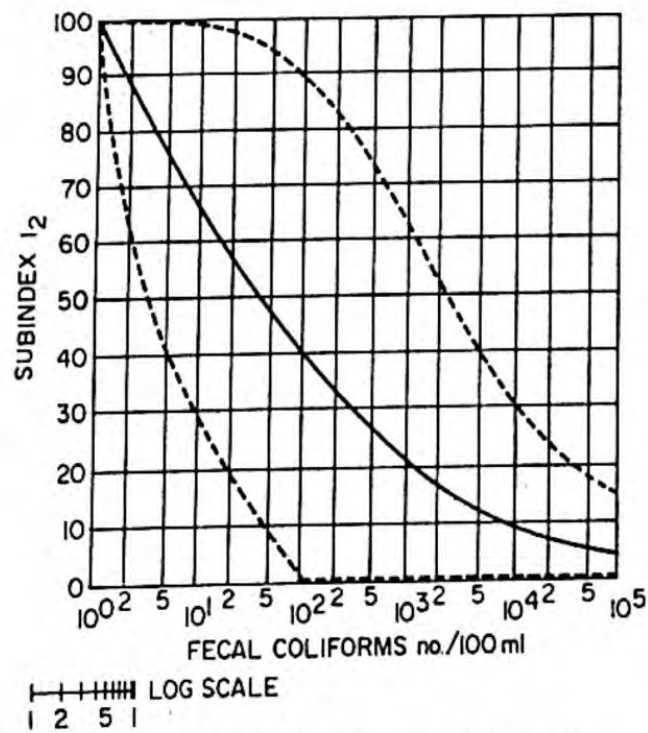


FIGURE 1b. Subindex function for faecal coliforms (average number of organisms per 100 ml) in the NSF WQ1

TABLE 1. Relative weights of the nine constituents of the water quality index developed by National Science Foundation

Constituent	Weight
DO	0.17
Faecal coliforms	0.15
pH	0.12
BOD ₅	0.10
Nitrates	0.10
Phosphates	0.10
Temperature	0.10
Turbidity	0.08
Total solids	0.08
Total	1.00

WQI is the weighted sum of all the subindices. This index has been field-tested and has been widely used in various geographical areas in the USA, even though it has not received the status of a national index. The most common water quality constituents used in six general-purpose and seven specific-use indices developed and used in the USA are shown in Table 2.

TABLE 2. The most common constituents of water quality indices

Constituent	No. of indices using this constituent
DO	11
pH	11
Temperature	9
Faecal coliforms	8
Turbidity	7
BOD	6
Chlorides	6
Colour	6
Nitrates	6

Table 2 might also be considered as the minimum list of constituents to be included in a national index for a developing country. By examining the criteria proposed in the indices and by using mathematical analysis, Ott (1978) compiled a list of criteria for an ideal quality index. These criteria are the following:

1. logical scientific rationale or procedure behind index development;
2. reasonable balance between oversimplification and technical complexity;
3. sensitivity to small changes in water quality;
4. no eclipsing;
5. no ambiguity;
6. linearity in the aggression process;
7. dimensionless;
8. clearly defined range;
9. understanding of the significance of data;
10. ease in application;
11. ease in accommodation of new variable;
12. possible probability of interpretation;
13. variables that are widely and routinely measured;
14. inclusion of toxic materials;
15. inclusion of variables having clear effects on aquatic life or recreational use;
16. testings in a number of geographical areas;
17. reasonable agreement with expert opinion;
18. reasonable agreement with biological measures of water quality;
19. compatibility with water quality standards;
20. inclusion of guidance on how to handle missing values; and
21. clear documentation of limitations;

Biological Indices

In addition to indices which directly measure water quality, ecological indices are also sometimes used. These indices measure the response of key species or groups of organisms to pollution. There have been generally two approaches to the development of ecological indices.

(i) **Pollution Indices.** These are derived from observations of the response to pollution of affected species. These indices incorporate such factors as the relative abundance of indicator species, the reduction in community diversity, and the progressive loss of certain groups in response to pollution.

(ii) **Diversity Indices.** These are based on theoretical concepts of the structure of ecological communities. The degree of pollution

is assessed by measuring the extent to which the community structure differs from that of an assumed model. In normal communities there are a few species represented by a large number of individuals, smaller numbers of several species, and many species which are represented only by very few individuals. Models have been established to describe this observation, and they are used as baseline data for pollution impact assessment. Any variation in terms of the number of species represented by a given number of individuals within a sample will indicate impact.

Hellawell (1978) has reviewed various ecological indices. As a general rule, ecological indices are highly site-specific and require skills of taxonomy for accurate identification and numeration. A clear knowledge of the local ecosystem is also necessary to establish base-line information for any 'before and after' study.

WATER QUALITY MODELLING

Water quality models are used to describe three principal phenomena: hydrological, thermal, and biochemical. Hydrological models essentially deal with the dynamics of the hydrological cycle. They are the most classical of the three types and play an important role in water development management.

Most of the biochemical water quality models in use today originated from two simple equations proposed by Streeter and Phelps in 1925 when they studied the pollution of the Ohio River. They observed that the BOD concentrations measured at successive points along the Ohio River below major discharges decreased as a function of distance travelled or time of flow. Accordingly BOD levels could be predicted by using a simple mathematical relationship based on time and a deoxygenation constant. The fundamental assumption in the Streeter-Phelps equations is that BOD and DO are sufficient to describe the biochemical processes of water pollution and natural purification. The model based primarily on this equation are helpful in predicting the BOD and DO concentrations or deficits as a result of a discharge of biodegradable wastes into a flowing water body. Solution of the Streeter-Phelps equation with different values of points in time produces a profile of DO known as the dissolved *oxygen sag curve* and is shown in Fig. 2. Beginning at a discharge point and moving downstream to the right, the DO decreases because deoxygenation occurs at a rate higher than reaeration. The deoxygenation rate increases in response to the increase

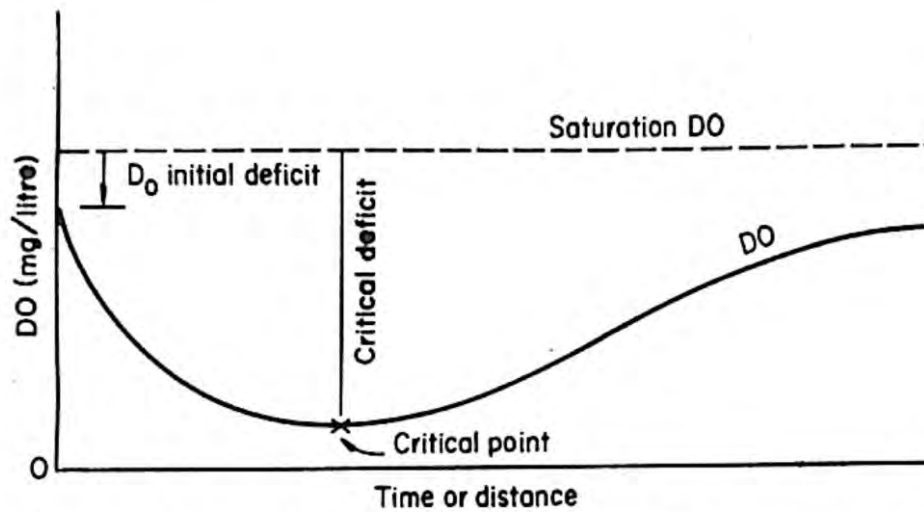


FIGURE 2. Example of an oxygen sag curve below a point-source discharge

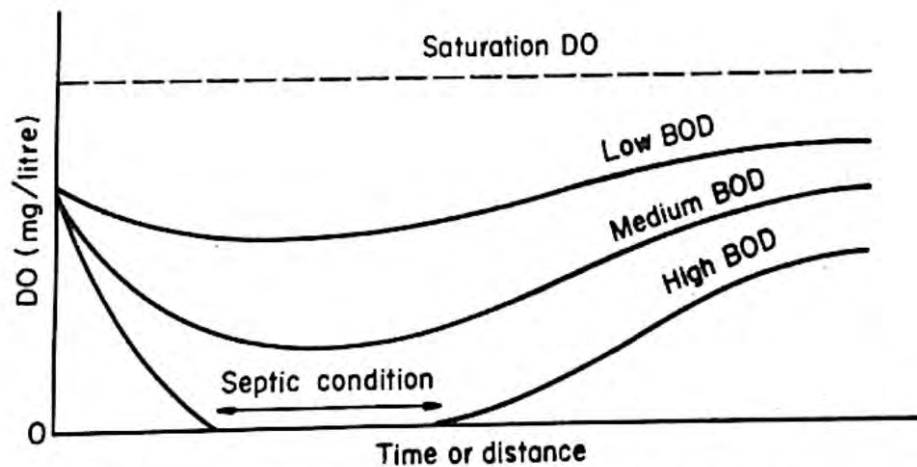


FIGURE 3. The effect of changing the BOD discharge into a stream on the oxygen sag curve

oxygen deficit. When the two rates become equal, the DO level reaches its lowest level—the critical point. From this point on, the re-aeration rate exceeds the deoxygenation rate, and the DO gradually recovers to the initial level. The exact shape of the oxygen sag curve will depend on the initial load of BOD at the discharge point, as shown in Fig. 3. Obviously there should be a careful balance between benefits and costs of wastewater treatment for BOD reduction. Too high a BOD load will reduce the DO concentration to zero, which will give rise to septic conditions, while too great of BOD reduction is too costly. Medium BOD loads with

moderate wastewater treatment will save costs while natural assimilation can be relied upon to purify the rest of the BOD discharged.

Some models based on the Streeter-Phelps concept also consider some additional biochemical phenomena. For example, the assumption in the Streeter-Phelps model that the deoxygenation rate and the BOD decay rate are equal is not always true. The decay rate could be higher than the deoxygenation rate because of sedimentation, or lower because of resuspension. Thus, first-order exponential decay dilution and sedimentation models have been developed based on the concept proposed by Streeter and Phelps. More and more complex multi-parameter water quality models can be developed to predict more accurately the physical, chemical and biological interactions of many aquatic constituents and organisms.

Water quality models can be used for steady-state or dynamic time-varying conditions. The first category is usually simpler, requires less computational effort, and is more relevant to long-term planning. The second is useful for evaluating transient conditions such as non-point storm runoff or accidental spills of pollutants.

Assumptions on the mixing of pollutants in surface water bodies determine spatial dimensionality of the model. One-dimensional models assume complete mixing in both vertical and horizontal directions. Two-dimensional models assume either lateral mixing (as in stratified estuaries), or vertical mixing (as in relatively shallow and wide-rivers). Even though real conditions are three-dimensional, one- or two-dimensional representations may give adequate accuracy and save costs.

Most models are deterministic in nature, that is, they simply give estimates of mean values of the constituents. Stochastic or probabilistic models take into account the probability distributions—not just the expected values—of various processes occurring in nature. These models require elaborate data inputs which are not always available. Model solution methodology varies from manual computation to the use of nomographs and computers. Most computer models are simulation type which provide the values of water quality parameters for given flows, pollutant discharge rates and the degree of pollution control. For each set of assumptions, a trial-and-error simulation run is performed until satisfactory results are obtained. The models are solved either by integrating basic differential equations, or by using numerical analysis techniques such as finite difference or finite element.

If cost or time constraints dictate against simulation models, optimization models may be used. The most common solving methods are linear programming and dynamic programming, but non-linear or mixed-integer programming is sometimes used. Optimization models are more limited in scope than simulation models, but they can help to define the range of acceptable alternatives that best satisfy pre-determined objectives. These alternatives may be double-checked using a verified simulation model which provides a more accurate basis for economic and technological comparisons, Biswas (1976 and 1981) and Rinaldi *et al.* (1979) provide further details on water quality modelling. The current status of water quality modelling for various constituents is summarized in Table 3 (Biswas 1981).

TABLE 3. Current status of water quality modelling

Water quality constituents	Modelling status
Transport	
steady state	good
dynamic	marginal
BOD-DO	good
Total dissolved solids	moderate
Suspended solids	marginal
Bacteria	marginal
Synthetic chemicals	poor
Simple industrial chemicals	marginal
Simple metals	marginal
Complex metals	poor
Zooplankton	poor
Viruses	poor
Turbidity	poor
Colour	poor
Algae	marginal
Nutrients	moderate
Temperature	good
Synergistic models	impossible

LAKE WATER QUALITY

Water quality management for lakes (including man-made reservoirs) is different from that for streams. Only some basic issues will be discussed here, but more detail can be seen in Jørgensen (1980).

Water inputs to lakes include streams, surface runoffs, groundwater inflows, and atmospheric precipitation. Chemically, consideration of the water quality of a lake is somewhat similar to that of the streams feeding the lake, but additional factors profoundly modify the water quality characteristics of a lake. Reduced velocity and turbulence allows a substantial portion of the solid particles brought in streams to settle, reducing the turbidity of the lake water. Also, internal mixing and the longer retention time reduce the range of quality variations far below those observed in streams. The result is a very stable aquatic ecosystem in a lake, which can be easily upset by any sudden change in the water quality regime. For instance, reduced turbidity results in increased light penetration, which could promote algal growth, which in turn changes the ecological balance in a way that is entirely different from that of streams.

A phenomenon that causes great impact on the quality of lake water as well as of the water downstream is thermal stratification. In deep lakes (more than 30 m) the top layer (*epilimnion*) becomes warmer than the bottom layer (*hypolimnion*) during the summer. For this reason, only water in the top layer circulates, and it does not mix with water in the colder bottom layer. A steep temperature gradient is created between the two layers, and the transitional zone is called the *thermocline*. If the thermocline is below the depth of light penetration, no oxygen production from photosynthesis will occur, resulting in constant anaerobic conditions in the bottom layer. This condition is called *summer stagnation*.

In temperate climates, during the autumn, the temperature of the upper layer drops until it is the same as of the bottom layer, resulting in circulation of the entire lake, and oxygen is brought from the surface to the bottom. When the upper layer temperature drops to 4 °C, it becomes heaviest and so sinks to the bottom, creating a *fall overturn*. Then, as spring arrives, the upper layer temperature increases from the freezing level up to 4 °C, which makes it sink to the bottom, creating a *spring overturn*. Figures 5 and 6 depict the seasonal profiles of temperature and oxygen respectively.

For tropical climates, the situation is quite different. In areas where the temperature never falls to 4 °C there is no fall or spring overturn. In comparison to temperate climates, the summer conditions exist year-round. In other words, the *summer stagnation* is permanent: only condition (2) exists in Figs. 4 and 5. The deeper the lake, the

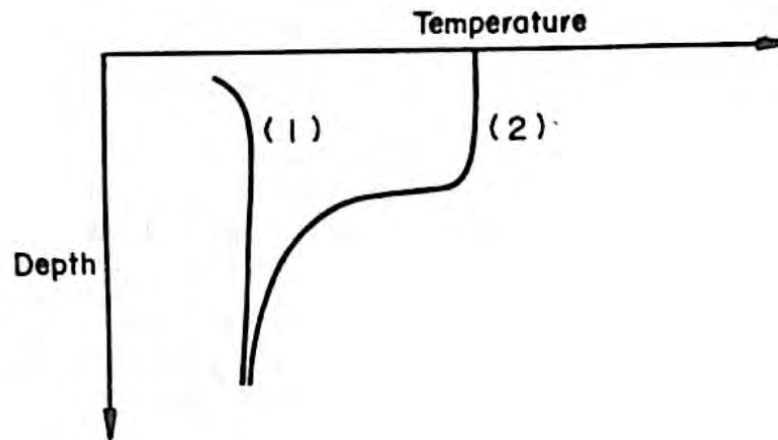


FIGURE 4. Temperature profile in a stratified lake:
(1) winter condition; (2) summer condition

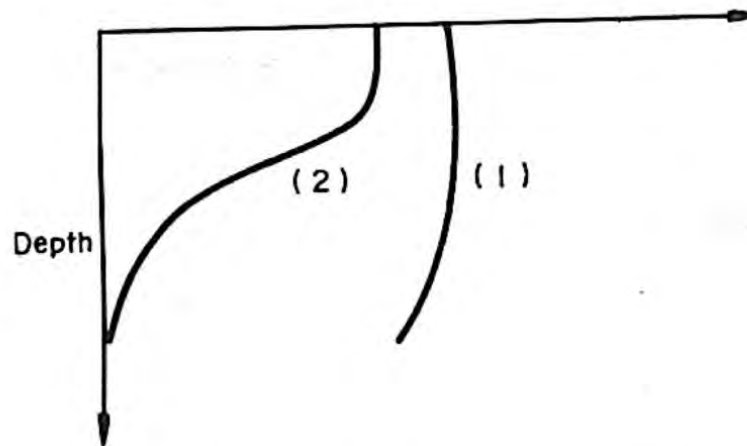


FIGURE 5. Oxygen profile in a stratified lake:
(1) winter condition; (2) summer condition

worse is the stagnation. Thus, without proper management deep man-made reservoirs usually have very large volumes in which the water quality is deteriorated and fishery is not productive

Mathematical modelling of lakes and reservoirs is a difficult process. Response times in lakes are long, many variables cannot be controlled or measured, and natural factors such as weather complicate the natural and biological processes in the water environment. Despite these constraints, under certain conditions modelling of lakes can prove to be useful for water quality management.

Modelling of the lake water quality in the 1960s was initially

meant to study severe eutrophication of some natural and man-made lakes. One of the well-known examples of such early application is the Lake Erie. Lake modelling was first attempted by limnologists to study the annual thermal cycle and the formation of the thermocline, by extending the modelling principles of the thermal structure of stratified water bodies. It was later refined by biologists and engineers in charge of pollution control and abatement.

Most current lake modelling work is concerned with the finite-element for horizontal layers. Mass and energy transports between layers are described using hydrodynamic approaches. These models are usually confined to two layers, the hypolimnion and the epilimnion. However, very few real examples are currently available of mathematical models successfully applied to lake water quality management.

WATER POLLUTION CONTROL

Various options available for collection, treatment and disposal of wastewater for water pollution control will be briefly discussed in this section. More details on mainly conventional technologies can be found in Metcalf and Eddy (1979). Various options for water pollution control are presented in Table 4 (adapted from Kneese and Bower 1968).

TABLE 4. Options of water pollution control

<i>Principle</i>	<i>Method</i>	<i>Example</i>
A. Reducing waste generation	1. In-plant recirculation of water	Water used for cooling purposes is collected for recirculation and reuse
	2. Segregation of concentrated waste streams	Removal of solid wastes by hand or mechanical means, to be disposed of easily in a separate way, rather than flushing them down the gutter which makes the wastewater stream more difficult to treat
	3. Waste elimination	Use residues of agro-industries (e.g. pineapple) to feed animals (e.g. pigs)
	4. Change type of raw material inputs	May be difficult
	5. Change production process	Change from pressure to solvent extraction to achieve better oil extraction efficiency in vegetative oil industry, reducing oil load in waste stream

<i>Principle</i>	<i>Method</i>	<i>Example</i>
B. Reducing wastes after generation	6. Change or modify product outputs	Detergents with lower contents of phosphorus. Change from disposable to recyclable packing material in packaging and bottling industries
	7. Material recovery	Collection of palm fruit fibres in palm oil industry, to be dried and used as fuel for boilers
	8. Byproduct production	Integrated farming, which consists of duck/pig production, aquaculture and crop production
	9. Waste treatment	Oxidation ditch, aerated lagoon, waste stabilization pond, land treatment, wetland
C. Improve assimilative capacity of receiving water	10. Effluent reuse	Aquaculture, composting, irrigation and fertilization, biogas production
	11. Addition of dilution water	
	12. Multiple outlets from reservoirs	
	13. Reservoir mixing	
	14. Reaeration of streams	
	15. Saltwater barriers	
	16. Effluent redistribution	
D. Corrective measures on ecosystem	17. Chemical treatment in reservoirs	Application of chemicals (e.g. aluminum sulphate) to precipitate phosphorus
	18. Reduction of biomass concentration	Introduction of herbivorous animals to graze aquatic weeds, or spraying of herbicides to control algae and weeds

For developing countries, the principles of reducing waste generation and improving wastes recovery are the most appropriate and feasible processes. In this regard the situation in many developing countries could be substantially improved. In almost every pollution survey, it has been observed that more pollutants are discharged than necessary, and with only minimal costs carrying out methods

1-3 of principle A, the pollutant load could be significantly reduced. The cost-benefit ratio in this case would be very favourable. And with more investment for methods 5-6, the situation would be changed even more dramatically. For example, in one palm oil plant in Thailand it was estimated that the amount of oil discharged in the effluent was as much as one-fourth of the plant's oil yield. Local people collected the effluent and boiled it over a open fire to recover the oil contents. With some modifications in the manufacturing process to increase the efficiency of oil extraction, the plant could have obtained more yields. Such modifications are not only cost-effective but also substantially contribute to the preservation of environmental quality.

Wastewater Treatment

There are a variety of wastewater treatment processes, but for developing countries, one of the most appropriate is a waste stabilization pond system (Biswas and Arar 1988; WHO EMRO 1987). The main driving force in this process is the sun, and natural organisms consisting of algae, bacteria and plankton help break down the organic matter and remove pathogens in the wastewater. A pond system typically consists of a series of 3-5 ponds. The first pond may be either anaerobic or facultative depending on the organic loading rate. Anaerobic ponds are more efficient in terms of pollutant mass removed per unit of land area, but could be objectionable to a nearby community. Most organic removal takes place in the first one or two ponds, whereas pathogen die-off in the remaining ponds, reducing the pathogen levels in the effluent to an acceptable level. The performance of stabilization pond systems is superior to many conventional treatment processes: organic removal efficiency can reach 90 per cent or more, while pathogens are removed by around 10,000 times. The only drawback in terms of effluent quality is the high levels of suspended solids which consist mainly of live algal cells, thus violating common effluent standards. High levels of algae may deteriorate the quality of downstream water.

Wastewater Reuse

Aquaculture using wastes has been practiced traditionally in many regions of the world (Edwards 1980; 1985). Throughout Asia, fish and aquatic plants have been grown in waters contaminated with faecal matter. Fishponds near Calcutta receive sewage from the

city, and the harvested fish are sold back to the city. Latrines are built over fish ponds in China and Vietnam, fish raised in cages submerged in faecal-contaminated streams in Indonesia, and vegetables (such as the water spinach) grown in canals fed with sewage in Thailand. Some public health threats may exist in such practices, especially when appropriate precautions are not taken. However, some important points should be kept in mind when dealing with this issue. First, these practices help produce substantial quantities of low-cost protein food for the poor local people. Any option that wipes out this protein source without adequate replacement will be disastrous. Second, for some systems such as overhung latrine-fish pond, the pollutants are contained quite well. An alternative waste management option which partially removes the pollutant load but advertently spreads the remainder will not necessarily be better. A more rational strategy is to use waste to grow aquatic plants, and use the plants to grow human food. Aquatic plants can be used in many other ways, and the various options are reviewed by Polprasert *et al.* (1986).

The cultivation of the water fern *Azolla* sp. as a green manure deserves attention. This aquatic plant grows in symbiosis with the blue-green algae *Anabaena azollae*, which is able to form its protein by fixing nitrogen from the air. The fern is grown in rice fields before the rice-growing season, and is fertilized with animal wastes. Due to its fast growth (doubling time of 3–10 days), a high amount of nitrogen fertilizer can be produced quickly, to be used later by rice paddy. *Azolla* cultivation and use techniques have been developed in China and Vietnam, and have received attention elsewhere for applied research and development (Polprasert *et al.* 1986).

Algal culture in shallow, high-rate ponds fed with treated wastewater has received a fair share of research, but its economic viability is still not favourable. The main problem lies with difficulty in parasite and predator control, the unavailability of affordable techniques for separating tiny algal cells from water and for processing (drying) the algae for marketing, and marketing itself. In some areas in China, the green alga *Chlorella* and the blue-green *Spirulina* have been cultivated with animal wastes, and the algal slurry is fed directly to pigs. The state-of-the-art of algal biomass production and use can be found in Shelef and Soeder (1980).

Irrigation/fertilization also includes land application as a treatment process. Throughout Korea, China, Taiwan, Japan, Vietnam and

to a certain extent, Thailand, the Philippines and Malaysia, nightsoil has been applied directly onto agricultural land. Sewage irrigation is also applied in several developing countries. In India, Bombay initiated sewage farming in 1877, followed by Delhi in 1913. The daily volume of sewage reaches 3.6 million m³, of which about 50 per cent is being utilized for crop irrigation. Near Mexico City, about 40 m³/s of sewage is used to irrigate 41,500 ha of fodder and grain not for human consumption. Some 16,000 ha grown with vegetables and salad crops receives the raw wastewater from the city of Santiago, Chile. These reuse practices have been done more by economic incentive than by environmental awareness. As a result, the environment does not necessarily benefit from it.

Wastewaters often contain higher levels of metals than natural waters do. For this reason, metals should be closely monitored to determine the use and management practices required. The impact of metals in irrigation water on soil and biota is summarized in Table 5.

With regard to public health threats posed by wastewater irrigation, an extensive investigation of available data (Biswas and Arar 1988;

TABLE 5. The impact of metals in irrigation water on soil and biota

<i>Metal</i>	<i>Recommended maximum concentration</i>	<i>Impact on soils and biota</i>
Aluminium (Al)	5.0	Can cause non-productivity in acid soils (pH<5.5), but more alkaline soils at pH>7.0 will precipitate the ion and eliminate any toxicity
Beryllium (Be)	0.10	Toxicity to plants varies widely, ranging from 5 mg/L for kale to 0.5 mg/L for bush beans
Cadmium (Ca)	0.01	Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/L in nutrient solutions. Conservative limits recommended due to its potential for accumulation in plants and soils to concentrations that may be harmful to humans.
Cobalt (Co)	0.05	Toxic to tomato plants at 0.1 mg/L in nutrient solution. Tends to be inactivated by neutral and alkaline soils
Chromium (Cr)	0.20	Not generally recognized as an essential growth element. Conservative limits recommended due to lack of knowledge on its toxicity to plants
Copper (Cu)	0.20	Toxic to a number of plants at 0.1 to 1.0 mg/L in nutrient solutions

<i>Metal</i>	<i>Recommended maximum concentration</i>	<i>Impact on soils and biota</i>
Iron (Fe)	5.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of essential phosphorus and molybdenum. Overhead sprinkling may result in unsightly deposits on plants, equipments and buildings.
Lithium (Li)	2.5	Tolerated by most crops up to 5 mg/L; mobile in soil. Toxic to citrus at low concentrations (<0.075 mg/L). Acts similarly to boron
Manganese (Mn)	0.20	Toxic to a number of crops at a few tenths to a few mg/L, but usually only in acid soils
Molybdenum (Mo)	0.01	Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum.
Nickel (Ni)	0.20	Toxic to a number of plants 0.5 to 1.0 mg/L; reduced toxicity at neutral or alkaline pH
Lead (Pb)	5.0	Can inhibit plant cell growth at very high concentrations.
Selenium (Se)	0.02	Toxic to plants at concentrations as low as 0.025 mg/L and toxic to livestock if forage is grown in soils with relatively high levels of added selenium. An essential element to animals but in very low concentrations.
Vanadium (V)	0.10	Toxic to many plants at relatively low concentrations
Zinc (Zn)	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH>6.0 and in fine-textured or organic soils

Shuval *et al.* 1986) has indicated that previous public health positions have been conservative. The main public health concern in wastewater irrigation in developing countries would be helminths, not bacteria or viruses. This problem could be alleviated by holding the wastewater in a settling tank/pond for 2 days before using the effluent for irrigation. A stabilization pond system with a minimum 20-day retention time can remove almost all bacteria and viruses and can produce an effluent suitable for unrestricted irrigation of vegetables. Wastewater irrigation offers various benefits of increased agricultural/forestry yields, improved food supply, reduced

environmental pollution and spin-offs such as job creation and rural development. In developing countries, these benefits have not been exploited to any extent while wastewaters are allowed to pollute the local water bodies.

There are three basic land application methods, namely slow rate, overland flow, and infiltration-percolation. These methods are depicted in Fig. 6. The slow-rate process is easier to apply in most conditions, since overland flow requires a gentle slope over the application area and infiltration-percolation is suitable only where the infiltration rate is high such as in sandy soils. Slow-rate irrigation is based on the idea of utilizing both the water and the nutrients of wastewater for crop production. More details on wastewater reuse in irrigation/fertilization can be found in Shuval *et al.* (1986) and Biswas and Arar (1988).

WATER QUALITY MANAGEMENT FROM NATIONAL PERSPECTIVES

Main issues at the national level for water quality management are summarized as follows (United Nations 1987):

- Water quality management legislation should be consistent with national requirements of economic and social realities, and human resource capabilities.
- Water quality legislation should be enforceable. An adequately staffed, equipped and functional monitoring system is crucial. The political will to prosecute violators should be created. Appropriate effluents standards should be adopted, and discharge levels of certain substance into water courses should be restricted. Permits should be issued only to economic activities using 'clean' processes or located in areas with adequate environmental assimilative capacity.
- Water quality management within the context of legislative actions may include:
 - creation of an appropriate institutional infrastructure;
 - requirements for industry and municipalities to treat their effluents in order to ensure water quality standards in surface and groundwater are not violated;
 - designation of protected areas or hydrological regions and aquifers;
 - requirements for adopting special designs or technology to

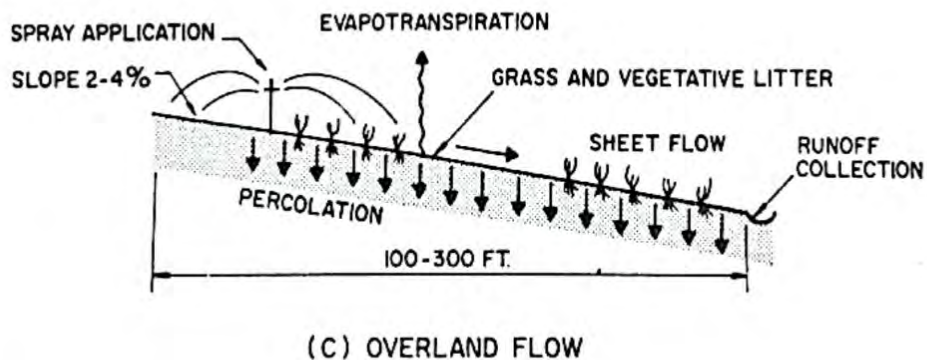
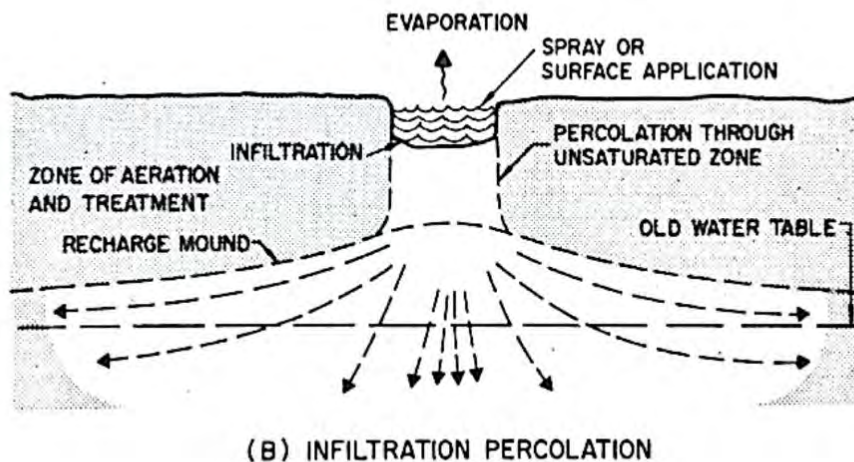
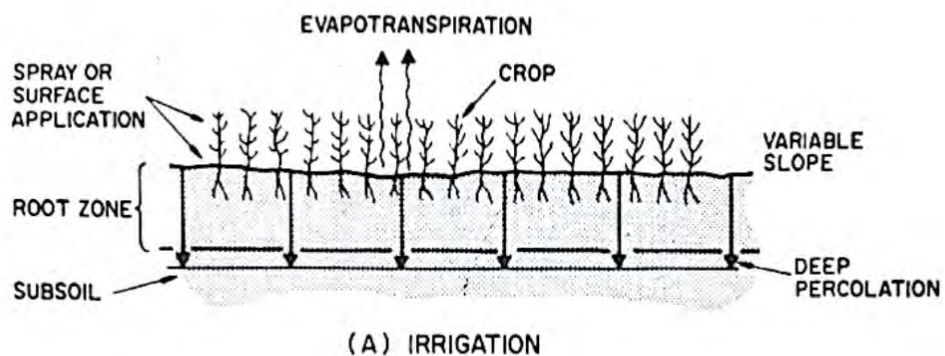


FIGURE 6. Methods of land application

reduce levels of wastes generated;
 prohibition against discharging specific pollutants that are harmful to public health or the environment;
 control of production, processing, transportation and storage of water pollutants;

- Mechanisms for coordination of water quality management programmes to ensure reduction of duplication of efforts among agencies and to eliminate institutional infighting.
- Environmental impact assessment and monitoring should be an integral part of the management process.
- Availability of an efficient and well-equipped emergency services and warning systems for controlling accidents involving water pollutants.
- Programmes should be developed to (a) train specialists in water quality and management; (b) teach environmental issues in universities, technical colleges and schools, and (c) focus on and place high priority on public education. Mass media techniques should be used, and environmental interest groups should be encouraged.
- Financial incentives should be considered with care, and their efficacy and redistribution impact should be assessed. User and effluent charge systems could be used as regulating tools and sources of pollution control funds. Approaches should reflect the specific local conditions and charges should be updated when appropriate.
- An effective water quality monitoring system is essential. It should include physical, chemical and biological parameters. This should be integrated with water quantity assessment network. Groundwater quality monitoring needs special emphasis. A good functional data management system is a necessary prerequisite for efficient water quality management.

Water quality management in developing countries is faced with numerous obstacles. It has generally been a neglected subject for various reasons among which are lack of political will, resource and manpower constraints, institutional inertia, and public apathy. As a crucial first step, public and political awareness should be raised so that it receives more attention, since water quality directly influences many issues; human health, agriculture, aquaculture, industry, and tourism—all of which are vital to national development.

Decision-makers should be convinced that investments in enhancing the quality of the nation's water will directly contribute to social and economic benefits, just like investments in other sectors. For example, in the Caribbean region, the lack of a comprehensive wastewater management or improper waste disposal has led to wide-scale pollution of tourist resorts, which has slowed down or even frozen further development. This could happen in other countries.

Determination of water quality objectives and criteria is the next important step. In many cases, standards are directly adopted from the West or from those recommended by the WHO, without considering the country's social, economic, cultural or climatic requirements and the manpower expertise and institutions necessary to implement them. The agency or the polluter cares much about enforcement and compliance since it is clear that those unrealistic standards cannot be achieved anyway.

This is perhaps rooted in the mentality that lower standards appropriate to the local conditions are insulting 'second rate', while it is desirable to have the high standards just like in any industrialized country. Developing countries should consider realistically what can be achieved and then take appropriate actions to enforce them. Otherwise best will continue to be the enemy of good.

The feeling against something 'second rate' also exists with innovative, low-cost appropriate technology. Despite much effort during the past two decades to promote waste stabilization ponds, it is still often difficult to convince government authorities that this technology is as good as, if not better than, conventional treatment processes, especially for countries in tropical and semi-tropical regions.

Blind adoption of western technology for water quality management has created more problems than they have solved. Technology implementation requires supporting 'software' and management. Among these are institutional strengthening, resources and expertise available, public information and motivation, community participation, including involvement of women. For instance, many industries still release unnecessarily high pollution loads into the environment. With better information motivation and minimum investment, levels of pollution could be substantially reduced.

This leads back to an old golden rule: prevention is better than treatment. At many factories storm runoff is mixed with process

wastewater, and this makes treatment so costly that the factory cannot afford and the authorities cannot enforce it. Large amounts of coarse solid particles are swept into the wastewater streams while they can be collected separately and easily disposed of by low-cost landfilling. To correct this situation, awareness, public information and motivation are necessary.

By combining awareness, realistic planning and decision-making, software supporting activities, and waste control at source, developing countries can have a good start, and many of their water quality problems would be greatly alleviated within a reasonable time frame.

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Groundwater Quality Management

R. MACKAY

INTRODUCTION

In most parts of the world, groundwater has generally been considered to be a readily available, good quality source of water for drinking and for agricultural and industrial uses. However, with increasing demands, significant changes in land use patterns and a vast increase in the quantities and types of industrial, agricultural and domestic effluents entering the hydrological cycle, the stresses on groundwater, both in terms of quantity and quality, are growing rapidly. In the past, groundwater managers have primarily been responsible for establishing the 'safe yield' of an aquifer system with little interest in how groundwater quality might change with time as a result of human activities. In reality, determination of the 'safe yield' for a groundwater resource must consider both its quantity and quality. Thus, over the last two decades there has been a substantial move towards a more complete understanding of groundwater contamination and how the impacts of contamination can be mitigated by appropriate management actions and technological developments.

In order to be able to develop an appropriate management plan for an aquifer system which takes into account the quality of the resource, the factors influencing the control of groundwater quality must be understood. Only with this knowledge can the groundwater manager assemble and interpret all the relevant data before deciding on a particular strategy. Assembling the data base depends largely on correctly formulating the problem. This may be undertaken by developing a series of questions appropriate to the definition of the problem. For example, an obvious question should be—'When does contamination become pollution?' Contamination is used here to indicate the presence of chemical, bacterial or radiological species in the groundwater at levels greater than the background values, whilst pollution indicates the presence of species at levels harmful in terms of the use of the water. To answer this question

properly, a range of further questions need to be posed and answered. Among these questions are:

- What contaminations are present in the groundwater?
- What are harmful levels for specific contaminants?
- How will the contaminant levels in the groundwater system change with time?
- Can the contamination levels be controlled, e.g. by altering abstractions?
- Can the source of contamination be controlled effectively?
- How will future plans for development and use of the aquifer system be affected by the contamination?

In the following sections an attempt is made to establish a basic framework for providing answers to the above questions and to define strategies for the management of groundwater quality.

Groundwater quality management is a relatively new field and as such there is still much research to be undertaken before an 'optimal' approach to groundwater management can be defined. However, given present stresses on groundwater resources in most countries of the world it is important that resource managers begin to come to terms with the very real problems of quality management. Managers must recognize the complex, multi-disciplinary nature of the problem and the need to enlist the skills of experienced specialists in the fields of engineering, hydrogeology, biology, chemistry and agriculture in order that appropriate solutions to groundwater pollution can be established.

Consideration is thus given in this chapter to the potential sources of groundwater pollution, the physical characteristics of groundwater systems controlling contaminant accumulation and migration, and the methods of monitoring and mitigating contamination. Possible approaches for regulating the potential for contamination are also presented.

SOURCES OF CONTAMINATION

Contamination may occur wherever the potential exists for transport of matter into the groundwater environment, either from the ground surface or by the drawing in of natural contaminations from adjacent subsurface or surface waters through human action. Whether the contaminant is considered as a pollutant will depend on the extent to which the use of the groundwater is affected by the presence

of the contaminant. Drinking water quality guidelines (WHO 1987) define the perceived acceptable limits with regard to the physical, chemical, bacteriological and radiological content of potable water. Thus any contaminant present in the groundwater system which increases the need for purification or treatment may be considered to be a pollutant. Obviously, the standards set for industrial and agricultural water supplies are different from those for potable water, although the parameters adopted will be similar. Therefore, end use must be considered, both for present and future demands, to define acceptable contamination levels of a resource. There are a wide range of potential sources of contamination for groundwater. Table 1 modified from Todd *et al.* (1976), subdivides contamination sources into six categories. Against each category the potential hazard in terms of the primary parameters for water quality standards is presented. Tabulation of this type provides a useful indicator of the relative pollution potential of a contamination source against a particular water use. However, considerably greater detail is required to establish the actual potential for damage to the groundwater system.

A further classification of contamination sources arises from the spread of the source. Sources such as drains, landfills, septic tanks and oil storage tanks are considered to be point sources whereas applications of fertilizers and pesticides and saline groundwater bodies are diffuse or non-point sources. Whilst point sources potentially offer a greater hazard arising from higher pollutant concentrations, their effect is generally limited to a more localized domain within the groundwater system. Thus, greater scope often exists for management of an aquifer system to minimize the impacts of point sources compared with diffuse sources, where such sources are unavoidable.

Although avoidance of contamination from all the sources identified in Table 1 would be the most satisfactory solution, such an option is neither practicable nor economically justified. This is particularly true where such sources are already in place. However, future planning must address the problem of minimizing the creation of such sources by improved industrial technology for waste re-use (Heath and Lehr 1987), better agricultural management (Schepers 1982) and better engineered containment of contaminants, including appropriate siting of waste facilities away from susceptible groundwater sources (LeGrand 1983). Only the last of these issues is addressed in the discussions that follow.

TABLE 1. Major sources of groundwater contamination and types of contaminants and their relative significance

Source	Type of pollutant				
	Physical	Inorganic chemical	Trace elements	Organic chemical	Bacteriological
<i>Municipal</i>					
Sewer leakage	Minor	Primary	Secondary	Primary	Primary
Sewage effluent	Minor	Primary	Secondary	Primary	Primary
Sewage sludge	Minor	Primary	Primary	Primary	Primary
Urban runoff	Minor	Secondary	Variable	Primary	Minor
Waste disposal	Minor	Primary	Primary	Primary	Secondary
Septic tanks and cesspools	Minor	Primary	Minor	Secondary	Primary
<i>Agricultural</i>					
Leached salts	Minor	Primary	Minor	Minor	Minor
Fertilizers	Minor	Primary	Secondary	Secondary	Minor
Pesticides	Minor	Minor	Minor	Primary	Minor
Animal waste	Minor	Primary	Minor	Secondary	Primary
<i>Industrial</i>					
Cooling water	Primary	Minor	Primary	Minor	Minor
Process waters	Variable	Primary	Primary	Variable	Minor
Water treatment plant effluent	Minor	Primary	Secondary	Minor	Minor
Hydrocarbons	Secondary	Secondary	Secondary	Primary	Minor
Tank and pipeline leakage	Variable	Variable	Variable	Variable	Minor
<i>Oilfield wastes</i>					
Brines	Primary	Primary	Primary	Minor	Minor
Hydrocarbons	Secondary	Secondary	Secondary	Primary	Minor
<i>Mining</i>	Minor	Primary	Variable	Minor	Minor
<i>Miscellaneous</i>					
Surface water	Variable	Variable	Variable	Variable	Variable
Sea water intrusion	Primary	Primary	Primary	Minor	Minor
Transport	Minor	Minor	Minor	Primary	Variable

(Based on data from Todd *et al.* 1976)

For existing sources of contamination the real problems to be addressed are how to evaluate the future impact of the contamination on the groundwater environment and whether there is a need for action to arrest the problem and/or to rehabilitate the groundwater system.

GROUNDWATER FLOW AND CONTAMINANT TRANSPORT

Groundwater is an integral part of the hydrological cycle. Water enters a groundwater system by infiltration of surface waters through the ground surface to the saturated zone of the aquifer. Unless the top of the saturated zone is at or very close to the groundwater surface, the infiltrating water passes through an unsaturated zone where the pores or voids of the soil or rock mass contain air plus water vapour in addition to water in its liquid state. Under most circumstances water is considered to migrate vertically in the unsaturated zone. Once in the saturated zone the water moves laterally as well as vertically in response to hydraulic forces acting upon it until it leaves through the ground surface again or is removed through abstraction points, such as boreholes, or is released directly into the sea. Groundwater is defined to be only that part of subsurface water found in the saturated zone at pressures greater than atmospheric. Water in the unsaturated zone is frequently referred to as soil water (Heath 1983).

Groundwater movement is dependent on the hydraulic properties of the formation and the hydraulic energy gradients across the flow domain. Groundwater flow rates are generally very slow and are often measured in metres per year. Thus, residence times for a groundwater system may range from months to many hundreds of years. For certain types of media the rate of groundwater flow may be very much higher. In fractured media where the dominant flow is through the fracture network or in Karstic formations containing enlarged conduits, groundwater may travel hundreds or thousands of metres in a few days. The directions of flow are largely dependent on the geometry of the geological formations comprising the aquifer system, their hydraulic characteristics and the topography of the land surface overlying the formations coupled to the available sources of infiltration or recharge water. The groundwater flow distribution within an aquifer may vary substantially over time in response to changes in the natural recharge/discharge distribution and through development of the aquifer system as a source of water supply.

Most frequently, contaminants are present in groundwater in solution and, consequently, are carried with the flowing water. However, as the contaminants pass through the voids of the rock they also come into contact with the rock itself and with other

chemical species as well as microbial populations. Thus contaminants are frequently retarded and altered by interactions within the groundwater environment. Such interactions may include adsorption (where the contaminant adheres to the rock surface), precipitation by chemical reaction, decay and reduction by bacterial activity and even volatilization as gases, which are released back to the atmosphere (Bear and Verruijt 1987). Additionally, contaminant concentrations will be changed by dilution and dispersion. Dilution arises from the mixing of the contaminated waters with uncontaminated infiltrating waters. Dispersion occurs because of the tortuous flow paths the water takes through the rock. In general, the hydraulic properties of a rock vary considerably from point to point within a formation. This results in migration of elements of the contaminated water at velocities different from the average rate of movement of the bulk water and causes the development of a mixing front or transition zone. Dispersion occurs both in the direction of groundwater flow and transverse to it. Where a point source of contamination occurs a groundwater contamination plume develops (Fig. 1).

The density of groundwater can be significantly altered by contaminant concentrations. Even relatively small increases in the density of groundwater may result in alteration of the flow direction of the groundwater and migration of the contaminant plume to the base of the formation. Furthermore, where relatively insoluble contaminants such as oils enter the formation the migration pathways may be substantially different to the natural groundwater flow paths; oil products will exhibit a strong tendency to remain at or near the top of the saturated zone (Fig. 2).

All of the processes of migration and alteration present in groundwater are also present in the unsaturated zone. However, the flow of water through the unsaturated zone is considerably more complex due to the presence of the air and water vapour phases. Nevertheless, it is important to note that attenuation mechanisms in the unsaturated zone can provide a powerful barrier to the passage of contaminants to the saturated zone.

ANALYSIS OF POLLUTION POTENTIAL

Pollution potential can be considered from two standpoints. First, whether a groundwater abstraction zone is liable to contamination and, secondly, whether a potential source of pollution is contaminat-

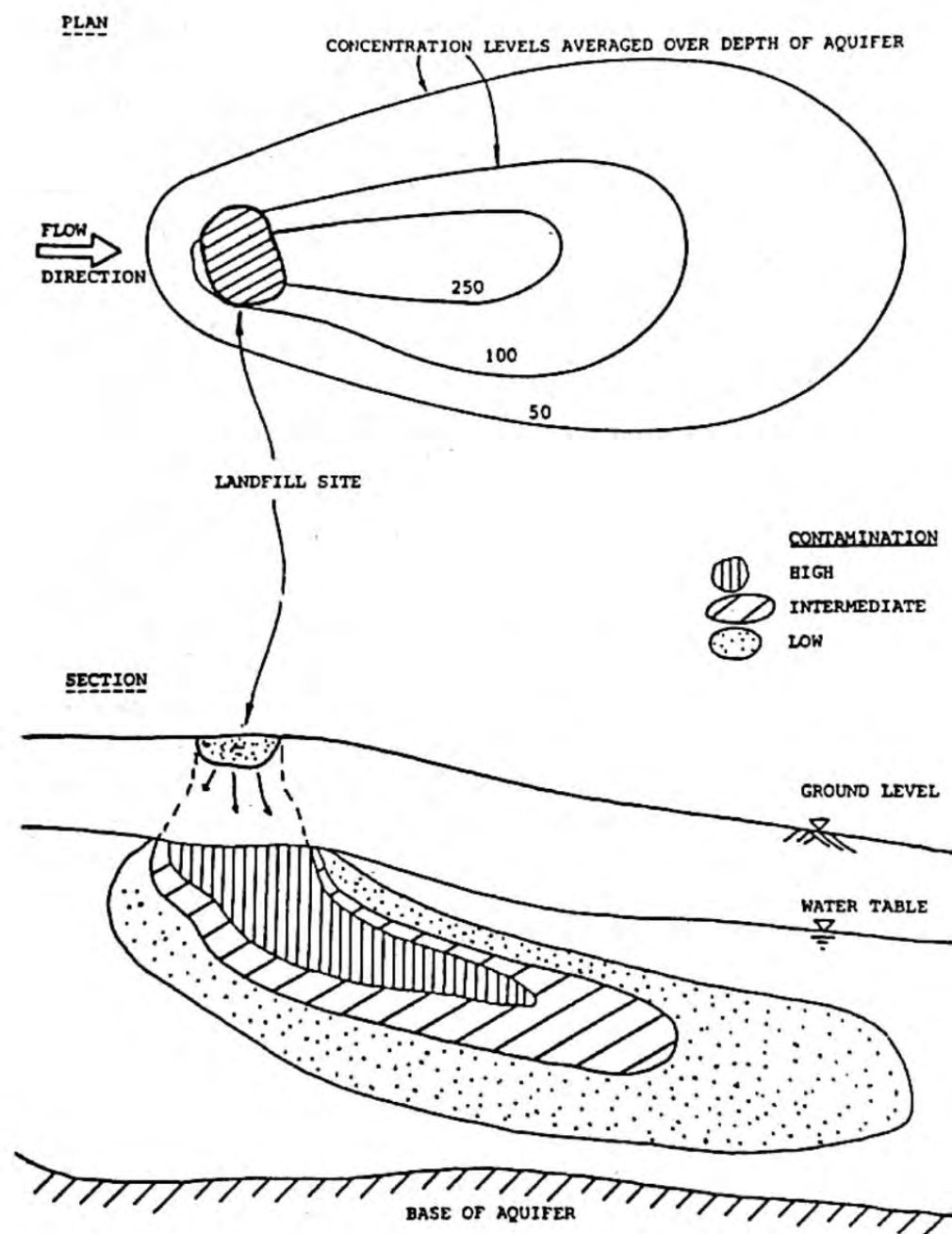


FIGURE 1. Typical leachate plume beneath a landfill site

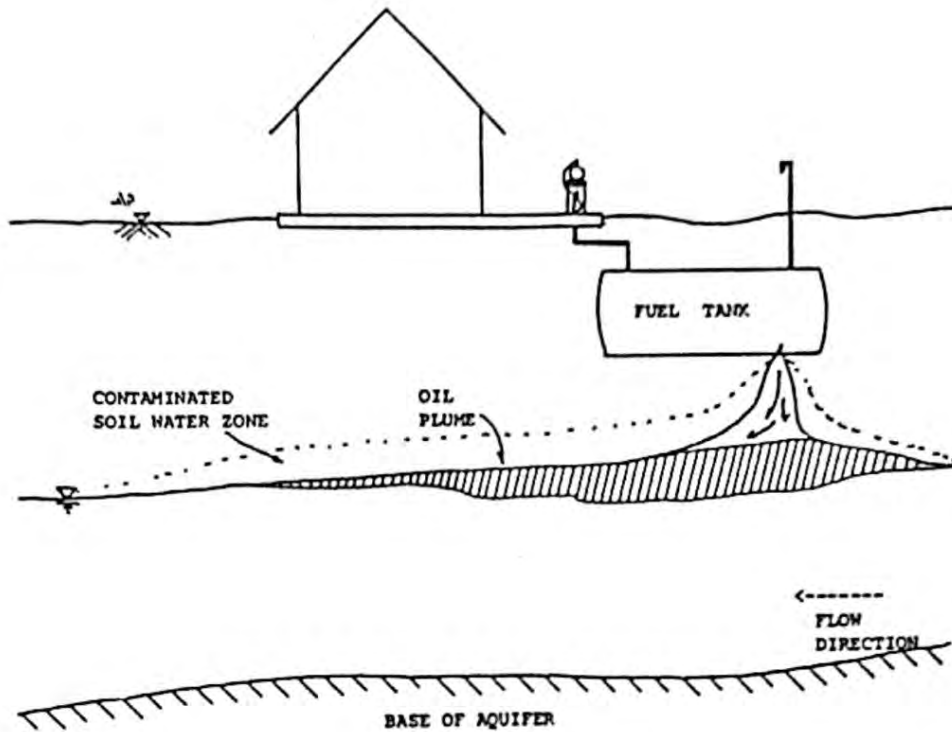


FIGURE 2. Section showing oil pollution plume overlying groundwater

ing the aquifer. In either case the present and/or future conditions applicable to the migration of contaminants must be determined. In the previous section the primary contaminant transport processes within an aquifer system have been identified. In order to be able to use this knowledge for analysis of pollution potential at a particular site, data describing the contaminants, their migration characteristics and the characteristics of the groundwater regime must be collected. Table 2 summarizes the primary variables of interest. The data to be collected can be categorized in terms of:

- (i) Hydrogeological conditions;
- (ii) Contaminant characteristics; and
- (iii) Engineering factors.

Engineering factors include the design of waste repositories, water abstraction points and the future programme for the development and use of the groundwater resource under investigation.

Simulation Models

Whilst inspection of the available data can provide a strong insight

TABLE 2. Variables influencing contaminant migration analysis from a pollution source

Variable	Distribution	
	Spatial	Temporal
<i>Geological</i>		
Aquifer media	x	
Form of porosity	x	
Aquifer geometry	x	
Confining beds	x	
<i>Hydraulic</i>		
Effective porosity	x	
Hydraulic conductivity/intrinsic permeability	x	x
Moisture/tension curves		
Storage coefficient	x	
Infiltration mechanisms	x	x
Discharge mechanisms	x	x
Stream/aquifer interactions	x	
Contaminated fluid density	x	
<i>Hydrological</i>		
Precipitation	x	x
Evapo-transpiration	x	x
Surface flow distribution	x	x
<i>Contaminants</i>		
Types	x	x
Adsorption		
Degradation		
Growth		
Dispersion	x	
Alteration		
<i>Anthropogenic</i>		
Demands	x	x
Abstraction designs		
Water supply economics	x	x
Surface water regulation	x	x
Agricultural practice	x	x
Contaminant source management		x

into a potential pollution hazard, the use of models may provide a more appropriate and rigorous method for integrating all the available data together and for evaluation of the response of the

aquifer system to a contamination event. Considerable use is now being made of models which allow the prediction of groundwater flow paths and, to a lesser extent, the prediction of contaminant migration pathways (Anderson 1979). These models are generally derived from the expression of the flow and transport processes in terms of mathematical equations, which may then be solved by incorporating appropriate parameter values and boundary conditions derived from the collected field data.

Due to the complexity of most groundwater systems, the solution to the flow and transport problem is generally derived by numerical treatment of the equations. A variety of numerical schemes have been applied to groundwater flow and transport problems using computers and a number of generalized computer codes are now available which can be used for the simulation of most aquifer systems (e.g. USGS-MOC, SUTRA, MOD-3D).

Simulation models may take account of as many of the flow and transport processes in the aquifer as are considered necessary for an accurate representation of the aquifer system. However, although simulation models can be very complex in their formulation, it must be remembered that they remain highly simplified representations of the true aquifer system. In general, they only yield information with a level of confidence dependent on the availability and quality of the field data and the skilful interpretation of the results by an experienced modeller with a strong background in groundwater analysis. Moreover, such models cannot replace data collection if this has not already been carried out or is deemed to be too expensive. Development of a model is an exercise in conceptualizing the true nature of the groundwater regime from the available data and not simply of the generation of numbers by a computer code. A flow chart describing the development of simulation model is shown in Fig. 3.

Frequently it has been possible to use historical data to calibrate and test the accuracy of model for the problem of groundwater flow simulation. Unfortunately this luxury is rarely available for the more complex task of simulating contaminant transport. Consequently, the reliability of results from contaminant transport models are more difficult to evaluate. Additionally, difficulties arise in the modelling of contaminant transport due to more complex problem of collecting data on the parameters such as dispersion coefficients (which define the spread of a contaminant in the

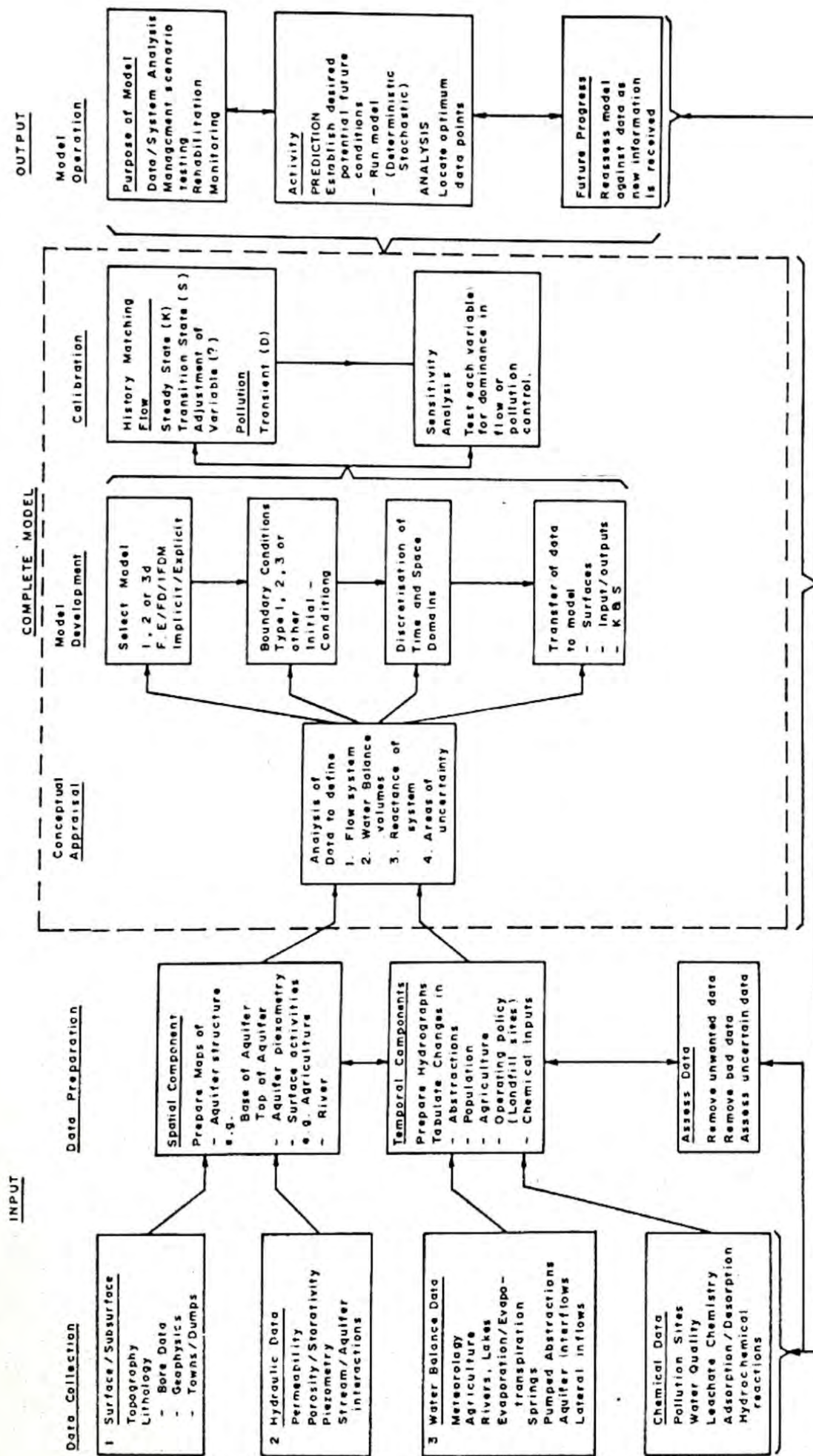


FIGURE 3. Numerical modelling schemes

aquifer) and at a more fundamental level, the quantity of contaminant entering the aquifer.

In spite of many difficulties with models, their real benefit lies in their ability to provide quantified estimates of the potential future states of a groundwater system. The groundwater manager may test, through application of a model, the response of the simulated aquifer system to different options for development of the groundwater regime. Additionally, testing may include the evaluation of the inclusion of contamination sources or the impact of changes to the hydrological cycle. Assuming that the model can be considered to adequately represent the real aquifer system, the manager can effectively distinguish between the different management choices in terms of simulated impacts of each choice of the groundwater regime.

The literature contains a wide range of studies demonstrating the use of simulation models to both groundwater flow and contaminant migration studies (Frind *et al.*, 1985; Gray *et al.* 1983; Mackay *et al.* 1988; Mills *et al.* 1986). However, it must be pointed out that by far the majority of studies presented in the literature have been related to research programmes and less to real management application. It is unfortunate that most real applications undertaken by consultants are not presented in the open literature. Moreover, while consultants are frequently employed to develop and use a groundwater model for analysing a particular problem, e.g. wellfield location, groundwater resource yield evaluation, it is rare, in the author's experience, for the client to take over these models and use them for continuous monitoring and appraisal of the groundwater resources of a region. The apparent reticence to use on a regular basis models for management must be overcome if the full advantage of the simulation models applied to resource management are to be realized. Nevertheless, given the limitation of the models, it must be stressed again that models require experienced personnel who have knowledge of both simulation methods and groundwater systems in order to maximize the benefit of a modelling exercise. Extensive training is therefore of primary importance in this field.

Monitoring

Monitoring is an essential element of the maintenance of a groundwater resource. As already indicated, the migration of contaminants

in the groundwater regime may extend over many scores of years. Therefore, unobserved long-term contamination may lead to extensive damage to the aquifer which could persist for a considerable period of time. However, regional groundwater quality monitoring programmes for an aquifer system cannot be carried out solely using the same type of monitoring networks adopted for establishing the storage changes in an aquifer. Such a monitoring network would be ineffective in all groundwater quality changes particularly from point source emissions. Monitoring for changes in groundwater quality characteristics is usually much more specific in terms of its location with respect of water supply points or to potential pollution sources.

Groundwater quality monitoring can be separated in four classes (Barcelona *et al.* 1983): *ambient*, *source*, *case preparation* and *research*. Of significance to the groundwater quality manager are the first three. Although research extends the knowledge base about the effectiveness of selected monitoring methodologies.

Ambient monitoring is used to establish the variations in groundwater quality over the domain and over time. Such monitoring can be carried out using existing water supply wells, as opposed to specially constructed monitoring wells. The data for ambient monitoring should also include sample data routinely obtained to detect significant groundwater quality changes at primary abstraction sources.

Source monitoring arises in response to known potential pollution sources. Until a pollution event is observed the level of monitoring is usually restricted to a small number of carefully sited indicator wells. The aim in using these monitoring points is to screen the groundwater passing through the potential contamination zone to see whether it is contaminated. Once a contamination event is noticed, the monitoring level will normally increase to delineate the potential impact of the leakage on the groundwater regime.

Case preparation monitoring is undertaken in response to an observed contamination event to produce evidence for legal action against a polluting agency. The obvious objective of this type of monitoring is the provision of proof of the source of contamination.

Research monitoring is used to address the problem of identifying the processes of contaminant migration and degradation as well as for testing new monitoring equipment and methodologies and is therefore both highly intensive and highly selective. Although a

necessary component of monitoring, it is seldom of immediate interest to a monitoring organization.

In each of the above cases it can be seen that the aim is to provide a monitoring programme tailored to the specific objectives set for the acquisition of quality data. Before implementing a monitoring programme the purpose of the monitoring must be clearly recognized. Failure to define the objectives of the programme will inevitably lead to inadequate data being provided and additional costs being incurred to rectify the problem.

Developing a monitoring programme should take into account a whole range of technical factors:

- observation network design;
- well designs and materials;
- well construction methods;
- sampling procedures;
- choice of groundwater quality measures; and
- sampling frequency.

Network design, well construction design and sampling frequency depend upon the characteristics of the groundwater regime and the contaminant species. Well construction methods and sampling procedures depend upon the accuracy needed for analysis of the groundwater. The choice of groundwater quality measures will depend on the objectives of the sampling programme and the anticipated contaminant species.

A strong body of literature on monitoring network design and sampling has been put together through the United States Environmental Protection Agency, which provides a valuable source of information for establishing the details of monitoring programmes (Todd *et al.* 1976; Barcelona *et al.* 1983; Barcelona *et al.* 1985). However, it is worth mentioning a few points of general note which affect the development of a monitoring programme. Chemical sampling and analysis must be carried out rigorously and with considerable care (Kirchmer 1983). There is much discussion in the literature about the protocols that should be adopted for a sampling programme. However, all authors agree that failure to appreciate the nature of the chemical conditions of the groundwater to be analysed may lead to erroneous results. Moreover, the methods of extracting the samples from the groundwater environment may produce significantly different sample analyses. Sampling procedures

adopted for ambient monitoring, for example, may not give comparable results to sampling procedures necessary for source monitoring.

The use of local materials and construction methods for monitoring well drilling and construction, whilst apparently cost effective, may significantly reduce the value of the monitoring exercise. In general, the materials used in construction will contaminate or interfere with the groundwater. It would be nice if the choice of materials and drilling techniques could be made solely on the basis of technical requirements and not on economic expedience. However, there are many occasions when accuracy can be compromised in favour of economic factors. Such an occasion might arise when the pollutants are known and the sampling is for qualitative comparison of the degree of pollution. Whilst the choice of drilling technologies and materials may be restricted by local availability, the adoption of good drilling practices must be encouraged during the performance of any drilling contract for monitoring well construction.

Chemical analysis can be both time consuming and costly. Therefore, appropriate decisions should be made about the choice of quality measures required for a particular purpose. For ambient monitoring and for source monitoring simple measures of the basic cations and anions, total organic carbon, and total dissolved solids may suffice as general indicators of pollution. Once a pollution event has been observed, more detailed analyses can follow.

Recently, there has been a growing interest in the use of sampling equipment designed to extract samples from the unsaturated zone (Bumb *et al.* 1988; Kirschner and Bloomsburg 1988). The reasoning behind this development is twofold. First, it reduces the uncertainty of observation inherent in the groundwater monitoring networks arising because of heterogeneities in the aquifer media. Secondly, it establishes at the earliest opportunity, the leakage of a contaminant from the source. Unsaturated zone monitoring devices are now being installed beneath new waste repository installations during their construction. One area of concern for such monitoring is the expected life of the equipment. A repository sited over an aquifer may have a life of many decades whilst the monitoring equipment may be rendered ineffective before the end of the first decade. Research and development is progressing in this area.

Groundwater Protection

The ultimate aim of the groundwater manager is the protection of the groundwater resource and, more importantly, the protection of the abstraction zones from contamination. Development of planning to achieve this objective will depend on the regulatory framework that may be implemented, the type of aquifer system, the potential polluting agencies and sources and the rights of existing and future users over the groundwater resource.

Protection Policy

In order to undertake regulation of a groundwater resource, planning policies must be implemented. For the purposes of establishing a framework for legal policing of the resource, the policy document should be set with respect to (Gladwell 1987):

- the origin of groundwater rights;
- groundwater use and users;
- recognition of groundwater users;
- reallocation;
- modification of or abolition of existing rights; and
- setting priorities for water allocation.

Most important is the existence of an operational regulatory institution. If no recognized body exists to handle that policing of a groundwater resource then one must be established at the earliest opportunity. Jackson (1980) notes that in addition to defining a framework for the conditions of use of groundwater, a complementary system should be established with the expressed intention of controlling those activities that have a potential for pollution of groundwater.

It can be seen that the groundwater manager must have access to a considerable body of data in order to be effective in the regulation of a groundwater resource. In addition, the regulatory body must have defined acceptable standards against which to measure whether or not an individual or group is in breach of or abiding by the policy. These standards will include monitoring requirements, restrictions on abstraction, standards for engineered contaminant structures, such as septic tanks, landfills, underground and surface storage tanks. Furthermore, maximum effluent levels can be defined depending on the value of the underlying aquifer and the hydro-geological characteristics of the region. Liability for aquifer damage

will need to be established and the basis for defining aquifer damage agreed. Thus the regulatory institution must develop data collection strategies, define policy documents, define methodologies for monitoring, be able to act on breaches of standards effectively, and act as arbitrator in conflicts of interest. This range of capabilities is onerous and care and time must be taken to develop each aspect of regulation to suit a country's or region's particular conditions. It will in general not be possible to make a transition to a comprehensive management system overnight. Again, adequate training of personnel at all levels in the management and evaluation of groundwater systems is of paramount importance.

Since groundwater systems vary considerably in their relative worth from region to region, policies should vary in accordance with the perceived needs of each individual region. A policy will therefore be different from country to country depending on the regulatory infrastructure, the use to which the groundwater is put and the scale of groundwater development.

Policies usually state that intention for maintenance of a resource only and do not cover the management of the resource to achieve the policy aims. Thus, policies can be divided into the following three categories (Henderson 1987):

- (i) Non-degradation policies;
- (ii) Limited degradation policies; and
- (iii) Differential protection policies.

Non-degradation policies attempt to protect all groundwater and maintain the existing or natural quality of the resource.

Limited degradation policies accept that to maintain a resource at present standards will be almost unachievable but aim to maintain the quality of the groundwater at as high a level as possible. The problem with this type of policy is 'how clean is clean' and at what point in the groundwater domain should limits for groundwater quality be set in practice.

Differential protection policies aim to establish for each individual resource zone a value on the resource in terms of acceptable levels of contamination and in terms of the present and potential future usage of the resource. Implementing this type of policy requires appraisal of the value of an aquifer or sub-aquifer system in terms of population served, the availability of other sources, the geological character of the region, and potential liability for contaminant

infiltration.

Whilst it may be argued that maintaining the quality of a resource at natural levels eliminates mistakes and errors of judgement about the acceptable limits for individual quality parameters, the possibility of implementing a management strategy to effect such a policy is minimal. A policy which cannot be adhered to is not worth declaring. In reality, the most appropriate type of policy is the differential policy. The level at which a differential policy is administered can, however, be varied, depending on the capacity of the regulatory authority to establish and control the development of pollution through aquifer zoning. At the simplest level it may be appropriate to implement bans on further developments overlying aquifers where strong pollution potential exists whilst accepting, in the short term, degradation due to present pollution potential. Mapping of a country's groundwater resources can be readily implemented in terms of the risk of contamination to groundwater and the distribution of contamination sources. This would then define a straightforward database from which to establish protection zones.

Protection Methods

Protection methods can be reduced to four basic types: *contaminant concentration limits*; *engineering design standards*; *abstraction licensing*; and *land use control*.

Groundwater quality guidelines or standards are generally established with regard to specific chemicals and identifiable bacterial populations indicating pollution. Standards can be set to enforce a minimum acceptable level for each pollutant in the groundwater. Enforcement of the standards is established through permits which acknowledge the rights of individuals or groups to discharge wastes, at or below the limits set, into the groundwater environment. Monitoring of the discharges is necessary and exceedance of the limits must trigger actions aimed at reinstating the quality of the discharge. The location of measurement of the quality of the water is as important as the actual standard. Therefore, discharge zones or boundaries are established around a discharge point beyond which the concentration level must be maintained at or below the standard. In order to place the emphasis of maintenance on the polluter, standards are also required to be met with respect to the sampling procedures and record keeping used to monitor the discharge and ambient groundwater quality. Since concentration of

a contaminant in groundwater is a function of the dispersal of the pollutant in the groundwater regime, a requirement for discharge planning may also be necessary to ensure that plugs of undiluted contamination do not enter the aquifer system.

Wherever pollutants are stored in proximity to a groundwater resource, adequate protection of the resource must be achieved by ensuring correct design of the facilities. Design standards relate to construction materials, location of the facility, sizing, operating conditions and monitoring equipment. Equally important is the operational lifespan of the facility. If possible, maintenance checks should be enforced towards the end of the lifespan of storage tanks. Replacement of facilities after a set time period may also be considered for enforcement where highly susceptible groundwater sources are at risk. Siting of a landfill site or other potentially hazardous site may be made with due regard to the hydrogeological conditions prevailing in a region to provide maximum protection against groundwater contamination in the event of failure of the engineered barriers. Siting of monitoring wells and equipment capable of registering pollution activity should be considered if the underlying groundwater resource is at risk.

Abstraction licensing is aimed specifically at controlling excessive local abstraction from an aquifer system. Over-abstraction from the aquifer has the potential to lower the quality of the groundwater supply by drawing in lower quality waters from surrounding zones (sea water intrusion) and from lower formations with older more mineralized waters. Moreover, the zone of infiltration around large abstraction zones may create the potential for long range migration of pollutants to the abstraction points, thereby increasing the difficulty of managing the resource. Good well construction and design practices appropriate to the geology of the region should also be implemented to minimize the risk of local pollution from septic tank emissions and pollution infiltration from the surface. The control of groundwater development can be most satisfactorily achieved through the licensing of local drillers and through the granting of licences by local water authorities to users on a first-come first-served basis. Established groundwater rights might effect how authority to control abstractions is implemented.

Land use control is perhaps the most direct method for controlling groundwater pollution. All actions liable to cause groundwater pollution are identified and rights to use the land overlying ground-

water sources are restricted. For this method to be appropriate, standards must be defined for land based on the underlying hydrogeological conditions and the potential for migration of contaminants from the land surface to the groundwater and within the groundwater to abstraction points. Recent articles on groundwater quality management have stressed the importance of delineating recharge zones to the aquifer since these zones are at greatest risk.

Another approach to delineating the relative importance of land areas for aquifer contamination potential is the establishment of vulnerability maps. Different land areas are identified and recorded on maps according to the expected time of migration of a contaminant from the ground surface to the water table (i.e. the residence time in the unsaturated zone):

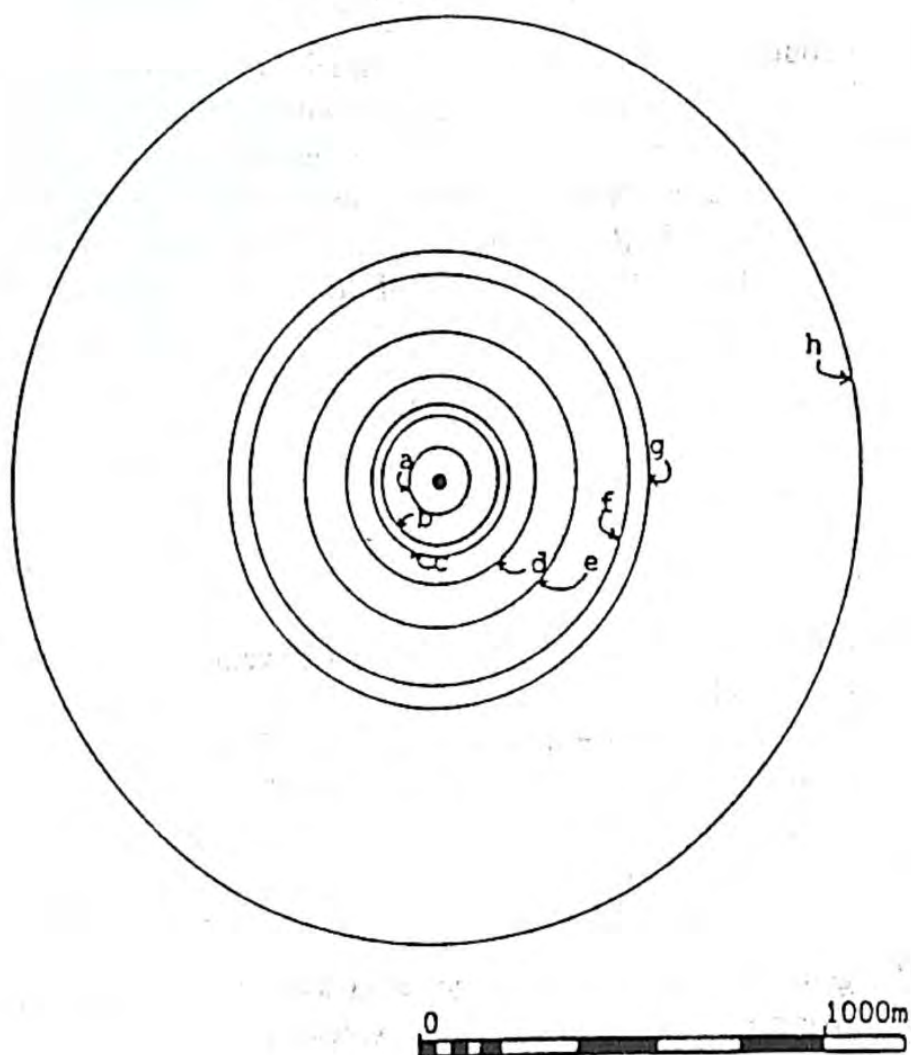
- Zone 1—Residence time longer than 20 years
- Zone 2—Residence time generally between 1 and 20 years
- Zone 3—Residence time generally 1 week to 1 year
- Zone 4—Residence time generally less than 1 week
- Zone 5—Highly variable distribution of residence times spatially which are not readily differentiable at the scale of mapping.

The generation of such maps coupled with those showing the underlying aquifer system and the levels of exploitation provide the necessary spatial data to define zones requiring groundwater pollution control.

Subsequent refinement of the zones to be controlled (zones 3 and 4 above) can then be achieved by delineating protection zones around abstraction points which define the limit of recharge to the abstraction point. A reduced zone can be implemented which operates on the basis of an acceptable time of travel to an abstraction source which allows due time for degradation, dilution and dispersion to control contaminant concentration levels (Shafer 1987).

Figure 4 shows an example of a borehole protection zone based on a two hundred days time of travel calculation assuming averaged quantities for the aquifer thickness, velocities, and pumping rates.

Protection zones and vulnerability maps are valuable in defining the potential sites for waste disposal facilities. Additionally, they allow protection from non-point sources of pollution such as agricultural fertilizers and pesticides.



	1	2	
Q -	1000	5000	m ³ /day (discharge from source)
t -	50	200	days (time of travel to well)
S -	0.1	0.01	- (porosity (eff.))
b -	30		m (aquifer thickness)

Combinations of Q, t, s and b values :

a =	(1,1,1)	e =	(1,2,2)
b =	(1,1,2)	f =	(2,1,2)
c =	(1,2,1)	g =	(2,2,1)
d =	(2,1,1)	h =	(2,2,2)

FIGURE 4. Idealized radial flow protection zones (based on times of travel)

REHABILITATION

Once effective pollution of an aquifer has been identified, the first step is to establish a rehabilitation programme. Such a programme can take one of two courses. In the event that a supply point has suffered pollution which is determined to be of limited duration or unavoidable in terms of elimination of the polluting body then treatment of the supply may suffice. If a pollution source is identified which will cause long term damage to the aquifer then rehabilitation of the source and the aquifer may be more appropriate (Sharefkin *et al.* 1984).

Supply Points

When a supply is contaminated, various alternatives may be envisaged for the maintenance of the supply to the end user:

- development of new or existing unpolluted water sources;
- blending of uncontaminated source water with the polluted source water to reduced contamination levels to within the defined safety standards;
- treatment at the supply point; or
- altering the groundwater flow regime to reduce contaminant uptake by the abstraction points.

Development of new or existing unpolluted water source will depend on the availability of such sources. In the case of groundwater supplies the development of adjacent aquifer zone, initially unpolluted, must be carried out with due regard given to the extent of the contamination which created the initial problem. If insufficient attention is given to the alteration of the flow paths in the groundwater regime then there may be a risk of migration of the contamination plume into the new supply point.

Blending is only feasible where multiple sources can be mixed to provide an acceptable water quality. However, such an approach requires careful evaluation and monitoring to ensure that the quality of the blended water remains below the specified limits for each quality parameter at all times.

Treatment of contaminated groundwater depends on the type of pollutants present, for example, turbidity, organics, inorganics, bacterial. Standard texts are available on the design of water treatment works for an appraisal of the most common and effective

treatments applied to supplies. These include coagulation, filtration, disinfection, gas stripping, etc.

Amendment of the groundwater flow regime can be achieved to reduce the total contamination level entering the source regime by a variety of hydraulic measures. These include:

- reducing pumping rates from each supply point to lower the hydraulic gradients and restrict the ingress of low quality waters from depth;
- lowering the screened section to prevent inflow from the upper aquifer layers if the contamination is restricted to these zones. Such an approach is often effective where oils and organics infiltrating from the surface are the polluting materials;
- establishing recharge wells to dam back the flow of contaminants to the supply point hydraulically;
- establishing contamination abstraction wells to withdraw the contaminated water and thus leave the supply wells withdrawing waters from uncontaminated zones. This approach requires the disposal of the contaminated water produced or its treatment.

The decision about which approach to adopt must depend on the type of contamination, the economics of each method, the technical feasibility of each method and the time available to effect a satisfactory solution. Mixing two or more of the methods outlined above may prove to be more viable than relying on any one technique alone.

Pollution Sites

Rehabilitation of a pollution site, such as a landfill, should be carried out by, first, establishing a recontrol of the site to restrict continued leaching of pollutants into the aquifer and second by examining all cleanup options and implementing the most appropriate method. Recontrol of a site is not a cleanup operation in itself but is merely intended to buy the manager time to evaluate the site properly.

Recontrol actions may include: vacuum extraction of volatile organics; covering the site with an impermeable membrane to prevent infiltration of surface waters; building temporary cutoff walls to keep out surface/subsurface waters and to retain hazardous materials; establishing withdrawal wells to reduce the groundwater flow away from the site; removing the bulk of the wastes and placing them at ground surface where they can be controlled temporarily until

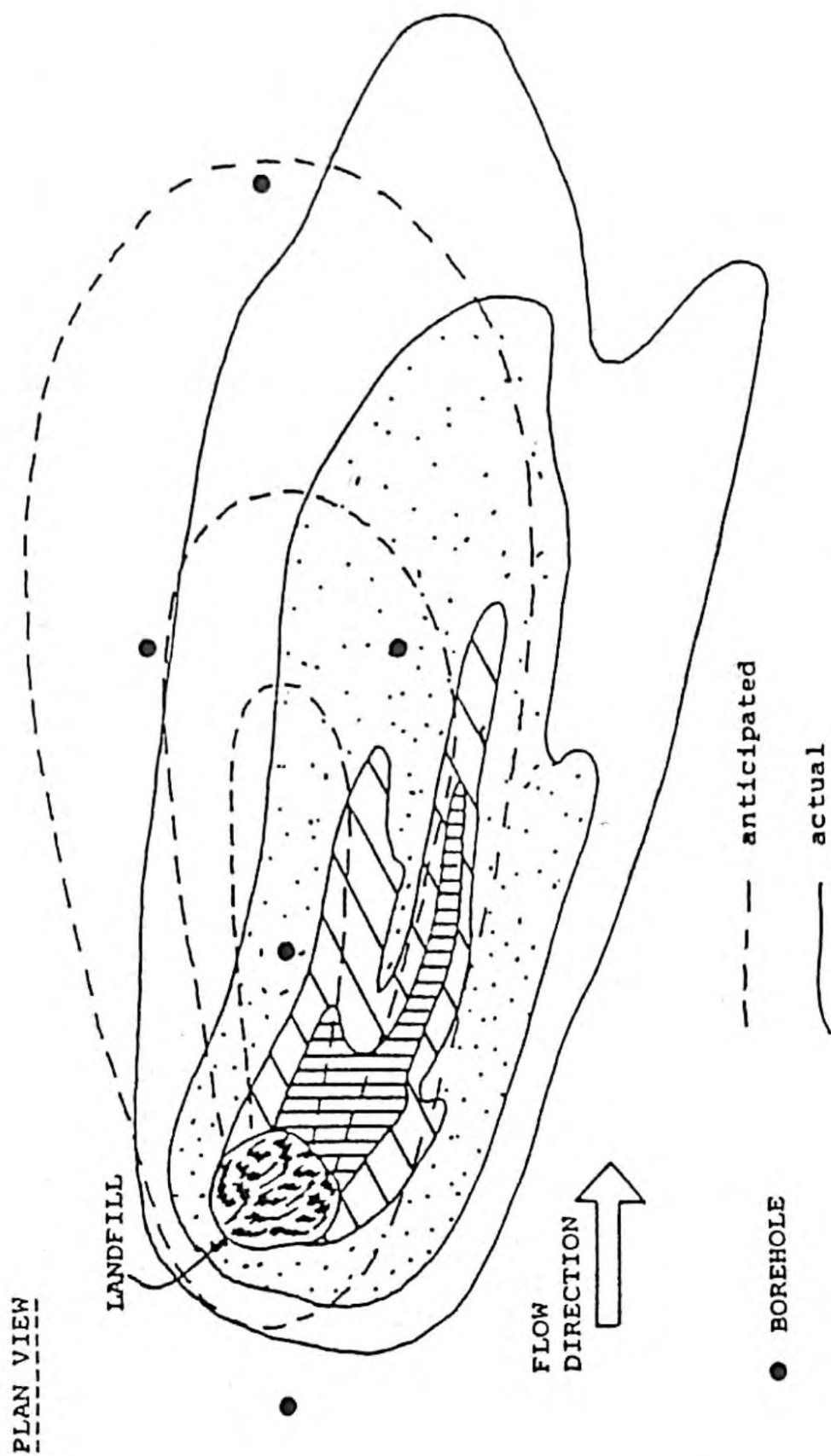


FIGURE 5. Effect of heterogeneity on plume geometry

proper disposal can be achieved.

Clean up of a pollution site is seldom easy and is usually very expensive. The technologies for clean up depend on the type of site, the quantity of materials involved and the prevailing hydrogeological conditions. However, of importance to the present discussion is the cleanup of the contaminated groundwater. Once the extent of the pollution plume has been identified, various options for cleanup can be considered. For the example of hydrocarbon-contaminated aquifers (Yaniga 1982), abatement or cleanup methods can include the following:

- skimming off oils accumulated at the top of the saturated zone;
- air stripping;
- activated carbon filtering;
- recharge of the groundwater to flush out light oils and petroils adsorbed onto the soil using infiltration galleries;
- reoxygenation of the groundwater to enhance microbial activity; and
- introduction of nutrients to stimulate bacterial growth.

One of the major causes of difficulty arising in the contamination of a groundwater zone is the unpredictability of the hydraulic characteristics of the regime due to the heterogeneity of the aquifer media (Fig. 5). Frequently, the efficiency of a decontamination programme is much lower than expected due to the problem of siting and designing an appropriate well network. Indeed, difficulties of data collection for characterizing a groundwater system, whether at the scale of a single pollution site, or over an entire regional aquifer system, remains the single most significant problem for any groundwater manager involved in groundwater quality control.

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CHAPTER 9

Environmental Impacts of the High Aswan Dam: A case study

MAHMOUD ABU ZEID

INTRODUCTION

'Egypt', said Herodotus, the father of history, 'is the gift of the Nile.' The importance of the Nile in the survival of Egypt is such that the Egyptian mythology is closely interwoven with the river.

In the long history of Egypt, there have been continuous attempts to build dams across the Nile to retain its water. These were, and still are, prompted by the urgent necessity to increase agricultural production for a rapidly growing population, now estimated at over 54 million.

Of the country's more than one million square kilometres, only 4 per cent is arable. This is concentrated along the thin, fertile strip of the Nile Valley from Aswan to Cairo and in its Delta area on the Mediterranean. Nearly 97 per cent of the population lives along this limited space, about two-thirds of them depending on agriculture for survival. Almost 90 per cent of the country's export earning comes directly from agriculture.

The construction of the High Aswan Dam can be considered to be an irrigation revolution for full utilization of the Nile water. When the Aswan Dam was completed more than twenty years ago, it became a global symbol of environmental and social problems caused by large-scale development projects. A series of papers and articles in scientific and popular media soon made the dam the most popular environmental problem in the world. It was promptly condemned for many reasons, among which were loss of the Mediterranean fishery, increase in schistosomiasis, rising salinity, erosion of Nile bed and banks, reduction in the fertility of the Nile Valley through the absence of the silt deposition, and coastal erosion of the river Delta.

This chapter, written after more than twenty years of operation

of the dam, gives the facts based on detailed monitoring and analysis of the positive and negative impacts of the dam by Egyptian and international experts.

REGIME OF THE NILE RIVER

The discharge of the River Nile is subject to wide seasonal variation. About 80 per cent of the total annual discharge is received during the flood season of August to October, the remainder is spread over the rest of the year. About 85 per cent of this annual discharge originates in Ethiopia, and 15 per cent in the lake Plateau in Central Africa. From this plateau rises the White Nile, which is the main source of water to the Nile Valley during the low flow period of the summer. This summer flow was the limiting factor for expanding perennial irrigation in Egypt.

The first attempt to store flood water to augment low flow occurred in 1902 when the old Aswan Dam was constructed. Its capacity initially was $1.0 \times 10^9 \text{ m}^3$. The height of this dam was increased twice to reach a capacity of $5 \times 10^9 \text{ m}^3$ by 1934.

Apart from the seasonal variation in the discharge of the Nile, the total annual discharge is subject to wide fluctuation from one year to another. The highest recorded discharge was in 1878 at $154 \times 10^9 \text{ m}^3$, and the lowest discharge was in 1913 at $42 \times 10^9 \text{ m}^3$. Thus, the short-term subannual storage proved to be inadequate during low flow years for irrigation. The long-term storage became the preferable solution. A suitable location for a long-term reservoir was finally selected at Aswan and the High Dam was constructed to guarantee a constant annual water availability of $84 \times 10^9 \text{ m}^3$ of water, of which $55.5 \times 10^9 \text{ m}^3$ was for Egypt and the balance, $28.5 \times 10^9 \text{ m}^3$, was for Sudan.

Natural Condition of the Nile

The natural annual flow of the River Nile can be divided into two periods: (i) a short 3-month long, high, muddy flow season, and (ii) a longer 9-month low, clear season. At Aswan, the flood period of the River Nile starts usually at the beginning of August and finishes at the end of October. The average annual yield of the river at Aswan is 84 milliard m^3 and the average annual suspended load in the Nile as measured at the tail of the Old Aswan Reservoir is about 134 million tons. The rising and falling period of the high flow is usually accompanied by high suspended quantities of silt

from the volcanic highlands of Ethiopia.

The sediment concentration figures vary from 50 to a maximum of about 6600 parts per million (ppm) while the average for the whole flood is about 1500 ppm. This silt is separated by a sedimentation process into sand, silt and clay. For the whole flood, the proportion of the constituents is as follows:

Coarse sand	: 0.2 to 2.0 m/m none or trace
Fine sand	: 0.02 to 0.2 m/m 30%
Silt	: 0.002 to 0.02 m/m 40%
Clay	: less than 0.002 m/m 30%

The flood period is divided into rising and falling periods. Generally, the flow in the rising period is accompanied by a high silt concentration. In this period, the analysis of comprehensive field data showed that the mean bed level of the river in the studied reach has increased by about 1.0 m due to siltation and the Manning's coefficient of roughness has decreased to about half its value.

It was concluded that the rising period is characterized by an aggradation trend and creeping of the bed material caused by deposition of the suspended matter, which is higher than the carrying capacity of the river. During the falling period, the mean bed level is further eroded because of the decrease in the concentration of suspended matters. The roughness coefficient 'n' increases again.

It was concluded that the falling period is characterized by a degradation and deformation of the bed resulting from a relative decrease in the suspended matter.

GENERAL DESCRIPTION OF THE ASWAN DAM

The Aswan High Dam is a rockfill dam, constructed across the Nile at a distance of 7 km south of the city of Aswan. The water is diverted into a diversion channel, at the middle of which there are six tunnels. The tunnel inlets are provided with steel gates to control the quantity of water passing through them. Each of the tunnels bifurcates before its end; and each of the twelve branches delivers its water to a hydraulic generating unit of the power station. The diversion channel is situated on the eastern Nile bank. The spillway is located on the western side.

The total length of the dam is 3600 m, of which 520 m is between the two banks of the river, and the rest extend along both sides. The height of the dam is 111 m above the river bed. Its width is

980 m at the bottom and 40 m at the top.

The body of the dam consists of granite and sand, in the middle of which there is a core of Aswan puddle clay to minimize water seepage. At the front, it is connected with a horizontal impervious curtain.

Since the dam bed consists of alluvial materials, it has a vertical cut-off curtain extending below the core, with the same depth as the sedimentary layer, so as to reach the bedrock.

On the downstream side, two rows of vertical relief wells have been provided to drain any water leakage. The reservoir storage capacity is $162 \times 10^9 \text{ m}^3$ distributed as follows:

- $90 \times 10^9 \text{ m}^3$: live storage capacity between levels 147 m and 175 m
- $31 \times 10^9 \text{ m}^3$: dead storage for sediment deposition
- $41 \times 10^9 \text{ m}^3$: storage available for high flood waters between levels of 175 m and 182 m

The hydroelectric power station is situated at the outlets of the tunnels and consists of 12 units with a capacity of 175,000 kW each, i.e. with a total capacity of 2.1 million kW, producing 10×10^9 kWh of power annually. Each generating unit consists of a Francis-type hydraulic turbine.

Work was started on the first stage of the project in 1960 and ended in May 1964. This stage included the excavation of the diversion channel, the construction of the main tunnels, and the construction of the body of the dam up to the level of 132.50 m (47.5 m above river bed). The diversion of the Nile's course to enable the completion of the dam and the power plant took place in May 1964; and the construction was completed in July 1970.

BENEFITS OF THE DAM

In October 1967, the dam body had reached the level of 172 m, and energy was first generated. It is clear that the benefits from the dam started to occur from 1964. From then on, as construction works progressed, the total benefits increased every year. Twenty years have now elapsed since the dam was completed. The following is a brief summary of the benefits based on comprehensive studies:

- improvement of the summer rotations and guaranteed availability of irrigation water at any predetermined period for agricultural production;

- expansion in rice cultivation;
- transfer of about one million acres from seasonal to perennial irrigation;
- agricultural expansion in 1.2 million acres of new land owing to increased water availability;
- protection from high floods as in 1964 and 1975, and from low floods and droughts as in 1972, 1979, 1982, 1985, 1986 and 1987;
- generation of hydroelectric power; and
- improvement of navigation, and further increase in tourism, as a result of the stability of water levels in the Nile course and navigation canals.

Among two other potential benefits are the following:

- Egypt has completed the Toshka flood water storage, about 150 km south of Aswan, to divert excess flood water to the western desert. This project would assist in cultivating some areas of land around the Toshka depression and in the New Valley in the future, when sufficient quantities of water are stored in the depression or in the groundwater aquifers;
- The dam enabled both Egypt and Sudan to begin a comprehensive study for optimal utilization of the Nile waters to increase water resources for the benefit of both countries. The first of such projects is the Jonglei canal, south of Sudan, which is now more than 60 per cent completed.

Many studies have now been carried out on the impacts of the dam on various aspects of the environment.

ENVIRONMENTAL IMPACTS OF THE DAM

Drop in Water Level Downstream the Dam

The Nile Barrages at Esna, Nagga Hammadi and Assiut (Fig. 1) are water level control structures, where gates are used to allow certain discharges through, while maintaining certain required upstream levels.

Back-water curves upstream of those barrages may extend to tens of kilometres in terms of gradually-varied flow. In all cases, the flow velocity is gradually reduced to a minimum immediately upstream of the barrage. The water passes through two vertical gates above the foundation level in all three barrages.

On the basis of extensive field investigations already carried out,

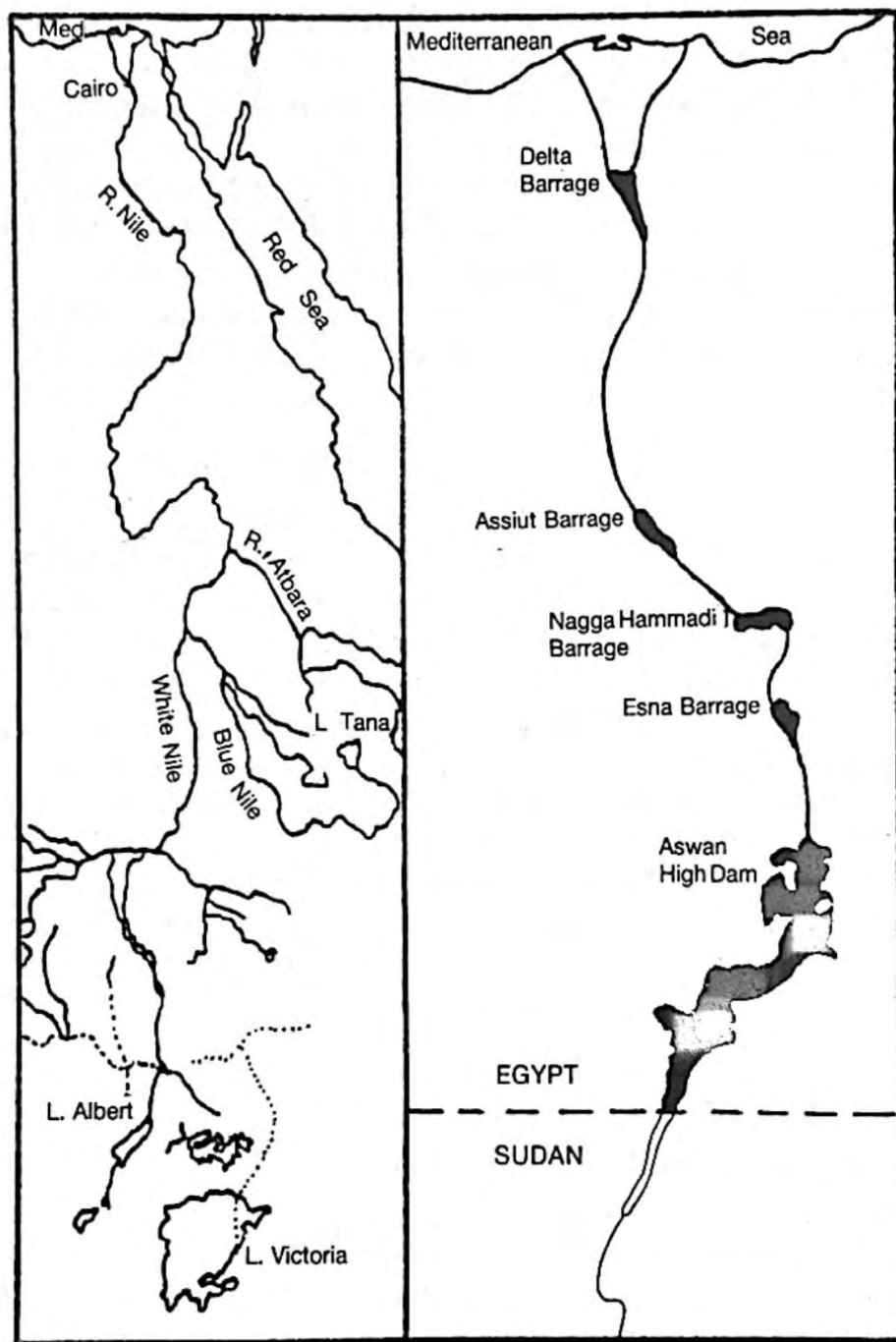


FIGURE 1. The Nile system

it is evident that in each reach of the River Nile, between two barrages, there is a general degradation region followed by an aggradation region with no appreciable amount of bed material moving into the next reach. However, whereas aggradation is taking place due to relatively fine bed material, degradation is accounted for by relatively coarse bad material.

Table 1 shows the actual drop in water levels caused by degradation at four sites along the River Nile from Aswan during the period 1963-86. It is assumed that the year 1963 represents the natural condition of the river.

TABLE 1. Drop in water level (W.L.) caused by degradation

Site	Distance from Aswan Dam km	Drop in W.L. (m) for daily discharge (million m ³)			
		80 Mm ³	100 Mm ³	150 Mm ³	200 Mm ³
Gaafra	34	0.9	0.76	0.44	0.28
d/s of Esna Barrage	167	1.03	0.95	0.76	0.6
d/s of Nagga Hammadi Barrage	360	0.72	0.92	0.85	0.6
d/s of Assiut Barrage	540	0.74	0.74	0.63	-
d/s downstream					

It is interesting to compare the results of predictions made by various water experts during the past 24 years with the actually observed data of bed degradation. Table 2 summarizes the result of degradation on the drop of water levels along the reach between Aswan and the Delta Barrage. It clearly shows significant variations between what were predicted by the experts, and the actual results.

Rise in River Water Levels

After degradation, the eroded materials move longitudinally downstream and are deposited in the deeper cross sections, which cause water levels to rise in those reaches. This phenomenon was observed at Ekhssas gauging station (68 km upstream of the Delta Barrage). Water level rose by 1.0 m during the period 1963-86.

TABLE 2. Intercomparison of theoretical predictions and observed data in drop of water levels (m)

Reference	d/s H.A.D. (Gaafra)	d/s Esna Barrage	d/s Nagga Hammadi B.	d/s Assiut Barrage
<i>Predictions by:</i>				
A. Fath (1956)				
G. Mostafa (1957)	8.50	8.00	7.00	6.50
V. B. B. (1960)	3.0-4.0	3.0-4.0	3.0-4.0	3.0-4.0
S. Shalash (1965)	2.0-3	2.0-3	2.0-3	2.0-3
D. B. Simons (1965)		3.50		
Hydro Project (1973)	3.00	3.50	3.50	3.00
S. Shalash (1974)	1.37	1.01	1.37	2.90
Hydro Project (1976)	5.30	7.00	11.00	
Hydro Project (1977)	3.00	2.50	4.00	8.00
M. El-Mottassem (1977)	3.2	2.1	2.4	
<i>Observed</i>				
Q = 80 Mm ³ /day	0.9	1.03	0.72	0.74
Q = 200 Mm ³ /day	0.28	0.60	0.6	

d/s downstream

Bank Erosion and Meandering

A meandering river such as the Nile has a series of bends. In the bends, deep pools are formed adjacent to the concave banks by the relatively high water velocities, which usually cause bank erosion. Because velocities are lower inside the bends, sediments are deposited in this region, thus forming bars which usually create navigation problems.

Studies have been initiated since 1973 to investigate the erosion levels and failures taking place at certain locations along the channel banks. In each case, soil samples were taken and tested and the problem was analysed to determine the cause of failure and to identify the steps that should be taken to prevent failures at other similar locations.

It was concluded that the total length of the eroded channel banks along the River Nile is about 500 km. This represents more than a quarter of the total length of the river channel bank from Aswan to Cairo (900 km).

The main reasons for the erosion of the Nile banks are the following:

1. meandering of the river;
2. groundwater seepage from the bank;
3. seepage of water from adjacent lands towards the river;
4. wave action due to navigation;
5. reduction of the water levels after the construction of the Aswan Dam; and
6. reduction of the river slope due to degradation.

The Downstream Scour Holes

Scour holes exist downstream of the existing barrages at Esna, Nagga Hammadi and Assiut. They are not located over the whole width of the river. At Esna and Nagga Hammadi barrages, there are two scour holes at the eastern and western sides of the river.

According to the periodic hydrographic surveys of these scour holes from 1973 to 1982, it has been observed that their volumes had increased by about 30 per cent under a constant datum. It was recommended that the scour holes be treated by filling them with rip-rap to be placed over an inverted filter, designed according to standard specifications.

Water Quality after Construction of the Dam

Before construction of the Aswan Dam, there were seasonal changes in certain water quality constituents of the Nile water. During the flood period, the Nile water is muddy, it has minimum dissolved solids but maximum suspended solids; whereas during the rest of the year, dissolved solids increase but suspended matters decrease.

After construction of the dam, the water released from the reservoir is practically silt-free, and the maximum discharge is about a quarter of the earlier flood discharge. In addition to the reduction of discharge, both the population and industrialization of the country have increased significantly during the past two decades. It is thus very necessary to assess the quality of the Nile waters for domestic, agricultural and industrial uses.

Some water quality monitoring has been carried out since 1976. Water quality samples are taken every 10 km from Aswan to the Mediterranean Sea and also within 200 metres upstream and downstream of the major discharge points. In addition, one sample is taken from the discharge point, where all the water quality variables are measured. The flow is also measured at the sampling

point. Chemical and biological analyses are carried out. Some 86 point sources were monitored between the Aswan Dam and the Delta Barrage, of which 20 were liquid industrial wastes and 66 were agricultural drains.

In 1986, the total annual discharge from the point sources monitored to the river, between Aswan and Cairo, was estimated at 3.6 milliard m^3 , of which 3.2 milliard m^3/year was from agricultural activities and the balance, 0.40 milliard m^3/year , originated from industry.

An earlier study on the variation of water quality of the River Nile, from Aswan to Cairo during the period 1976 to 1985, showed that there was significant deterioration in terms of the Water Quality Index. The following parameters were used to estimate the index: temperature, pH, dissolved oxygen, biochemical oxygen demand, total dissolved solids, suspended matters, phosphates, nitrates, ammonia and faecal coliforms.

The index had a lower value in 1985 as compared to 1976, which indicated that the water quality deteriorated owing to increased industrial and agricultural discharges. It was also found that the index is affected by water levels upstream of the dam. The index was high for a high water level and vice versa, which means that the more water stored in Lake Nasser, higher is the water quality. This indicates that the water pollution control law (No. 48 of 1982) must be more strictly applied and all waste discharges to the river must be treated properly.

Siltation in the Reservoir

The mean annual sediment load of the Nile at Aswan has been estimated at 134 million tons. Siltation in the reservoir generally depends on the volume of the flood water, and also on the distribution of the flood water within the reservoir.

When the reservoir was in the process of being filled, silt deposition covered wider areas depending on the size of the floor. More recently, siltation has been confined to the most southern 200 km of the reservoir. Particularly heavy siltation occurs in the area between 360 and 430 km south of the dam. In this region, the level of siltation has already affected the life storage zone (Fig. 2). Nevertheless, sediment transport phenomena tend to be in a northerly direction.

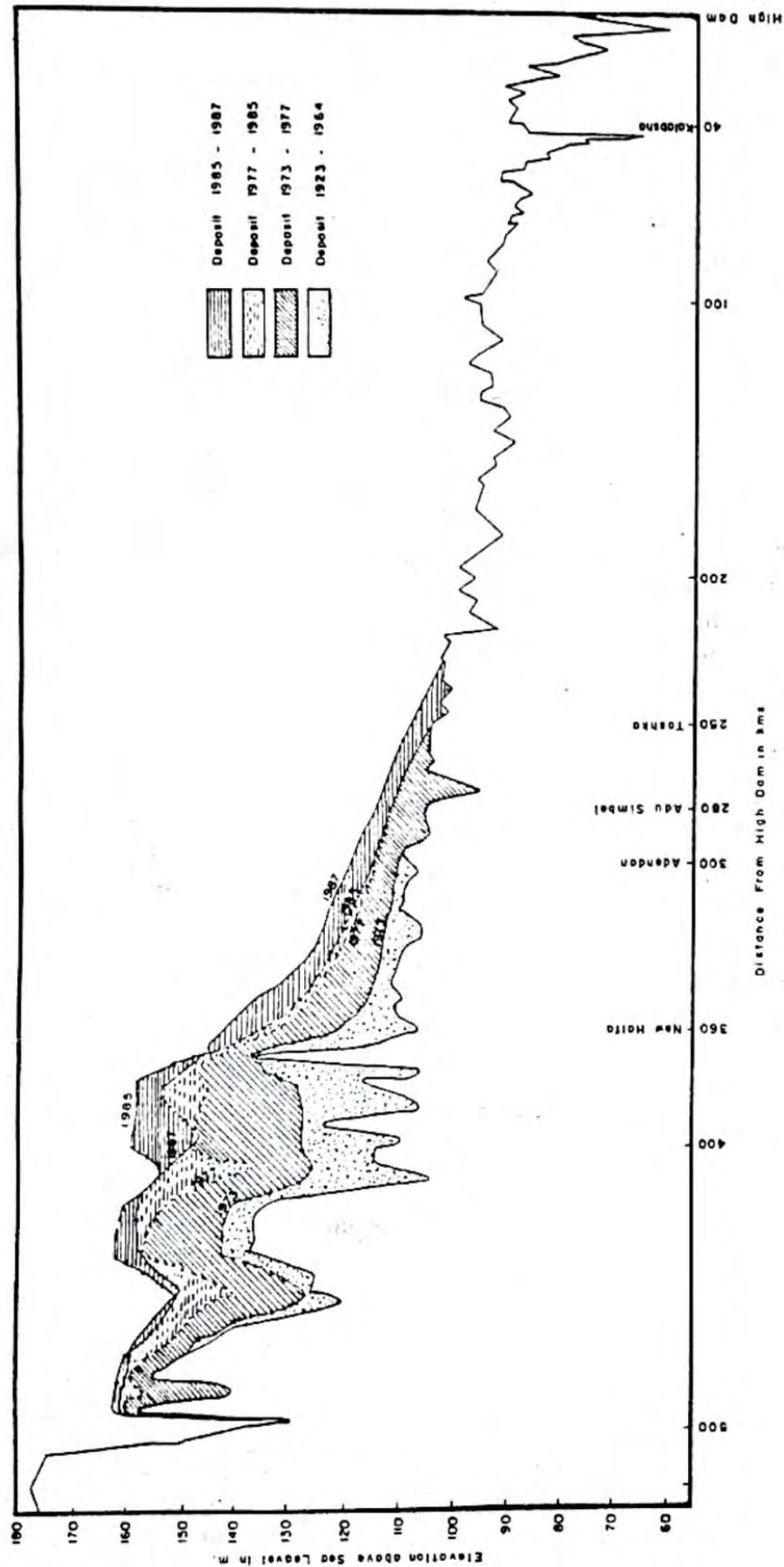


FIGURE 2. Siltation in Aswan High Dam Reservoir

Eutrophication Trends

The growth of algae and macrophytes in rivers is governed by flow, nutrients and light penetration. Classically the headwaters of rivers and streams are fast flowing, poor in nutrients and low in biological productivity. As the river proceeds downstream, it gets slower, receives more nutrients, and biological activities increase.

Streams are enriched from both point and non-point sources. Whenever streams get adequate nutrients, certain types of plants appear in great abundance in locations determined by the type and extent of enrichment, flow rate, water temperature morphology of the watercourse and other factors.

The effect of nutrient enrichment in larger rivers is uncertain, unless soil erosion and bank washouts take place. In such rivers, fast flowing waters cover long distances before phytoplankton growth is witnessed.

Growth factors reach surface water in various forms depending upon the source from which they come. As soon as a nutrient carrier reaches a water body, it undergoes a series of changes resulting from physical, chemical and biological processes taking place in the aquatic ecosystem. Redox conditions, solubility, complexion, ionic strength, type and amount of solids, salt ratio and concentrations and organic content and bio-degradation determine the state of the nutrient in the aquatic environment. The forms of elements or compounds that occur in natural water govern, to a large extent, the availability of the nutrients to aquatic plants.

Lake Nasser can be visualized as a huge biological reactor which releases a large number of planktonic organisms. The main algal species in the Nile belong to the *Cyanophyceae* (blue-green algae), *Chlorophyceae* (green algae) and *Bacillariophyceae* (diatoms). The change from the lacustrine to the riverine conditions, as the Nile water leaves the reservoir, is accompanied by significant changes in the algal distributions. Typically, the *Cyanophyceae* will decrease and diatoms and the *Chlorophyceae* will increase. Further changes downstream will reflect local flow control patterns and nutrient inputs.

After the initial decrease in Upper Egypt, *Cyanophyceae* reappear in large numbers during the summer at the end of the two Delta branches, Rosetta and Damietta. This is an indication of stagnant river conditions. In addition to causing taste and odour problems, these undesirable organisms are toxic to certain types of fish.

Estimation of Evaporation from the Reservoir

The maximum width of Lake Nasser is about 60 km, with an average width of about 10 km. It has a surface area of about 5000 km² at the 175 m water level. The average depth of the lake is 25 m and the maximum depth is 90 m. The lake is surrounded by desert and hilly land. It lies in a hot and extremely arid climate. Four meteorological stations were constructed at the dam site and along the lake. The main climatological factors at the meteorological station 3 km west of the High Dam are as follows:

- Mean maximum air temperature varies from 23.5 °C in January to 41.8 °C in June.
- Mean minimum air temperature varies from 8.1 °C in January to 24.8 °C in July.
- Mean relative humidity varies from 13 per cent in May and June to 37 per cent in December.
- Mean wind speed at 2 m height varies from 7.8 km (4 m/sec) in December to 9.3 km (4.7 m/sec) in April. The prevailing wind direction is northerly.

Several studies were carried out to estimate the evaporation from the lake. In a recent study, the average monthly evaporation was estimated by the heat budget and bulk aerodynamic approaches, using monthly estimations of different meteorological elements over the lake.

Table 3 shows the mean daily values of evaporation calculated on this basis. It shows that the mean daily evaporation is maximum in June (10.9 mm/day), and minimum in January (3.8 mm/day). The mean daily value of evaporation for the year as a whole is 7.35 mm/day. Highest evaporation during a period of four consecutive months occurs between June and September when evaporation accounts for 45 per cent of the total yearly value.

The monthly total water losses by evaporation are proportional to the rate of evaporation and the lake surface area, which is maximum during the flooding season. Maximum losses occur from June to September. The total annual losses at the average lake level of 175 m above mean sea level is estimated at 13.7×10^9 m³, which is about 11 per cent of the water stored.

Coastal Erosion

The formation of the Nile Delta is due to the direct result of silt

TABLE 3. Mean daily values of evaporation calculated by the heat budget method (E_H) and the bulk aerodynamic methods (E_B)

Months	(E_H) (mm/day)	(E_B) (mm/day)
January	3.59	3.93
February	4.95	4.08
March	5.40	4.77
April	5.52	7.32
May	8.95	9.31
June	11.66	10.11
July	10.42	10.01
August	8.39	10.68
September	8.61	10.47
October	6.98	7.83
November	4.87	5.17
December	4.90	4.52
Mean	7.35	7.35

deposition. During the prehistoric period, the Nile had several mouths to the Mediterranean Sea. The northern coast has assumed its present shape since ancient times. This is indicated by the lakes (Edku, Burullus and Manzala) between and on the sides of the two remaining branches of the Nile. A quasidynamic equilibrium was established between silt deposition and wave actions. Observations made since 1898 indicate the erosion of the delta in some locations at Rosetta and Damietta.

Some scientists believe that recent erosion has resulted from the change of the Nile regime caused by construction of the Aswan Dam, which prevents silt releases to the Mediterranean. This is now being seriously investigated. It should, however, be noted that some 15 years before the dam was constructed, the problem of coastal erosion was of great concern to the Egyptian ports and lighthouse authorities. In 1930, coastal engineering works were built on the central hinterlands of the delta to protect the relocated village of Burg El-Burullus. In 1940, the famous jetty of west Damietta was built. These and other protective structures, erected at different places along the coast, worked to some extent until the construction of the Aswan Dam. Since then, the rate of erosion has increased. The silt that used to be carried every year to the Rosetta estuary (about 90 million tons) and to the Damietta (about

30 million tons) has now decreased considerably. This annual sedimentation compensated the erosion due to the effects of sea currents and wave action. Studies of all the elements affecting the new regime of the Nile and the Delta coastline were started in 1970 and are continuing. Enough data are available to recommend important protective measures.

In 1985, a comprehensive coastal protection plan was outlined and approved by an international panel of experts. Some of the protective works were implemented in 1986, namely, above Abu-Quir and Rasheed protective walls.

Groundwater Regime

The Nile Valley and the Delta, from Aswan to the Mediterranean, cover an area of about 3 million ha. Within this region, there is a groundwater aquifer which is hydrogeologically connected to the Nile. The aquifer system consists of graded sand and gravel, overlain by a semi-pervious layer of silty-clay.

Before construction of the Aswan Dam, the river flood was the major factor affecting groundwater levels in the Nile Valley and Delta aquifer. Groundwater levels used to rise after the flood wave, but with a reduced amplitude and a time lag depending upon the distance from the Nile. These levels then used to decrease gradually, reaching a minimum in June, just before the next flood.

Due to the difference of levels between the Nile and groundwater, an exchange of water used to take place. In general, the Nile was the main source of groundwater replenishment. Vertical seepage also occurred due to irrigation and natural drainage used to take place laterally to the Nile during low flow periods.

After the dam was constructed, water releases were according to requirements, and the river water levels are very similar all through the year. As a result, the cyclic behaviour of the groundwater levels was greatly reduced. However, with the increasing cropping intensity and expansion of perennial irrigation, more irrigation water is now being released, which has increased vertical seepage. The lack of effective drainage in some areas of the valley and delta has resulted in a continual increase in both shallow and deep groundwater levels. Figures 3 and 4 show two typical groundwater hydrographs in the Delta and Nile Valley.

Figure 5 shows an iso-salinity contour map of the Delta aquifer for 1978. The iso-line of Revelle ratio which is equal to 250 is

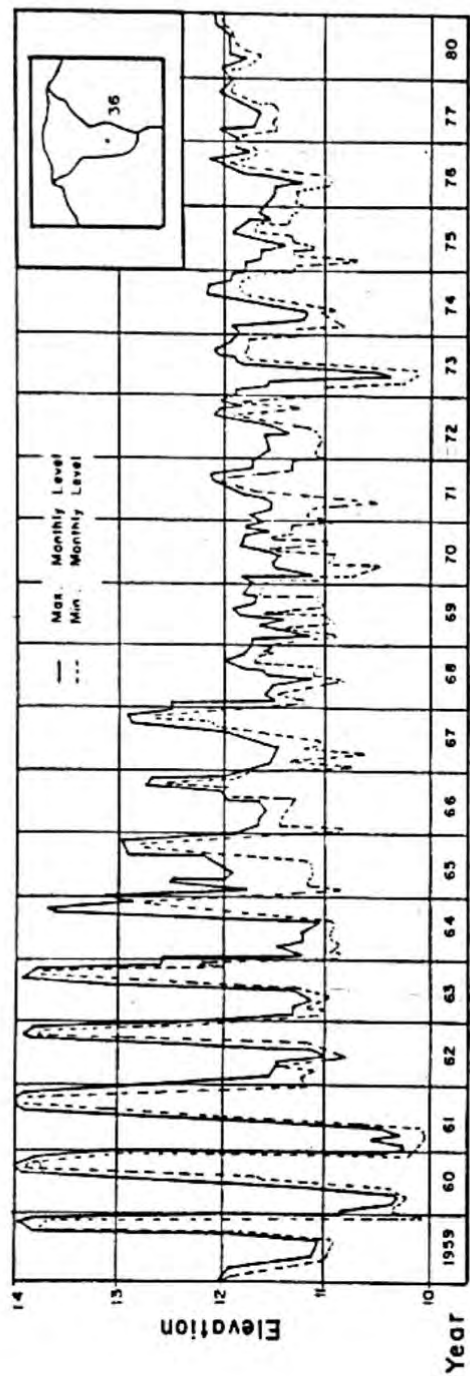


FIGURE 3. Groundwater hydrograph for well no. 36 (Nile Delta)

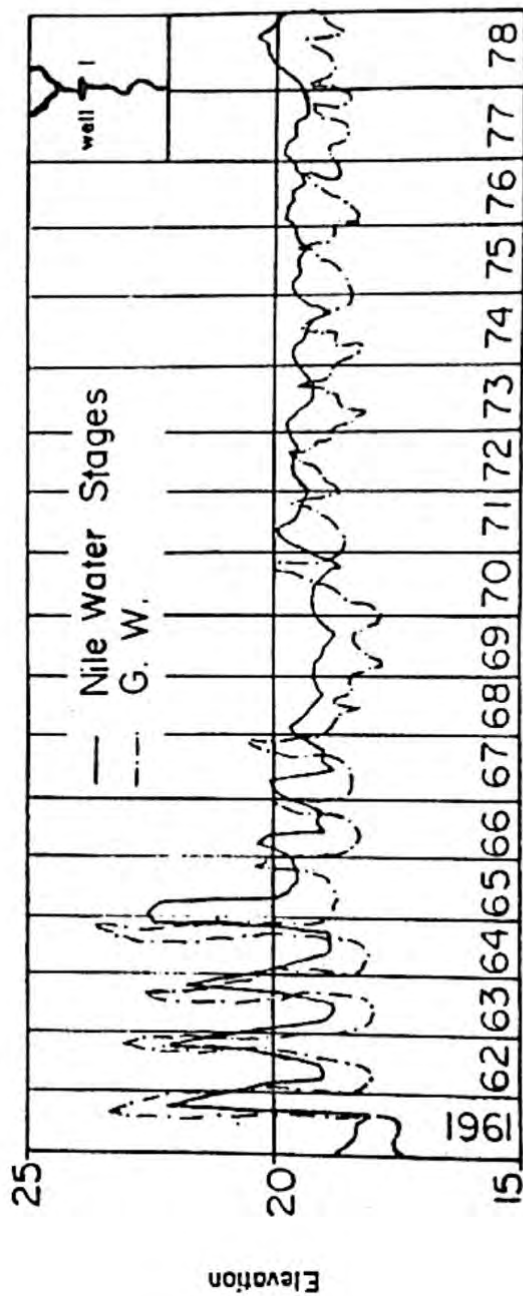


FIGURE 4. Groundwater hydrograph for well no. 1 (Nile Valley)

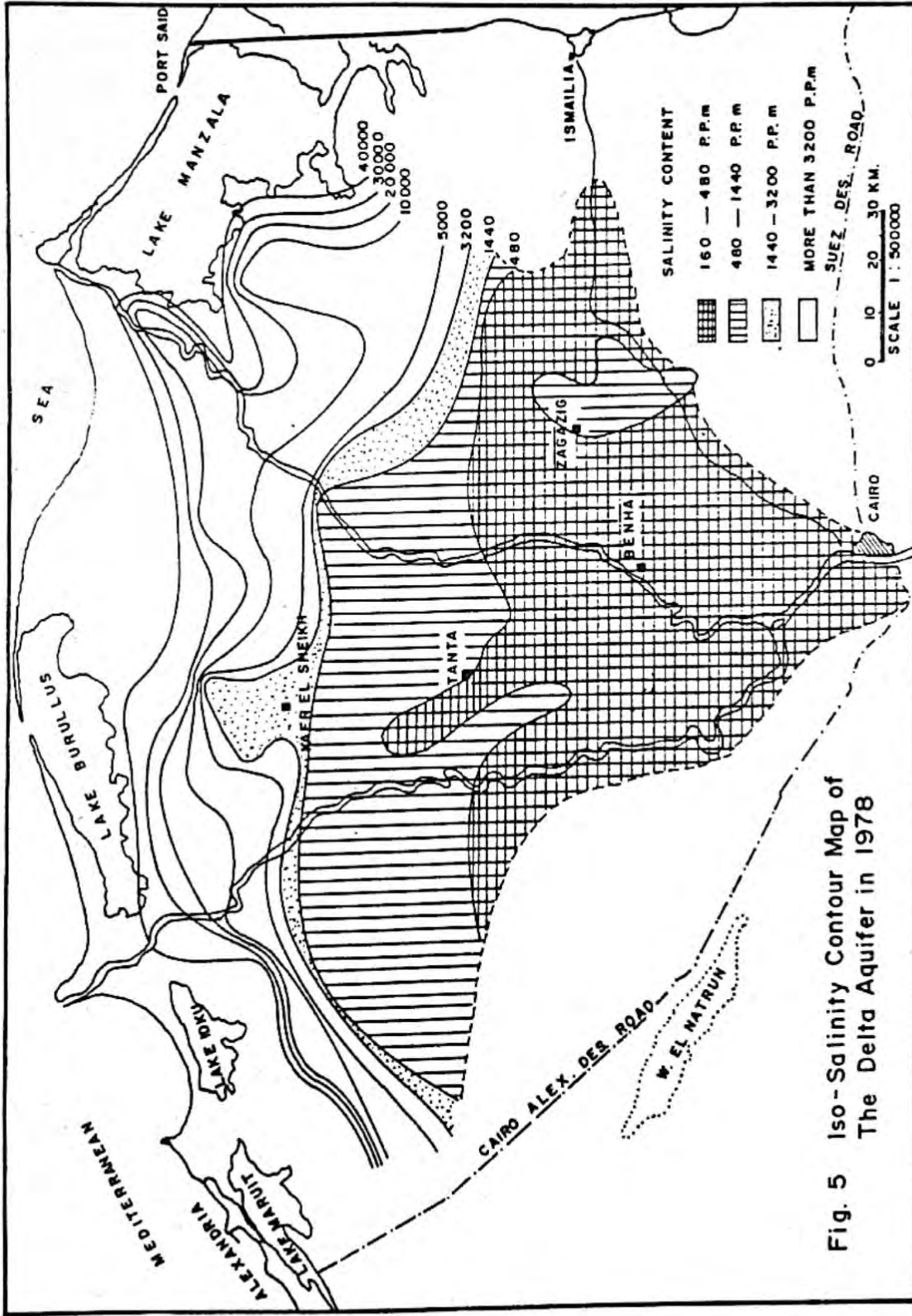


Fig. 5 Iso-Salinity Contour Map of
The Delta Aquifer in 1978

FIGURE 5. Iso-salinity contour map of the delta aquifer in 1978

considered an index of the Mediterranean water in the coastal part of the Delta aquifer. It may define the locus of the upper point of the sea water wedge intrusion in the aquifer. When this was compared with the 1968 data, it was found that within 10 years this line moved seaward by approximately 2.5 km, indicating an increase in groundwater gradients towards the sea.

If the iso-salinity contour lines of 1000 ppm (fresh water) and 30,000 ppm (salty water) for the years 1958 (flood period), 1966 (after dam) and 1978 are compared, it is evident that for the flood period, these lines moved inland and seaward with the flood. Between the years 1966 and 1978, a transition appears to have taken place in terms of continual seaward movement. If the present water balance of the Nile Delta is unchanged, the iso-salinity line of 1000 ppm is likely to continue moving seaward, improving the quality of the groundwater in the southern Delta.

In the Lake Nasser area, on the basis of hydrogeological investigations carried out before the construction of dam, it was estimated that annual seepage losses would be around 750 million m³. Current studies indicate that seepage losses are within the earliest estimate.

Drainage Before and After the High Aswan Dam

Perennial irrigation has been used in Egypt for multiple cropping since the early part of this century. Because of the absence of proper drainage, both water table and salinity in many areas have increased. The conversion of basin irrigation to perennial irrigation for about 0.5 million ha in Upper Egypt took place in parallel with the construction of the Aswan Dam.

Inadequate drainage has been a problem since 1938. Salinity and waterlogging problems developed even though some natural leaching took place in many areas close to the Nile channel and branches as the annual flood water receded. This does not occur any more since the Nile levels are now relatively stable and farmers in general have been over-irrigating, causing an alarming rise in the water table. The need for field drainage became more serious for the following reasons:

1. the horizontal expansion in agriculture in sandy or light soil, and the fact that much of these lands lie on the Nile Valley fringes of higher elevations;

2. seepage from new irrigation systems;
3. increased cropping intensities from one to two crops a year; and
4. increase in rice and sugarcane growing areas, requiring higher water applications.

Table 4 shows the relation between irrigation and drainage water for the period 1960 to 1986.

The total area requiring sub-surface drainage is estimated at 2.1 million ha. Before 1960, only 100,000 ha were provided with tile drains. It is expected that all of 2.1 million ha will have sub-surface drains by the end of 1991. The cost of field drainage system is being repaid by the farmers on 20 year interest-free annual instalments, starting by the third year after completion of implementation.

Social Impacts

The Aswan region, which has remained dormant for centuries but was an important centre during the early kingdoms, has become a focus of economic activity since the construction of the dam.

TABLE 4. Irrigation and drainage water before and after the High Aswan Dam

Year	Irrigation water (million m ³)	Drainage water (million m ³)	%
1960	23.459	10.658	45
1961	21.925	10.497	48
1962	26.053	12.623	49
1963	26.735	13.597	51
1964	26.990	14.025	52
1965	30.054	14.386	49.5
1966	32.003	14.847	46.5
1967	29.173	16.020	54
1968	29.731	15.528	52
1969	30.246	15.941	53
1970	31.178	16.238	52.5
1971	32.175	16.261	50.5
1972	32.591	15.989	50
1980-3	34.980	16.418	46
1984	36.097	16.840	46
1985	34.505	16.501	47
1986	34.929	16.415	46

With the establishment of large-scale industries, such as fertilizer, iron and steel, sugar, ply wood, milk industries, pulp and paper, as well as phosphate, kaoline and other mines, new population centres have emerged around the dam area. The population of the Aswan area has increased from 280,000 in 1960 to around one million, mainly because of the increase in job opportunities.

Furthermore, the deserted Nubia, flooded by the reservoir, has begun to flourish again. In Abu-Simbel, the rescue of the two famous temples of Ramsis II has transformed the area into a major tourist centre.

Fish Production

Extensive studies have been conducted on fish production in Lake Nasser. Fish distribution and abundance varies among the different sections of the reservoir. Furthermore, different khores frequently exhibit different fish distribution. The migration of certain types of fish has been dependent on the arrival of the turbid floodwater and their preference to riverine or semi-riverine conditions. Fish behaviour partially accounts for the difference in their contribution in catches, which is quite significant for species of economic importance.

The Tilapia species are the most predominant in fish landings, followed by *Lates niloticus*, Catfishes and Cyprinids represented by *Labeo* and *Barbus* species. Recently, *Tilapia galilaea*, which was sporadically recorded in the early years of the impoundment, has become the most abundant species in fish landings.

Sardines which breed at the estuaries of the Nile have almost disappeared. The mineral rich silts which nourished the sardines are now deposited behind the High Dam. The annual catch of sardines has dwindled from 80,000 to 60,000 tons annually.

The HAD Lake Authority, charged with developing the potential of the lake and its environs, is now encouraging former residents to return to the area to help develop the fishing and farming industry. Fish production through hatcheries and intensive fish farming is seen as having a major potential. Already there are about 7000 fishermen on the lake. The main problem is industry and marketing.

Effect of the High Aswan Dam on Soil Fertility

Some researchers have claimed that the trapping of the sediments in Lake Nasser will affect the fertility of old lands, and thus chemical

fertilizers have to be used to maintain soil fertility. Studies indicate that 88 per cent of the Nile's annual sediment load used to go to the Mediterranean. It was estimated that only 6000 tons of potash (K_2O), 7000 tons of phosphorous pentoxide (P_2O_5) and 17,000 tons of nitrogen (N) were added to the land annually. In relation to the fertilizer need for large yields, these amounts are insignificant.

More significant to the fertility requirement of the land is the increase in yield through reliable supply of irrigation water, the growing of two or more crops per year, and the resulting high levels of production with consequent increases in withdrawals from the soil. These withdrawals require replacement and supply of adequate amounts of the major nutrients like nitrogen, phosphorous and potassium. This is probably a major contributing factor to the need for a number of trace elements in recent years. The continuing nutrient requirements for increased production has an effect many times higher than due to the sediment loss.

Studies have indicated too that there is no direct cause and effect relationship between the High Dam and the lack of certain trace elements. There is no direct evidence that trace elements were present in adequate quantities in the soil prior to the High Dam and that the deficiency did not exist prior to its construction. Furthermore, trace elements can be easily and economically added to the soil.

Effect on Historical Monuments

Lake Nasser did inundate some monuments but the major ones, Abu-Simbel and Kalabsha Temples, were saved by international efforts. These were reconstructed on higher elevations. UNESCO organized a rescue team which accomplished one of the greatest engineering feats of recent times. Engineers, architects and archaeologists from many nations participated in saving monuments which were built by the ancient Egyptians along the Nile. Several temples were in fact relocated, but the biggest challenge was the two temples at Abu-Simbel cut into the solid rock. The statues, columns and frescoes were systematically cut into blocks, numbered, lettered and transported safely to a plateau above the level of the lake. The 1050 blocks were reassembled without a single block being broken or cracked. The joints have been made so carefully that they are almost undetectable.

There was some concern that the increase in groundwater levels, waterlogging, and salinity would damage the monuments down-

stream, or that the increase in groundwater would decrease the bearing capacity of the soil and wells of temples which might collapse. the higher water table would allow salts to move up into the monuments by capillary action. Both these actions have occurred in the past and could occur in the future.

However, it should be noted that during floods, temples and monuments were flooded. More research is now being undertaken on the action of the water on the monuments and efforts needed to preserve them. However, it appears unlikely that the High Dam had a significant adverse effect on the monuments downstream.

Health Impacts

Since the construction of the dam, there have been a number of plans drawn by several agencies for economic development of the region along the shores of the reservoir. These include the establishment of human settlements (e.g. irrigation, land reclamation), industrial development, and tourism and recreational projects.

An important risk is that such development schemes will affect water quality and the aquatic ecosystem of the reservoir. Furthermore, the deterioration of the quality of the reservoir will affect downstream river uses.

A serious consequence could be the propagation of schistosomiasis and the northward migration of malaria mosquito vectors from Sudan. The *Anopheles gambiae* has invaded Egypt on several occasions, the last of which was in 1942. The vectors of both *Schistosoma mansoni* and *Schistosoma haematobium* have already been found in Lake Nasser. The assumption is that the fishermen brought the disease with them to the region.

Policy-makers should consider the alternative of keeping the reservoir area largely free from human activities, i.e. restricted and protected area, in an attempt to avoid possible pollution problems and the spread of water-borne diseases. Alternative plans for the development of the shores of the reservoir should incorporate more realistic assessments of the environmental impacts and the cost of pollution control.

CONCLUSION

In retrospect, an objective evaluation of the impact of the Aswan Dam based on more than twenty years of operational data clearly indicates that it has overall been overwhelmingly positive, even

though it has contributed to some environmental problems. These problems, however, are significantly less than most people originally feared. As the Executive Director of the United Nations Environment Programme, Dr Mostafa Kamal Tolba, said at the recent World Congress of the International Water Resources Association in Ottawa, 'the real question is not whether the Egyptians should have built the Aswan Dam or not—for Egypt realistically had no choice—but what steps should have been taken to reduce the adverse environmental impacts to a minimum'. It is clear that after more than twenty years of operation, the Aswan Dam now deserves much more credit than it has received so far for beneficial contributions to Egypt's overall development.

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