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Irrigation and the Environment

A Review of Environmental Issues

Part I

Influence of Irrigation on the Environment and Vice-Versa

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IRRIGATION AND THE ENVIRONMENT

A review of environmental issues

Part I Influence of Irrigation on the Environment and Vice-Versa

Part II Environmental Considerations in Planning and Operation

Part I
Influence of Irrigation on the Environment and Vice-Versa

IRRIGATION AND THE ENVIRONMENT

A Review on Environmental Issues

Preface

This working document is intended as a sourcebook which reviews and discusses relevant publications on various issues governing the interrelationships between irrigation and the natural environment. Intensive use was made of recent publications, either textbooks, or symposium proceedings and journals which often have limited circulation amongst interested scientists, planners, and those involved in implementation and operation of irrigation systems.

Due to the large variety of disciplines involved in such a review, the selection and depth in which some issues are reviewed may appear to some readers as imbalanced; some sections may even give the impression being inadequate to the specialist. Therefore, it is intended to up-date this sourcebook as soon as possible with the assistance of anyone who feels prepared to submit additional information or who wants to address amendments or eliminate errors.

The working document draws heavily on various sources most of which are cited at the end of each section. Short excerpts are sometimes not explicitely quoted. Therefore, the sourcebook published as an internal working document.

An important part of this study is the compilation of **references**. The interested reader is referred to these publications to obtain in-depth technical or scientific details. In addition, a large number of tables and figures are used to illustrate the information and to serve as a 'manual'. These tables and figures were extracted from the references quoted.

This sourcebook complements existing **textbooks** and **symposium papers** which deal with environmental impacts either by giving a generalized overview (eg Zonn) or emphazising specific issues. The reader is thus refered to the following sources:

FAO/UNESCO 1973. Irrigation, Drainage and Salinity. An International Source Book. (Kovda/van den Berg/ Hagan ed.)

ICID 1975. Environmental Control for Irrigation, Drainage and Flood Control Projects. General Report by Holy, M.; in addition, 19 articles on environmental issues, eg. Hagan/Roberts 1975.

COWAR 1976. Arid Lands Irrigation in Developing Countries. Environmental Problems and Effects. COWAR-UNESCO-UNEP-ISSU. Cairo (see also: Worthington 1977)

White 1978. Environmental Effects of Arid Land Irrigation in Developing Countries. UNESCO-UNEP-SCOPE. MAB Technical Notes 8

Zonn 1979: Ecological Aspects of Irrigated Agriculture

Kharchenko/Maddock 1982. Investigation of the Water Regime of River Basins Affected by Irrigation. UNESCO. See also other UNESCO/UNEP documents.

ICID 1990. 14th Congress on Irrigation and Drainage in Brazil. Question 42: The Influence of Irrigation and Drainage on the Environment with particular Emphasis on Impact on the Quality of Surface and Ground Waters. General Report: Holy 1990. Question 43: The Role of Irrigation in Mitigating the Effects of Drought. General Report: Pereira (1990). Socio-economic and technological impacts of meachanized irrigation systems. Gernal Report: Kruse (1990).

Case studies with environmental issues are for example published by ODI, Irrigation Management Network. Overseas Development Institute. UK.

German references are rarely used because special references on irrigation are few, although many are dealing with **agricultural impacts** and **water resources development** related to fertilizers and pesticides pollution. Important german textbooks are for example

Busch/Fahning 1992, Domsch 1992, Blume et al. 1992, Krumm/Stumm 1992, UVP-Förderverein 1993, Zauke et al. 1992, Hötzel 1986, Sauerbeck 1985, Diercks 1985, RSU 1985, Welte/Timmermann 1985, Domsch 1985, Baumann et al. 1984.

Fig. 1-1

Key Environmental Issues in Irrigation Schemes

Problems related to natural conservation and quality of life values

N 1	Use of agro-chemicals and ecotoxicological impairments
N 2	Direct intervention into protected conservation areas
N 3	Interventions into wetlands & other ecologically sensitive areas
N 4	Hazards to public health
N 5	Impacts on socio-cultural values
N 6	Resettlement and migration

Problems related to the use of natural resources

R 1	Impacts on sensitive water resources
R 2	Water use conflicts: volume changes and quality impairments
R 3	Land use conflicts
R 4	Soil productivity problems: salinization, alkalinization, water-logging, fertility, biological imbalances, soil contaminations
R 5	Degraded watersheds
R 6	Use of non-renewable resources (energy, water)

Positive effects of agricultural development by irrigation

Increased yields & diversified agricultural production
Increase in income and living standard
Improvement of health conditions
Improvement in water sanitation standards
Social and cultural development in rural areas

1 Introduction

Few environmental concerns now occupying public attention are as fraught with emotions as are the **large dam** and **irrigation** issues (Fig. 1-1 and Tables 1-1, 1-2). However, dogmatic assertion is an inadequate substitute for truth, and it is hoped that judicious use of the information in the following sections will help reduce emotional debate over irrigation and its associated water development and agronomic practices, leading to rational analysis and reasoned debate. Through such an approach the environmental and socio-economic problems of the majority of people in developing countries may again be focused on the major issue - that of ensuring adequate food supply and sustainability of agricultural production, improving public health conditions, and the conservation of land, water and biological resources.

Sources: Gardner in: Cheng ed. 1990; Biswas/Quipeng ed. 1987; Goldsmith/Hildyard 1984; Goldsmith/Hildyard ed. 1984

It would be misleading to speak of the environmental impacts or problems caused by irrigation systems (or individual irrigators). There are, in fact, **multiple effects** and **various types of impacts:**

- some impacts are applicable to the majority of irrigation schemes, some only to specific agro-climatic regions, and others only to specific locations, scheme types, irrigation methods or agronomic practices,
- some impacts are adverse to other human users, land uses or to fauna and flora, but others are benficial to agricultural production, other land uses or fauna and flora,
- some impacts are unavoidable, but many impacts which contribute to the degradation of water and land resources are induced by certain human-made management practices which are usually changeable and which can be influenced with regrad to their magnitude,
- some impacts are significant, others are insignificant or neutral to human users or ecosystems,
- similar irrigation management activities may result in different environmental responses with changing environmental and/or socio-economic contexts.

It is important to recognize significant physical differences between various qualities and quantities of impacts, their causes and their effects on other human users and ecosystems. This review attempts to distinguish between those important differences where appropriate and avoid inappropriate generalizations.

It should also be worthwhile to mention that the **perception** of impacts on human-made or natural ecosystems has changed over the decades. Historically, some degree of, for example, increased salt concentrations in soils or waters as a result of irrigation was usually accepted as the 'price' for irrigation. In some areas, however, there was so little attention to environmentally sound management that degradation has become a serious matter. As pressure on land and water resources, resulting from increased population and increased necessity to produce food becomes greater, there are increasing demands for effective control of river systems, water quality and soil degradation, including salinisation. The perception that environmental control is required for irrigation, drainage and flood control projects is not a recent development but has been of topical interest since the late 1960s, and various national and international symposiums and workshops were convened in the mid 1970s to discuss relevant environmental issues (eg ICID 1975; COWAR 1976).

A prerequisite for the understanding of irrigation problems is the knowledge of **processes** which may lead to the deterioration of natural resources required for successful irrigation development. For example, successful soil management requires a knowledge of the pro-

Fig. 1-2

Subjects and Qualities of Environmental Appraisals

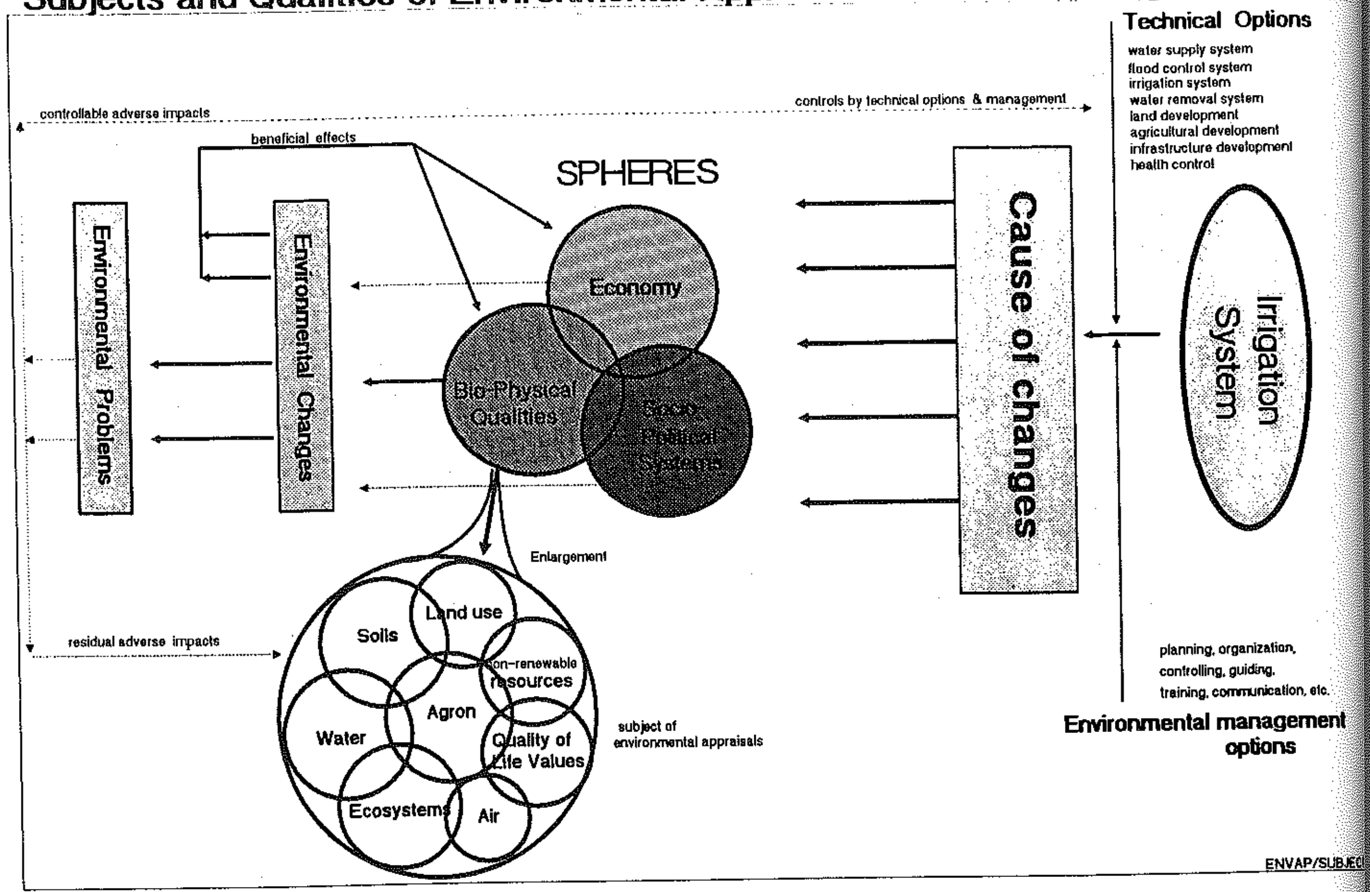
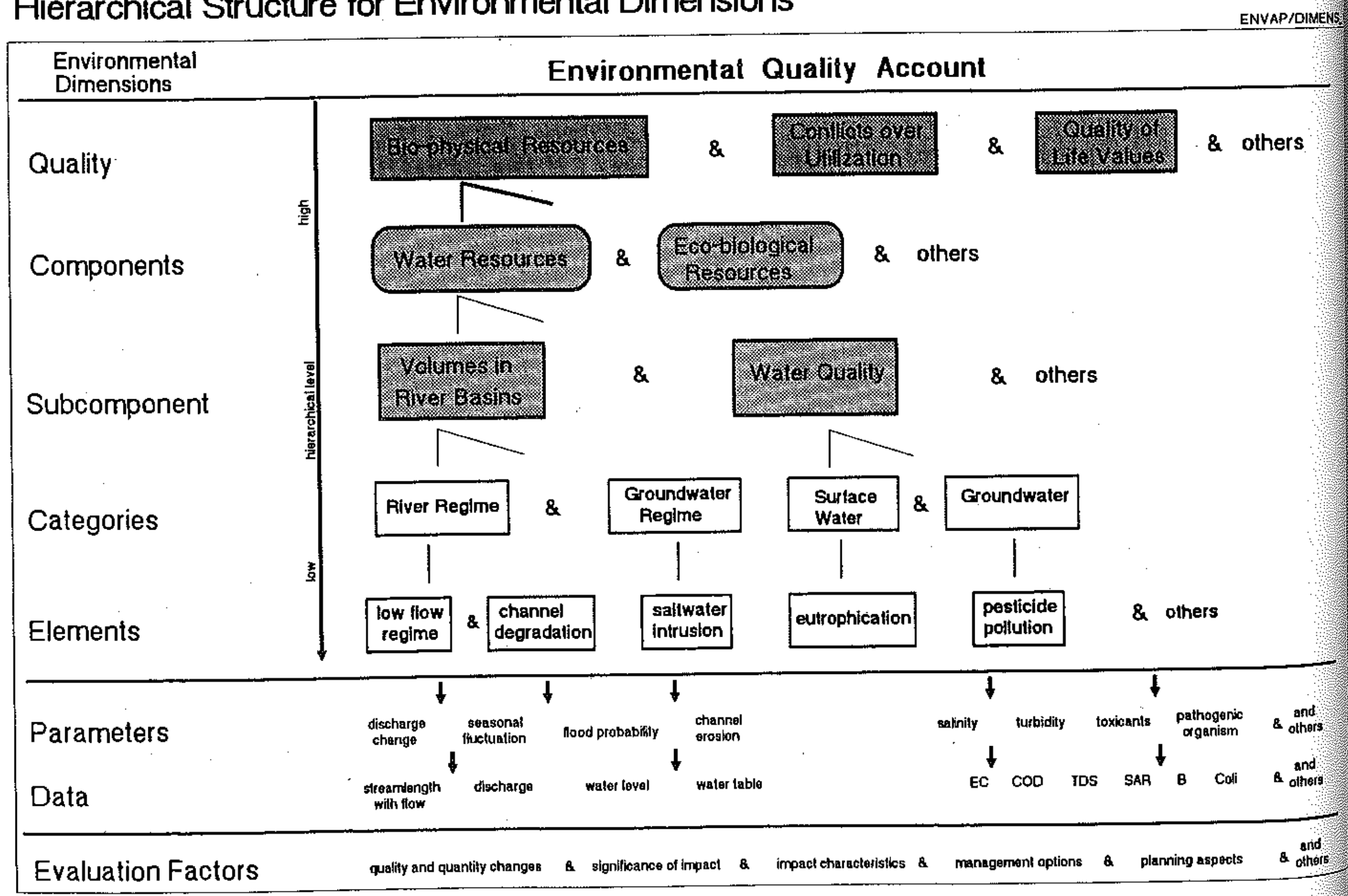


Fig. 1-3

Hierarchical Structure for Environmental Dimensions



cesses of salt accumulation and leaching in soils under irrigation and plant response to inceased salinity and moisture deficits under different agro-climatic conditions.

1.1 Characteristics of Environmental Impacts

Land and water resources development is associated with environmental changes within and outside the developed areas. However, these changes can be either positive or negative unless one takes the attitude that any environmental change is bad. In order to assess the many types of changes which are associated with irrigation projects it is necessary to define the environmental problem and the characteristics of potential impacts.

Environmental impacts of irrigation activities (see Fig. 1-2) can be divided to

(i) ecological, agricultural, hydrological and engineering aspects, ie. mainly physical and biological parameters are altered,

(ii) economic aspects,

(iii) social aspects.

Economic impact analyses are generally included in feasibility studies, although economic appraisal may become important in assessing economic impacts of environmental degradation and the formulation of alternative developments which reduce environmental impacts. On the other hand, social impact analysis (SIA) is a component of other planning appraisals and, therefore, may not necessarily be a main focus in environmental impact assessments (EIA). Nevertheless, some socio-**cultural** issues are clearly related to environmental problems in irrigation schemes or associated water development projects (see section 10). Vice-versa, environmental management must be seen in the socio-economic context of sustainable development. Hence, the social and environmental development issues are to be treated complementary, especially in the development of environmental management objectives and measures (see section 3.1).

In ecological literature, environment is often defined as the biophysical system in which human intervention takes place (eg Duinker 1989). In this sourcebook, environment is used synonymously as **'natural human habitat resources'** (natürliche Existenzgrundlagen, see Weimert/Kresse/Karpe. BMZ. 1981). The environment may also be understand in a broader sense as the biological, physical and socio-economic systems that surround a development activity (following the Stockholm Conference 1972; Horberry in: DSE 1984).

1.2 Taxonomy of Environmental Dimensions

The taxonomy of environmental dimensions comprise four **levels** (Fig. 1-3):

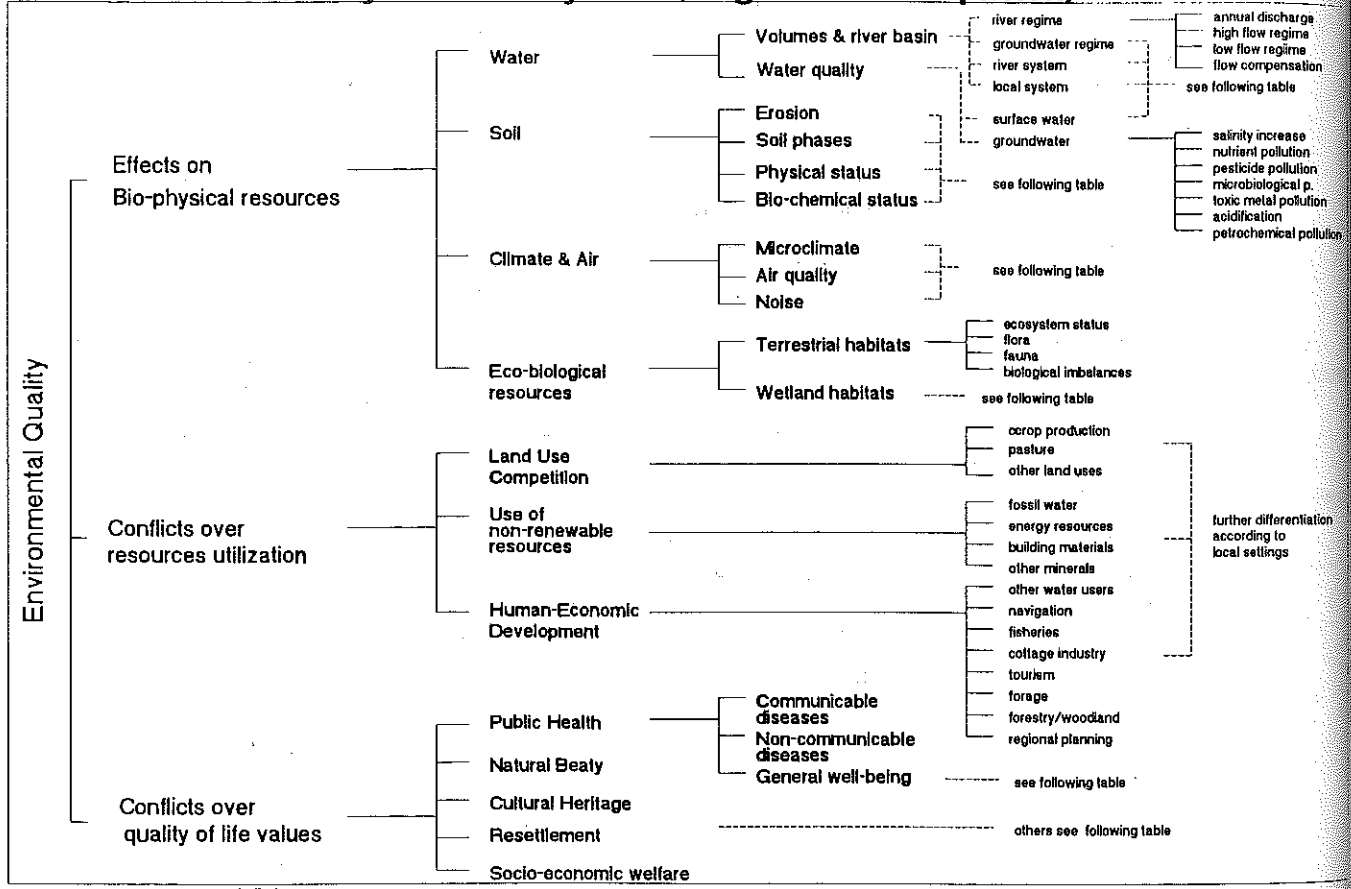
Level 1 Environmental Quality (aggregated natural goods and services; human uses)
Level 2 Environmental Components/Subcomponetns (eg water, soil, human health)
Level 3 Environmental Categories (specification of the component: river regime)
Level 4 Environmental Elements (eg low flow regime)

Environmental analysis requires an inventory and evaluation of the state of the environmental categories, ie the particular type of natural resource (eg river, soil, ecosystem) in the concerned area. Each category in that inventory would then be evaluated in terms of five **evaluation** factors:

Quantity
Quality
Human influences in both directions: human upon resources and visa versa
Uniqueness of affected resource
Irreversibility of changes.

Fig. 1-4

Environmental Quality Account System (Irrigation Development)



Under each factor, a number of measures may be taken for quantitative (eg river discharge in m^3/s, ppm salts) or qualitative assessments (eg visual landscape beauty on an ordinal scale). A complete list of environmental elements to be compiled for water resources development is in OECD 1985 and for irrigation projects in Petermann 1992.

Environmental qualities, components and categories

Environmental qualities (see also Fig. 1-4) may be distinguished under:

- **physico-chemical**: soil (land), surface- and groundwater, atmosphere, noise,
- **biological**: flora and fauna,
- **human**: health and safety, aesthetic and cultural, socio-economic.

Soruce: Biswas/Geping ed. 1987

A similar classification gives emphasis to quality criteria in the context of natural goods and services (see Part II 1.1) and their values for human qualities of life:

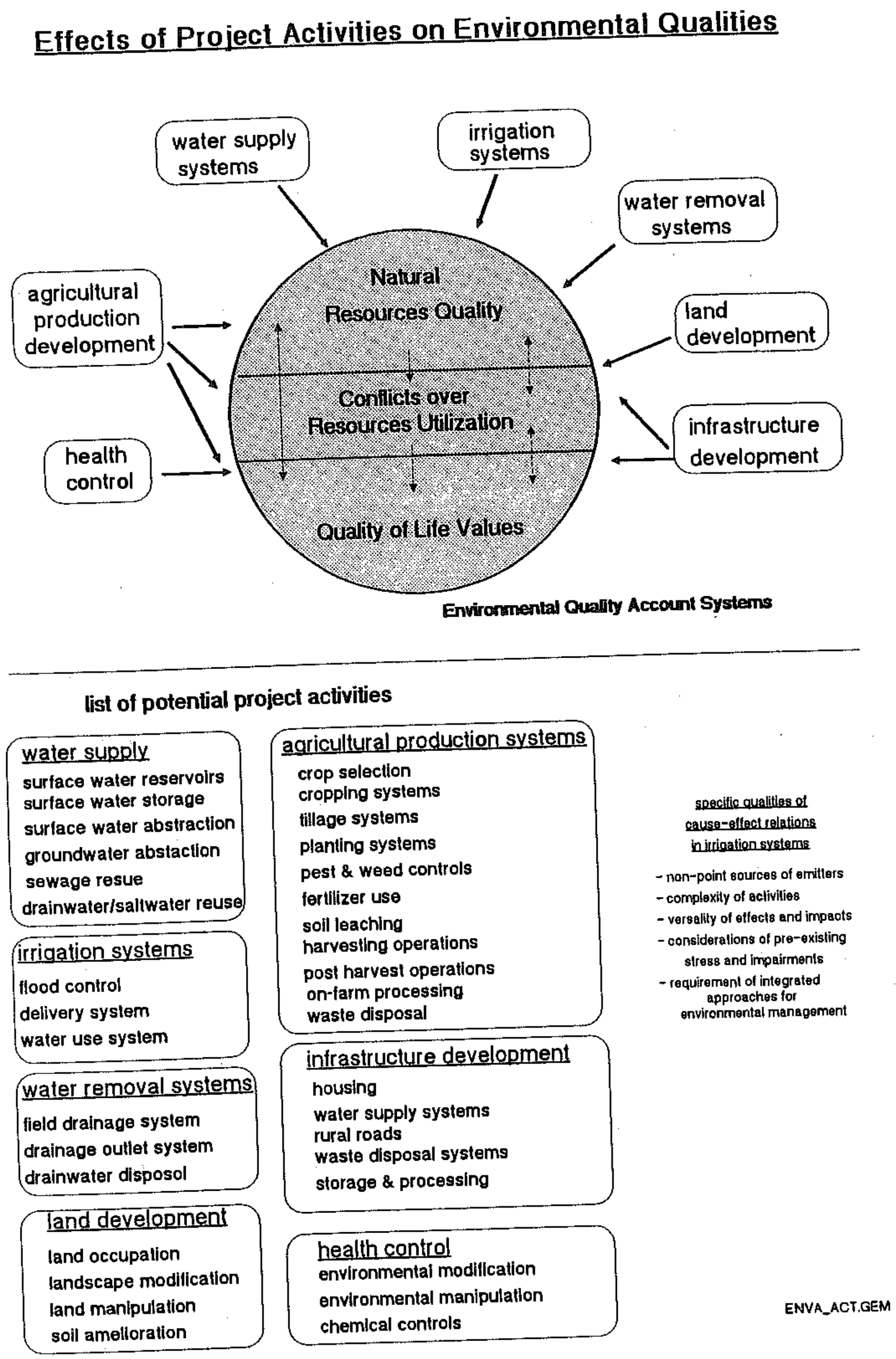
	Component	Category
I	**quality for human use**	land, groundwater, surface water, soil, air quality/ climate for productive use of resources; visual, geological resource
II	**quality for human health**	air, water and food qualities; noise; soil/water pathogens, and well being vector habitat; exposure to natural hazards (floods/earthquakes); crop production, housing, infrastrucutre
III	biological, ecological	biological resources (flora, fauna), ecological systems
IV	areas of natural beauty and human enjoyment	forests, open space, watercourses, rivers, lakes, reservoirs, wetlands, wilderness, estuarine areas
V	socio-cultural	cultural, historical resources, settlement area, visual, recreational use, traditional land use

Source: modified after: OECD 1985, Part IV

The following detailed environmental **components** and their **parameters** may be used for irrigation appraisals:

	environmental component	environmental parameters (examples)
1	water quality	Salinity, pH, temp, organic/anorganic toxins, N, P, BOD, organic C, TDS, bacteria, viruses, parasites, SAR
2	water quantity	flow rates, total volumes, daily or annual fluctuations, flooding hazards, flood level
3	land/soil quality	physical and chemical soil characteristics: EC, SAR, pH, nutrients N, P, K, total CEC, ESP, infiltration, water retention, permeability, land drainage; erodibility, soil moisture status, runoff, sedimentation, bank erosion, leaching facilities, presence of toxins, pathogens

Fig. 1-5



4	air quality	toxic volatiles, N-volatiles, particulates, greenhouse gases, pathogenic aerosols (from wastewaters)
5	microclimate	changes in temperature, humidity, windspeed
6	noise	traffic, machinery, power plants, construction
7	amenity/recreation	clean water, turbidity, colour/odour, visibility, surface appearances (oil, bacteria films), weeds
8	aquatic ecosystems	breeding and migration of fish; maintenance of natural and genetic heritage, including endangered species; habitat of aquatic plant systems
9	terrestrial ecosystems	breeding and migration of fauna species; maintenance of natural and genetic heritage including endangered species and vegetation communities
10	aesthetics	loss of rare and valued scenery
11	socio-cultural	loss of rare and valued historical or cultural sites, loss of traditional settlement area,

Sources: modified after: OECD 1985; a modified system was developed by Petermann 1992 (Fig. 1-3)

1.3 Environmental Impact Identification

Adverse impacts may vary in **time**, **space** and **intensity**, and they may act **directly** or **indirectly** through another environmental category (water, soil, air). Some impacts may be simple, of minor importance and, therefore, require only local and timely limited action to mitigate, but others occur on a large-scale and may be associated with complex developments and potential impacts on national or even international natural resources (eg rivers).

Cause of impact. Environmental impacts from irrigation are caused by either

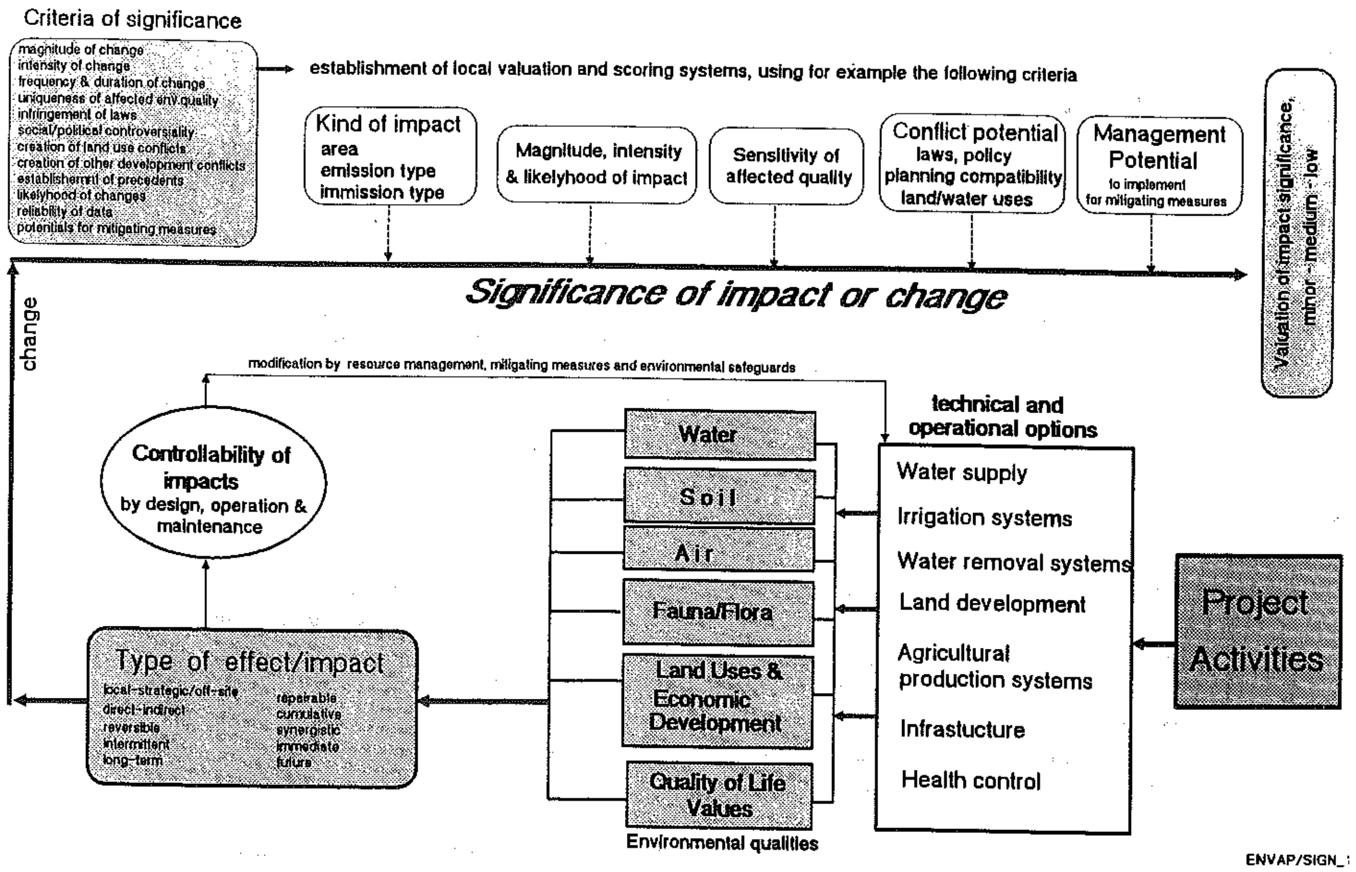
- minor, medium or large scale irrigation projects: typically centrally organized and with substantial public financial support. Farm operations may be centrally or individually organized; water supply and irrigation scheduling are typically centrally organized, either by public authorities or by cooperative institutions
- individual irrigation by farmers without direct public support. Farm operations, water supply facilities and irrigation scheduling are generally individually organized, but parts of the services may be organized by cooperatives or by other institutions.

Causal **factors** of impacts can be identified at various levels and they may be caused by different activities (Fig. 1-5). Impacts may be attributed to

(i) irrigated agriculture as a part of the complex farming system (eg livestock farming)
(ii) activities related to irrigated agriculture, such as crop protection, tillage practices, other crop production activities
(iii) irrigation system components such as:
 * multi-purpose reservoirs, tanks
 * water supply systems (including wastewater & drainage reuse)
 * water distribution systems
 * water application systems (field water management)
 * water disposal systems (drainage systems).

Fig. 1-6

Environmental Impact Analysis: Significance Assessment



Nature of impact. The nature of the impact determines which environmental **component** and **category** is beneficially or adversely affected, eg groundwater quality or human health.

Levels of impact. Irrigation developments may pose direct or indirect impacts on resources or neighbouring ecosystems;

* **direct impact**: eg pollution of surface water with solid particles, nutrients or salts resulting in a degradation of fish habitat(s)
* **indirect impact**: eg. reduction in the number of fish species or population caused by habitat degradation.

These levels can also be grouped as 'first order' (direct) and 'higher order' (second order, third or indirect) impacts. Indirect impacts are much harder to identify and to assess in quantitative terms. For example, the fish habitat may also be affected by other human activities such as pollution from dryland/rainfed farming or from untreated domestic sewage, or by natural processes, such as low rainfall which reduces discharge and flow velocity which affects chemical water qualities.

It is certainly possible to make some estimates of their importance and magnitude, and even to assess tertiary effects, eg on fisheries (number of catches per fisherman per day) or even higher order impacts on trade and local markets, for example. But such examinations of higher order impacts are only required in the case of such an environmental effect being critical to the success or failure of the irrigation development planning application.

Impact analysis. The following specifications apply to all kinds of development activities and impact analysis (Fig. 1-6).

There are various **characteristics** of impacts:

1) spatial dimension: area or spatial extent of impact, eg on-site versus off-site
2) probability: likelyhood of occurence
3) time dimension: immediate effects to medium- or long-term effects
4) reversibility or irreversibility; potential for recovery
5) importance and magnitude, intensity
6) type of disturbance of ecosystems: cumulative, synergistic, antagonistic effects: cumulative effects of many small actions; chain reactions; or secondary effects of interrelated activities

There are several **criteria** of impacts and effects:

- people adversely affected: identification of groups, individuals, communities
- natural resources affected: land, soil, water, air, fauna/flora
- duration/length of impact
- controllability; the know-how and technology that can be used in mitigation and reversing impacts.

The **magnitude** of impact or the degree of ecosystem disturbance can be assessed by:

- measurement of quantifiable parameters, eg salinity, erosion rate, pollution rate, population affected
- ordinal scales of non-quantifiable impacts (visual beauty) or estimates of quantifiable parameters in case of lack of precise data, eg high-medium-low erosion rates.

The **signficance** criteria may include:

- degree of irreversibility
- spatial extent of effects (see also below: local versus strategic impacts)
- degree and rate of changes
- uniqueness of threatened organisms/goods; rareness of a natural resource
- dependance of various important organisms on affected component/category
- degree of disturbance of ecosystems' function and structure
- anticipated public interest (local, national, international; government or non-government)
- local as opposed to national or even international impacts (strategic impacts)
- salience of environemental problems in their social, economic and cultural context.

The **severity** of impacts can be assessed by

- social costs
- direct costs (in economic terms: loss in value, costs for mitigating measures)
- human health hazards (costs for health control programmes)
- indirect socio-economic costs (eg ecosystems degradation with a long-term perspective: future development potential).

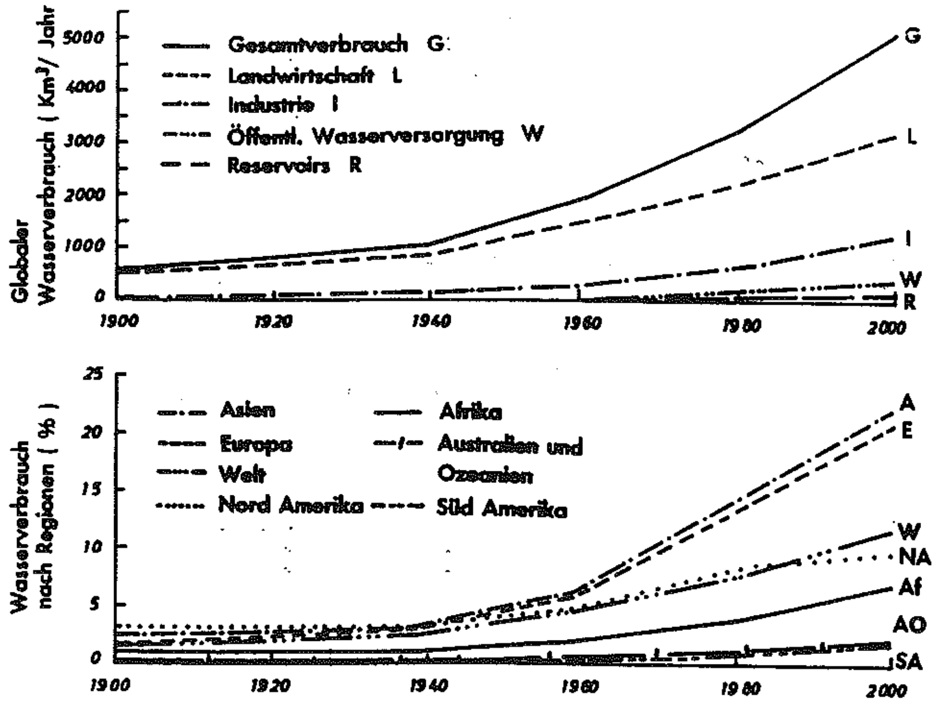
Although there are studies emphasizing the environmental costs of human development (or economic activites), there is still some debate about appropriate methodologies and techniques to be used in **environmental economics**. It is recognized that any deterioration of natural resources will eventually result in the scarcity of these resources and, hence, the deterioration of the environment is also an economic problem. A major problem in such analyses remains the non-tangible nature of some resources (aethetics, biological diversity, socio-cultural values) and the time dependency, eg which time frame will be used for evaluation of effects on non-renewable resources? For further details the reader is referred to OECD 1991b, IIED, Barbier/Markandya 1989, Barbier 1989, Barbier 1990, Michel/Pearce 1990, Pearce/Barbier/Makandya 1988. German readers are referred to Hampicke 1991, Hampicke et al. 1991.

Sources: Biswas/Geping ed. 1987; Roque in: ADB 1986; OECD 1985; Horberry in: DSE 1984

Further readings: DSE 1984; Gassneer/Siederer 1987

Fig. 2-1

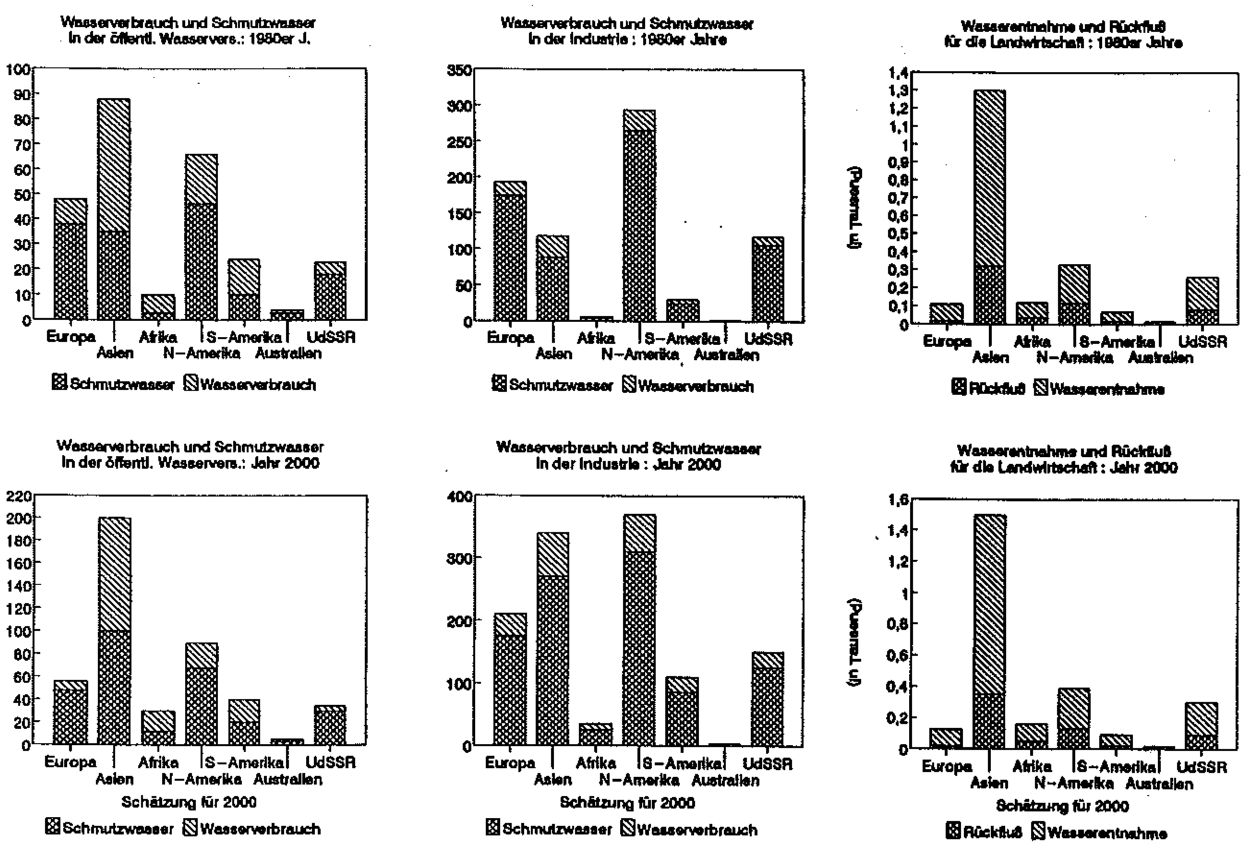
Abb.4-4: Entwicklung des Welt Wasserverbrauchs



Quelle : World Resources Institute, World Resources 1990 - 1991. New York, Oxford

Fig. 2- 2

Abb. 4–5: Wasserentnahme und Schmutzwasser/Rückfluß nach Sektoren, 1980er Jahre und 2000



Quelle: World Resources Institute, World Resources 1990–91, New York, Oxford, 1990

Source: GITEC 1992

2 Impacts on Water Resources

There are three major impacts on water resources, (1) the extraction of water for irrigation from rivers, lakes or groundwater aquifers, (2) the subsurface or surface return flow into ground- or surface waters and (3) changes in water quality of the return flow. These impacts are assessed in the following sections.

General reference with numerous case studies in: Kharchenko/Maddock (UNESCO) 1982

2.1 Irrigation as a Major Water User

2.1.1 Introduction

Irrigated agriculture is typically the **largest** single consumptive water user in both industrialized countries and developing countries (Fig. 2-1). Global figures estimate that irrigation uses is some 2,200 km^3 out of total 3,500 km^3 of total water abstraction (WRI 1990). OECD figures for the late 1980s show that irrigation withdrawals (out of total human use) ammunt to 41% in the USA, 57% in Italy, 66% in Spain and Japan, and 79% in Turkey. In Pakistan, almost 98% of the annual withdrawal is for agricultural use. This high quota may be representative for most arid countries with developed irrigated agriculture, eg countries in the Near East. In subhimud to humid South and East Asia the percentage of agricultural use is also high, ie ranging between 50 % to over 95% of total consumption. The actual annual withdrawal in terms of annual renewable freshwater resources is rather low, accounting for just some 1-18 % (ADB 1991).

A more intense **competition** for good quality water will in future result from increased non-agricultural demands (Fig. 2-2, Tables 2-1 and 2-2) and from increased groundwater extraction by tapping deeper aquifers. It is estimated that irrigation demand will increase by 10% over the next decad (WRI 1990).

References: WRI 1990; German reader: GITEC 1991 (summary on water issues)

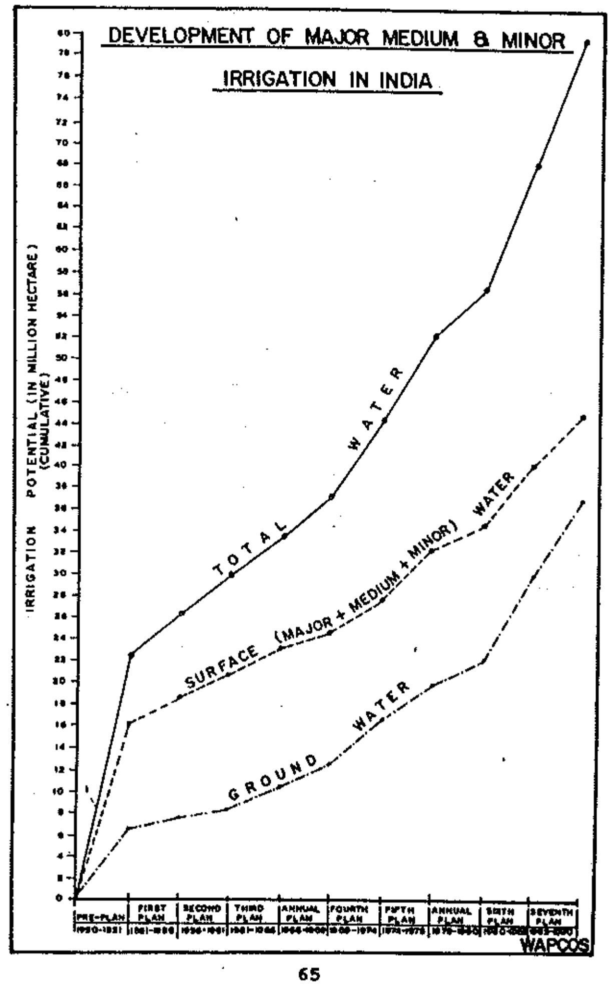
2.1.2 Surface Water Withdrawals

Agriculture uses water from rivers or lakes or human-made canals and reservoirs. It is estimated that agriculture uses some 2,200 km^3 on 227 Million ha anually (Table 2-3). A part of the extracted water returns groundwater or through surface runoff to rivers (see section 2.2) but a larger proportion is lost to the atmosphere through evaporation from the soil surface, water bodies (inundated fields) and evapotranspiration from crops, other plants or aquatic weeds. Return flow is estimated to some 1/4 of total supply, assuming that evaporative uses amount to some 7,200 mm per season (Fig. 2-1; WRI 1990).

Typically, the total farm irrigation supply amounts to some 1 l/s per ha (= 10,000 m^3/ha per crop; double cropping about 15-20,000 m^3/ha) under average management and arid agro-climatic conditions. This amount may be substantially reduced by good water management (high system efficiency, low transmission, conveyance and application losses; on-demand supply) to some 5-7,000 m^3/ha per crop. Overall figures for various continents are shown in Table 2-3a (figures added in the 2nd column).

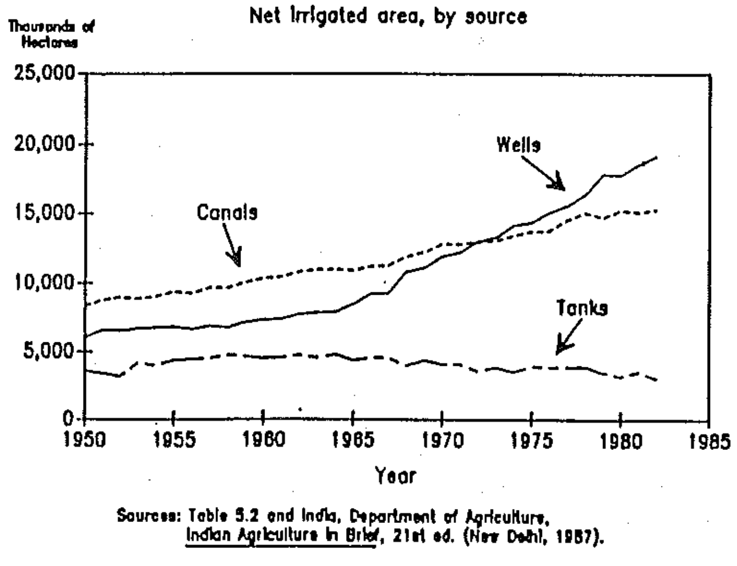
Surface water withdrawal may also have some beneficial effects when a larger proportion of seasonal flood water is used in irrigated floodplains (eg paddy), retarded and returned to the downstream river section and probably subsequently repeatedly used in irrigation. Under conditions of a good quality of drainage return flow, such a system, which covers for example in Japan some 54% of agricultural lands located in watersheds, counteracts floods in lowlands and prevents soil losses, ie reduces sediment loads in rivers (OECD 1991).

Fig. 2-3a



Source: INCID 1991

Fig. 2-3b



Source: Meinzen-Dick/Svendsen 1991

2.1.3 Groundwater Withdrawals

Groundwater plays an increasing role in water supply for irrigation. Over the past two decades many surface water sources are already fully developed and groundwater aquifers are increasingly used for supply, although groundwater irrigation has a long tradition, eg in the Indus valley since some 2,500 years ago (APO 1991). For example, the groundwater utilisation in Asian countries is shown in Table 2-3b. Hroundwater use has a long tradition in Asia, and Detailed figures for selected countries are illustrated in Table 2-3c.

Case Studies

In India, the area irrigated by groundwater increased from 12 M ha in 1969 to 28 M ha in 1986. Thus, almost 50% of the total irrigated area of 62 M ha in 1986 was irrigated by groundwater (INCID 1991) (Fig. 2-3a). Detailed figures for uses by different sources are shown in Table 2-3 d.

In North China some 168 M mu (1 mu = 1/15 ha) are irrigated by shallow wells and 12.5 M mu by tubewells (some 401 M mu are irrigated by surface water). In North China the annually pumped groundwater amounts to 45-50,000 MCM and about 35-40 000 MCM are used for irrigation, which was 90% of shallow groundwater. It is estimated that the groundwater is exploited by 55 to 70% in most northern provinces (CNCID 1991). Some 2.2 M tubewells were installed (APO 1991).

In Iran, the present distribution of irrigation water is as followsgroundwater 30 MCM, surface water by traditional methods 18 MCM and surface water supplied by modern dams and irrigation structures is 13 MCM (IIMI 1987)

In many arid and semi-arid regions, groundwater is the only reliable source of irrigation water supply. However, in these dry regions, one major concern is the withdrawal in excess of the long-term rate of recharge, called **mining** or **overdraft**. Groundwater mining for irrigation is common in arid and semi-arid areas in the USA, the| Near East, North Africa, India, Pakistan, and Australia, but it may also be practiced locally in other countries. Increasing shortages are reported in many locations in the southwestern USA (Canter 1986). Since the efficiency of water use is rather low in irrigation there is a growing perception in many countries that fossil groundwater reserves or overdrafting should be restricted to more important industrial activities or be reserved for irrigation of high value crops.

Mining of **fossil groundwater** is common in most arid areas in the Near East and North Africa. The large scale abstraction commenced in the 70s with development of new pump technologies and the availability of huge financial resources in some oil-exporting countries such as Libya, Algeria and Saudi Arabia. In most locations the groundwater is either used for the development for settlement schemes of traditional farmers or for production schemes which typically produce staple foods to substitute for grain imports. Ocassionally other crops, fruit trees and ornamenals may be grown. Some large scale groundwater transfer projects convey fossil groundwater to the main population and agricultural centres, eg in Libya. In general, large scale development schemes using non-renewable groundwater resources are under debate, but conservation objections are usually from outside (eg. Allan 1991). Responsible agricultural and economic planners of these countries regard groundwater as a resource similar to oil.

Groundwater abstraction is also practiced in subhumid climates under seasonal irrigation. Here, groundwater is considered as a **renewable** natural resource, eg in Bangladesh:

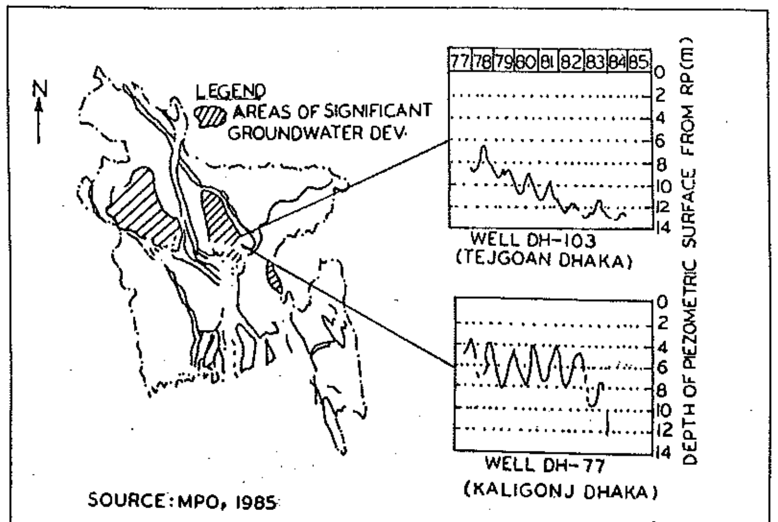
Case Study

Bangladesh: it is estimated that in Bangladesh the net groundwater abstractions for irrigation amount to 5,227 MCM/a, whereas domestic and industrial uses are of about 908 MCM/a (Khan 1988). The annual groundwater recharge is about 24,400 MCM with a total usable groundwater quantity of about 47,700 MCM (1987).

In 1979, some 24% of the total net irrigated area was supplied with groundwater, ie some 0.35 M ha out of 1.1 M ha (Khan 1988).

In 1985, the irrigated area supplied by groundwater increased to 1.2 M ha, ie 50% of the total irrigated land of 2.5 M ha. There are about 20,000 deep tubewells, 156,000 shallow tubewells and 285,000 manually operated shallow tubewells in operation.

Fig. 2-4 a, b



SOURCE: MPO, 1985

FIG. 4 THE EFFECTS OF GROUNDWATER ABSTRACTION ON GROUNDWATER LEVELS.

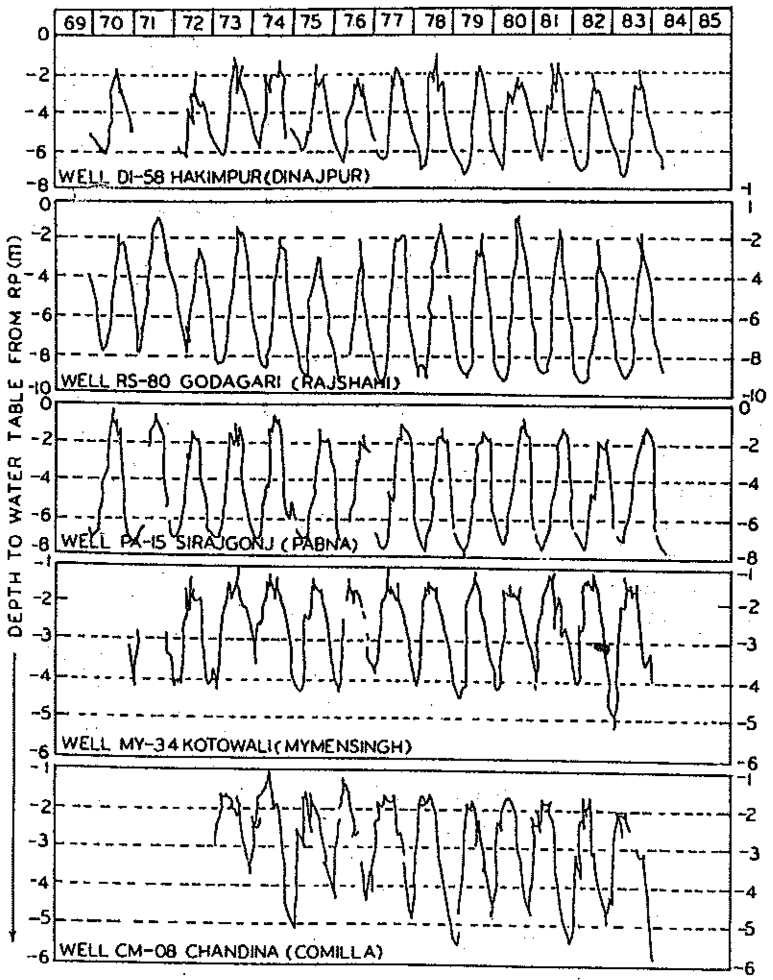


FIG. 2 WELL HYDROGRAPHS SHOWING GROUNDWATER LEVEL FLUCTUATIONS (SOURCE MPO, 1985)

Source: Khan 1988

By 1990 some 3.1 M ha were under irrigation, ie about 70% of the irrigable land. Most newlands are developed by groundwater exploition.

In 1987, some 21% of the available groundwater was used for irrigation on a national scale. However, in some areas the groundwater abstraction resulted in serious decline of water tables. Groundwater levels typically decline during the dry season due to irrigation demands (intra-annual decline), as a temporary overdaft. In many areas, however, replenishment during the wet season does not restore the previous watertable level and a continuous inter-annual decline occurs (Fig.2-4a,b). In some northern parts of the country many shallow tubewells, including drinking water wells, have failed because the pumping head has increased beyond the maximum suction lift limit of centrifugal pumps. Furthermore, some 40,000 ponds have almost dried up (1987) resulting in acute shortages of surface water for irrigation and aquaculture. In addition many traditional fruit tree areas and non-irrigated croplands suffered from the groundwater decline.

Groundwater overdraft is a typical feature of **commercialized farming** areas or of large scale government operated development schemes because it often requires increasing financial investments and operational costs with increased abstraction volumes and pumping depths. However, in areas with easy and cheap access to groundwater, overdrafting may also occur in minor irrigation projects, for example in India and Pakistan (Shah 1990; Toulimin/Tiffen 1987), especially under supportive government policies which make subsidies and credit available for private groundwater development. With new technologies available for groundwater development to more farmers, incentives for private farmers are favourable to promote crop intensification. Consequently, more irrigation areas are developed, up to three crops a year are possible and new crops with higher water demands replace traditional crops (or varieties). Typically, little attention is given to groundwater overdraft until the often limited aquifers are fully exploited or negative impacts are recognized:

- decline in **water levels** with negative impacts on ecosystems and/or increasing development and operational costs for future domestic, agricultural or industrial uses
- reduction in **river flows** caused by reduced throughflow, ie discharge from hydraulically connected shallow unconfined groundwater aquifers, with detrimental impacts on navigation, fishery and other downstream users. In larger watersheds the increasing abstraction of water from upstream locations may make the river baseflow more dependant on the aquifer strorage in the floodplains (eg in India-Bangladesh); hence, excessive groundwater abstractions near the river are usually directly at the expense of river flow
- interference in traditional downstream **water rights** (to some limited extent also upstream affects); groundwater decline may alo have adverse socio-economic aspects because well deepening is typically practices by the 'well-off farmers'
- land **subsidence** problems caused by water level decline: damages to buildings, hydraulic infrastructure, eg flood protection works, irrigation and drainage canals. Severe damages are known for example from Japan, Mexico, Taipeh and USA, eg the Southern Great Valley of California. where maximum land settlement has exceeded 4.5 m. Bangkok City area has also experienced a subsidence of about 1 m. Todd reported an average subsidence ratio of 1/13 indicating that 1 m land subsided for every 13 m lowering in water table (Khan 1988)
- water **quality** problems caused by extraction of fresh water lenses, eg depending on geological stratification
- in coastal areas and deltas **intrusions** of saline **seawater** may be experienced, eg in Egypt, India, Pakistan and Bangladesh (Shah 1990; Birch/vanWonderen 1990, Khan 1988; ODU). In Bangladesh, saline seawater intrusions are reported from various coastal districts and several production wells had to be abandoned (Khan 1988).

Sources: INCID 1991; CNCID 1991; Shah 1990; Toulimin/Tiffen 1987; Khan 1988

Fig. 2-5

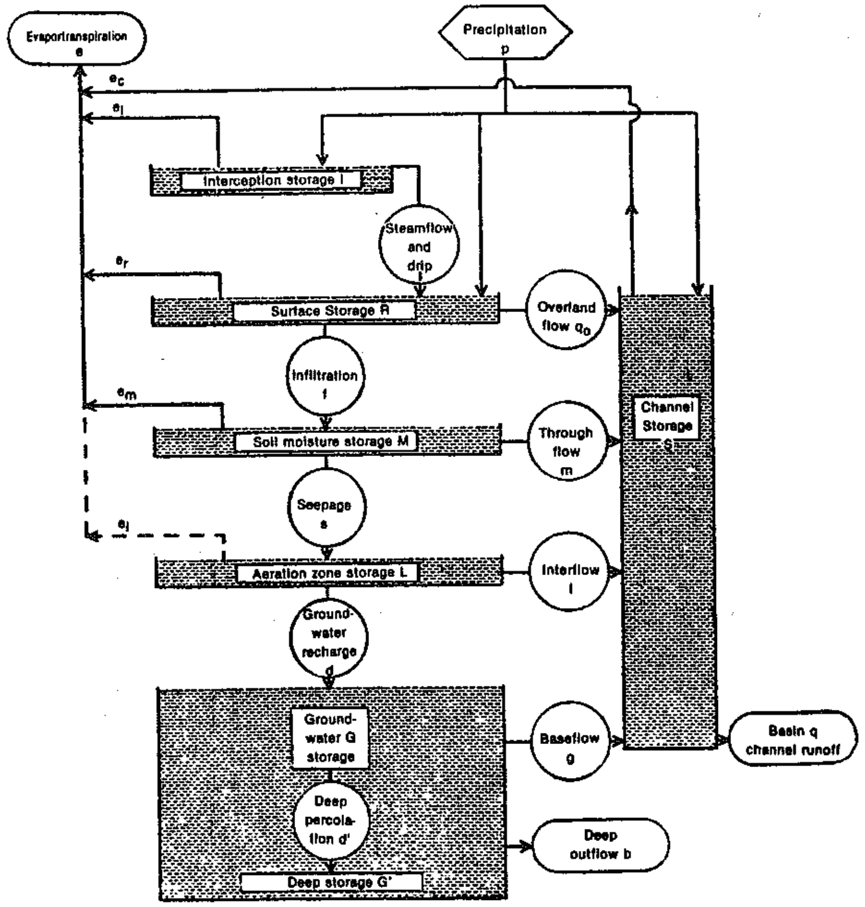


Fig. 35-1. Conceptual view of the basin hydrologic cycle depicting inputs, outputs, storage units, and transfer processes (More, 1969).
Source: Tanji / Hanson, in: Stewart et al. 1990 p. 1058

Source: Stewart et al ed. 1990

2.2 Irrigation Surplus and Drainage Return Flow

2.2.1 Introduction

This section focuses on the type, quantity and quality of irrigation surplus and drainage return flows as affected by irrigation. Details on agricultural and water management measures for control or reuse of these flows are given in Part II section 2. Further cross-references should be made to relevant sections dealing with water quality (2.3), soil salinity (3.1), soil erosion (3.3), and wastewater applications (3.6).

The practice of irrigation is to provide water to supplement effective rainfall in order to meet the evapotranspiration needs of crops. The actual relation between rainfall and irrigation depends on the climate and the soil water balance. Irrigation is practiced in desert, arid, semiarid and subhumid climates (Table 2-4 a,b). Thus, drainage return flows may occur in various agro-climates and may become mixed to varying degrees with runoffs from rainfall. The basin hydrological cycle is defined by rainfall plus change in storage which equals outflow plus evapotranspiration (Fig. 2-5).

Surface and subsurface return flows, either wanted or unwanted, are considered as significant impacts of irrigation activities and as significant components of water resources. In the past, irrigated agriculture discharged its return flows to the hydrologic system with little or no restrictions and constraints. Increasing interest is now being placed on these return flows because of

- decreasing return flow quality which includes salinity, sediment load, nutrients (mainly N and P), pesticide residues, and organic or inorganic toxic or harmful trace elements,
- increasing perception that irrigation may not efficiently use water resources,
- extension of irrigated areas in the past decades which resulted in a sharp rise in the total water volume used by irrigation.

All this will force irrigatators to use water more conservatively in future. This trend is more acute in industrialized countries (eg in the USA, Australia) with higher competition for water by various sectors of the society, but with rapidly increasing growth of irrigation this will also be evident in developing countries in the near future (eg Egypt).

2.2.2 Diversion and Return Flow

Whenever water is diverted from a river or extracted from groundwater aquifers for irrigation use, the quality of the return flow declines. The degraded return flow then mixes with the natural flows in the river system, except in arid areas, where the drainage water may be conveyed straight to an evaporation lake. This mixture is then available to other downstream users (agricultural, industrial, domestic, ecological systems) to satisfy their water needs. This process of diversion and return flow may be repeated several times along the course of a river.

The degree of degradation depends on:

i) quantity of total river flow (dilution or concentration effects),
ii) quantity of extraction (in % of total flow),
iii) quantitiy of return flow (in % of total flow),
iv) quantity of pollutants in river flow upstream,
v) quantity of pollutants in return flow (eg total salts, sediments, specific ions).

If water is diverted several times from the major rivers, the water typically shows a continual degradation of quality in the downstream direction. If water resources in the lower reaches are utilized without effective controls, the quality in the lower reaches of the ri-

Fig. 2-6

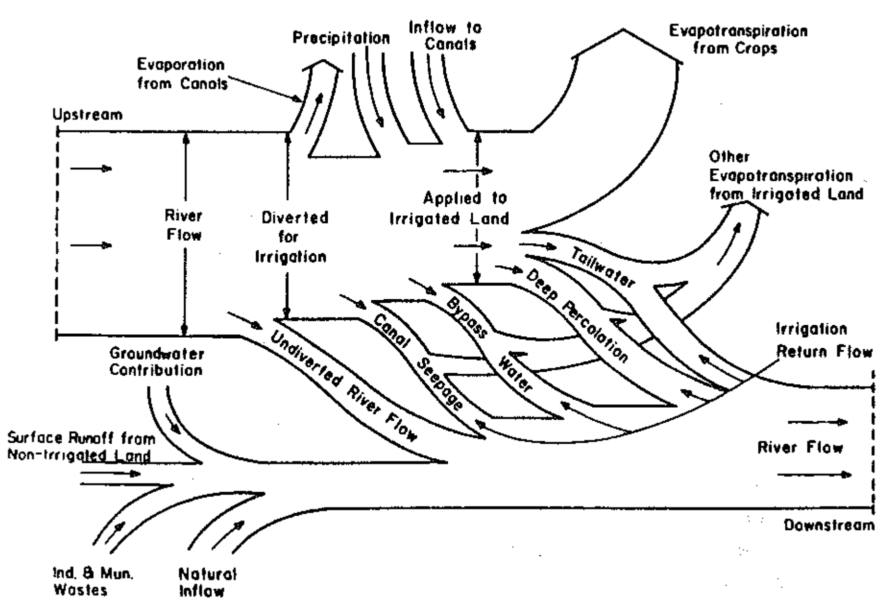


Fig. 35-2. Conceptual diagram of the irrigation return flow system for a given reach of a river system (Utah State Univ. Foundation, 1969).

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Fig. 2-7

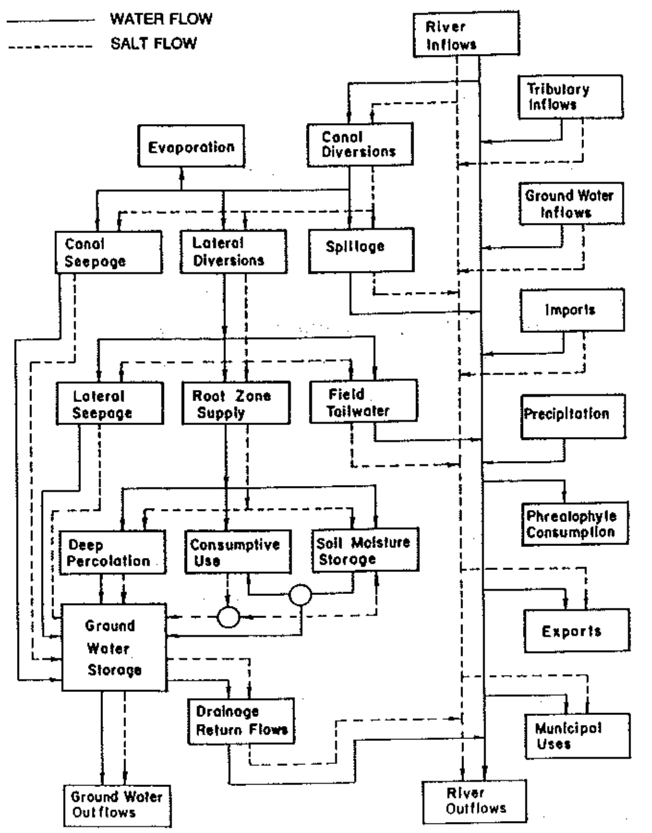


Fig. 35-3. Conceptual diagram of water and salt flows for a generalized hydrosalinity model (Hornsby, 1973).

Sources: all in Stewart et al ed. 1990

ver are likely to become degradated to such a point that the remaining flows are unsuited for many users, and previous uses may no longer be possible.

The irrigated agricultural system can be conceptualized in a similar manner (Fig. 2-6), depicting a reach of a river from which water is diverted for irrigation, and evapotranspiration (ET) losses and a number of return flow paths to the river are identified. Another irrigation system model visualized water and salt flows based on on-farm components (Fig. 2-6). In following these models, the irrigation system consists of the following **hydrological subsystems**:

- water delivery system (reservoirs, diversions, wells),
- water conveyance (irrigation main canals),
- irrigation distribution system (secondary and/or field canals),
- soil-water system (storage),
- drainage system (surface and subsurface),
- groundwater system (aquifer characteristics).

The components typically assessed in irrigation projects are:

rainfall; water supply (from intake); operational spill: distrubution losses, operational wastage; surface and subsurface return flows (marked in the flow diagram).

Generally, there are methodological problems in measuring components such as surface runoff from fields unless the tailwaters or other losses are collected immediately behind the fields (eg Tanji/Hansson 1990). Sometimes, tailwaters are reused for irrigation within the same command area. Another bias in analysis may derive from the differentiation between storm and irrigation return flows; a separation is often impossible for areas where significant rainfall occurs during the irrigation season. Time lags and long distances between measurement stations can also complicate assessments.

2.2.3 Type and Quantity of Return Flow

The quantity and type of irrigation return flow from fields mainly depends on the irrigation application method and its operational management. Irrigation return flow into river systems may be via the following **routes**:

(i) disposal of drainage water from subsurface drainage systems via collector drains,
(ii) disposal of drainage water from open field drains and collector drains,
(iii) surface run-off from irrigated fields either (1) directly into the river or (2) via natural channels or drainage canals,
(iv) deep percolation, finally intercepted and collected by the river or its tributaries.

Return flows can be **beneficial** or **detrimental** to the different water users:

- poor quality water may have negative impacts to downstream users, either human-made or natural ecosystems; it contains suspended sediments, soluble salts or agro-chemicals,
- good quality return flow - either planned or incidentally - has typically beneficial off-site or downstream effects because a part of water extracted for irrigation is returned back to the surface (or groundwater) hydrological subsystem with insignificant quality changes. The term good quality is defined in relation to needs of various users (see Part II section 2.1),
- stagnant water caused by surface runoff from fields is detrimental due to increased health risks, and the development of waterlogged and saline soils in downslope areas; similar effects are often caused by stagnant rainwater pools.

Aspects of beneficial drainage water reuse are treated in depth in Part II section 2. Water reuses may occur at two spatial dimensions or levels:

- on-site, ie within the farm area itself,
- off-site, differentiated by various downstream users, or by hydrological subsystem levels: regional, river basin, or interbasin levels.

Typically, beneficiaries use slightly or mildly affected return waters for pasture land, for pasture lands, livestock water supply, wetlands/ wildlife habitats, for domestic and industrial applications, fisheries, navigation, recreation, etc. This is actually the case in most large river basins in Asia, Near East, and the USA.

Further beneficial effects may be attributed to

- repulsion of saline water in tidal habitats and coastal groundwater bodies,
- groundwater recharge,
- maintenance of flow in rivers during low flow season.

Irrigation return flows consists of two **components**:

(i) **surface** irrigation return flows, either from conveyance, distribution canals or tailwaters from surface applications: irrigation water that does not infiltrate but runs off the lowest portion of the fields and which is drained off by open ditches or which flows directly into a watercourse or reservoir, or remains as stagnant pools in depressions. In some irrigation systems tailwater losses are planned, eg in cascade rice terraces or specially designed basin irrigation systems,

(ii) **subsurface** irrigation return flow: water that has drained through the rootzone and which is intercepted and removed by drains or which moves laterally along the hydraulic gradient. A certain quantity of subsurface flow is intentional in many irrigation systems where salts are present in the irrigation water. These must be removed from the rootzone to maintain productivity for crop growth (see section 3.1, Part II sections 2.4 and 3.3).

Surface return flow occurs when the application rate exceeds the infiltration rate of the soil on an inclined area (see also sections 3.3 and Part II section 2.4). Factors which determine runoff under sprinkler irrigation include application rate, uniformity of application, total amount applied, tillage system, crop type, soil infiltration rate (compaction and aggregation), and field topography. Under surface irrigation systems the length of run, slope of field, and infiltration rates are more important. Subsurface return flow is caused by overirrigation and by non-uniform applications when water is leached through the root zone into the groundwater at some depth.

Excessive seepage losses from canals and laterals (ditches) can be attributed to poor operations and/or the use of unsuitable construction materials or earth canals. In some large schemes these losses may account for 30-50% of the total water supplied (Bos/ Nugteren 1974), whereas minimum losses in the range of 10 to 15% are attainable. Despite the fact that these losses are uneconomic, they do not usually present a pollution hazard to surface or groundwater unless a large proportion evaporates and thus increase the salt concentration of the return flow. These losses, however, often contribute to rising water tables in the command area and waterlogging and salinity build up within the rootzone (see section 3.1).

The attainable **application efficiency** at the field level, which is a direct measure of water losses, would theoretically be almost identical for properly designed and managed irrigation systems, but in practice there are immense variations due to soil properties, conditions of irrigation, drainage and water management (see following list).

Potential Attainable Uniformities and Application Efficiencies of Irrigation Systems

System	Uniformity	Application Efficiency	Typical Efficiency
	---------- %	------------	-- % --
Drip/Trickle	80-90	75-90	80-90
Sprinklers			
periodic move	70-80	65-80	60-70*
continuous m.	70-90	75-85	
solid set	90-95	85-90	
Surface			
furrow	80-90^	60-90#	50-60*
border	70-85^	65-80#	
basin	90-95^	75-90#	55-60*

^ soil variability may increase the uniformity by 5 to 10 %

higher values for tailwater recovery systems or cutback flow

these efficiencies represent USA-experience; the application efficiency is defined by the ratio of the average amount of water stored in the root zone to the amount of water applied

* values of field application efficiency determined by Bos/Nugteren 1974 in developing countries

In surface irrigation systems a high deep percolation rate is often unavoidable, because the minimum application is typically 70-1000 mm which exceeds the water holding capacity of many sandy soils.

Source: Tanji/Hanson 1990 in: Stewart et al 1990; further figures are given in Kharchenko/Maddock 1982:33

In general, both types of return flow are prominent characteristics of surface (gravity) flow systems as compared to pressureized systems (sprinkler, spray, drip) with typically higher uniformity and lower application rates. Tanji/Hansen (1990) provide the following figures for surface return flow:

* furrow irrigated rice fields in California: 19% of total surface inflow,
* furrow irrigated tomato in California: 29% runoff.

Further quantification of return flows are given in the next section in the context of water quality changes.

Sources: Tanji/Hanson in: Stewart ed. 1990

2.3 Surface and Groundwater Pollution

2.3.1 Introduction

This section addresses the type and severity of pollution problems induced by irrigation, whereas Part II sections 2.2, 2.3, 3.4 and 5.2 provide an overview of present techniques and methods to minimize potential water pollution impacts.

Irrigation may lead to water quality degradation, eg through an increase in salinity levels. All water contains dissolved salts and the consumptive use of irrigation water by crops always results in an increased concentration of total dissolved solids (TDS) in the subsoil drainage water. Fertilisers and pesticides likewise are not totally removed by crops,

Fig. 2-8 a

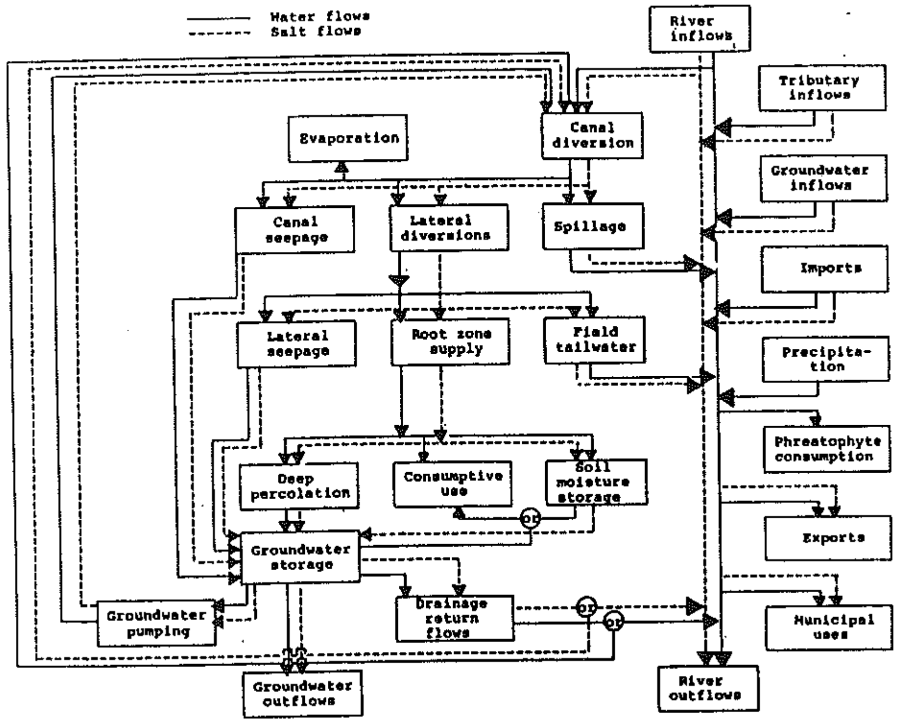
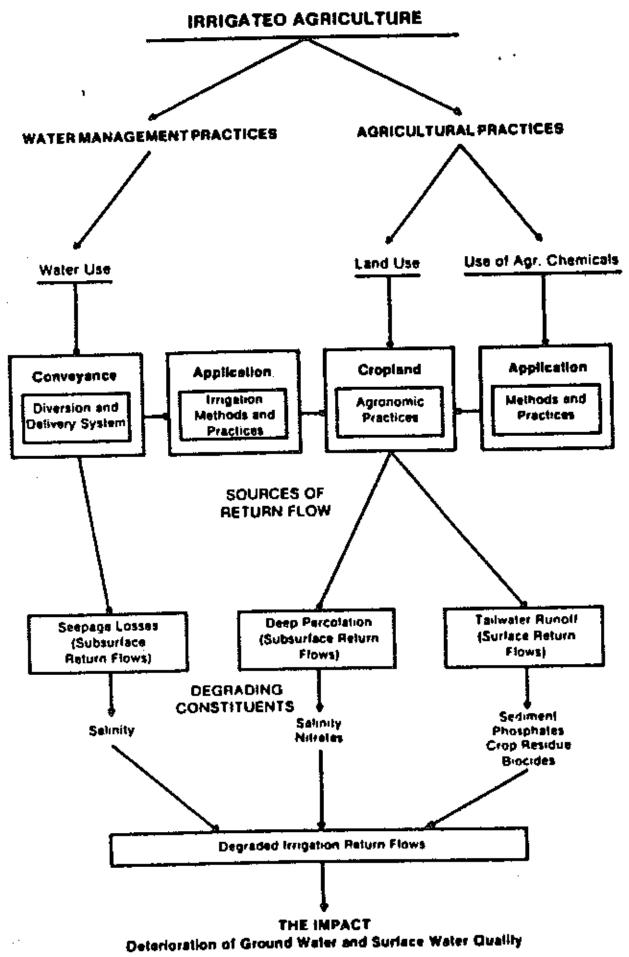


Fig. 2 Water and salinity flow diagram for an irrigated area

Source: FAO (IDP 31) 1979

Fig. 2-8 b



Source: Canter 1986

Figure 13: Water Quality Problems from Irrigated Agriculture (U.S. Environmental Protection Agency, 1978)

transformed to harmless constituents, or degradaded before reaching the rivers and groundwaters and eventually the consumers of these waters. Agro-chemical but also organic fertiliser residues are an unavoidable consequence of agricultural production. At the same time, the public demands increased quantities of water and high quality foodstuff, safe drinking water, and maintenance of wealthy natural ecosystems.

Polluted irrigation return flows will usually have detrimental impacts on the **downstream** water resources. The significant intensification of agriculture in both developing and industrialized countries in some cases caused an increase in erosion, pollution of water, and the contamination of soils. Some generalization is possible about the extent and significance of these processes which ultimately lead to the degradation of soil and water resources (eg OECD 1991. Environmental Data). GITEC (1992) prepared a world-wide list of water quality assessment (Table 2-5a). However, the actual extent of pollution in a specific situation may well differ from these generalised values and conditions are rapidly changing. Unfortunately, reliable and detailed investigations are very limited for developing countries in general and for irrigation projects in particular. Only recently, in some intensively utilised areas such as the Nile Delta have programmes of water quality monitoring been enforced (eg El Quosy in: ICID 1990). International hydrological monitoring programmes are now focusing on establishing reliable data bases, for example the International Hydrological Programm (IHP), Operational Hydrology Progamme (OHP), Global Environmental Monitoring System (GEMS/WATER), World Climate Programme (CP/WATER).

Pollution occurs from the following **sources**:

- runoff into streamflow and groundwater recharge from **non-irrigated farmland** (rainfed crops, pastures): 47% of land in USA from which streamflow is generated
- runoff into streamflow and groundwater recharge from **irrigated fields**: 2% of land in USA: 4.4% of streamflow (may be higher)
- streamflow recycling from **industry** wastewaters: 12% of river streamflow
- streamflow recycling of **domestic** wastewaters: 3% of streamflow.

These figures are estimates and in individual watersheds the values for comparent catchments may **deviate** considerably from these nationwide figures for the USA:

- in upper watersheds, the human extraction of water for irrigation is typically lower than in lowland watersheds where more favourable conditions for irrigation on the floodplains exist
- the relative importance of irrigation as a water user is much higher in developing countries than in most industrialized countries because industrial and electrical cooling, which amounts to some 85% of total industrial uses, is not widely used.

Sources: WRI 1990; ADB 1991; OECD 1991; Chanlett 1973

Irrigation (or agricultural) induced pollution is regarded as a **nonpoint source** of pollution. Agricultural water pollution sources are

(i) **fertilisers** and dissolved salts which are derived from fertilisers
(ii) soluble **salts** in the irrigation water itself or soluble soil constituents (see Fig. 2-8a)
(iii) **pesticide** residues
(iv) degradadable **organic wastes**, mainly from livestock production (eg feedlot runoff).

Typical **pathways** which result in deterioration of water quality are shown in Fig. 2-8b. Typical concentrations of agricultural pollution sources in comparison with other pollution sources are shown in Table 2-5b-d.

Hydrological system **models** are used to assess and to simulate impacts from agricultural sources and to evaluate their significance as compared with natural sources, point sources and non-point sources. These models are based on monitoring data and may also be

Fig. 2-9

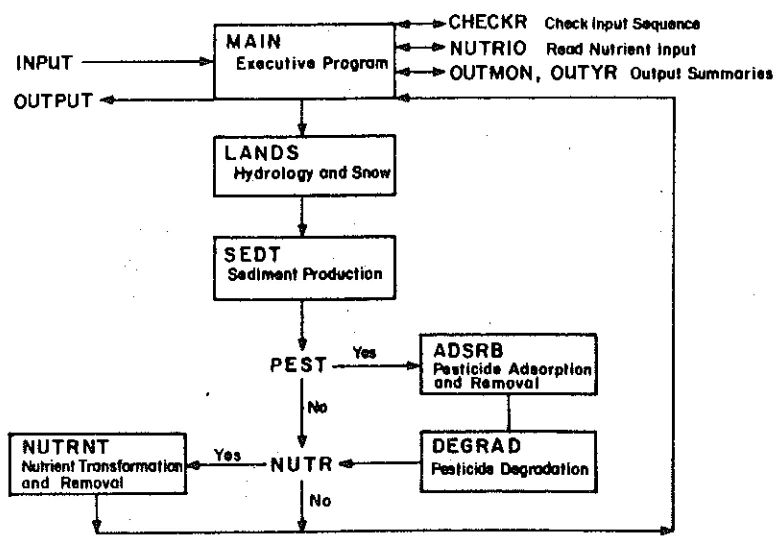


Fig. 14.18. ARM model structure and operation.

Skogerboe 682

Fig. 2-10

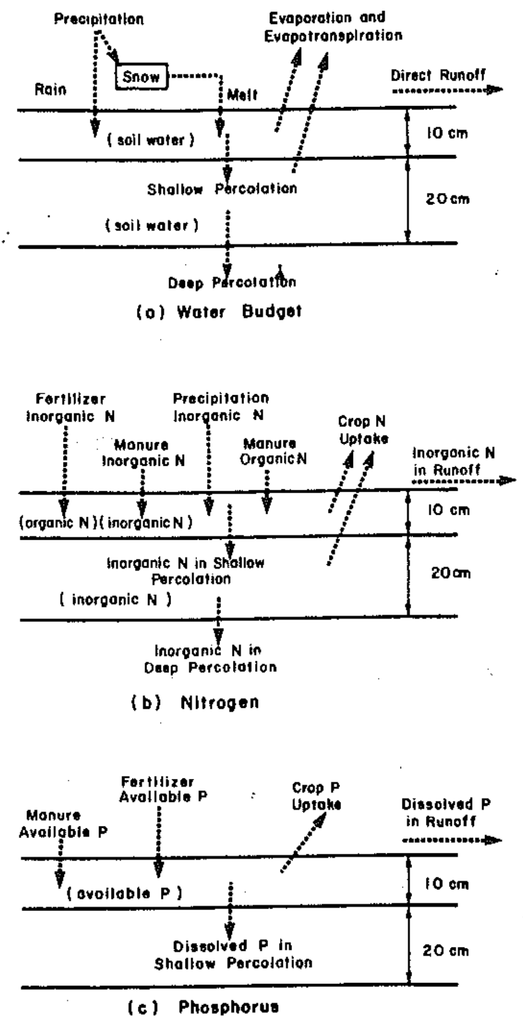


Fig. 14.20. Cornell Nutrient Simulation Model.

Fig. 2-11

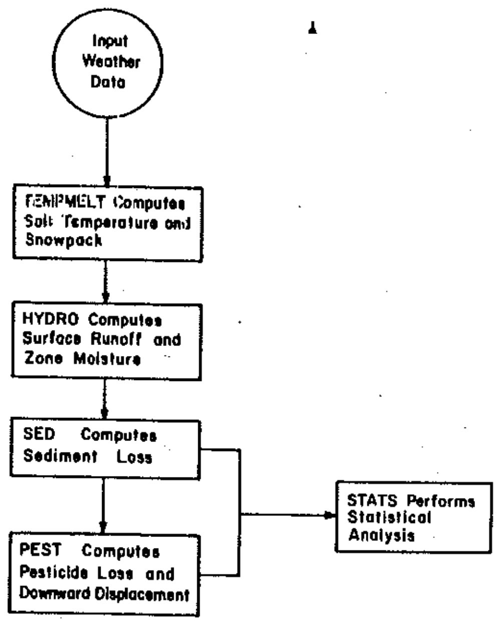


Fig. 14.21. Flow chart for Cornell Pesticide Model.

Sources: all in Joergensen ed. 1983

well suited for development of 'best management practices'. Some of these models are described and reviewed in Biswas et al (1991), Canter (1986) and Skogerboe/Walker/Evans (in: Joergensen ed. 1983). Many models are applicable to both irrigated and non-irrigated agriculture. For example,

* Agricultural runoff management model (ARM) simulates nutrient, salt or pesticide movements in the watershed by water or sediment; it consists of five submodels (Fig. 2-9)
* Cornell nutrient simulation model (CNS) is deterministic and based on daily water balances, daily erosion calculations and monthly N and P inventories; Fig. 2-10
* Cornell pesticide model (CPM) consists of five sub-models (Fig. 2-11)

Sources: Skogerboe/Walker in: Joergensen 1983; Canter 1986; Biswas/Khoshoo/Khosla 1991

2.3.2 Salts in Irrigation Return Flow

It is estimated that agriculture including irrigation is responsible for virtually all non-point pollution in surface waters in the USA (USA, Canter 1986).

Whilst the salinity removal from the command area may be a beneficial on-site effect (except in sodic soils), it has detrimental off-site impacts. Agricultural, domestic or industrial downstream users have the burden of increased salinity derived from irrigation. The impacts of water salinity on crop yields are discussed in sections 2.6 and Part II section 3.3. Important processes which lead to saline irrigation return flows are

(i) over-irrigation and nonuniform field application which leads to excessive leaching, from at least part of the field
(ii) major reclamation activity of naturally saline soils, for example desert soils, and soils deteriorated by irrigation,
(iii) residual salt enrichment in soil solutions resulting from evaporation (through the soil surface and plants) of irrigation water. Under good irrigation management some 60% of the irrigation water is used by crops for growth. Salts are removed to a lesser extent thus leaving higher concentrations in the remaining solution (see section 3.1)
(iv) natural saline deposits which are dissolved as drainage or groundwater water percolates through them.

Analysis of impacts

An assessment of the hydrological impacts induced by irrigation must be based on inflow-outflow analyses. For example, regional watershed modelling as presented by Skogerboe/Walker/Evans (in: Joergensen ed. 1983) can be used. Basic data are river and tributary inflows, subsurface inflows, irrigation inputs, surface and subsurface outflows, reservoir operations, and the associated water quality parameters (eg salinity, N-contents) of each of the above.

These modelling methods also allow 'best management practices' and their effects on the hydrological cycle to be identified. The planning framework for developing the best management practices for one specific irrigation area is shown in Fig. 2-12 (opposite next page). Unfortunately, in many irrigation projects most of these data are not available as direct measurements. Estimates are the most common practice in evaluating the impacts of irrigation projects on the hydrological cycle.

Case Studies

Iraq, Tigris: Irrigated agriculture has long been a major user of water in the Tigris river system which has an average annual flow of 38 MCM. Agricultural activites, in turn, are a significant source of increased salinity along the river course. Salts and other chemical constituents are derived from dissolved mineral salts from soil materials or dissolved evaporation residuals which are transported in irrigation return flow, and in modern times from pesticides and fertilisers. In addition, some 1.9

Fig. 2-12

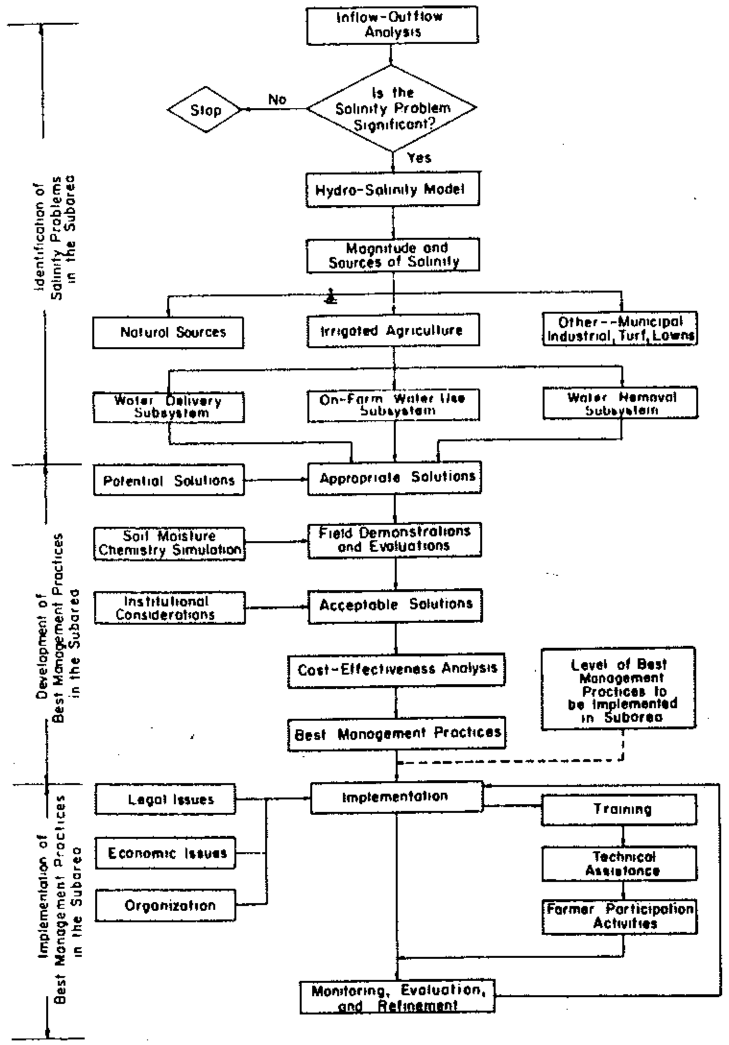


Fig. 14.5. Planning framework for developing best management practices for only one irrigated area.

Source: Joergensen ed. 1983

Fig. 2-13 a, b

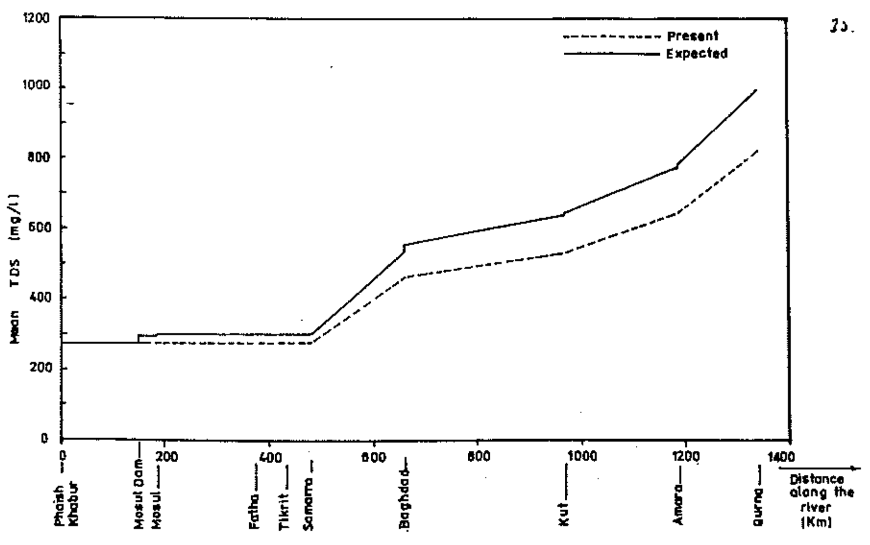
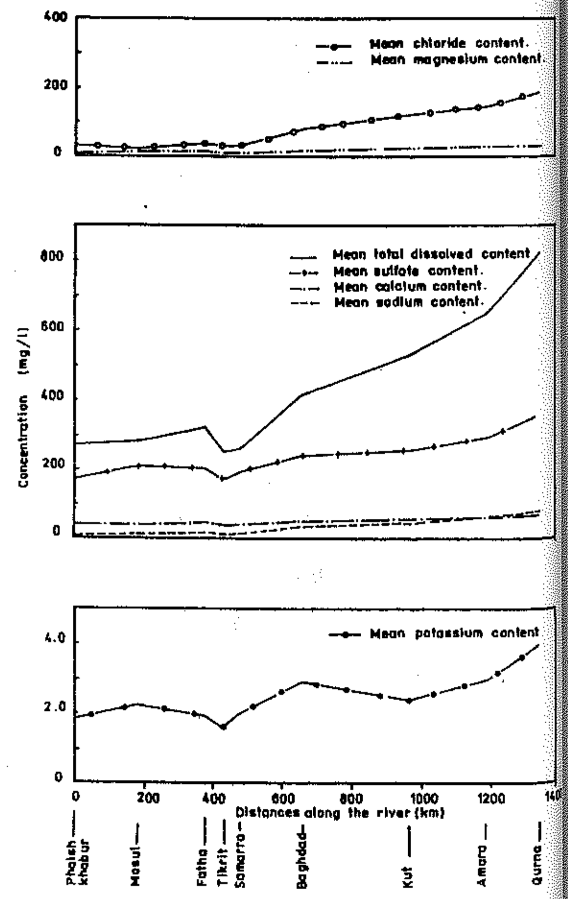


FIG. 4: Expected salinity (TDS) variation along Tigris river.



Source: ICID (STS-C14) 1991

MCM of industrial and municipal wastewaters are annually discharged into the river system without treatment (excluding Baghdad since 1990). By 1995 it is predicted that the total water requirement will amount to 63 MCM, and the total water disposal will be 22 MCM. About 50% will be derived from irrigated lands.

The electrical conductivity (EC) of drainage water from these irrigated fields ranges from 9 to 19 dS/m. During reclamation, the EC of the leaching water may reach 30 dS/m. Return flows from flooded fields (mainly rice) have EC values ranging from 1.1 to 2.5 dS/m. (Dimensions dS/m = mS/cm = mmhos/cm)

River water analyses show an increase of total salts and individual ions: Fig. 2-13 a, b.

Source: Abdel-Dayem et al. in: ICID (STS-C14) 1991 Beijing

Egypt, Nile Delta: Here, irrigated agriculture is the main user of Nile waters with about 90% of the irrigation water is supplied from the river. In 1988, total irrigation deliveries to the Delta amounted to some 34,000 MCM/a, of which some 2,600 MCM/a were derived from drainage backflow. In some new Eastern Delta projects drainage water may amount for 50% of the total water applied. Reuse of drainage water should increase to 7,000 MCM/a by the year 2000. The present average salinity of re-used water was 1.4 dS/m in 1988; drainage water with less than 1 dS/m is used directly for irrigation, others being blended with Nile water. The average Nile water salinity is 0.35 dS/m (Delta inflow) (see also section 11)

Source: Al-Layala/Fathalla in: ICID 1984. Brazil; see also: El Quosy in: ICID 1990

Others: Data for Murray-Darling River Basin (Australia) and Colorado River (USA) are shown in Fig. 2-14 a and b, respectively (see opposite next page).

Further readings: Westcot in: Hoorn 1988; French ed. 1984

2.3.3 Nitrogen

Nitrogen losses from agricultural land may occur directly from surface **runoff** into surface water bodies or as **leaching** losses to groundwater. Losses are typically associated with high or inefficient N-applications and inadequate measurs to prevent soil erosion. N-fertilisers may even be removed before they can be taken up by plants.

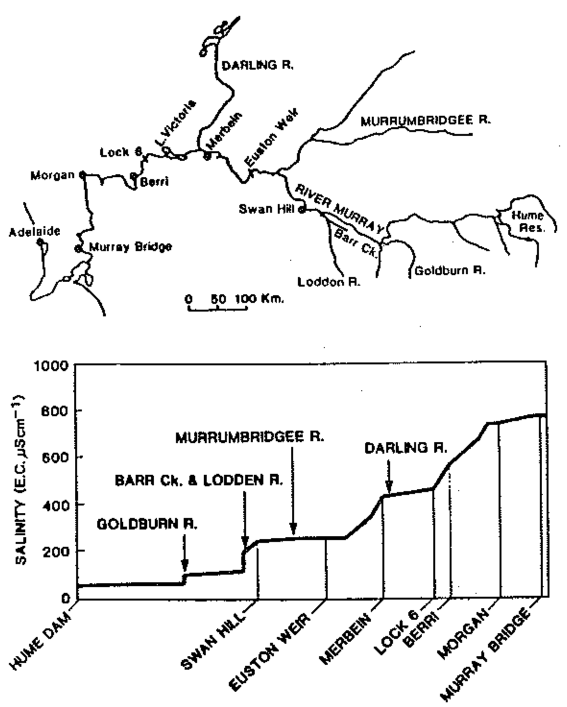
While most industrialized countries are experiencing rising trends in nitrigen levels in ground- and surface waters, with concentrations sometimes exceeding the critical value (drinking water standard) of 45 mg nitrate/l, there are still very few reports of serious N-pollution in developing countries, though this may reflect a lack of investigation. With regard to irrigation, high nitrogen concentrations in waters represent a (usually wanted) supplementary supply of nutrients, eg in domestic wastewaters.

It is estimated that agriculture including irrigation, contributes about 40-45% of the total nitrogen and phosphorus non-point pollution of ground- and surface waters in the USA (Canter 1986).

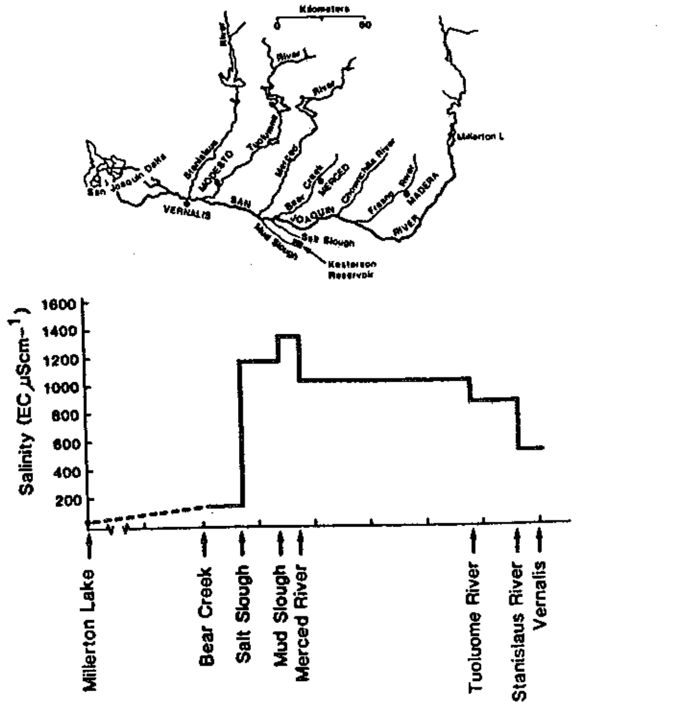
Sources of **non-point** N pollution in developing countries may be open defaecation, latrines or untreated sewage from small settlements. In some areas, livestock wastes may contribute to non-point pollution (Loehr 1976). Usually, high concentrations of nitrates are combined with faecal coliform bacteria which clearly indicates human and animal wastes as the pollution source. Factories may become important point pollution sources in many developing countries due to either poor sewage treatment standards or the complete lack of treatment (Conway/Pretty 1988).

Excess nutrients may lead to accelerated **eutrophication** of surface water bodies. At high nurtient concentrations, algae populations flourish (blooms) and subsequent concentrations of O_2 in rivers and especially in reservoirs results in fish habitat deterioration. The aest-

Fig. 2-14 a, b



Average salinity for August - April for the period 1977-1983 at various points along the River Murray in Australia (adapted from O'Brien, 1984 with permission from Butterworth Publishers, Stoneham, MA)



Median salinity for June - September 1985 at various points along the San Joaquin River in the U.S.A. (adapted from Gilliom, 1986)

Source: Westcot in van Hoorn 1988

Fig. 2-15

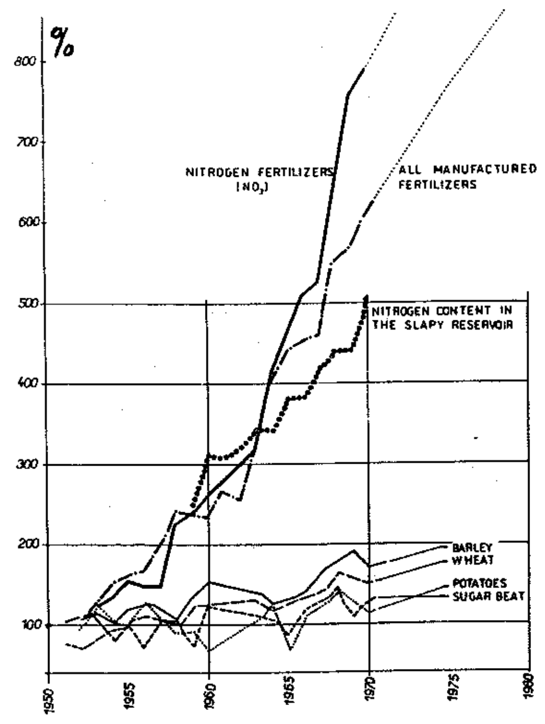


Fig. 85. Water pollution due to fertilizers.

Source: Holy 1980

Fig. 2-16

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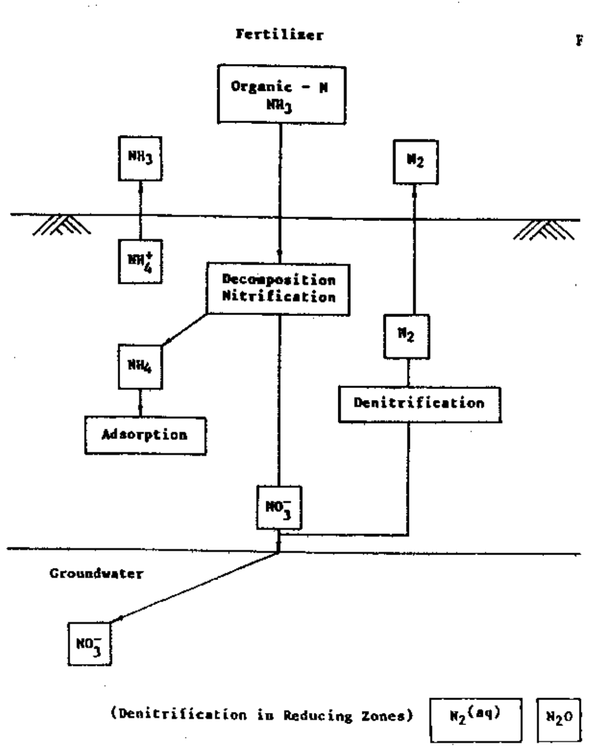


Figure 16: Form and Fate of Nitrogen in the Subsurface Environment

Source: Canter 1996

hetic and recreational value will be diminished and navigation or fishery may be restricted.

Human **health** problems are related to high concentration of nitrates in water. They are especially hazardeous to infants because NO_3 is converted to toxic NO_2 in the digestive system. NO_2 reacts with blood hemoglobin to form methemoglobin which reduces oxygen transport in the blood. By the age of about 12, enough acid (HCL) is produced by the body to kill the bacteria which convert NO_3 to NO_2.

Case studies:

Average N and P contents of different water sources in industrialized countries are shown in Table 2-6 and the increase over the past decades is shown in Fig. 2-15.

The form and **fate** of nitrogen in the subsurface environment is shown in Fig. 2-16.

The nitrogen balance of an average field in Sweden is shown in Fig. 2-17.

The results show that the **efficiency** of N-flux is very low, ie typically only 20% of the applied nirtogen is used by the plant. The yields increased considerably at even low input levels. Perennial plants use nitrogen most efficiently. Actual N-losses in irrigated fields also depends on the soil moisture status. On-demand irrigation systems, ie sprinkler or drip systems, may minimize deep percolation. Thus they minimize nutirent leaching losses. In irrigated agriculture, the level of N-flux efficiency can be increased by good management practices when compared with non-irrigated crops because of the increased biomass production under irrigation..

Nitrates which are not removed by plants or lost by volatilization usually reach the groundwater because of their high solubility and anionic form. They migrate with minimum transformation and over long distances with groundwater movement. A decline in the redox potential of the groundwater can effect this migration. The quantity of nitrogen lost may be higher in the **tropical regions** than in temperate climates.

Some important factors which enhance losses are high runoff (caused by high rainfall intensity), surface irrigation, low level of soil conservation tillage practices, and higher rates of mineralization through repeated wetting and drying at high temperatures. Some crops with a low canopy cover during development stages (eg maize, cotton) may enhance runoff from natural rainfall or sprinkler irrigation at high intensities. Typical losses to ground- or surface waters from tropical **dryland** fields are up to 40-50% of the applied nitrogen. Even under controlled conditions and improved application methods losses are rarely below a level of some 30-35% (Conway/Pretty 1988). Total nitrogen losses (including volatilization) in **paddy** rice irrigation may reach 60% (DeDatta/Buresh 1989), especially when a continuous flow is maintained from one field to the next and surface drainage systems collect and convey the excess flow into surface water bodies.

Case Study

Thailand. Losses of nitrogen from runoff in **paddy** fields (40,000 ha; double cropping) were estimated for a lake catchment in terms of total nitrogen load

wet season (60 kg N/ha applied to all fields)

fertiliser broadcast	total N outflow	5.6 kg N/ha
fertiliser incorporated into soil	total N outflow	3.7 kg N/ha

dry season

fertiliser broadast	total N outflow	6.8 kg N/ha
fertiliser incorporated into soil	total N outflow	3.8 kg N/ha

total annual N load to Laguna de Bay: human 1400 t/y
paddy 400 t/y (average loss of 5 kg N/ha)

Source: Singh et al., cit. in: Conway/Pretty 1988. Further case studies in section 2.3.4

Fig. 2-17

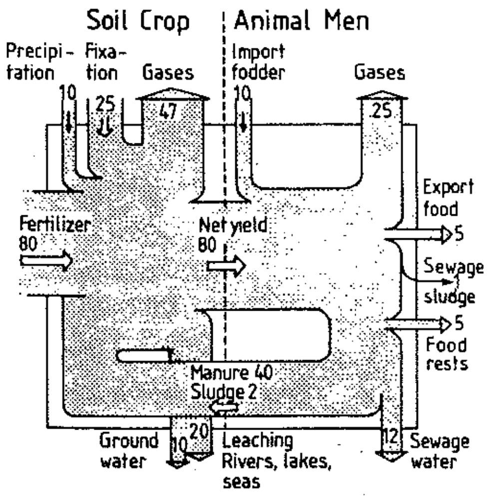


Figure 1 - Nitrogen balance sheet of an averfage hectare of arable land in Sweden. Values in kg.ha^{-1}.yr^{-1}

Source: Brink in Lessafre ed. 1990

Greatest losses occur when fertiliser is broadcast and irrigation flow continues over fields also in the dry season. Hence, water and fertiliser management practices offer the possibility of reducing losses by almost 50%. Eutrophication and explosive algae blooms may also occur within flooded paddies with detrimental consequences on the N-availability to crops - up to 30% is fixed by algae - and increasing pH due to carbonate releases from algae with subsequent increased volatilization of nitrogen as ammonia.

For further details refer to references on N-pollution, eg Blume ed. 1990; Canter 1986; De Datta/ Buresh 1989; Summer (USCID) ed. 1986, 1988, 1989; Anderson in: USDA 1988; Conway/Pretty 1988; Nieder et al. 1985; Obermann in: Nieder et al. 1985; IRRI 1978.

2.3.4 Phosphates

Phosphates are easily fixed in the soil by chemisorption (eg on Fe- and Al-minerals as relatively insoluble P-compounds) and chemical precipitation (eg Ca-phosphates). The actual movement through the soil depends on fertiliser application rates, percolation rates, pH-values and presence of free sorptive agents such as clays, carbonates, and oxides of iron and aluminum. In sandy and peaty soils, however, phosphorus may move rapidly through the soil profile. In most soils, however, phosphate losses are closely related to soil erosion when particels are washed off, containing adsorbed phosphates.

Large cow stables, dungyards and silage bunkers are frequently the most important polluters of rivers in industrialized countries (Brink 1990; Loehr 1976). They are usually associated with intensive cultivation methods and livestock farming. Phosphate pollution problems may be less critical in developing countries due to lower application rates and less intensive organic manure applications on fields. However, in areas with high P applications and high soil erosion (because P is fixed to washed soil particles), surface waters may be polluted, too.

Sources: Brink in: Lesaffre ed. 1990; Conway/Pretty 1988; Canter 1986; Holy 1980; Loehr 1976

Case Studies: (Nitrogen and Phosphates)

USA. Drainage studies showed no evidence of significant P-transport to groundwater (Evans/Gilliam/Skaggs in: ICID 1990).

Bangladesh: nitrate problems in groundwaters are not yet encountered in rice fields (Khan 1988).

India: a survey on 350 rivers did not result in concentrations > 10 mg nitrate/l (Handa in: Conway/Pretty 1988). However, groundwaters may contain higher levels: about 20% of 3000 analysed well waters contained nitrate in excess of 50 mg/l, though deep aquifers showed less than 10 mg/l. In all surveys, pollution was greater in wells near villages than those in open fields, suggesting that domestic excreta was leaching to the groundwater.

In Sri Lanka, drinking water contains up to 0.1 mg nitrate/l; the Mahaweli River contains 1.1 to 2.4 mg nitrate/l in upstream and downstream sections respectively. Kandy Lake contains up to 45 mg nitrate/l, and the drainage canal into the Lake may contain concentrations as high as 310 mg nitrate/l. Contamination may be caused by latrines or villagers using the canal for open defaecation as well as algae pollutants (Weerasooriya in: Conway/Pretty 1988).

In Central Nigeria, some 50% of village well waters had concentrations in excess of 45 mg nitrate/l, the maximum value of 400 mg/l contrasting strongly with a maximum of only 6 mg/l from wells in fields.

In Southeastern Namibia, concentrations exceeding 90 mg nitrate/l were found in 75% of wells polluted by livestock wastes. Similar results exist from other southern African countries (Conway/Pretty 1988).

Fig. 2-18

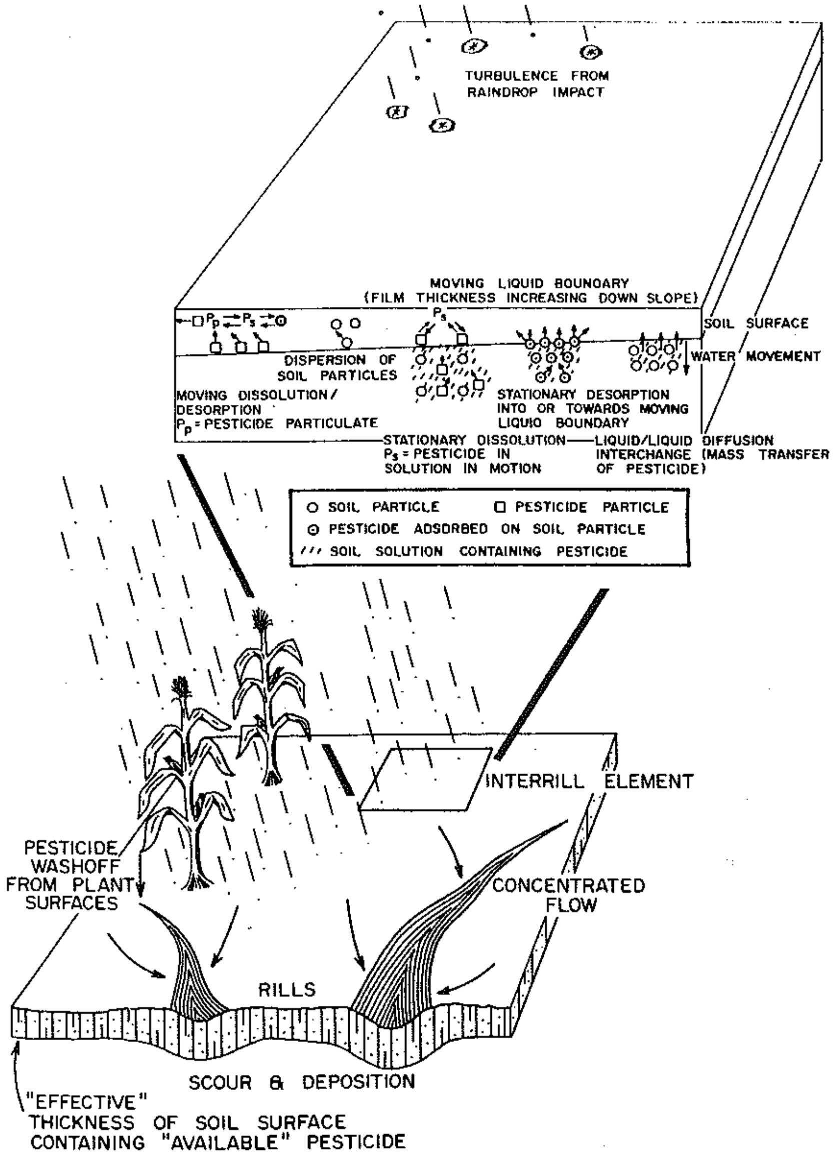


Fig. 9-1. Processes of entrainment and transport of pesticides in surface runoff. (Modified from Bailey et al., 1974 and Leonard & Wauchope, 1980.)

Source: Leonard in Cheng ed. 1990

Fig. 2-19

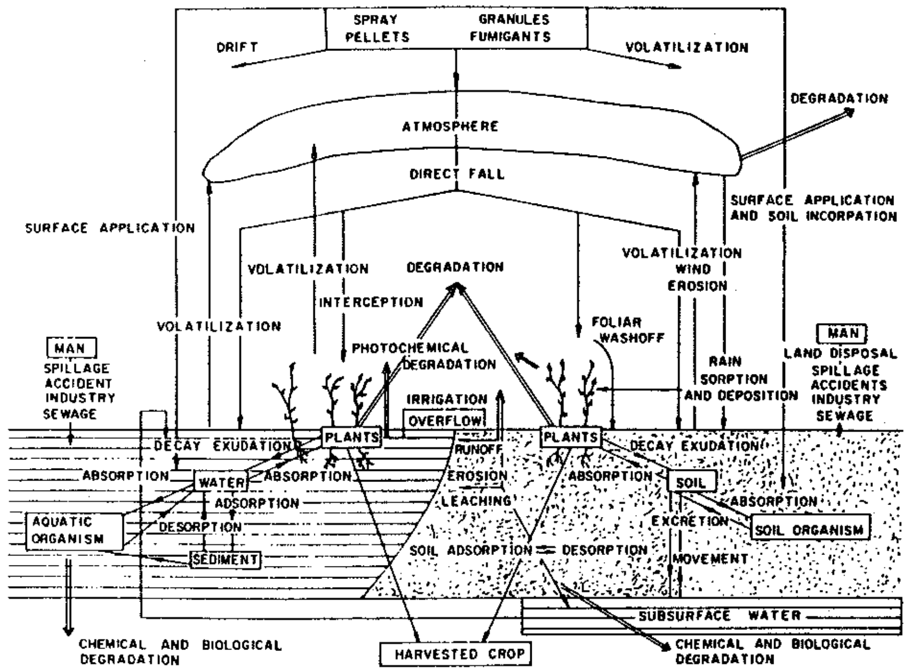


Figure 15: The Pesticide Cycle in the Environment (Bailey and Waddell, 1979)

Source: Canter 1986

Other (natural) sources of excessive nitrogen may be the mineralization of organic material derived from waterside vegetation and aquatic plants and animals. Large increases in nutrients may occur in human-made lakes and reservoirs especially during the initial stages of filling (Zauke et al. 1992). Blooms of algae and aquatic weeds (eg water hyacinth) may cause problems unless the vegetation is removed.

2.3.5 Pesticides in Runoff and Drainage Effluent

The agricultural application of pesticides is a main source of water pollution with potentially toxic chemicals in rural areas (see also section 3.4). In North America, it is estimated that some 40% of the agricultrual land is treated with pesticides (Freedmann 1989). Despite the previously widespread opinion that pesticides usually do not leach in substantial amounts through soils to surface and groundwater (eg Halberg 1987) there are numerous examples of serious contamination of rivers in industrialized countries (eg Leonard 1990; Brink 1990; Cohen et al. 1987). Typically, this may be attributed to **incorrect handling** of application equipment, **over-dosages** and **spray drift**, but other transport processes exist, namely transport during **runoff** (Fig. 2-18). Transport from soils with a high percentage of large pores (sandy soils, structured clayey soils) is mainly responsible for **leaching** losses into the groundwater.

Many pesticides render an undesirable and unpleasant odour and taste to the water and they are a health hazard for humans and domestic and wild animals not only by direct contact but also through the food chain. Some pesticides are extremely toxic to fish and other aquatic fauna. The main concern with the application of pesticides lies in the fact that they are often very **mobile** and relatively **persistent** in the environment. This is illustrated in Fig. 2-19 which shows the possible pesticide cycle and numerous transport mechanisms and pathways that can lead to soil contamination (see sections 3.4 and Part II section 3.2), water and air pollution (see section 5).

Sources: Leonard 1990 in: Lesaffre ed. 1990; Brink 1990 in: Lesaffre ed. 1990; Cohen et al. 1987

Case Study DDT

The environmental impacts of the persistent pesticide DDT, banned in many industrialized countries since the early 1970s, are clearly demonstrated by numerous investigations. DDT was used in human health programmes, forestry and crop production. The bioconcentration and food-web accumulation effects of DDT are illustrated in Fig. 2-20 which shows the typical concentrations of DDT in a variety of atmospheric, terrestrial, aquatic, and biotic compartments of the environment. Concentrations in soils are relatively small, compared with the concentrations in organisms. Residues increase in the following order: plants-herbivores-predatory mammals-fish-birds-humans-predatory birds (Freedman 1989: chapter 8).

On the other hand, many agrochemicals are not acutely toxic, do not persist for prolonged periods, and do not accumulate in food chains. The **relative environmental hazard** posed by a pesticide depends upon

- characteristics of the pesticide (dosage, solubility, mode of transport, toxicity, persistence)
- chemical and physical conditions (see section 3.4 and Part II section 3.2)
- soil-water-conditions, microbiological activity
- soil and air temperatures and humidity gradients.

Generalized quantifications of the transport and fate of agro-chemicals are almost impossible, because site specific conditions must be assessed. In evaluating the effects of pesticides it is also important to remember that the use and mix keeps altering: because of changes in cropping pattern, pest resistence, appearance of new chemicals, use of more

Fig. 2-20

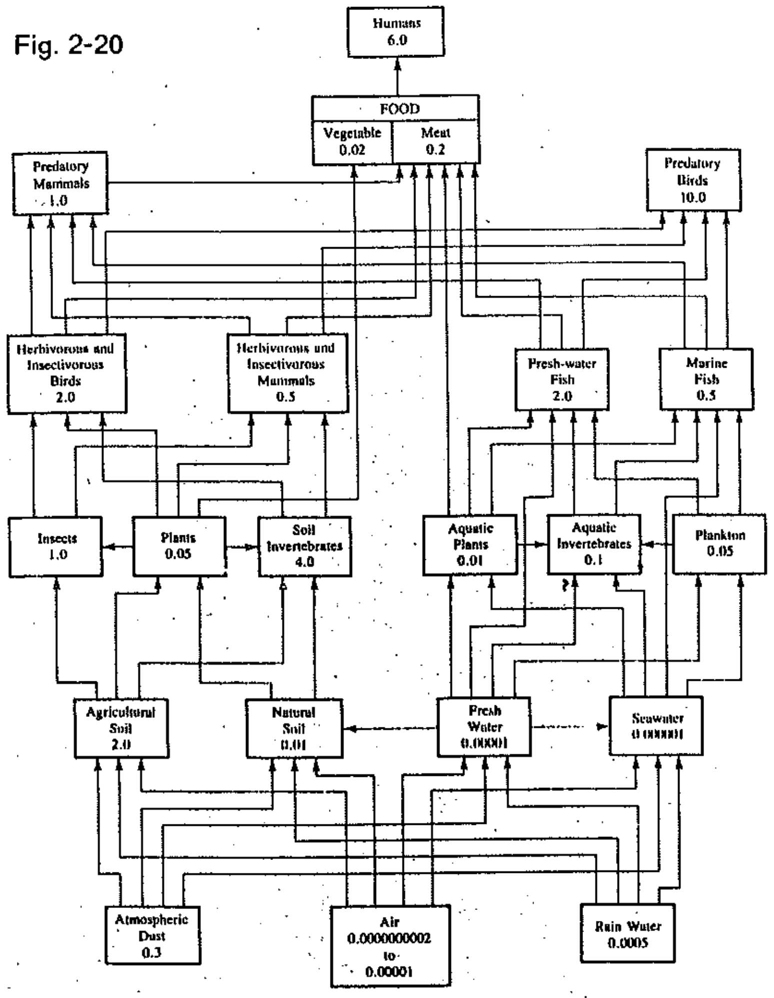


Fig. 8.1. Typical concentrations of DDT in the environment (ppm). Data were derived from a literature review of DDT residues. From Edwards (1975).

Source: Freedman 1989

318 LEON

Fig. 2-21 a, b

316 LEONARD

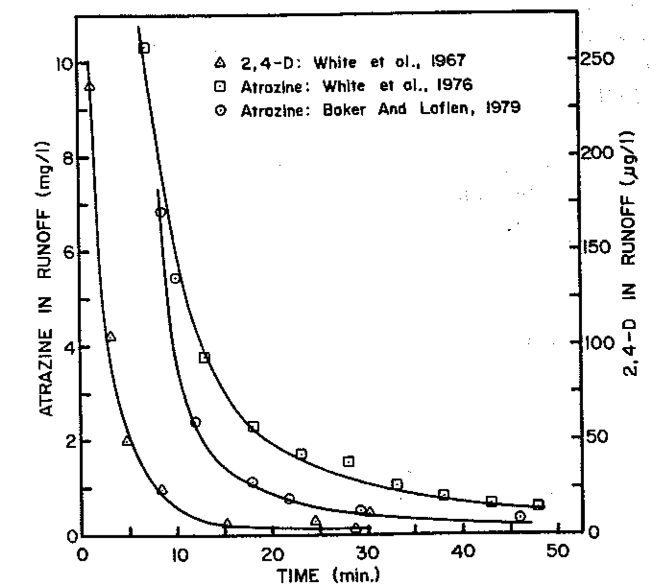


Fig. 9-4. Runoff concentration of pesticides from small plots as related to time after start of runoff. From Leonard (1988).

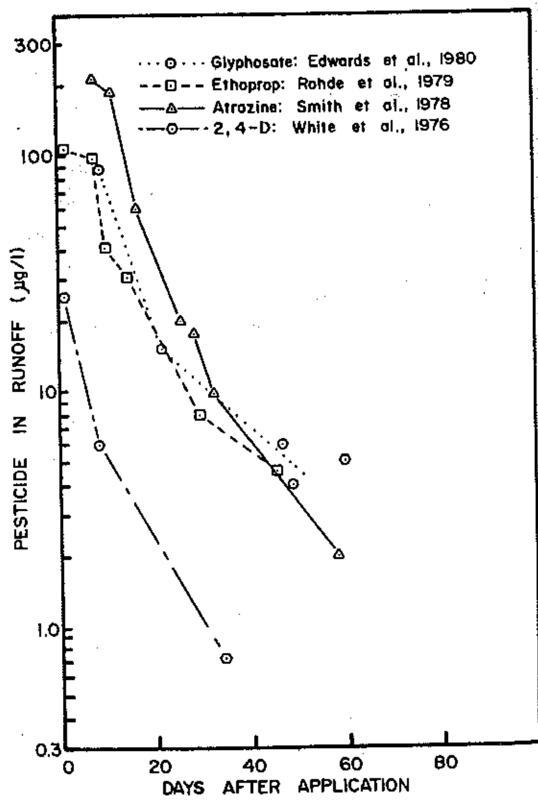


Fig. 9-6. Concentration of pesticides in runoff in relation to time after application. From Le (1988).

Sources: Leonard in Cheng ed. 1990

selective and less resistent insecticides, changing agronomic AG- of other means of integrated pest management (see section 3 del proved application methods and timing, and changes in far cals. Usually, there is lack of adequate information and risks.

Source: Leonard in: Cheng ed. 1990

The pesticides that cause most serious hazards to aquatic systems are .. **insecticides** and certain **herbicides** (eg triazines). The more soluble pesticide washed out from aquatic systems relatively quickly, but the less soluble and mo. stent chemicals are usually bound to suspended organic particulate matter which gra. ly falls into the bottom sediment, where it remains until brought back into suspension by turbulence. Once pesticides reach river systems, they become transferred gradually downstream. In aquatic systems, pesticides are either degradated to simplier compounds, or they move into the atmosphere by volatilisation (see also section 3.4).

Source: Edwards 1987

Case studies and key findings

For the majority of pesticides, total losses in runoff waters from rainfed fields are 0.3 to 0.5% or less of the amount applied. This applies mainly to water-soluble and soil-incorporated pesticides. Losses of organochlorine insecticides and insoluble pesticides (emulsions) may amount to 1% because of their long persistence. Losses of wettable powder formulations of herbicides may be 2-5%. Pesticides are mainly washed off as solutions from soil surfaces whereas organochlorine pesticides, paraquat and arsenic pesticides are strongly adsorbed by sediments, and their transport depends on soil erosion (Wauchope 1978). Most losses occur immediately after runoff starts (Fig. 2-21a). Traces of pesticides in runoff can be detected during more than 60 consecutive days after application (Fig. 2-21b, Leonhard in: Cheng ed. (SSSA) 1990).

Improved agricultural practices with the introduction of soil conservation tillage often requires an increase in herbicide use for weed control. Herbicides account for more than 80% of all pesticide use in USA. Field experiments showed atrazine losses in subsurface and surface drainage systems in the range of 1.4% to 3.2%. Metochlor losses were 1.2 and 2.4%, respectively (Bengtson et al. cit. in: Hoffman 1990, in: Lessafre ed. 1990).

Generally, much higher herbicide losses occur as runoff compared to leaching losses (Schwab et al. 1973, cit. in: Hoffman 1990).

Some herbicides are transported by runoff in solution and others only on adsorbed sediments. For example, DCPA 5% in water, 95% in sediment; Prometryn 100% in water; Trifluralin 35% in water, 65% in sediment; Paraquat mainly on sediment (Yaron/Gerstl/Spencer 1985.).

There exists a relationship between herbicide concentration in topsoil layers and concentrations in runoff from non-irrigated and irrigated soils (Fig. 2-22, opposite next page). The relationship between pesticide runoff and pesticide distribution and persistence in the runoff-active zone is shown in Fig. 2-23. Table 2-8 lists climatic, soil, pesticide, and management factors that are known to affect pesticide runoff. (Leomard in: Cheng ed. (SSSA) 1990).

Comprehensive data on **pesticides in surface runoff** from small plots, single cover fields and watersheds are compiled in Table 2-9.

Source: Leonard in: Cheng ed. 1990

Nonpoint source prediction models for estimations of losses of dissolved and solid-phase pesticides in cropland runoff are numerous and are used in pesticide leaching assessment.

Fig. 2-22

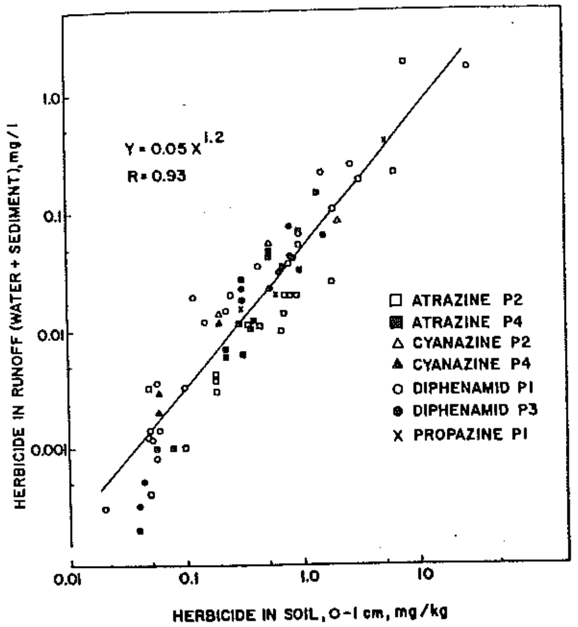


Fig. 9-2. Relationship between pesticide concentrations in 0 to 1 cm surface soil layer and concentrations in surface runoff (Leonard et al., 1979).

310 LEONARD

Fig. 2-23

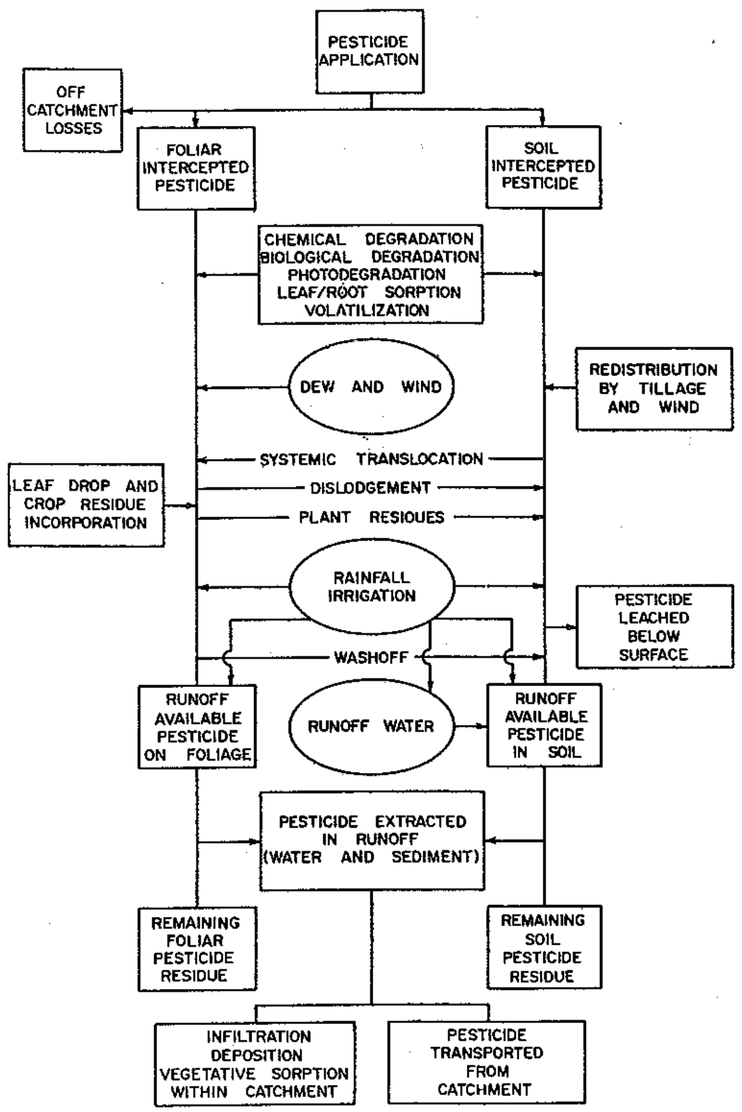


Fig. 9-3. Relationship between pesticide runoff and pesticide distribution and persistence in the runoff active zone.

Sources: Leonard in Cheng ed.

Review in: Green/Loague/Yost in: USDA 1988; Canter 1986; recent models for example: SWAG-groundwater model in: Enfield/Yates in: Cheng ed. (SSSA) 1990; CREAMS-surface water model in: Leonard in: Cheng ed. (SSSA) 1990; PRZM-model in: Green/Loague/Yost in: USDA 1988.

Semi-empirical predictions on pesticides (and toxic elements) are available for rapid assessments of potential soil contamination and water pollution risks. Soil models are described in section Part II 3.2. Pesticides are classified into four groups in the likelyhood of runoff losses in Table 2-10.

The maximum concentrations in runoff events can be predicted within one order of magnitude if pesticide formulation, use, and application rate are known, together with the time elapsed between application of the pesticide and subsequent runoff.

Sources: Cheng in: Cheng (SSSA) ed. 1990; Madhum/Freed in: Cheng (SSSA) ed. 1990; Severn/Ballard in: Cheng (SSSA) ed. 1990; Leonard in: Cheng (SSSA) ed. 1990; Hoffman in: Lesaffre ed. 1990; Blume ed. 1990; Freedman 1989; Nielsen/Lee (USDA) 1987; Cohen/Eiden/Lorber in: Garner et al. eds. 1987; Edwards 1987; Canter 1986; Spencer et al 1985 (cit. by Leonard in: Cheng)

Further readings: Cheng (SSSA) ed. 1990; Blume ed. 1990; Summers (USCID) 1986, 1988, 1989; Garner et al. ed. 1986

2.3.6 Metals and Toxic Substances

Chemical pollution is typically a feature of industrial wastewaters (OECD 1991). Toxic trace elements are only occasionally found in agricultural drainage effluents. They may be derived from soil weathering (case studies section 2.3.9) or originate as concentrations from irrigation waters. Typically, toxic trace elements are not a severe problem in drainage waters because most metals are fixed and transformed in soils if they occur at normal concentrations (Canter 1986). During reclamation leaching, however, some toxic elements may be leached from the soils, eg boron. Other elements such as selenium, cadmium, lead, chromium, mercury, and molybdenum are also occassionally found in drainage water in the USA (Deason 1989).

Case Studies

USA. Extensive surveys are under way to identify potential sites with irrigation-induced contamination problems. To date a comperehensive survey of about 600 irrigation projects and major wildlife areas is nearing completion, and 14 sites have been identified as having evidence of contamination from agricultural drain water (Hoffman 1990).

Sources: Hoffman in: Lesaffre ed. 1990; Blume ed. 1990; Deason 1989; OECD 1991; Canter 1986

2.3.7 Pathogenic Microorganism

Pathogenic microorganisms may be found in drainage effluents of wastewater irrigation projects (see sections 3.6, 8.1 and Part II sections 2.5, 4). On the other hand, pathogens are typically introduced into irrigation water by non-agricultural upstream sources, municipal or rural wastes, where water may be either treated or untreated. Agricultural wastes from farmsteads may also contribute to pathogen enrichments, eg from septic tanks or nightsoils (excreta resuse). On the other hand, irrigation may have overall beneficial off-farm impacts by reducing the number of pathogens released to downstream users through the intensification of soil biological processes of adsorption, fixation and transformation (see section 3.5 and Part II section 3.2).

Source: Loehr 1976

2.3.8 Sediment Pollution

It is estimated that agriculture (including irrigated agriculture) contributes about 40% of total sediment loads from non-point sources in the USA (Canter 1986). The off-site impacts of sediment pollution include:

- clogging of structures, including downstream irrigation facilities
- deterioration of aquatic habitat by influences on light penetration and temperature
- impaired quality of recreational waters or lakes
- increased water treatment costs
- transport of chemicals and fertilisers which are adsorbed by suspended load
- transport of organic material and pathogenic or harmless micro-organism which are adsorbed by fine materials
- changes in soil properties at deposition sites which is often associated with a reduction in soil fertility.

More details are discussed in section 3.3 (soil erosion), including other such impacts as reduction in water storage capacity of reservoirs and lakes and changes in stream bed hydrology.

2.3.9 Consequences of Water Pollution by Agriculture

The gravest problems accrue to domestic users which extract surface water or groundwater for consumption. Some substances may cause health risks, eg pesticides or high concentrations of phosphates, nitrates and chlorides.

Apart from the food industry, most wastewaters from agricultural lands in general are <u>not</u> a hazard to industrial uses (Loehr 1976). More seriously, however, are the detrimental impacts on the biological balance of rivers and lakes posed by ample supply of nutrients. This causes the rapid growth of algae, which gives an unfavourable taste and odour to water, reduces the efficiency of filters and structures by clogging and reduces available oxygen to such an extent that fish populations and other aquatic life suffers.

Case Studies

<u>USA</u>: San Joaquin Valley California. High salinity of drainage flows (10-15 dS/m) with selenium toxicity. Selenium is derived from rock weathering and transport in drainage effluents. This process is intensified under irrigation. A drainage programme with various management options was enforced in 1984 to reduce the toxicity problems. (Tanji/Hanson in: Stewart 1990).

<u>Taiwan</u>: Fertiliser pollution is generally not serious due to their rather restricted use caused by high costs. Average use per ha is 276 kg N, 65 kg P2O5 and 105 kg K2O and there has been no significant increase in use since 1971. Occasionally high nitrate and ammonium was detected in shallow wells under double cropped rice. Rice pest losses range from 9 to 45% (average for 1st crop 15%); hence, pesticides are widely used. However, most organochlorine pesticides are banned. Three programmes analysing for residues of commonly used pesticides detected traces of diazinon and parathion in one case. Generally the pollution by pesticides is not a serious problem in Taiwan. Nevertheless, control programmes have been introduced (Wen 1986).

2.4 Changes in Groundwater Regime under Irrigation

Under irrigation the groundwater regime will usually change as a result of increased deep percolating water compared with conditions under natural rainfall. The excess water input will cause the waterlevel to rise until a new equilibrium is established between deep percolation and the natural land drainage capacity of the substratum. The latter is controlled by the groundwater flow which, in turn, depends on the hydraulic potential of the local groundwater drainage system.

Under good soil and water management conditions it is unlikely that wetness problems will occur in permeable soils with a high hydraulic gradient towards the local drainage outlet and a low groundwater table. However, a number of serious problems may occur under long-term irrigation especially with poor operation:

- rising watertables will cause waterlogging within the rootzone and eventually the build-up of a shallow watertable,
- in semiarid to arid regions groundwaters are often saline and they will eventually cause a build-up of soil salinity within the capillary fringe zone. Occasionally, this process may also occur in subhumid or humid areas in the presence of marine brakkish water intrusions,

Agronomic problems related to waterlogging are:

- impaired crop growth due to temporary oxygen deficiency (except paddy soils); growth of some better adapted weeds may be accelerated; anaerobic conditions may have adverse effects on microorganisms and eventually on soil structure,
- excess water applications will impede farm operations as optimum workability of soils is limited; traditional farming systems are typically less affected than mechanised farming systems,
- ponding water may cause the destabilisation of soil aggregates which will result in impeded infiltration.

Although potential waterlogging and salinity build-up are typically the two major problems in many irrigated areas (section 3), an increasing water table is not an inevitable process. They result from by poor water management, inadequate site selection during planning, and lack of commitment to install an adequate drainage system.

Groundwater tables may rise under surface irrigation systems as a result of one or a combination of the following factors:

(i) **deep percolation:**

- application of irrigation water which percolates to the groundwater table: poor water management due to over-irrigation and excessive application depth may enhance deep percolation unnecessarily,
- restricted natural land drainage due to low permeability of soils or geologic conditions, eg stratification of substratum or inadequate discharge capacity of natural waterways and channels,

(ii) **seepage**, ie groundwater flow into the irrigated area from adjacent areas within the command area or elsewhere:

- as an indirect effect of river regulation by dams when the low flow regime is replaced by a continuous medium or high flow regime: the seasonal low flow regime is no longer effective in providing efficient land drainage,
- inadequate open ditches for disposal of water from the command area resulting from poor drainage design,
- insufficient capacity of surface or subsurface drains resulting from either poor design or lack of maintenance,

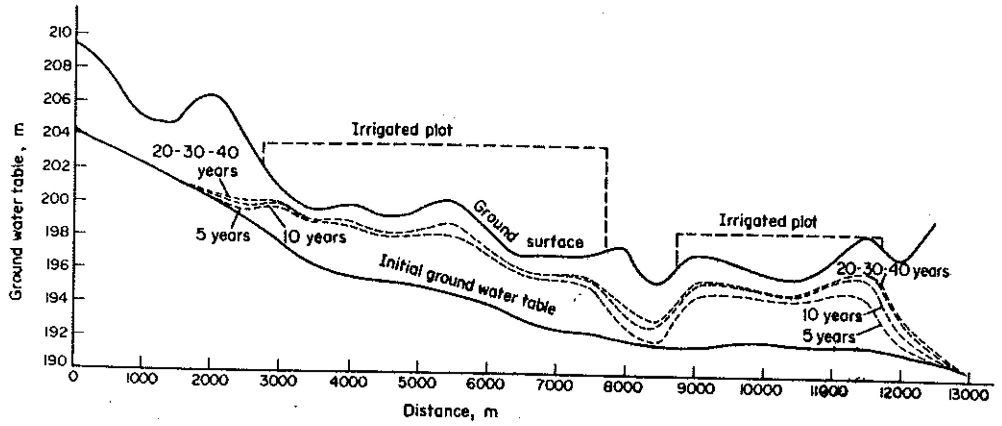


Fig. 4.16.

Source: ICID 1980

Fig. 2-24 a, b

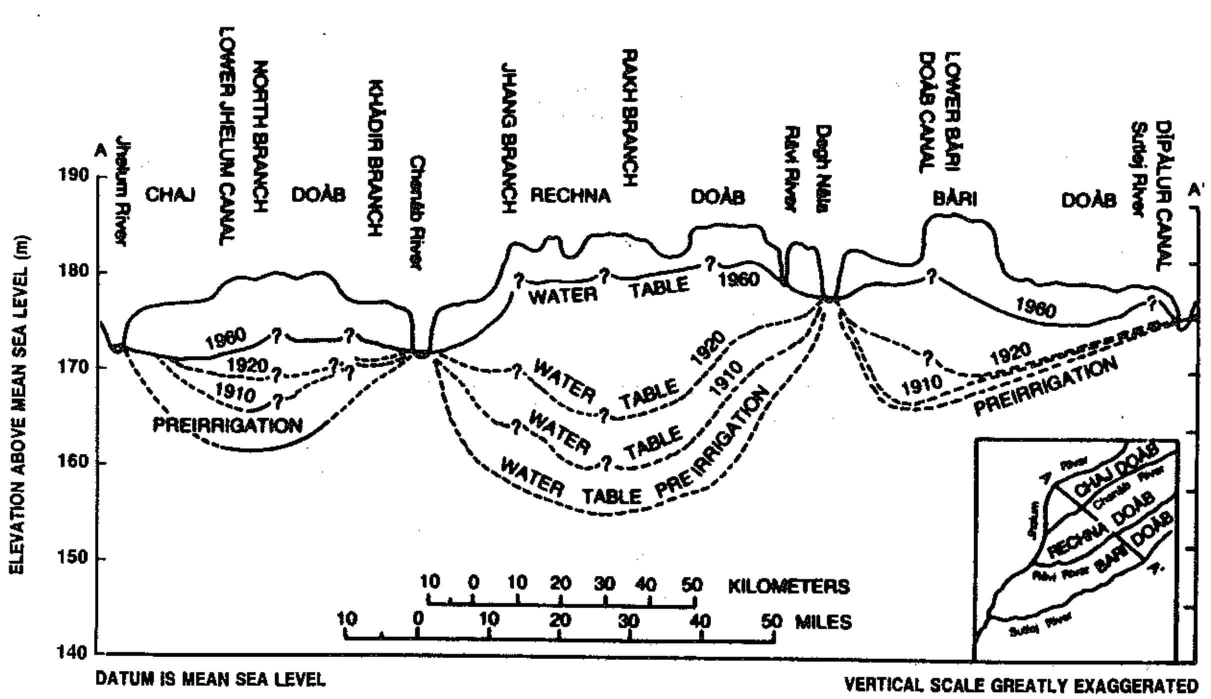


Fig. 3-1. Water table profiles, Chaj, Rechna, and Bari doabs (Greenman et al., 1967).

- inadequate design, maintenance or operation of conveyance system canals,
- blockage of natural drains by human activities, eg drifts, roads,
- blockage of human-made drainage canals by sedimentation. This sedimenation or siltation may be caused by off-site (ie upstream induced) or on-site erosion; if resulting from poor maintenance it may aggravate other problems,
- lateral inflow from adjacent reservoirs: poor design and incorrect siting of reservoirs,
- lateral inflow from adjacent irrigation schemes.

The most effective provisions to avoid rising water tables which should be undertaken during the **planning** stage are:

- selection of soils which are relatively permeable and choice of soil and water management practices which retain this permeability (the permeability depends on the hydraulic conductivity of single layers and the stratification of profiles)
- selection of sites which show adequate natural land drainage properties, ie sufficient hydraulic gradient and a natural 'outlet'.

If these conditions are not met the installation of an adequate **drainage system** is required. This may be a surface or subsurface system, or a combination of both.

References: Smedema/Rycroft 1983; vanSchilfgaarde ed. 1974; Eggelsmann 1973; ILRI 1972-74

Case studies and examples

Four typical situations of groundwater regime changes under irrigation are described.

1) Decrease in water table depth in areas where large quantities of irrigation water are **pumped** from underlying groundwater aquifers. For example in the upper Gonaives Plain (Haiti) a decrease of the water table occured between 1965 and 1986 in the range of 0.5 to 1.5 m (Petermann 1986). Short-term seasonal fluctuations may be superimposed on these long-term trends.

2) In **paddy** rice culture, it is a water management goal to maintain a perched water table at shallow depths or to restrict infiltration by puddling. For example, a shallow perched temporary watertable at some 25-50 cm depth is favourable for rice cultivation in valley soils (Northern Ivory Coast. Petermann 1985).

3) The temporary or **cyclic build up** of a perched water table depends on irrigation practices and variations in percolation (or seepage) rates. These cycles may occur on a seasonal or short-term basis and they may cause damage to some sensitive crops at certain development stages. The cycles typically occur also under non-irrigated conditions and under irrigation they are to some extent manageable by field application methods. In the New Valley soils (Southern Egypt) a shallow perched water table developed within 0.9 to 1.4 m depth below the surface after few weeks of continuous irrigation. One month after irrigation stopped, the water table dropped rapidly to the original depth of some 3 to 5 m below the surface (Petermann 1984).

4) **Long-term rise** in water tables induced by seepage or/and deep percolation and impeded land drainage. The prediction of groundwater table rises may be derived from modelling: Fig. 2-24.

Ther are numerous examples of irrigation projects which have resulted in rising water tables. A few examples are given:

project	original depth (m)	depth under	rise (m/y)	Source
Bhatinda, India	15		0.6	Smedema 1990
Khaipur, Pakistan	4-10		0.1-0.3	Smedema 1990
SCARP IV, Pak.	10-15		0.4	Smedema, 1990
Nubariya, Egypt	15-20		2-3	Smedema 1990
Ben Amir, Marocco	15-30		1.5-3.0	Smedema 1990
Amibara, Ethiopia	10-15		1.0	Smedema 1990
Salt Valley, USA	15-30		0.3-0.5	Smedema 1990
Gonaives, Haiti	2-4	0.6-1.5 (after 21y)		Petermann 1986
Eshkedia, Libya	3-10	1-5		Petermann 1983
Hamera, Libya	4-15	2-10 (after 10y)		Petermann 1982
Hamam, Libya	>10	1.5-4 (after 8y)		Petermann 1982
Sanghar, India	>3.6	1-2 (50y)		Birch/vanWonderen1990

Sources: Birch/van Wonderen in: ICID 1990; Mistry/Purohit 1989; Smedema 1990; Lesaffre 1990; Smedema/Rycroft 1983; Petermann unpublished project reports

Off-site effects

In many locations detrimental effects of rising groundwater tables do not only affect the command areas but also neighbouring lowlying areas where groundwater throughflow collects. In cases where these low lying areas are traditionally used for irrigation, pastureland or fruit tree gardens (eg date palms), detrimental impacts are expected. For example, in the Fezzan region of Southern Libya there have been several instances where the development of new large scale irrigation projects on sloping land caused water tables to rise in traditionally irrigated downslope locations: Murzuq, Braq, Wadi Adjal, Um-el-Araneb, Esch-Schergia, Goddwa. Economic losses to farmers' families were limited because the owners of traditional arable areas benefited from the new smallholder irrigation developments. However, some farmers, especially elderly people, were not allocated new farms.

2.5 Hydrological Impact of Land Drainage

The installation of drainage systems on irrigated or non-irrigated lands results in changes in hydrology brought about by the lowering of the watertable and the collection and disposal of excess water. The magnitude of changes vary with location and depend on the type of drainage, soil properties (and stratification), and the climatic and topographical setting. The potential effects of drainage are summarized as follows:

- Effects of subsurface drainage are lowered watertable levels and increased soil moisture storage especially for rainfall; this may temporarily lead to increased soil moistore storage of excess irrigation and rainfall, thus reducing the runoff hazard. Flow (erosion) is also diverted to deeper, less permeable horizons within the soil profile. the combined effects tend to smooth out and prolong hydrographs of flow from fields.
- Hydrological impacts of field drainage are generally small on a catchment scale, mainly on account of the trade-off between reduced runoff and increased subsurface drainflow.

Fig. 2-25

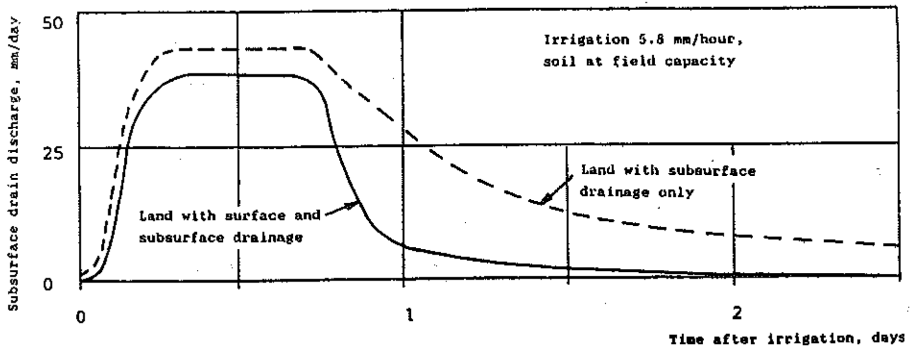


Figure 4 - Effect of surface drainage on subsurface drain discharge, after Schwab et al (1963)

193

Fig. 2-26

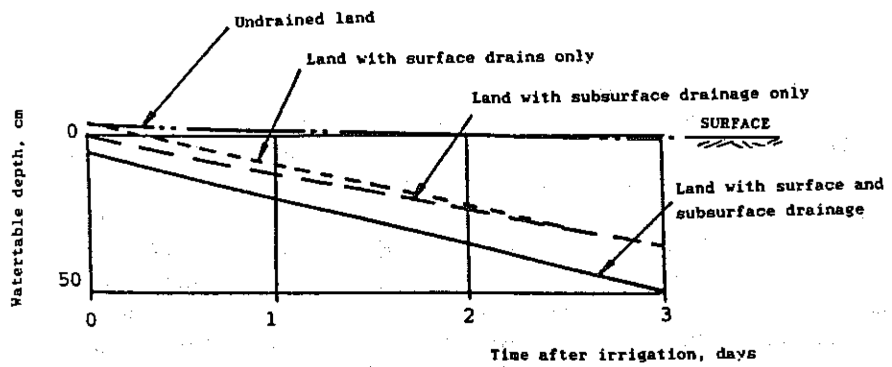


Figure 5 - Watertable recession following irrigation of grassland during growing season, after Schwab et al (1963)

Source: Rycroff in Lessafre ed. 1990

- Improvements to **main drainage channels** (outlet) which evacuate water from the area can significantly reduce the catchment response time and thus increase peak discharges.
- Improvements to main drainage channels in previously undrained areas such as lakes, swamps or depressions can significantly increase total flow as well as peak flow rates and reduce response times.

Source: Rycroft in: Lesaffre ed. 1990

Typical effects of subsurface drainage on surface runoff, drain discharge and watertable levels are illustrated in Fig. 2-25 ab b.

In general, field drainage systems in irrigation systems have relatively small off-site impacts, ie on the downstream watershed. However, drainage channel (outlet) maintenance and improvements (cleaning, dredging, deepening, lining) generally have large impacts on downstream watersheds, resulting in watertable fall within the channel influence area, and increasing total flow and discharges at downstream sections. The magnitude of impacts may increase linearly with increased areal extension of the drained area. The hydrological response may be investigated using models such as DRAINMOD (Skaggs 1982).

Large scale irrigation projects and associated drainage systems may have detrimental impacts on entire river systems. There are several example, where irrigation caused increased salinisation of river water and serious off-site disturbance of wetlands with detrimental impacts on wildlife within the riparian plain (Lakey in: Lesaffre ed. 1990; see also section 4). Long-term and off-site effects have often not been considered in many large scale irrigation and drainage schemes elsewhere in the world (eg Hoffman in: Lesaffre ed. 1990), although potential impacts are well known (eg Kienitz 1979).

In arid areas the development of natural drainage lakes outside the project area may create brackish water habitats in previously arid terrestrial habitats which can be seen as a gain in habitat diversification.

Drainage systems are designed to modify the soil-water status of irrigated fields, namely the watertable depth and its fluctuation. Consequently, drainage related impacts on cultivated lands are planned interventions to create favourable conditions for optimum plant growth. Environmentally sound planning and operation of such systems should be focused mainly on minimising or avoiding detrimental off-site effects (Part II section 2.4). Such effects relate to downstream water pollution, changes in discharge of rivers and in lowering of watertable levels next to drained fields.

A case study for Pakistan is provided in: Mohtadullah in: Lessafre ed. 1990

Further readings: Gardiner ed. 1991 ; Hoffman in: Lesaffre ed. 1990; Newson/Robinson 1983; Skaggs 1982; Hornsby in: Stewart et al. 1990; Carter in: Stewart et al. 1990; Tanji/Hanson in: Stewart et al. 1990; Skogerboe/Walker in: Yaron 1981; Hotes/Pearson in: COWAR 1976

Fig. 3-1 a

Sources: ILRI 1980

3 Impacts on Soil Resources

3.1 Salinity Problems in Irrigated Agriculture

3.1.1 Introduction

It is common knowledge that soil salinity is the most prevalent and widespread problem limiting irrigated crop production under arid and semiarid conditions. However, the process of salinisation not only has direct impacts on irrigated soils. Detrimental impacts may also occur to water and soil resources in river basins. Impacts vary in time and space, and they may affect biological resources and human activities further downstream.

Saline soils are defined by a high content of soluble constituents in the soil solution which adversely affect plant growth and yields. The degree of salinity is usually measured as the electrical conductivity of water extracted from the soil paste or other soil-water ratios. Salinity usually fluctuates seasonally, depending on evaporation, rainfall and water management practices. Salinity often occurs together with sodicity (or alkalinisation), ie when sodium is present at high percentage (usually >15%) at the soil's exchange surfaces. Alkaline soils may become non-saline, especially after sucessful leaching. For simplification, the term 'salinity', as used hereunder, refers to all kind of saline soils regardless of the predominat type of salts present.

General references: Ghassami et al. 1993 (forthcoming); Kandiah (FAO) 1990; Rhoades/Loveday in: Stewart ed. (1990), Bresler et al. (1982), Shainberg/Shalhevt ed. (1984),, FAO/UNESCO 1973.

3.1.2 Salinity: A Worldwide Problem

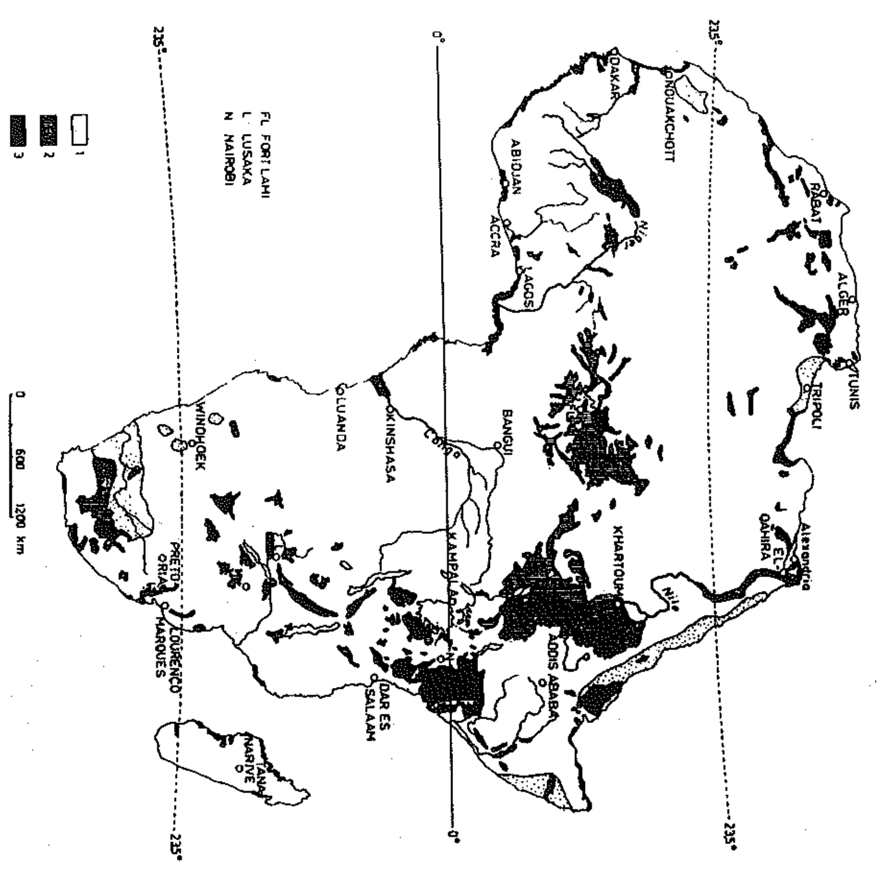
Previous estimates suggested that salinity and waterlogging affects about 50% of all irrigated land (FAO, Kovda 1982; FAO 1976; Framji 1976; Kovda et al. (FAO/UNESCO) 1973). The areas concerned include regions where the climate is humid, subhumid, semiarid and arid. The problems are more widespread and acute in arid and semiarid than in subhumid or humid regions. High salinity in soils may adversely affect yields on irrigated lands to such an extent that the land is abandoned.

Salinity problems under irrigation have existed ever since irrigation enhanced crop productivity, namely along the Nile, Euphrates, Tigris and Indus Rivers and the Gangetic- and Chinese plains. Well before 2,000 B.C. irrigated land was abandoned in the Mesopotamian Plain because of extreme salinity. Increases in cropping intensities and the use of water resources for irrigation of more and more - even marginally suitable - land over the last 40 years have resulted in widespread salinity and waterlogging problems.

On all continents there are vast areas of salt-affected soils, either natural or human-made.

- In the USA, about 28% of irrigated land suffers from depressed yields due to salinity (Yaron 1981).
- A rough estimate of the distribution of salt and alkali-affected soils has been compiled for affected regions, based on the FAO/UNESCO soil map. The global area of salt-affected soils was estiomated to some 950 M ha (Table 3-1 a-b and Fig. 3-1 a-c; collected and compiled in: Szabolcs 1979; Beek in: ILRI 1980).
- Framji (1978) estimated that some 27 M ha of saline soils were irrigated (Ghassemi et al. using correced figures from Framji 1976) which was about 30% of the irrigated area.
- Kovda (1983) estimated that some 1 to 1-.5 M ha are salinised per year and that the total land affected by salinisation from both natural and human factors to be about 20-30 M ha.

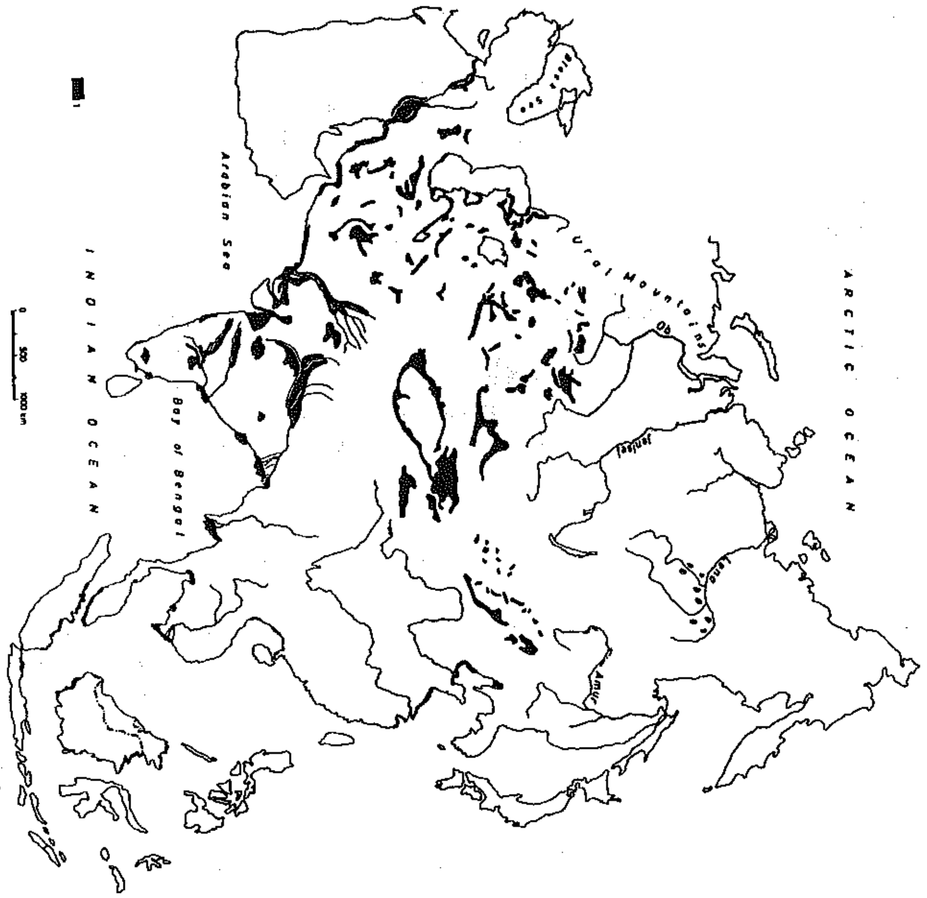
Fig. 3-1 b



Review of research on salt-affected soils

FIG. 15. Distribution of salt-affected soils in Africa (after G. Aubert, 1970).
1. Potentially salt-affected soils
2. Alkali soils
3. Saline soils

Fig. 3-1 c



Review of research on salt-affected soils

FIG. 7. Distribution of salt-affected soils in Asia (after V. A. Kovda et al., 1964).
1. Areas of salt-affected soils

- Postel (1990) estimated that 38 M ha or 24% of irrigated soils are affeced by salinity in the five most important countries (see Table 3-1 c). On a global scale, he conclude that some 60 M ha (of the 250 M ha irrigated soils) are affected by salinity.
- Oldeman et al. (1991) estimated worldwide that some 77 M ha are affected by salinity (Table 3-2 a-b) but no differentiation was made for irrigated and non-irrigated lands (revised FAO/UNESCO maps).
- Dregne et al. (1991) estimated that about 43 M ha of irrigated land in arid and semi-arid areas is affected by various degress of degradation, mainly salinity, waterlogging and alkalinisation. Annually, some 1.5 M ha of irrigated lands are lost due to land degradation, mostly salinisation.
- Ghassemi et al (draft 1993) concluded from detailed figures from 11 countries that some **45 M ha or 20% out of a total 227 M ha irrigated land are salt affected** (Table 3-3). A total global of 31 M ha can be attributed to secondary salinisation of non-irrigated lands if it is accepted that 77 M ha of land is affected by human-induced salinisation (Oldeman et al. 1991).

The spread of degradation affects not only older, traditional irrigation but also modern schemes. Although such global figures are not very precise, it is obvious that salinity is a major problem under irrigation, except in humid rice irrigated agriculture. On the other hand, continuous efforts are made to reclaim these soils and soil reclamation programmes attain high priority in both soil research and development plans.

The process of irrigation-induced salinisation and the progress in reclamation is illustrated from examples from China and Egypt. In a project in North China, salinisation increased shortly after irrigation was introduced (Fig. 3-1/d). Salinity declineed after the installation of drainage systems in the late 1960s, but poor functioning of the systems remained a problem and the area of moderately salinie soils inceased. Reclamation programmes in the mid 1980s were successful to control salinity. In Egypt, proper water managment and drainage systems controlled salinity in irrigated land (Fig. 3-1/e).

Extremely saline soils under irrigation occur widespread in parts in India and the Near East (eg Pakistan, Iraq, Iran), USA (COL, CAL), Mexico, former USSR (Central Asia, eg Caspian Sea) and N-Africa. Some examples are given in Table 3-3 b for various countries. Table 3-3 c summarises the available data on area, hydrology, water uses, cultivated land and irrigation-induced salinisation from 11 countries wich cover 70% of the world's irrigated area (Ghassemi et al. draft 1993).

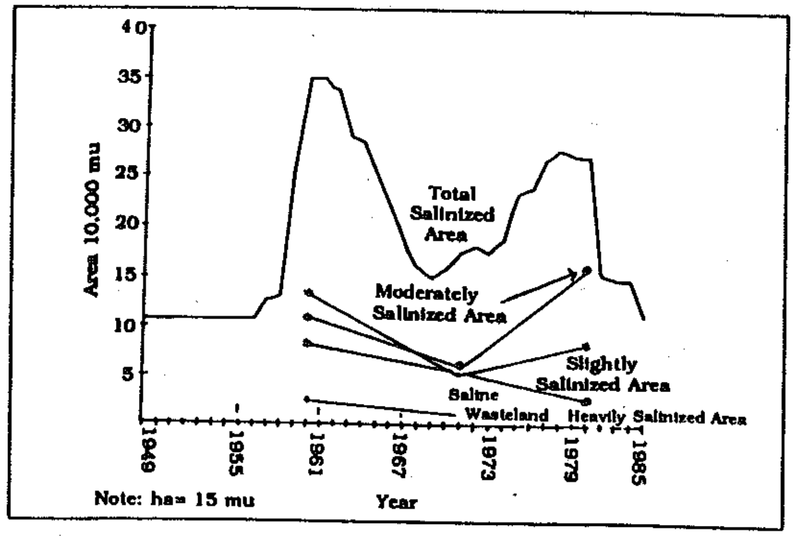
Alkali soils (pH > 8.0) occur over considerable areas in the Western USA, India, Pakistan, Egypt, Mesopotamia, Russia, Hungary (see also Table 3-1b).

3.1.3 Development Trends

In arid areas almost all land suitable for irrigation is salt-affected to some degree and it is the main objective of soil surveys to identify those locations which offer the best reclamation options and that minimize future risks of salinisation. In many subhumid or semiarid areas saline soils occur in floodplains, ie areas with reliable and easily available water resources, with ideal topographic conditions for cultivation, and with high population densities. Therefore, in many countries agricultural development is focused on these susceptable and fragile salt-affected areas.

In the Near East (including Pakistan) the increase in irrigated lands - from 36% of arable land to some 51% during the period 1962 until 1985 - took place mainly in locations adjacent to major river systems and within low-lying alluvial plains. These extensions further exacerbated problems in salinisation since most of them have high risks of salinisation due to adverse hydrological and soil conditions (waterlogging, use of saline water). The same correlation recently developed irrigated agriculture and increased problems in salinity was observed in the USA, for example in the Colorado River Basin and the Imperial Valley (Yaron ed. 1981). Important lessons can be learnt from Iraqi conditions, where local salinity problems have existed since ancient times, but salinity problems have only recently become wiespread due to increased utilisation of limited water and soil resources and

Fig. 3-1 d *Figure 1. Salinized area in Yucheng County.*



Source: Maurya in Yoder ed. (IIMI) 1990

Fig. 3-1 e1

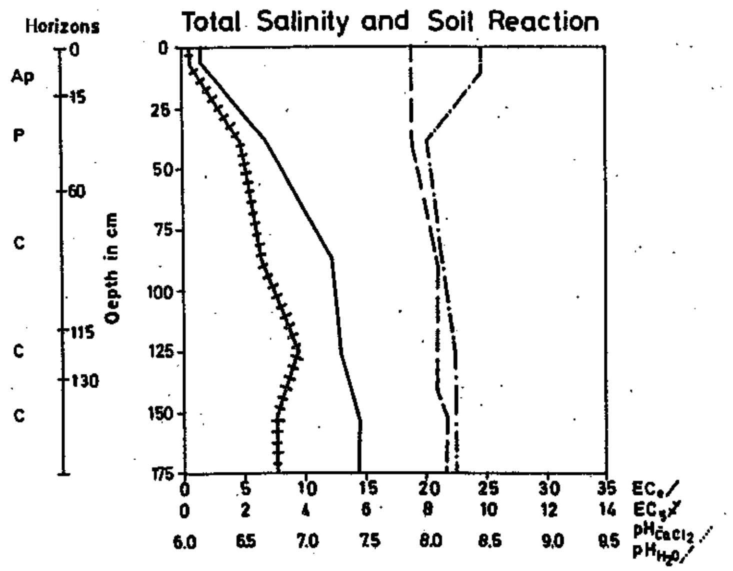
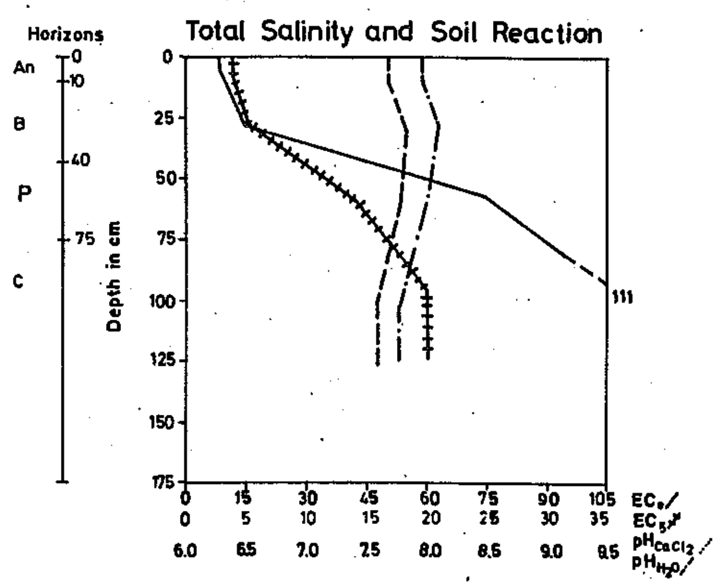


Fig. 3-1 e2



Source: Petermann 1986, New Valley Egypt

cumulative effects over centuries (Dieleman et al. 1977). In most of these areas, although potential salinity problems caused by shallow water tables were recognised, drainage systems were not established, often due to financial contraints.

3.1.4 Causes of Salinity in Irrigated Agriculture

Soil salinity originates from evaporation residues of soluble constituents of the soil solution. Consequently, the actual salt content of a soil depends on the dynamics of its soil-water system. All soils contain some native salts which are derived from either weathering, rainfall or lateral transportation. In addition, some soils are saline due to having been farmed under saline conditions (utilising marine/lacustrine sediments) or from saline surface deposits, either aeolian (eg dust) or fluvial. In coastal regions, salt water intrusions and/or submergence of low-lying areas sea water accumulate saline deposits. All these are refered to as native salts.

In irrigation, any salinity problem stems from the fact that practically all water contains some dissolved salts. During irrigation, these salts tend to concentrate in the root zone as the water, but little of the salt is extracted by the crop. The salt accumulation takes place progessively unless salts are removed towards the groundwater by either rainfall or irrigation water in excess of potential evapotranspiration. The addition of salts from irrigation may vary from 0.1 t/ha to 7 t/ha per year or more.

Factors which contribute to salinity problems under irrigation are (i) inherent soil and water properties and (ii) soil and water management practices or cultivation patterns:

> Enhancing factors are: low soil permeability, inadequate natural drainage, use of saline water, use of sewage for irrigation, hydromorphic conditions, high potential evapotranspiration, high water table, presence of natural salts, crop selection (which determines irrigations scheduling), fertilisers and soil amendments.
>
> Poor water and crop management may intensify or modify salinisation: inadequate leaching practices and water scheduling, cultivation/cropping pattern.

Under natural condictions, three major factors cause salinity, namely climate and rainfall, shallow groundwater, and soil-forming processes (mineral weathering, mobilisation).

Climate is an important factor because salts within the rootzone are redistributed towards the soil surface through the upward flux of water driven by evaporation. Salts may move up the soil profile from groundwater by capillary rise. The rate and extent of capillary rise depends mainly on physical soil characteristics, namely texture and porosity. Potential evaporation is controlled by climate, namely air and soil temperature, windspeed and air humidity. Evaporation usually shows pronounced seasonal and high inter-annual variations in subtropical regions.

Salts accumulate on irrigated surfaces when they are left behind as the soil water is used by plants or lost by evaporation. The root zone and the soil surface can become salinised by these processes, especially where shallow saline water tables occur. These typically develop in irrigated lands, usually in downslope positions, when the portion of water (including irrigation channel seepage and excessive rainfall) is not dissipated through crop use or drainage beyond the root zone.

Soil formation, the release of soluble constituents from the mineral phase, depends on abiotic and biotic factors. High temperatures and abundant water create favourable environments for all kinds of biological activities in soils which contributes to the transformation of minerals and also promote chemical and physical weathering. Therefore, irrigation usually creates favourable conditions for weathering and transformation (decomposition) of organic and inorganic soil materials; thus, in the long-term salinity may eventually increase or toxic substances may be released (eg Selenium in San Joaquin Valley, California).

Factors which contribute to salinisation problems in irrigation are summarized as follows:

(1) Use of saline soils for irrigation development without adequate prior soil reclamation.

(2) Use of saline irrigation water without adequate counteractive reclamation measures such as efficient leaching practices or drainage systems.

(3) Inadequate irrigation application practices, namely over-irrigation, which may cause water tables to rise, waterlogging or ponding water, resulting in subsequent evaporation deposits in the upper soil profile.

(4) Secondary salinisation caused by capillary uprise of saline water from a shallow water table. The extent of such capillarity depends on climate and soil properties.

(5) Use of low permeable soils without adapted water management and tillage practices to avoid waterlogging and ponding water.

(6) Use of land without adequate natural land drainage without the provision of an artificial drainage system.

(7) Seepage losses from reservoirs and conveyance canals which cause water tables rise. In unlined canals, about 50-60% of the water nmay be lost by seepage.

(8) Lack of efficient control of field canals (tertiary systems) which may cause temporary stagnant pools and subsequent saline evaporation deposits at the surface.

(9) Inadequate soil tillage practices which, for example, may facilitate the rise of saline soil water from deeper layers into the upper rootzone or which may lead to uneven distribution of saline layers in the deeper rootzone.

(10) Inadequate land preparation methods during the preparation of virgin land for irrigation by ineffective deep loosening, chiseling, land levelling.

(11) Inadequate control of intrusion or inundation by saline (brackish) water, either from the sea (daily, tidal, seasonal) or inland sources (rivers, lakes).

(12) Inefficient soil reclamation methods in problem soils, eg peat, sandy or clayey soils.

(13) Inadequate lay-out of irrigation systems in relation to water and soil quality, topographic conditions, and managerial skills of farmers.

(14) Application of fertilisers, manure or chemical amendments which add salts to soils.

It is obvious that many salinity problems in irrigation are related to changing the preexisting natural balance of the soil-water-climate system. Soil deterioration by salinity will occur under irrigation when the response is inadequate either to maintain the existing salt balance or to introduce efficient reclamation and control measures to manage the salt balance in both soils and water. Since many causes of salinisation under irrigation are interrelated consequently also the management of salinity problems requires a holistic view, and the understanding of the soil-water-climate system is a prerequisite for the solution of water management problems in irrigation. Concepts of water and crop mangement practices to control salinity under irrigation are given in Part II sections 2.3 and 3.3.

3.1.5 Salinity and Crop Growth

Salinity problems cause the decrease of crop yields which adversely affect the economics of irrigation, and they cause agricultural development to be non-sustainable. Eventually salinity contributes to the deterioration of soils and surface- or groundwater resources, accelerate wind erosion risks and hence contribute to the degradation of regional resources which may hamper future development options (desertification).

Fig. 3-2

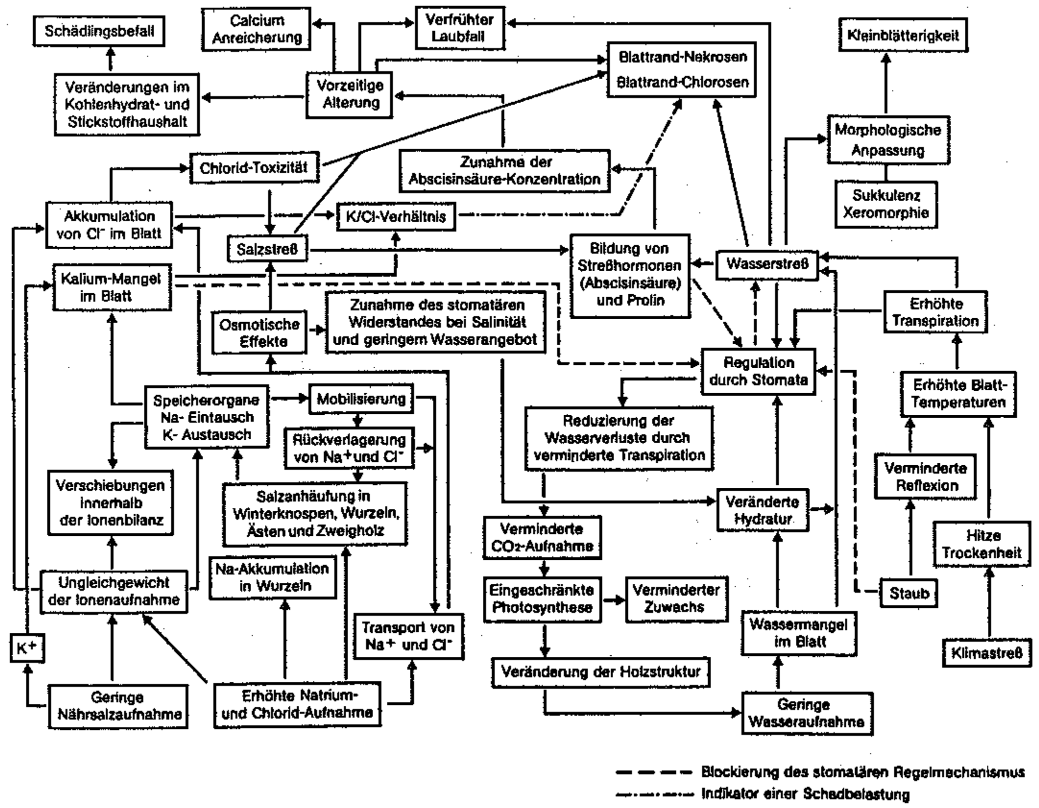


Abb. 2.7.4/2: Interaktionen zwischen Salz-, Wasser- und Nährstoffhaushalt – Betrachtungsebene Pflanze (aus HABERMANN 1989)

Source: Blume ed. 1992 307

The effects of salts on crops production are manifold: emerg ... f areas be hampered, rates of plant growth and yields are reduced ... failure occurs. Decreases in yields are crop specific and h ... s- sensitive crops and crop rotations adverse effects can be ... re are two principal factors which affect crop growth:

- Firstly, excessive salt concentrations in the soil s ... growth directly through the **osmotic** effect which re ... absorb water from the soil solution. Specific-ion ... or the toxicity of specific ions (physiological processes, ... factors.
- Secondly, salts have effects on physical and chemical **soil properties** an... ming processes. Most important is the secondary specific-ion effect of sodiu... which may lead, if present in excess, to adverse physical soil properties such as soil swelling and dispersion, causing water infiltration, aeration and root penetration problems.

The detrimental effects of salts, on plants and soils, differ greatly with the composition and concentration of salts present. Furthermore, crop salt tolerance varies significantly between different types of crops, growth stage and cropping patterns. Hence, simple statements regarding risk, actual degree of degradation, natural causes and contributions of mismanagement are not possible and each scheme must be assessed individually. The complex nature of soil-plant-water relationships and their interactions with salinity are illustrated in Fig. 3-2.

3.1.6 Assessment of Degradation by Salinity

The process of soil degradation by salinity refers to a human-made increase of salinity in soil. The process may take place in saline or non-saline soils and may be the result of the use of saline or non-saline irrigation water, in the case of non-saline soils the use of saline water may initiate the degradation process.

Soil degradation by salinisation may form part of the process of desertification (impoverishment of terrestrial ecosystems by human) and it is measurable in different soil strata, ie topsoils (main rootzone), subsoils; deeper substratum; soils adjacent to reservoirs and conveyance canals, drainage outlets. Biological resources may be affected and examination of habitats downstream and adjacent to watercourses and irrigated fields may assist in quantifying the extent of degradation.

The spatial distrubution of the impact can be classified by soil salinisation

- within the command area (on farm, adjacent to canals, reservoirs)
- in downstream areas (saline ground- or surface water resulting in secondary effects on soils).

The impacts of overall degradation be <u>identified</u> as:

- reduced productivity of irrigated lands
- limited selection of suitable, less sensitive crops
- increased skilled management requirements (eg tillage, irrigation scheduling) to maintain productivity
- increased needs for capital and/or labour intensive reclamation measures to maintain productivity,
- temporary or permanent ababdoning of irrigated lands
- need for increased quantities of water for leaching

- undesirable changes in the diversity of micro- and macrofauna and flora of areas adjacent to irrigated lands and downstream areas
- loss of potential for future agricultural or non-agricultural uses.

Thus, soil degradation by salinity may be described in its final stage as desertification especially when irrigated lands have been abandoned. It is obvious that in dryland areas (semiarid or arid ecosystems) the prevailing climatic conditions are already a limiting factor in the resilience of an ecosystem, ie the ability of land (soil) to recover from the transformation to saline conditions. Therefore, in these environments salinisation may ultimatively become an irreversible process when viewed on the time scale of human lifespans and normal restoration capabilities. Resilience potential may be higher in subhumid or humid environments.

3.1.7 Risk Assessment

The risk of salinisation under irrigation depends on a variety of environmental factors, which can only be modified to a limited extent by land development and soil reclamation measures, or the irrigation and cropping system itself. The levels of natural salinity of parent materials and groundwaters and climatic conditions differ substantially, and require a precise study and specific analysis for each area concerned. Methodologies which identify potential salinity hazards and aid in planning are given in Part II sections 3.2 and 3.3.

Generally, the following natural factors may contribute to a substantial risk in soil salinisation under irrigation:

- low total rainfall (less than about 200 mm), very low rainfall intensity (about < 5 mm/hr)
- low soil permeability (about 10 cm/d) down to the watertable
- flat topography, low hydraulic gradient of watertable
- presence of salts in subsoil strata, relevant for areas where lateral flow takes place and dissolved constituents can be translocated and enter the surface flow system.

Salinity problems in irrigated soils are likely to occur, if,

- irrigation water contains high amounts of salts
- shallow groundwater tables exist; the critical depth is between 1.5 to 6 m, depending on soil and climatic properties such as pore size distribution and evaporation
- the shallow groundwater is already of medium or high salinity
- a rise in groundwater takes place resulting from irrigation
- naturally saline soils are irrigated without prior reclamation
- internal drainage conditions (soil permeability) are poor, ie they do not allow for adequate downward flux of soil water
- soil tilth conditions cause reduced infiltration rates; conditions may be poor due to cultivation methods (tillage etc) or due to soil dispersion (sodium induced)
- land drainage conditions are poor, ie flat topography, shallow slope towards the local dainage basin (eg river, valley), low hydraulic gradient to the watertable
- saline soil layers are exposed or lifted upwards by deep ploughing or subsoiling (mechanical melioration)
- high evaporation rates occur without a continuous downward flux of soil water
- over-irrigation when water is stagnant (ponding) for prolonged periods and evaporation rates are high

- rainfall conditions in a particular year are insufficient to remove salts from the root-zone (natural leaching); this applies to supplementary (seasonal) irrigation systems or in semi-arid regions where rainfall is used for leaching
- insufficient leaching water is applied; the appropriate quantity depends on the salt concentration in the irrigation water, the method, frequency and intensity of irrigation, the initial salt content in the soil, groundwater level and the permeability of the soil.

Thus, a reliable method to predict the **risk of salinisation** must include the source of salts, the salt balance (depending on the climatic factors and groundwater tables), characteristics of the water regime influenced by irrigation practices, and influences of water quantity and cultivation methods on infiltration and permeability.

There are three methods to determine the actual degree of salinisation:

- field samples and laboratory tests (total salinity, specific ion analyses)
- visual appearance, areal affected
- air photo interpretations and satellite imagery can be suitable for a reconnaisance of the areal extent
- indirectly by field observations of crops/trees and yield data (often of limited value because ther are many factors governing yields).

Existing data on actual soil salinity may be obtained from soil survey departments, soil survey reports (soil maps, land suitability maps), agricultural extension services, and research stations. Information may occasionally be obtained from private farmers, governmental and non-governmental schemes and agricultural agents (ie suppliers of farm inputs). However, in any analysis, changes of salinity under cultivaton, seasonal fluctuations, depending on evaporation and rainfall, groundwater fluctuations, cropping season (consumptive use of crops), and on-farm irrigation practices should be considered as factors contributing to a high variability of salinity data in time and space.

Method of Degradation Assessment. FAO/UNESCO (1979) gives the following indices of soil degradation by salinity:

for **status**, consider max. ECe (dS/m) in upper 75cm of soil; max ESP in upper 75cm; plant yields (%of yields in similar non-saline soils); new formations; morphological observations; salts in t/ha/ 1.5m soil depth; t/ha/0.75m soil depth.

for **rate**, consider: ECe increases in dS/m/yr in upper 75cm; ESP increases in upper 75cm in % per year; yields in % decrease per year; surface affected by soluble salts in %.

for **risk**, consider: climatic index for salinisation; number of dry months (in absence of data on critical depth to groundwater table); average depth of groundwater table (cm); salt concentration of irrigation water.

EC = electrical conductivity, a measure of total salinity in the soil solution

ESP = exchangeable sodium percentage, a measure of sodicity in soils.

The present state of salinity and sodicity (ECe > 15dS/m; ESP >15%) and the degradation rate (increase of ECe and ESP per year), and risks are shown for Africa and the near East region in: FAO/UNEP/UNESCO (1979) on a scale of 1: 5 M.

3.1.8 Future Scarcity of Freshwater

There is every reason to suppose that irrigation water resources will become increasingly saline and that an increasing demand in irrigation water will arise which will lead to its increased scarcity. This can be learned from experiences in both industrialized countries, namely the USA and Israel, but also from developing countries, eg Egypt, Iraq, and India.

Fig. 3-3

SALINITY IN IRRIGATED AGRICULTURE 1107

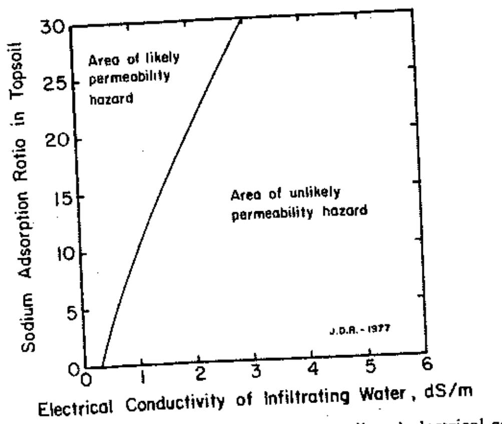


Fig. 36-4. Threshold values of Na adsorption ratio of topsoil and electrical conductivity of infiltrating water associated with the likelihood of substantial losses in permeability. After Rhoades (1982b).

Source: Loveday in Stewart ed. 1990

The manifest pressure of scarcity of food supply plus the availability of capital in some arid countries (eg Near East) resulted in incentives to increase irrigation and in consequence to permit less and less fresh water to drain further downstream and eventually into the sea. This tendency has been exacerbated by the introduction of new crop varieties ('green revolution') that both need and respond effectively to irrigation. Less salts will tend to be flushed from land through surface and subsurface channels, and the salinity of waters, especially in arid areas, will tend to further increase.

Some technical measures are available to reduce these detrimental impacts, eg diversion of natural or human-made saline inflows, diversion canals, cultivation of high yielding crops, less sensitive crops, modern irrigation techniques. Such measures, however, rather require heavy investments and excellent management and they adapt to salinity rather than control it which still reduces the flexibility with which the affected water be used downstream. In addition, most of these measures are unlikely to be introduced on a world scale, especially in the least developed countries, due to economic constraints, lack of management, and more recently, due to environmental concerns.

Examples of rapid large scale deterioration of water and land resources can be seen from:

USA:	Colorado River, Imperial Valley
UdSSR:	Aral Sea, Caspian Sea
Israel:	all rivers on the coastal plain.

Source: Kovda 1983

3.2 Sodic and Alkaline Soils

Sodification problems, casued by the increase of exchangeable sodium ions in proportion to other cations (ESP), are associated with a loss of favourable **soil structure**. Eventually tilth problems will occur in agricultural soils. Sodification as a result of irrigation is a common process when water of a poor quality is applied, for example water with a high sodium adsorption ration (SAR-value). The final ESP reached in a soil in equilibrium with a given irrigation water, depends on the SAR-value, ionic composition, total salt concentration as well as various soil properties, eg its buffer capacity and the actual concentration and composition of the soil solution.

However, irrigation practices are important, too: sodification processes will be favoured if water with a high salt concentration is followed by water with low salt concentration. In practice this may occur if poor quality irrigation water is followed by good quality water, eg during the rainy season or when blended water is applied. A similar situation arises in coastal regions if soils which are inundated with seawater (typically SAR > 100, EC >40 dS/m) are leached with good quality water, either with rainwater or river water. Sodification is a common process in saline-alkaline soils which are reclaimed by leaching. The desalinisation process will cause severe sodification unless further ameliorative measures are undertaken.

The assessment of **sodicity** hazard (sodium concentation in the soil solution) is complicated by the fact that there exist a variety of factors contributing to the deleterious effects of high sodium percentages in soils, which ultimately may lead to alkalinity (pH-values above 8.5). Under irrigation, the processes which occur during infiltration and percolation are to be considered. These may vary considerably according to the status of the soil structure which is time dependent, too. In medium to fine textured soils, sodicity is most important because of their high buffer capacity, ie they are less susceptible to changes in the soil solution and hence, less easy to reclaim by leaching. Furthermore, soil structure is the prominent feature in these soils, governing infiltration and permeability.

The sodicity hazard is related to potential permeability and tilth problems. Fig. 3-3 serves as an approximate guideline for assessing sodicity hazard in relation to total salinity of

Fig. 3-4

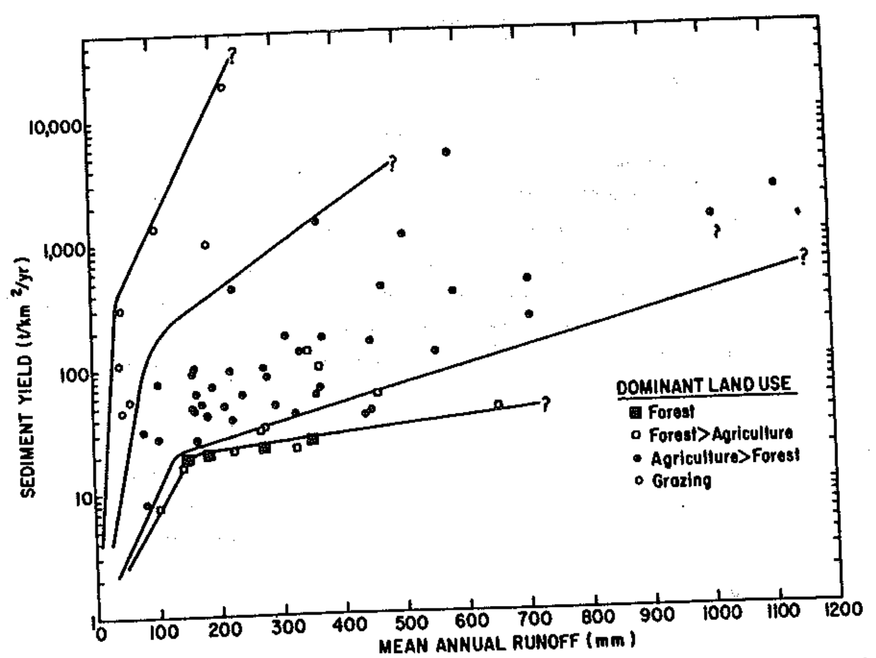


Fig. 1. Mean annual sediment yield and mean annual runoff for catchments with indicated dominant land uses. (After Dunne, 1979.)

Source: ASA 1986

the irrigation water and the known SAR in the topsoil solution. Other inherent soil factors such as mineral composition (eg cementing materials such as $CaCO_3$, oxic or siliceous compounds) and the presence of organic materials may contribute to the stability of soil aggregates. It is advisable to establish site specific relations for irrigation projects to test the susceptibility of soils to sodicity-induced disaggregation, clay dispersion and reductions of permeability whenever possible (Rhoades/Loveday 1990).

The term **alkalinity** refers to the pH-value, depending on the hydrogen ion concentration in the soil solution. Alkaline soils tend to be sodic, although the reverse is not always the case: eg Solonetz soils or sodic Solonchaks have high ESP-values but may be almost neutral or even acid in reaction, eg Solods or solodized Solonchaks. Strong alkaline reactions depend on high concentrations of carbonate and bicarbonates in the soil solution. Alakali sodic soils will eventually be formed if irrigation water contains an excess of carbonates and bicabonates over calcium and magnesium ions (RSC value). In the long run, carbonates and bicarbonates added in the water will precipitate with calcium and magnesium exchanged from the soil, until the adsorption complex is saturated with sodium. Continued addition of water will cause accumulation of dissolved sodium-carbonate, leading to pH-values in excess of 10, even in well-aerated soils (Bolt/Bruggenwert 1978).

Sources: Rhoades/Loveday in: Stewart et al. ed. 1990; Szabolcs 1979; FAO/UMEP/UNESCO 1979

3.3 Soil Erosion

3.3.1 Introduction

Erosion is an important soil degradation process which may become a major hazard to agricultural production. Cultivated land produces 10 to 100 times more erosion than other land use types and it is estimated that 16 t/ha of soil (equaivalent to 1-2 mm) are annually lost on croplands. In modern agriculture, the detrimental effects of erosion on crop yields are hidden by agronomic measures, eg by fertilising or the use of new varieties. However, the problem is obvious in many subsistance agricultural systems in developing countries (Brown/Wolf 1984).

Erosion impacts are twofold: erosion implies the loss of soil material, usually fertile topsoils from erosion sites, and **sedimentation** at deposition sites. This sedimentation may occur on-farm or off-farm and it may contribute to increased suspended loads in rivers before the sediments eventually deposit on flooded areas or along river banks or is transported further into lakes or the sea.

Soil erosion may be **beneficial** or **detrimental**, depending on the point of view. Erosion on agricultural lands is usually regarded as detrimental: it lowers soil productivity through a loss of storage capacity for water, loss of plant nutrients, degradation of soil structure, and decreased uniformity of soil conditions within a field. The characteristics of each individual soil profile, however, can strongly affect the actual quantitative impact of erosion upon productivity. Sedimentation on agricultural lands can be beneficial by improving soil characteristics (eg the fetility of floodplains is largely due to the deposition of eroded material furtehr up the catchment), increasing land height (polders) or increasing the depth to groundwater but it can also be detrimental by burying seeds and plants. Therefore, scale and time factors as well as magnitude and the users' view must be considered when evaluating the effects and impacts of erosion.

Soil erosion is induced by either water or wind forces which can be far more important than in the 'normal' (geological) erosion process because of human interference in natural ecosystems. Most human ecosystems are significantly more prone to erosion than natural ecosystems (except extreme deserts) mainly due to changes in the vegetative cover and interference in hydrological cycles (Fig. 3-4 and Table 3-3). The natural-induced rate of

Fig. 3-5

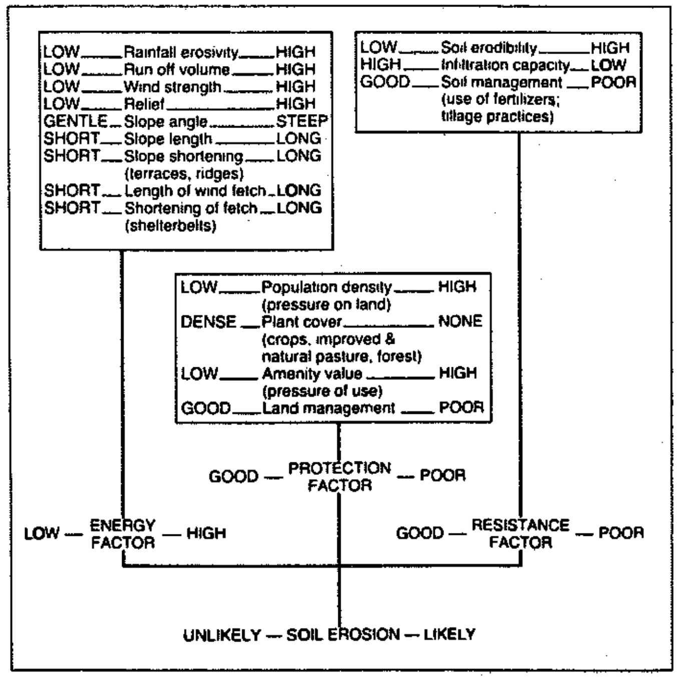


Fig. 1.1 Factors affecting soil erosion.

Fig. 3-6

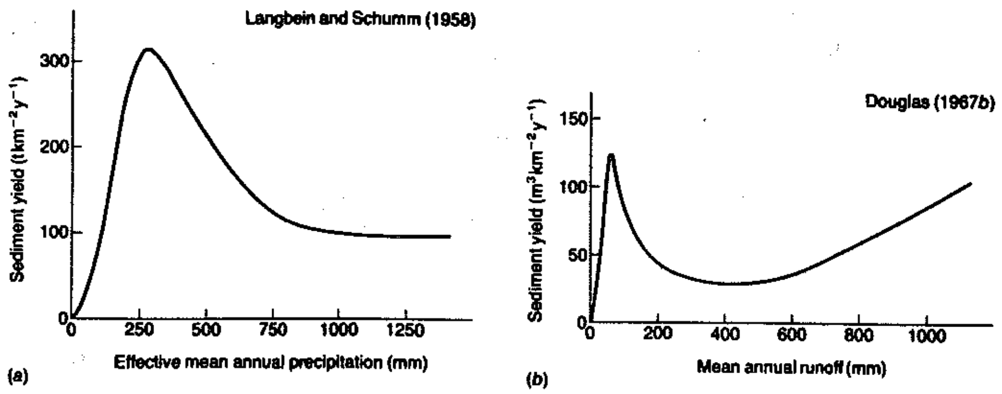


Fig. 1.2 Proposed relationships between sediment yield and (*a*) effective mean annual precipitation; (*b*) mean annual runoff (after Gregory and Walling, 1973).

Source: Morgan 1981

erosion varies with climatic, geological, topographic conditions and soil. In common soil conservation practice an acceptable rate of soil erosion is 5 to 25 tons/ha per year or 0.2 to 1 mm/y. However, this rate may be too high to keep pace with the rate of soil weathering, and recent approaches set values closer to 0.02 to 0.2 mm/y.

Table 3-4 shows recommended maximum **permissible** rates of soil loss on various scales. Controlling factors for erosion rates are: rainfall energy, and vegetation cover at the field level and **runoff** at the drainage basin level (macro-scale). Rainfall energy is used as an indicator of rainfall intensity and total amount.

Source: Morgan in: Kirkby/Morgan ed. 1980

Irrigated agriculture may contribute to accelerated erosion in similar ways as in non-irrigated systems. In the following section, a brief review of irrigation-induced erosion is provided. Control measures are outlined in Part II section 3.4.

3.3.2 Water Erosion

The difference in erosion on irrigated and non-irrigated croplands is that on the latter water erosion is caused solely by natural rainfall and flooding. Under irrigation, additional water is added by man, which increases the potential for water erosion.

The erosion of soils by water consists of the **detachment** and the subsequent **transport** of soil particles. These may be detached by the kinetic energy of impacting water droplets or by the energy of flowing water. The transport for water to flow over the surface of detached particles occurs when the land slope is sufficient to transport them as suspended sediment or bedload. This process occurs wherever infiltration into the soil profile is lower than the rate of water application or rainfall intensity.

The most important factors determining the degree of water erosion on irrigated fields are: soil stability, exposure of soil particles (or reverse: the vegetation cover), slope and length of slope, infiltration rate, application rate, and the energy of water droplets (relevant for sprinkler irrigation). These factors are described as the **erosivity** (runoff, droplet impact) and **erodibility** (related to soil, vegetative cover- and topographic conditions). Most of these factors may be manipulated for agricultural systems (see Fig. 3-5).

Semiarid to subhumid tropical regions (definition in Table 2-4) are characterized by a high 'erosivity', resulting from rainfall pattern and intensity, which is a major hazard on most non-irrigated croplands (Fig.3-6 and Table 3-5). Erosion was controlled by **terraces** in traditional irrigation systems in the Andean and Asian regions, even in mountainous areas. Such areas would otherwise be considered unsuitable and prone to severe erosion risks. Consequently, erosion on irrigated areas occurs where **soil and water conservation measures are inadequate.** Erodibility can be reduced under surface irrigation systems by improving water retention properties by changing the length and grade of slopes and by partitioning the field, eg by farming basins or bunds. Irrigation may therefore have indirect beneficial effects by intercepting rainfall, improving soil moisture in situ and reducing river sedimentation because runoff is limited within the field boundaries.

Water harvesting is another type of water management which immediately intercepts rainfall for its on-site use and, hence, indirectly controls erosion on arable land (eg Boers/Ben-Asher 1982; Hudson (FAO) 1987). Level dam terraces in mountain areas (eg rice terraces in Southeast-Asia) are a special combination of water harvesting and irrigation farming (see also: Klemm 1990; Pacey/Cullis 1986, Kutsch 1983).

Irrigation usually increases cropping intensity, ie the arable land is less frequently under fallow than non-irrigated areas are and consesquently, rainfall erosion is further reduced by a protective vegetative cover during one or two additional cropping seasons compared with rainfed systems. This may apply to semiarid to subhumid areas.

In arid regions irrigation-induced water erosion becomes important because these areas have low potential and actual erosion rates by virtue of limited rainfall (extreme rainfall events are not considered here). On the other hand, vegetative cover in arid areas is limited by moisture deficits and irrigation compensates for those deficits. Consequently, irrigation may contribute to reducing (water and wind induced) erosion hazards by providing favourable environments for vegetative growth, allowing the build-up of organic matter which stabilizes soils and increasing soil cohesion by keeping soil surfaces wet.

<u>Generalized impacts of water erosion</u>

The primary impacts of water erosion is a reduction of <u>agricultural productivity</u>. Yield reduction on eroded fields may occur as a result of decreasing topsoil depth and eventually the exposure of less fertile subsoil layers, the loss of organic matter and other nutrient rich layers from topsoils, the loss of seed or damage of yound plants, and loss of arable land due to gully erosion.

These factors contribute to a reduction in available soil moisture and reduced water-use efficiencies in non-irrigated cropping systems. Additional economic losses may occur due to losses of fertilisers and pesticides. Actual productivity losses on specific sites are extremely variable because of the interrelation of numerous factors. General conclusions from loss estimates drawn from experiments should be treated with caution, especially if decreasing soil depth is used as an indicator. Some generalised yield loss estimates on eroded non-irrigated fields which occur after a few decades are

> about 40% on some soils in the CIS, 30% on eroded soils in Haiti, 50% decline in some Nigerian soils, 17 to 50% yield loss in some US states (Carter in: Stewart et al. 1990). Carter estimated yield reductions of some 25% after 80 seasons of irrigated furrow erosion on approximately 1 M ha of furrow-irrigated land in the USA.

Other impacts are increased downstream <u>sedimentation</u> with impacts on downstream agriculture through siltation of irrigation canals or blocked structures, reduced reservoir lifetimes, stream aggregation, damage to fishery, increased maintenance costs in waterways, and increased costs in harbour maintenance.

Downstream <u>water quality</u> may be impaired by overland flow which contains solid or soluble constituents of fertilisers or pesticides. There may be increased downstream flooding, probably in connection with sedimentation, and on a large scale level, ie for large watersheds there may be a decrease in dry season stream run-off, due to reduced interception by soil and vegetation.

<u>Erosion on Irrigated Fields</u>

Erosion may occur whenever water flows over agricultural land. Where irrigation is practiced on almost level land and low flow velocities occur during flooding of close growing crops, erosion is usually slight. Likewise, no surface flow should occur with properly designed sprinkler irrigation systems. Drip irrigation is regarded as best suited to control erosion. Irrigation-induced erosion can be divided into the following types

(i) <u>Furrow erosion</u>. Furrow irrigation was identified in the USA as a serious source of surface water pollution (sediment load) and regulations were established to control erosion. Parameters which influence the intensity of furrow erosion are: furrow shape and grade, furrow roughness, soil particle size, soil stability, previous water contents, infiltration rates, duration of irrigation, and flow rate. Sediment loss on a specific site can be about a 2 to 3-power function of furrow slope and about a 1.5-power function of flow rate. Furrow irrigated fields on slopes steeper than about 2% are usually prone to erosion due to uncontrolled concentration of runoff water and excessive flow velocity. Erosion will always occur when flowing water comes into contact with friable, unstructured soils, and even flow at the design rate will produce some unavoidable erosion on the upper 25 to 40% of each furrow and sedimentation on the lower half. The furrow stream must be large enough to carry enough water to irrigate the entire furrow length, and infiltration time should be ideally the same over the entire length to provide uniform applications. Hence, erosion along furrows is difficult to control. Irrigation field practices are usually focused on assuring complete flooding at the lower ends of furrows with greater runoff than necessary along upper furrow sections; as a result, furrow erosion may be severe with up to 40 to 50% of the applied water running off the field into the surface drainage system (Carter in: Stewart et al.1990).

(ii) Erosion under sprinkler irrigation is similar to that under rainfall: soil particles are detached by falling drops, and transported by drop splash and sometimes flowing water. The actual rate of erosion depends on the design of sprinklers and the operating pressure.

Erosion risks may be assessed on the basis of the applied kinetic energy in the following ascending order of magnitude: center pivot systems, mobile hand moved sprinklers, wheel line systems and finally rain-guns (high kinetic energy). Low-pressure sprinklers and spray heads are in practice often less favourable because the application rate per unit area on the wetting areas must be greater to achieve the same total application. Typically, erosion under sprinkler irrigation occurs when water application rates exceed infiltration, water ponds in small depressions and eventually moves downslope and concentrates in tillage tracks or previous erosion channels. The flow rate in these rills increases downslope as a result of increasing collecting areas. Eventually larger channels may develop further downslope or in adjacent irrigated areas and drainage channels or off-farm areas may be partially flooded, causing on- and off-farm damage.

Actual rates of on-farm erosion under various sprinkler systems vary considerably and they are easily controllable by the operator. The amount of erosion under center pivot irrigation is relatively small when only 30-50 mm of water is applied at low rates (10-20 mm/hr). The threshold value of rainfall intensity (ie when significant overland flow and erosion occurs) has been given as 25 mm/h for Zimbabwe, 6 mm/h for Germany and 10 mm/h for Britain (Morgan in: Kirkby/Morgan ed. 1980).

(iii) Sheet erosion by uncontrolled flooding on border dyke or border strip systems is essentially the same as under furrow irrigation. Topsoil redistribution often occurs when slopes exceed 2%. The actual rate of erosion largely depends on land preparation (eg levelling) and tillage practices. Uncontrolled flooding requires strict control during the application of water in order to avoid topsoil redistribution.

(iv) Erosion caused by overtopping of dykes and levees may occur under consitions of uncontrolled flooding of basin or border strip systems. Under controlled conditions checks and level basins offer an effective control of rainfall- and irrigation-induced erosion and the avoidance of any off-field losses. However, in practice flooding is often uncontrolled. Large ponded areas may result and rills and gullies may develop finally from overland flow as under sprinkler irrigation. Highly regimented time schedule operations and poor on-farm water supply control may contribute to this type of erosion.

Reference: Carter in: Stewart et al.1990; Mech/Smith in: Hagan et al. 1967

Further reading: Morgan 1986; Morgan ed.1981; ASA 1982; Greenland/Lal 1977

3.3.3 Wind Erosion

Wind erosion is a natural hazard in dry climates and in areas with clustered or diffuse natural vegetation or where vegetation is destroyed by human. Severe erosion by wind occurs whenever a loose and dry soil surface is unprotected by vegetative cover and winds are sufficiently strong. Critical wind speed velocities were established as some 4 m/s at 1 m height (although the lower limit of erosion is at some 0.5 m/s). This is the threshold value when severe erosion commences under average conditions. These conditions are usually met in areas which are prone to natural drought. Yet, wind erosion occurs in many irrigated regions and irrigation is affected by wind erosion although it does not

Fig. 3-7

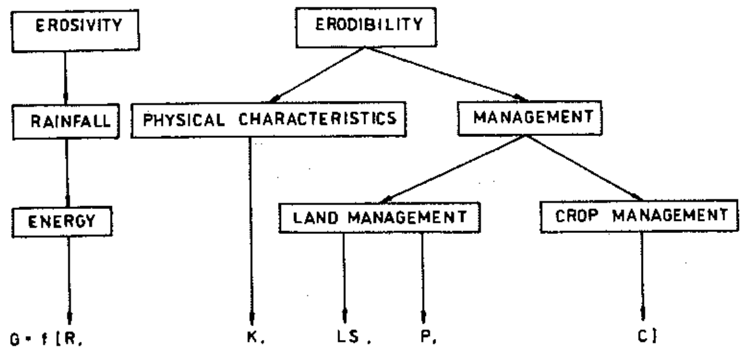


Fig. 65. Diagram expressing erosion intensity in dependence on the erosivity of rainfall and soil erodibility after N. Hudson.

Source: Holy 1980

contribute to it. In other words, wind erosion is an inherent hazard on many irrigated lands because of high potential erosivity and erodibility.

Factors related to **erosivity** are: wind velocity, duration and prevailance of a particular wind direction; surface roughness affected by vegetation, tillage practices, windbreaks and shelterbelts and by local changes in topography. Surface roughness is significantly increased by vegetation cover; the effectiveness depends upon the height and continuity/uniformity of the canopy, the density of the ground cover and the root system.

Factors affecting the **erodibility** of individual grains or soil aggregates are: moisture content, soil cohesiveness, texture and organic constituents.

Source: Morgan 1986; Wilson/Cooke in: Kirkby/Morgan ed. 1980; FAO 1960

The effect of irrigation on wind erosion hazard is related to increased water contents in soils, tillage practices and changes in vegetative cover. Most of those effects are beneficial, ie vegetation growth is enhanced by irrigation, the soil surface is kept moist, and the surface roughness of bare soils is increased with adequate tillage practices.

The physical effects of wind erosion can be summarised as:

- **soil damage**: fine material, including organic matter, may be removed; soil structure may be damaged by disaggregation; coarse layers of stones or pebbles may remain as residues; fertilisers and herbicides may be redistributed or lost,
- **crop damage**: seedlings may be covered by sediments; sandblasting may cause foliage abrasion; seeds and seedlings may be blown away; fertiliser redistribution may cause uneven growth conditions or even locally toxic concentrations; soil borne disease may be spread (as particles, aerosols); rabbits and other pests may inhabit dunes trapped in hedges and feed on the crops,
- other **on-farm damage**: soil is deposited in ditches, canals, roads, windbreaks, hedges; fine material may clog irrigation structures; farm machinery and irrigation equipment may be abraded,
- **irrigation**: strong winds may hamper timely sprinkler applications; other work may be delayed by unpleasant conditions; drip systems may become blocked by sediments.

Reference: Wilson/Cooke in: Kirkby/Morgan ed.1980; Mech/Woodruff in: Hagan et al.1967; FAO 1960, 1965, 1979

3.3.4 Erosion Risk Assessment

There are numerous methods for risk assessments on croplands, considering the potential and actual hazards. These comprise theoretical **numerical** solutions (eg Kirkby in: Kirkby/Morgan ed. 1980), **empirical** quantifiable predictions (eg USLE-formula, Wischmeyer/Smith 1978), rule of thumb **field observations** (eg Hurni 1988) and generalised **assessments** on a world-wide scale (FAO/UNEP 1983, FAO/UNESCO/UNEP 1979; FAO (SB 13) 1971).

Despite these efforts to develop practical guidelines a basic constraint to quantitative approaches remains that soil erosion is a **complex process** involving the interaction of environmental, physiochemical (soil) and agronomic factors as seen in Fig. 3-7.

Empirical models have the disadvantage of comprising complex interactions of many factors whose simplification (from site specific experience) may result in an unacceptable reduction in the accuracy of predictions on other sites. **Conceptual** models are often too complex for simple application and a large number of coefficients may need to be be experimentally determined.

Reliable empirical predictions of erosion hazards must consider all individual factors of erosivity and erodibility, and their interrelations. Site specific assessments still require educated guesses of some of the factors and parameters involved. Furthermore, economic considerations must be introduced so as to evaluate the feasibility and viability of site specific erosion control measures. For further details the reader is referred to specialist literature on soil erosion, eg proceedings of national or international soil science societies and scientific journals). No generalised models have been developed for predicting erosion hazards in irrigated agriculture, but many models can be used for both, irrigated and non-irrigated farming.

Comprehensive reviews in: Blume ed. 1990; Landon ed. 1984; Holy 1980

3.3.5 Costs of Soil Erosion

Costs due to erosion occur on-site and off-site. On-site costs are related to

- long term loss of soil fertility (bio-chemical and physical properties)
- short and medium term lower yields per unit area
- replacement costs of fertilisers and pesticides
- crop damage
- implementation and maintenance of technical control measures for sheet runoff: strips, terraces, interception ditches, ridges, storm drainage canals
- implementation and maintenance of technical measures to control concentrated runoff: runoff (retention) reservoirs, gully and ravine control; torrent control
- application of agricultural and forestry measures for control: special tillage methods, vegetation methods, afforestation (windbreaks, shelterbelts)
- siltation of reservoirs (on site)
- repair and maintenance costs for cleaning drainage structures
- repair and maintenance costs for cleaning water intake structures and canals
- replacement of material and infrastructure; additional working hours.

Off-site costs are difficult to assess because they are often indirect and quantification would require considerable research:

- siltation of larger downstream reservoirs at accelerated rates; reduction of effective storage capacity
- increased water treatment costs for downstream domestic water users if water is contaminated, carries high sediment loads or pathogens
- indirect losses to fishery if water contamination causes reduced fish growth, increased mortality (total population) or changes in fish species
- aeolian deposits which contain salts might cause salinisation
- damage to processing equipment in industrial plants if polluted or contaminated water is used without prior treatment
- eutrophication of rivers, lakes and reservoirs due to increases in phosphate and nitrogen; subsequent loss in recreational value etc.

Case Studies

Java. High sediment loads in the irrigation water, caused by upper watershed erosion, may cause damage to irrigation systems. An estimate for Java assumes that irrigation system siltation causes annual costs in the range of US $ 9-13 M (Table 3-6). Sedimentation imposes high costs in terms of shortened beneficial investment time, high maintenance requirements, and reduced services. Siltation of reservoirs, some of them also used for irrigation water supply, causes cost in the range of US $ 16 to 75 million annually (Doolette/Magrath 1990).

Fig. 3-8

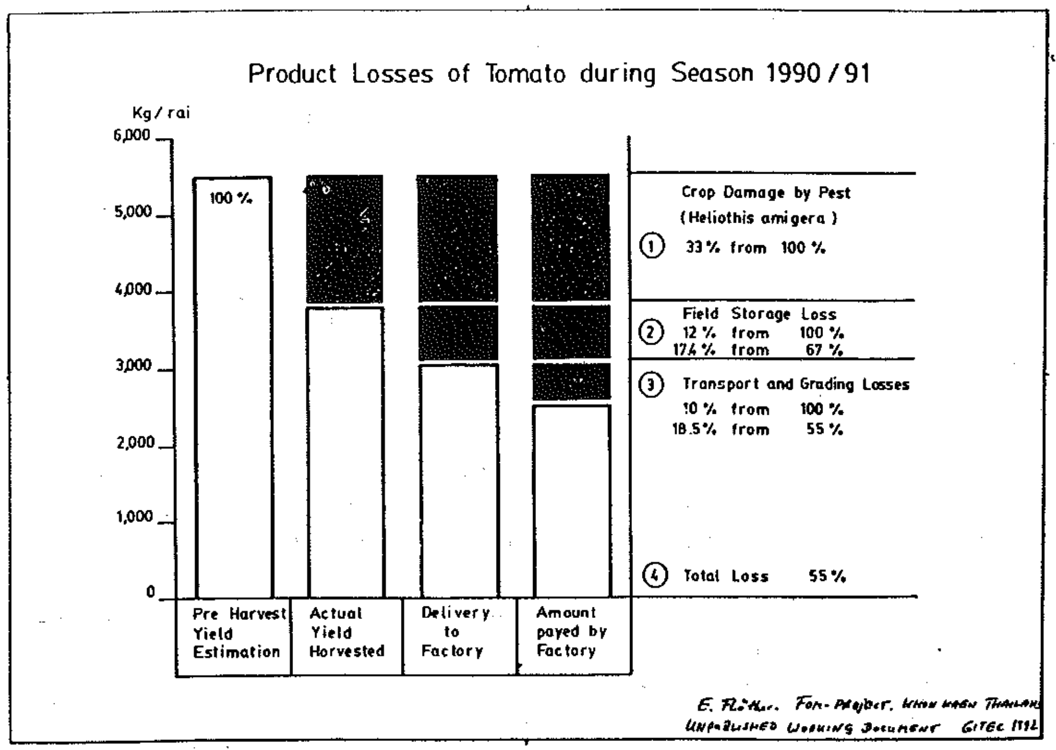
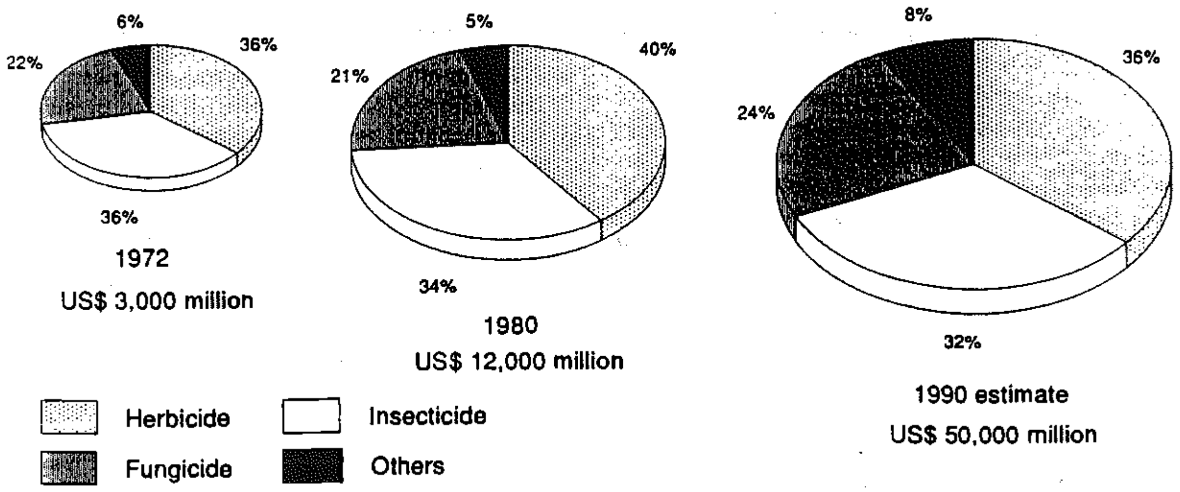


Fig. 3-9

App. 4-7(i): Entwicklung der Verkäufe bei wichtigen Pestiziden



Quelle: Meybeck, M. et at., Global Freshwater Quality, Oxford, 1989

Source: GITEC 1992

Luzon. Without watershed management control actions, high sedimentation rates in the upper watershed of San Roque Multipurpose Project (Luzon) will cause losses about $ 200 M over a period of 50 years. The watershed control costs will be some $ 27 M (Briones in: Easter et al. ed. 1986)

Sources: Easter et al. ed. 1986; Morgan 1986; ASA43. 1986; Morgan ed. 1981; Kirkby/Morgan ed. 1980; Holy 1980; FAO/UNEP/UNESCO 1979

Further readings: Barbier 1990; Kratz 1989; Hurni 1988; Lal 1989; FAO/UNEP 1983; Schwab et al. 1981; Hudson 1971; FAO 1965; FAO 1960

3.4 Contamination of Soils with Pesticide Residues

3.4.1 Introduction

Pests destroy up to one third of the world's food crops during growth, harvest and storage (example in Fig. 3-7). Therefore, synthetic organic pesticides have become a major element in modern agricultural production practices (Fig. 3-8). The advent of pesticide use has coincided with the tremendous increase in agricultural productivity together with expansion of agriculture over the past century. Together with the adoption of improved varieties, use of synthetic fertilisers, improved irrigation practices, and more efficient farm machinery, pesticides have been credited as one of the major contributors to modernized agricultural production which led to dramatic improvements in crop yields and nutritional quality of most products (quality may also have been declined in some products, see Pacey/Payne 1985). Synthetic chemicals have essentially replaced inorganic chemicals and many tillage and cultural practices. The recent trend towards minimal tillage (projected to be practiced by the year 2010 on some 60% of US farms) has also meant an increased reliance on pesticides, although recent integrated pest management approaches combine non-chemical means with chemical use

Further figures on pesticide uses are given in Part II section 5.2, especially 5.2.2

Remark: In the USA, about 70% of pesticides in 1983 were for agricultural purposes (Leonard in: Cheng ed. (SSSA) 1990). Other important users are health programmes and agroforestry.

The **advantage** of chemical pesticides include their effectiveness in controlling pests and their rapid and (relatively) easy application. The **disadvantage** is that few pesticides possess a high degree of specificity and most of them are also toxic to non-target organisms. Their use also constitutes a potential health hazard to the person who handles them as well as to consumers of treated crops as well as posing serious entvironmental threats.

Conventionally, it is believed that the careful handling and application of pesticides under appropriate soil and environmental conditions is proven to be effective in pest control with little adverse effects on the surrounding environment. Growing evidence, however, indicates that **trace** amounts of pesticides are present in **soils**, **groundwater** and the **atmosphere**. Since pesticides are toxic by design, there is a natural concern on the impact of their presence in the environment on human health and envrionmental quality (soil/water/air resources/biotic life). In addition to concern for the acute and chronic toxicity of chemical pesticides, their potentials as carcinogens, teratogens, and mutagens have led to questions about the acceptability of continued use.

The purpose of this section is to review the presence and fate of pesticides in soil environments based on recent publications on pesticide issues, mainly from studies conducted in industrialized countries.

Remarks: Most analyses and assessments are made in **industrialized** countries, namely USA, Canada and Europe. Analytical data from developing countries are rare but the **increased use** of pesticides and fertilisers in developing countries make it more likely that contamination and pollution problems will increase in the near future. Problems in developing countries are often exacerbated by lack of infrastructure and resources to deal with them (see also: Bull 1982; Davies et al. 1982, both cit. in: Madhun/Freed, in: Cheng ed. 1990).

Drastic changes in pesticide characteristics and uses over the past 10-15 years require that data in earlier publications and generalisations should be treated with caution.

Sources: Cheng; Severn/Ballard; Leonard all in: Cheng ed. 1990; FAO 1985a;

3.4.2 Nature and Scope of Contamination Impact

Impacts are a function of the **nature** of the chemical (eg toxicity and properties) and the **exposures** received (eg amount/concentration, frequency and duration). Generally, pesticides create several problems including widespread accumulation of residues, resulting in impairments to wildlife, fisheries, beneficial insects, and even humans. Impacts on wildlife may result in

- increased mortality due to **acute** toxicity,
- **subtle** effects on reproduction and behaviour due to chronic toxicity or habitat deterioration,
- **long-term** impacts through accumulation of residue.

Impacts may occur on-site and off-site, during storage and handling, and during or after application on target plants. They include (1) pollution of soil and water resources, (2) contamination of humans which are in contact with the the chemical or the products treated with pesticides, and of biotic life which is in contact of affected air, soil and water. The impact on the natural environment is often not obvious, but insidious and it has more serious effects than is apparent. The nature and magnitude of the impact are influenced by many factors with respect to pesticide formulation, organism and biological interaction. For example, regarding impacts on fish species for a given pesticide, levels of toxicity vary with temperature, water chemistry, and biological factors such as age, sex, size, and health conditions as well as species (Madhun/Freed in: Cheng ed. 1990).

Table 3-7 indicates the physico-chemical characteristics of pesticides and their relationship to such fundamental environmental behaviour as adsorption, leaching, vaporisation, breakdown, and in terms of biological effects, bioaccumulation (Madhun/Freed 1990). On the basis of persistency and toxicity, pesticides can be classified as:

<u>Persistent</u> chemicals which can exert pressure on ecosystems for considerable periods and what constitute one of the greatest potential hazards to the environment are organochlorine insecticides (eg DDT, dieldrin, endosulfan). Organophosphate insecticides (OP) are less persistent but many have higher toxicity to mammals and some are systemic in plants. Carbamates include insecticides, fungicides and nematicides; they are more persistent than OP and differ considerably in mammalian toxicity. A few fungicides (eg mercury compounds) and herbicides (eg triazines) are also moderately persistent.

<u>Transient</u> chemicals, including certain insecticides of high toxicity, occasionally account for spectacular incidents and kills of wildlife, but populations usually recover quite rapidly and the contamination disappears quickly. Most nematicides (eg D.D., chloropicrin, methyl bromide, aldicarb) are of very high mammalian toxicity and have a broad spectrum of toxicity. They can cause drastic localised impacts. Molluscicides cause few environmental problems if used as baits. Systemic herbicides (eg 2,4,5T, 2,4-D, MCPA, CMPP) are selective and of low mammalian and fish toxicity. Although soluble and mobile they have been thought not to pose serious environmental hazard, atlhough recent research challanges these assumptions. Contact

Fig. 3-10

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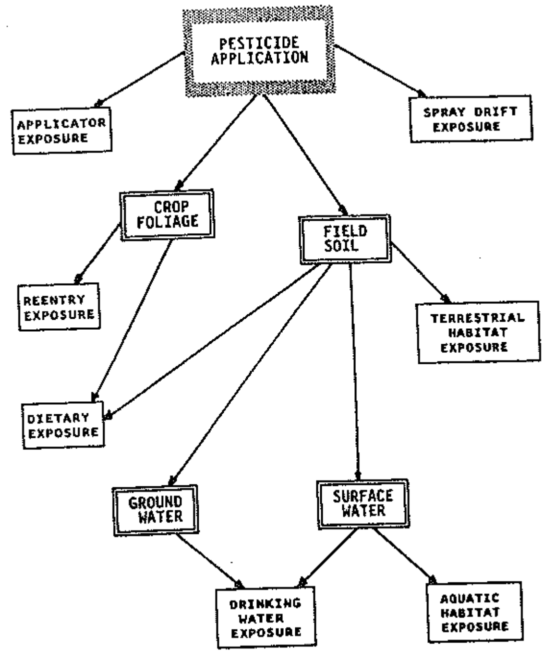

Fig. 13-3. Pathways of pesticide exposure.

Fig. 3-11

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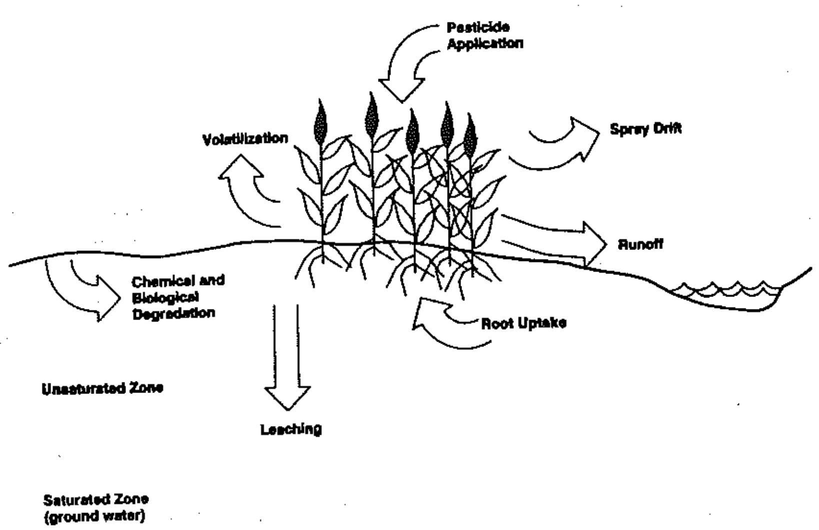


Fig. 13-2. Pathways of pesticide degradation and transport.

Source: Sever/Ballard in Cheng ed. 1990

Fig. 3-12

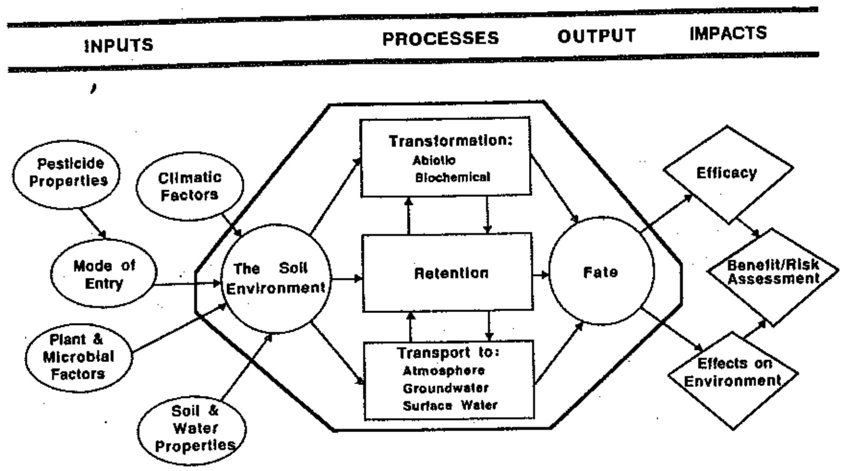


Fig. 1-1. A conceptual framework depicting the factors and processes that govern the fate of pesticides in the soil environment and how pesticide fate affects their efficacy and their impact on the environment.

Source: Cheng in Cheng ed. 1990

herbicides (eg paraquat) are of low mammalian toxicity and cause few problems, although some of them have a medium toxicity and they may accumulate. Fungicides differ widely; most have low mammalian toxicities and have a low range of toxicity to soil and aquatic organisms.

Sources: Edwards 1987; Madhun/Freed in: Cheng ed. (SSSA) 1990

On-site impacts, due to pesticide use may occur to

- target or non-target plants
- soil microorganism and invertebrates: mortality, subtle and long-term impacts may occur to target or non-target organisms. Insecticides, nematicides and molluscicides have the greatest direct impacts on vertebrates but herbicides may affect them through effects on vegetation. Negative effects may occur to predators that help to control pests (eg mites, centipides and carabid beetles)
- insects, birds, mammals: mortality, subtle and long-term impact may occur
- exposed humans through respiration, dermal (skin) exposure or ingestion; direct toxic or subtle reactions from acute or chronic impacts may occur if proper precautions and protective clothing during storage, handling and application are not employed. The major route of exposure for farmers is dermal due to spillage, splashes, or contamination of clothing. The respiratory exposure during mixing and application varies largely with type of chemical application method and individual handling. The potential pathways of pesticide exposure to humans are shown in Fig. 3-10.

Off-site impacts due to pesticides may occur on:

- all users or consumers of polluted ground- and surface waters further downstream of the application area, especially to fish, birds and mammals,
- all consumers of contaminated plants. There is no consensus amongst scientists about the actual human health threat posed by pesticides at legal concentrations in consumed food.

Sources: Madhun/Freed in: Cheng ed. (SSSA) 1990; Edwards 1987

Further reading with references and examples of impacts in: Madhun/Freed in: Cheng ed. (SSSA) 1990

3.4.3 Pesticide Entry into the Environment

Pesticides may be introduced directly into the environment in a liquid phase, as a dispersion or solution, or in the solid phase, eg as a powder, dust, microcapsule, or granule. Environmental entry can occur during application as spray drift and during rainfall/irrigation due to foliar wash-off. Pesticide sources and environmental exposure pathways are shown in Table 3-8 and Fig. 3-11.

The fate of pesticide in soils is governed by retention, transformation, and transportation processes, and the interaction between them (see conceptual framework in Fig. 3-12.)

Retention (or sortion) is the consequence of interaction between the pesticide chemical and the soil particle surface or soil components. It may be reversible or irreversible, retard or prevent pesticide movement, and affect its availability for plant or microbial uptake or for biotic and abiotic transformation.

Transformation is a change in the chemical nature of the molecule. Changes may be purely chemical in nature (eg catalysed by soil constituents or induced photochemically) or by biochemical means, such as soil microorganism.

Degradation tends to decrease the toxicity although occasionally the metabolic products may be even more toxic than the original compound.

Fig. 3-13

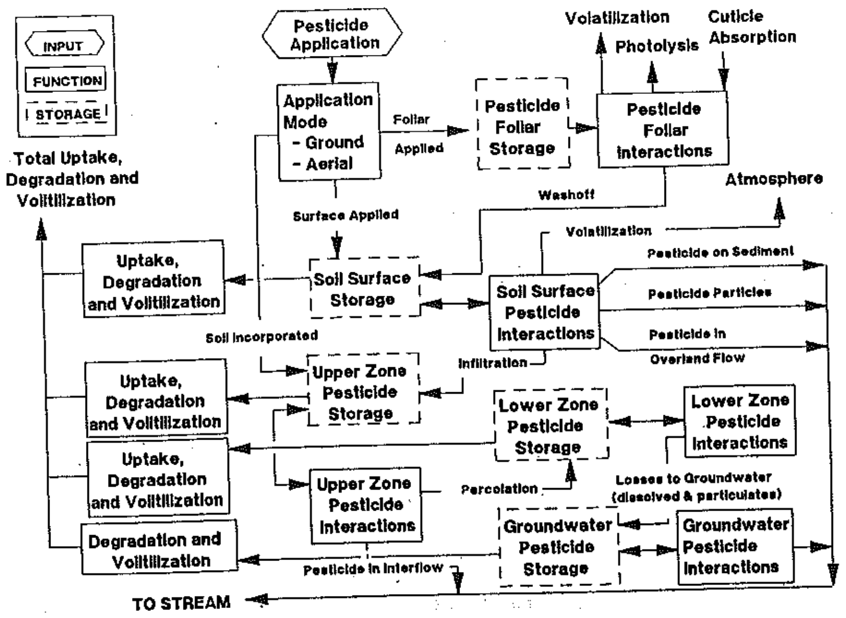


Fig. 2-1. Pesticide transport and transformation in the soil-plant environment and vadose zone. After Donigian and Crawford (1976).

Fig. 3-14

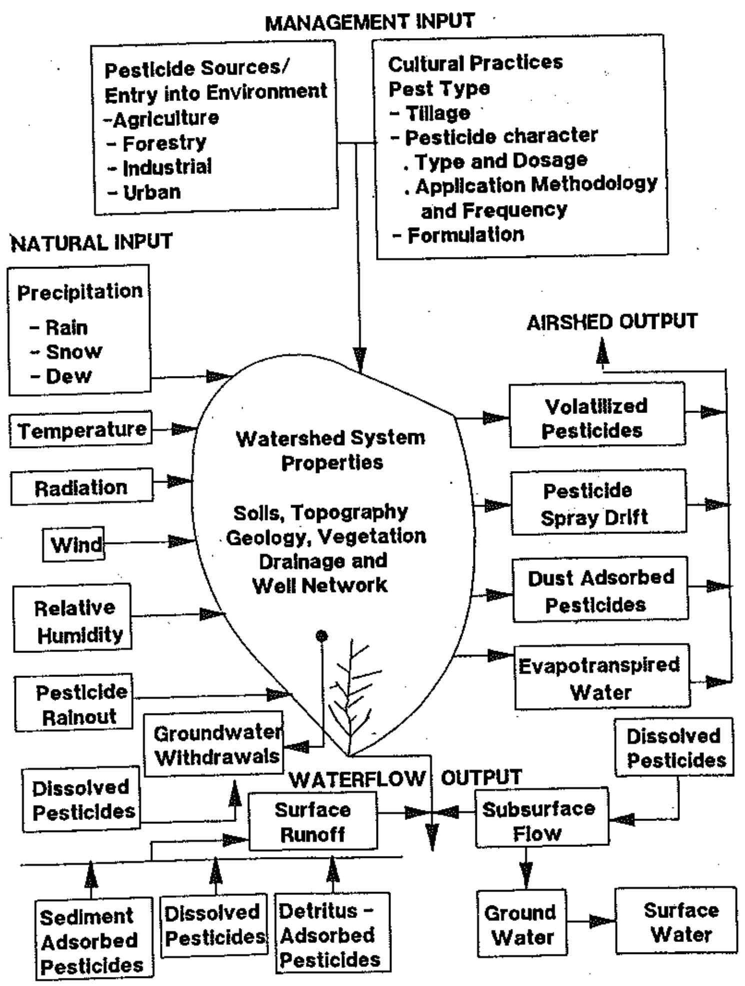


Fig. 2-2. Factors influencing the behavior and export of pesticides from a watershed. After Bailey et al. (1985).

Source: Himel et al in Cheng ed. 1990

Transformation and degradation processes dictate whether and how long pesticides may be present and transportation processes dictate where the pesticides are present. Volatilisation and direct evaporation from plant tissues lead to the distribution of pesticides from the soil/plant to the atmosphere, leaching results in movement towards groundwaters and overland flow moves pesticides into surface waters. Soil properties determine the flow characteristics (of both water and pesticide), sorption determines the availability for transport (vapour vs. aqueous vs. particulate vs. dissolved), and the kinetics of transformation/bioaccumulation determines the concentration present to be transported. The hydrological cycle interacts with chemical properties and soil characteristics to transform and transport pesticides in runoff and leachate to water sources.

Source: Cheng in: Cheng ed. 1990; Himel et al. in: Cheng ed. 1990; Bailey in: Cheng ed. 1990
Further reading: Leistra/Green in: Cheng (SSSA) 1990; Blume ed. 1990; Edwards 1987

Pesticide transport and transformation processes in the soil-plant-groundwater environment are shown in Figs. 3-13 and 3-14. The current state-of-understanding of the pesticide-soil porous media-plant system and the nature of these interactions can be seen in Fig. 3-15 and Table 3-9. Land use, cultural and irrigation practices determine the crop type, the pesticide type and formulation, and the application technology used. Exogenous environmental factors are typically uncontrolled and determine the stochastic nature of pesticide fate in, through, and from the soil to connected groundwater and surface water systems.

Source: Bailey in: Cheng ed. (SSSA) 1990

3.4.4 Herbicide Behaviour in Irrigated Soils

Five main factors affect the behaviour of herbicides in irrigated soils:

i) **Chemical** characteristics of the pesticides: solubility, vapour pressure, chemical and biological stability to surface or biologically induced reactions determine the behaviour in the soil-water system; this in turn is governed by irrigation practices. Biodegradation of herbicides, ie the structural transformation by oxidative, reductive, hydrolytic, or conjugative reactions, are governed directly or indirectly (via microbial metabolic activities) by soil properties, temperature and moisture contents. Enhanced herbicide biodegradation occurs with increased temperatures and at moist (not wet) soil conditions. Hydrolysis is the most important means of chemical degradation. Wet (irrigated) soils may bring about additional reactions. The volatilization from soil surfaces is also controlled by soil moisture, ie the concentration of the desorbed pesticide and the rate of movement in the soil solution. Volatilization from moist soils (or wet plant tissues) can approach 90% within 3 days for volatile pesticides but much less (three orders of magnitude) for dry surfaces.

ii) Properties of the **soil** and their spatial variability: the composition of the liquid-solid phase in soils determines adsorption-desorption from and into the liquid phase. The most significant properties are the clay and organic matter contents and pH-values of the soil. The presence of salts in the soil solution can cause a decrease in the adsoprtion of cationic herbicides due to competition for exchange sites; neutral soils are less effective but may show increased adsorption (Table 3-10).

iii) Herbicide **application techniques**: Surface broadcasting may favour volatilisation or transport by runoff. Application with irrigation water (herbigation) results in distribution within the soil profile and there may be subsequent leaching. Mechanical incorporation may reduce volatilisation but increases the heterogeneity of distribution.

iv) **Irrigation** technology: Significantly affects distribution patterns which may or may not lead to an increase or decrease in application efficiency accompanied by leaching processes. For example, using surface irrigation methods to apply highly volatile herbicides is an extremely inefficient method considering the high volatilisation los-

Fig. 3-15

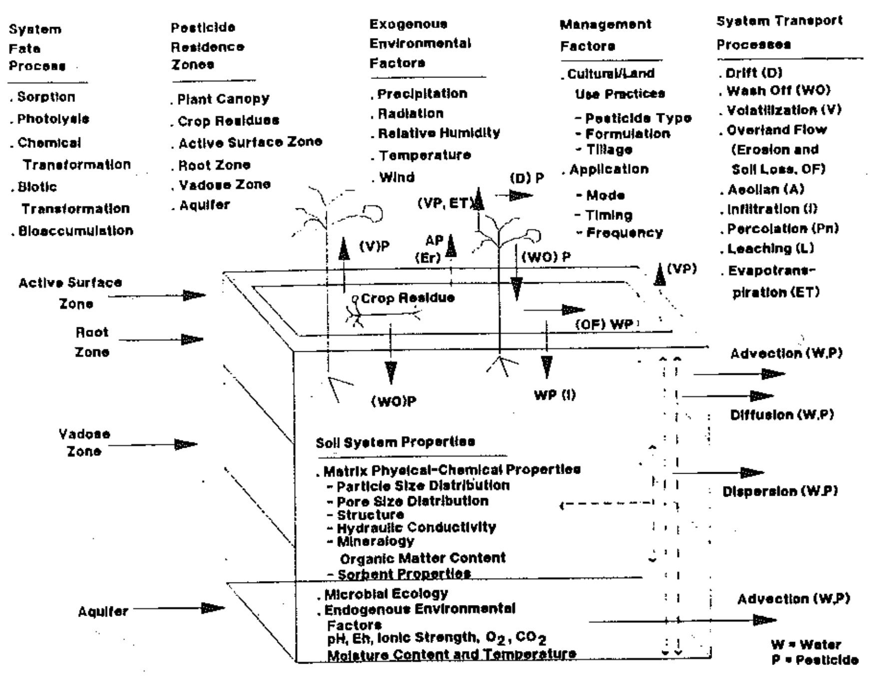


Fig. 14-1. System description of pesticide-soil/porous media-plant interactions.

Source: Bailey in Cheng ed. 1990

ses. On the other hand, deliberate volatilisation can be induced by irrigation scheduling in order to minimise leaching losses (agronomic option). Low rates of irrigation application may restrict downward leaching of deeply injected pesticides.

Basin and border strip irrigation induce one-dimensional flow and uniform, vertical transport. Furrow and drip irrigation induce two-dimensional flow while subsurface irrigation favours three-dimensional flow. Here, the dynamics of flow are more complex and matric potentials govern flow and redistribution once the water enters the soil. Unsaturated conditions are predominant under sprinkler, drip and furrow irrigation methods, whereas saturated conditions in surface horizons are predominant in other surface methods. Anaerobic conditions (ie <10-20% of pore space is gas-filled) during saturated flow inhibit the microbial activity, which affects the fate of herbicides.

v) Fluctuations in the **environmental conditions** during the season: irrigation modifies fluctuations in water content and temperature of the soil which in turn directly affects the herbicide behaviour (see Table 3-11).

It may be concluded that **irrigation technology** and **scheduling** can be used to increase the application efficiency of herbicides and to minimise losses to the environment (ground- or surface water or volatilisation losses). This can be achieved by careful applications of herbicides through modifications of processes like adsorption-release, volatilisation, decomposition and leaching losses. Irrigation can also be used to increase the efficacy of herbicides and to hasten their losses to prevent residual carry-over to the next crop or to groundwaters. If herbicides are applied to moist soils following irrigation, excessive volatilisation may occur before they can be incorporated. Irrigation can also be used to prevent volatilisation by the timely redistribution of the chemical into the soil and by preventing capillary rise to the surface. Howevr, the type of herbicide must also be considered:

For example, non-polar herbicides may be more effective when applied to prewetted soils due to the competition between water and chemicals. Likewise, the application of herbicides with a high vapour pressure to wet soils may increase volatilisation.

Source: Yaron/Gerstl/Spencer 1985

Fate of herbicides in irrigated soils. Herbicides may be directly applied to the soil surface and then wetted by irrigation, applied to the soil in irrigation water, or sprayed onto flooding water:

- Herbicides applied prior to irrigation: the behaviour of herbicides is defined by the irrigation regime (method, rate, total amount, and frequency) because its spatial distribution, the extent of dispersion and the fluctuation of anaerobic-aerobic conditions is affected. Consequently, the degradation rate is also affected. Herbicide losses induced by runoff under furrow irrigation can be in the range of 1 to 2% (Yaron/Gerstl/Spencer 1985)
- Herbigation: this requires strict control of the amount of water applied per unit of land. Pressure systems (sprinkler, trickle) are most convenient for herbicide incorporation into soils via irrigation water. Exessive application may cause harmful biocidal effects on the irrigated crop, eg injury to foliage. Potential evaporation losses of water and the herbicide may be in the range of 10% (atrazin) to 85% (trifluralin). The application of chemicals with a high vapour pressure or unstable photochemical properties is by this method questionable.
- Herbicides applied to flooded soils is common practice in rice culture and in open channels conveying water to fields. Rice fields contain reactive nucleophiles such as hydroxydes characterized by a pH between 8 and 10, ammonia, amines, sulfides, dissolved oxygen and other oxidants, organic and inorganic reducing agents, and

Fig. 3-16

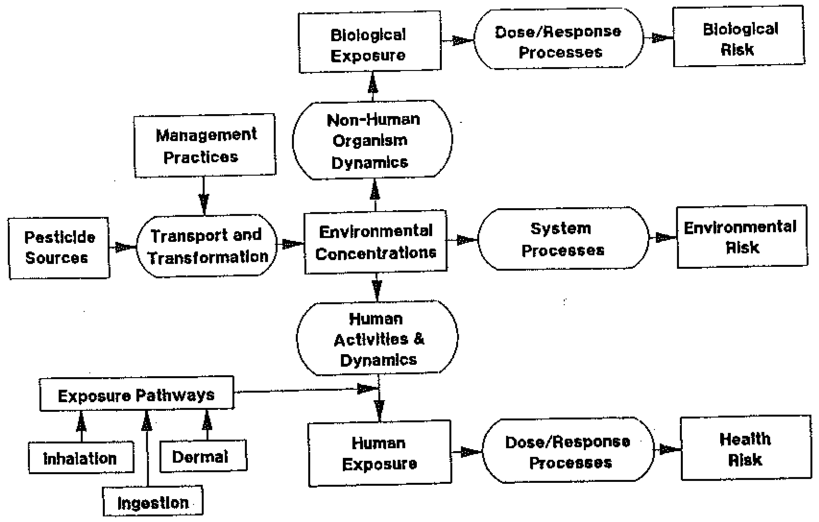
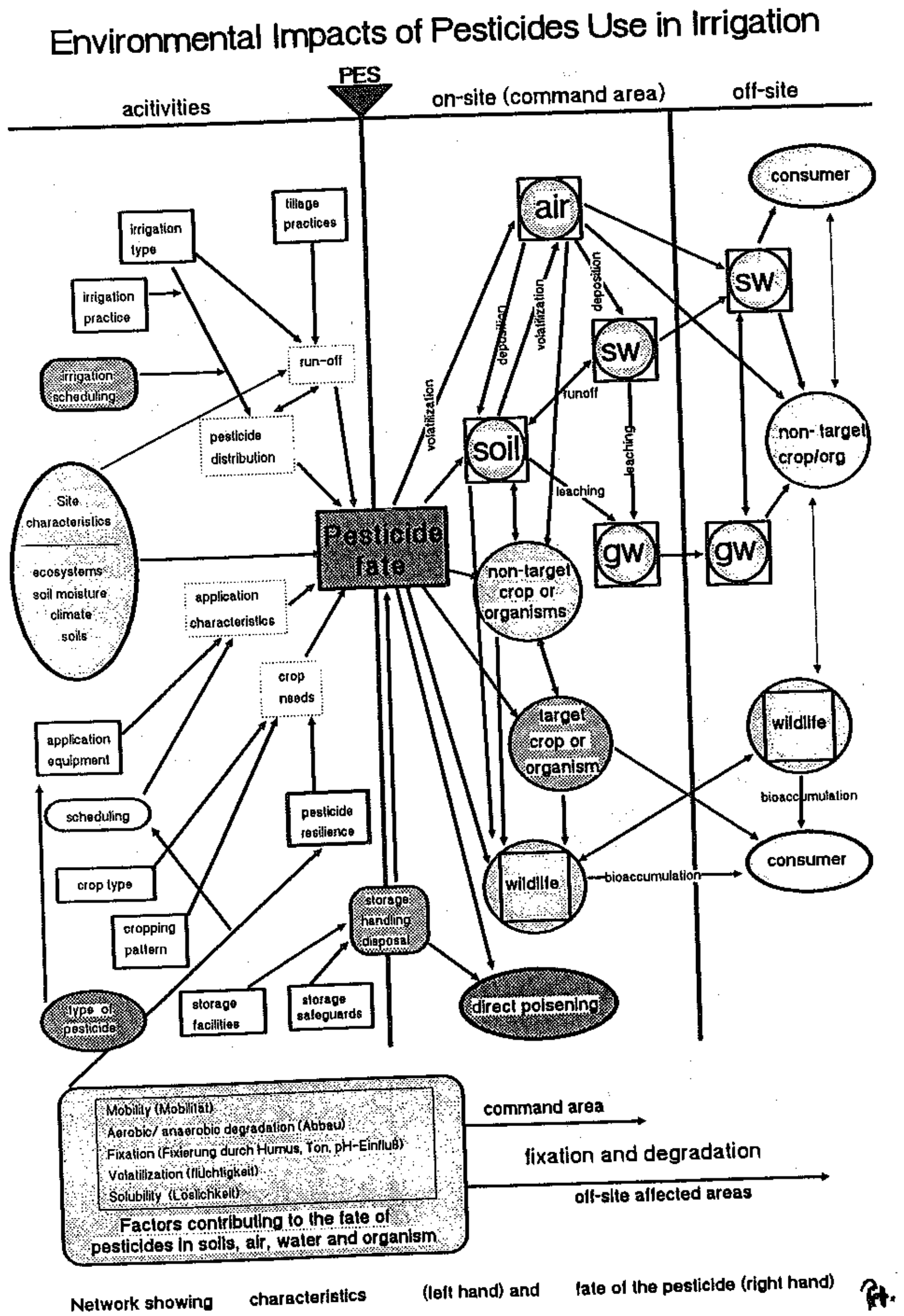


Fig. 2-3. Concept of pesticide exposure and risk assessment. After Bailey et al. (1985).

Source: Himel et al in Cheng ed. 1990

Fig. 3-17



biochemical compounds resulting from intensive microbiological activity. Herbicides released into this environment are subjected to dissolution, adsorption, leaching, runoff, volatilisation, and biological, chemical, and photochemical conversion. Volatilisation is often one of the main dissipating pathway in a flooded soil. Leaching of herbicides will be greater than on upland fields because in submerged fields there is continuous leaching. In fact, runoff can be a major pathway of dissipation in a flooded ecosystem. Photochemical and biochemical degradation govern the fate of herbicides in flooded environmentes. The high pH induces intensive hydrolysis. Microbial degradation is less important due to anaerobic soil conditions. A summary of the residual periods of herbicides in flooded ecosystems is presented in Table 3-12. The fate of (non-persistent) molinate, when applied in paddy, is shown in Table 3-13.

Source: Yaron/Gerstl/Spencer 1985

3.4.5 Pesticide Source Characterisation and Risk Assessment

Risk assessment is a tool used to evaluate the probability of an adverse impact that a pesticide may have on human health, or the environment. To assess the risk which may be encountered under any given set of circumstances, the route and rate (dose/amount) of the chemical reaching the organism must be known. The key role of detailed knowledge of soil physical conditions and their spatial distribution can be seen from Fig. 3-16. The role of management practices on pesticide transport and transformation are shown in Fig. 3-17.

3.4.6 Irrigation and Pesticide Use

Irrigation has specific influences on the use, behaviour and export of pesticides from fields. **Transportation** processes of pesticides are accelerated during sprinkler irrigation applications through foliar wash-off. Also increased surface runoff from surface irrigation applications (eg furrow) may contribute to rapid on-farm and, under poor water management, to off-farm dislocation of pesticide residues. Improved drainage systems increase subsurface flow and contribute to increased leaching losses from soils.

Furthermore, it can be expected that transformation and probably also **degradation** processes are accelerated by irrigation due to the higher soil moisture status in irrigated soils and the presence of ample moisture for enhanced chemical and biotic processes.

In addition, irrigation contributes indirectly to the increased use of pesticides in agriculture by

- the tendency towards **monoculture** in large schemes; pest control can then only be achieved by pesticides
- providing a favourable soil (moisture) and plant (increased growth and prolonged seasons) **habitat** for many pests to survive and reproduce abnormally
- indirect changes related to the intensification of the production system, eg stimulating the **mechanisation** of agricultural production which may enhance the use of pesticides
- sprinkler and trickle/drip irrigation systems allow easy, rapid/flexible and labour-saving **application** of pesticides.

3.4.7 Pesticide Impacts on Birds and Mammals

Many pesticides, particularly insecticides, are toxic to birds when their food becomes contaminated. The greatest hazards appear to be from persistent organochlorine insecticides. These are taken up in the birds' food, and although they may not kill them immediately, they are stored in fatty tissues and may have drastic effects when fat tissues are mobilised. Moreover, several insecticides have been found to cause thinning of the egg shells of birds of prey.

Organophosphates and carbamates which have replaced the organochlorines are not stored in the birds' tissue in large quantities, although they have a higher acute toxicity to birds. Consequently, since the 1970's, reports of large-scale adverse effects on birds are relatively rare, although there have been many localised bird kills.

There is much less evidence of pesticides having effects on mammals than on birds. Although organochlorines are stored in the tissues of mammals, there is little evidence that these residues are toxic or have major effects. However, there is more evidence of mammal kills resulting from organophosphate insecticides which have a high mammalian toxicity.

Source: Edwards 1986)

3.5 Contamination of Soils with Heavy Metals

Soil contamination with trace elements (or 'heavy' or 'toxic' metals) may be due to inherent soil properties, atmospheric additions or deliberate (farm-initiated) additions:

i) **air pollution** (see section 5)
ii) **wastewater** effluent applications, often containing Cd, Pb, Zn, Ni, (see sections 2.3 and 8.1)
iii) **animal waste** or sewage sludge applications, often rich in Cu, Zn, and Cd derived from weathering of parent material
iv) polluted ground- or surface **water** which is used for irrigation (see Part II 2.2)
v) additions by metal-containing substances such as **fertilisers**, soil amendments.

The following metal ions are of environmental concern in soil: Al, As, Be, Cr, Cd, Hg, Ni, Sb, and Sn. In addition, the following ions are of ecotoxicological importances, but are plant nutrients: B, Co, Cu, Fe, Mn, Mo, and Zn.

Cadmium is often regarded as the most important heavy metal because of its relatively frequent occurence, mobility and toxicity.

Sources: Schimming in Blume ed. 1990; Blume in: Blume ed. 1990; Finck 1992; Tiller 1989

Some agricultural **chemicals** and **fertilisers** may contain heavy metals as incidential impurities derived from raw material. The highest concentrations usually occur in phosphate fertilisers, eg raw phosphate or treated phosphatic fertilisers which contain Cd in the range of 2 to 100 (156) mg/kg. Zinc salts, copper and lead arsenates and metallo-organic compounds are frequently used for pest control. Applications are common in horticulture soils (Finck 1992; Tiller 1989).

Soil weathering may be an important source of heavy metals in irrigated soils, because irrigation is usually carried out on fine-textured soils, which have potentially high contents in trace elements and it typically enhances physical and chemical weathering processes by providing additional water to the soil profile. Enrichments of heavy metals may occur in clay, humus and iron enriched layers. The type and intensity of transformation processes vary with climatic regimes (eg temperature, moisture), cultivation, water management practices, soil chemical properties (eg pH, sorption properties; synergistic influences), and soil parent material. Average contents of trace elements with potential toxicity are shown in Table 3-14 for typical locations in Germany. Such high concentrations are often caused by air pollution from industrial point sources (Table 3-15). They are are usually less important in most rural areas in developing countries.

Irrigation may have a distinct influence on reducing the concentration of heavy metals in the soil solution. Typically, under proper irrigation the soil is moist during most parts of the growing season, compared with dryland farming, and thus, due to dilution, the concentration of heavy metals is reduced.

Irrigation also influences the transportation of heavy metals within or below the root zone. Typically, irrigation enhances the translocation of trace elements by runoff and leaching. However, high concentration of metals in drainage effluents are rarely encountered in rural areas in industrialized countries (eg Germany. Schimming in: Blume ed. 1990). The use of polluted river water for irrigation may become an increasingly important factor in soil contamination in the future. The occurence of the Itai-Itai desease in Japan is a well documented example of the problem (Tiller 1989).

Only recently have large scale investigations on soils contaminated by heavy metals commenced in industrialized countries. Most studies have revealed that there may be a potential long-term effect. Current hazards appear minimal, although monitoring is recommended.

> Germany. An investigation on Cd-contamination on 12 M ha of cropland found that some 1% of agricultural soils have slightly increased Cd values, 0.6% have increased values (<3 mg Cd/kg soil) and 0.4% are contaminated (>3 mg Cd/kg soil). Generally, in Germany some 1% of agricultural soils are slightly to moderately contaminated with one or more heavy metals. Atmospheric, then geogenic, then anthropogenic factors (eg wastewater applications) are the most important means of contamination (Schimming in: Blume ed. 1990).

Data on soil contamination in developing countries are scarce and, therefore, all statements should be considered as **preliminary** only. Data analysis is hampered by the fact that trace element analyses are usually very costly, require sophisticated laboratory equipment and trained staff, and high sampling densities are needed for reliable evaluations. It may be concluded from general observations on present levels of air pollution and the limited use of waste slurries, sewage sludge and wastewaters for agricultural use that contamination of soils is generally less a hazard than in industrialized countries. Typically, contaminations in irrigated soils are often restricted to wastewater treatment areas, to horticultural areas with heavy chemical treatments or to locations close to industrial sites.

> *Case Study*
>
> Egypt, Irrigation is practiced in the Helwan district with polluted wasterwater and on soils prone to airborne pollution (dust). Wastewater originates from urban-industrial areas. Water supply is from main canals. Analysis were made of Fe, Mn, Zn, Cu, Ni, Cd, and Cr.
>
> Soil contents of Fe (35000 ppm), Mn (600 ppm), Zn (80 ppm), and Cu (40 ppm) were almost normal for alluvial soils in Egypt. Ni and Cr contents of some 40 ppm were well below critical limits (100 ppm). Cd was below 1 ppm. Pb in soils was significantly increased up to 20 ppm in the vicinity of the industrial sites up to some 6 km distance from the plants. Plant (corn) contents showed significantly increased levels of Fe, Mn, Zn and Cu which may be beneficial as they are micronutrients (see Sillanpää 1982) unless toxicity levels are reached. Actually, contents are about 2-10 times higher than normal. Increased Pb (5-20 ppm) and Cr (5 ppm) values in crops, however, may be potentially hazardous, though they are currently below critical levels (El-Falaky/Hussein in: ICID 1989).

The impact of heavy metals may be beneficial (growth stimulation) or detrimental (toxic) to certain plants, microorganism and soil fauna. Many metals (and other trace elements) are necessary for growth but at high concentrations they may be toxic (Table 3-16). Typical **contents** in soils, **transfer coefficients** between soil and plants and critical **limits** for plants and fodder are indicated in Table 3-17a. Average contents of heavy metals in various soils in Germany are shown in Table 3-17b.

Ecological consequences of heavy metal contamination are related to metal mobility and solubility. These chemical factors determine transmission through the soil to the water table, availability to microorganism, soil animals, agricultural crops and animals, and ultimately to humans.

- high heavy metal contents may inhibit microbial **enzyme activity** and reduce the diversity of microorganisms and soil fauna. Reductions in populations of soil animals are documented in orchard soils at very high concentrations. Contaminated soil animals may introduce heavy metals into the food chain of higher animals and thus humans. Soil biological processes considered especially sensitive to heavy metals are mineralisation of N and P, cellulose degradation, and possible nitrogen fixation. Although the potential of hazards is recognized, there is little evidence to date that soil biological processes are being affected significantly in most (mildly) contaminated soils (Tiller 1989).
- at moderate heavy metal concentrations (ie above the deficiency range), most soils act as a **sink** or repository without any obvious effects on soil biological behaviour.
- the extent of transfer from soil to plant depends on the kind of plants. The relative accumulation of heavy metals by several crops and vegetables is shown in Table 3-18. The actual uptake reflects the concentration in the soil solution. Here, additive, synergistic, or antagonistic effects may be important. It must also be observed that potentially dangerous levels may be reached in the plant food diet of animals or humans without any evidence of deleterious effects on plants because of different toxicity tolerances.

Further details on the behaviour of soils to heavy metals are given in section Part II 3.2.

Sources: Cheng in: Cheng ed. (SSSA) 1990; Himel/Loats/Bailey in: Cheng ed. (SSSA) 1990; Madhun/Free in: Cheng ed. (SSSA) 1990; Severn/Ballard in: Cheng ed. (SSSA) 1990; Blume in: Blume ed. 1990; Schimming in: Blume ed. 1990; Litz/Sattelmacher in: Blume ed. 1990; El-Falaky/Hussein in: ICID 1989; Tiller 1989; Edwards 1987

Further readings: Cheng ed. (SSSA) 1990; Blume ed. 1990; Tiller 1989; Sillanpää (FAO) 1982

3.6 Impacts from Wastewater and Application of Excreta

3.6.1 General

Contamination of soils can occur during the application of excreta and wastewater. In this context, wastewater refers to domestic sewage and municipal wastewaters that do not contain substantial industrial effluent. Excreta refers to 'nightsoil' and excreta-derived products such as sludge. Details and examples of human waste reuse are given in section 2.5; further details on impacts to human health are covered in section 8. The use of industrial wastewaters or sludges is not considered here, because it is not recommended for agricultural use under conditions in developing countries (Biswas/Arar ed. 1988).

Human wastes are regarded as a resource in many parts of the world, and they have been widely used since ancient times for various purposes in agriculture, aquaculture and water resources planning. In agriculture human wastes are regarded as:

- a **water resource** (under limited supply conditions)
- **soil fertilisers** (nightsoil, sludge, dissolved and solid constituents in wastewaters) to improve soil nutrient status and physical properties.

Fig. 3-18 a

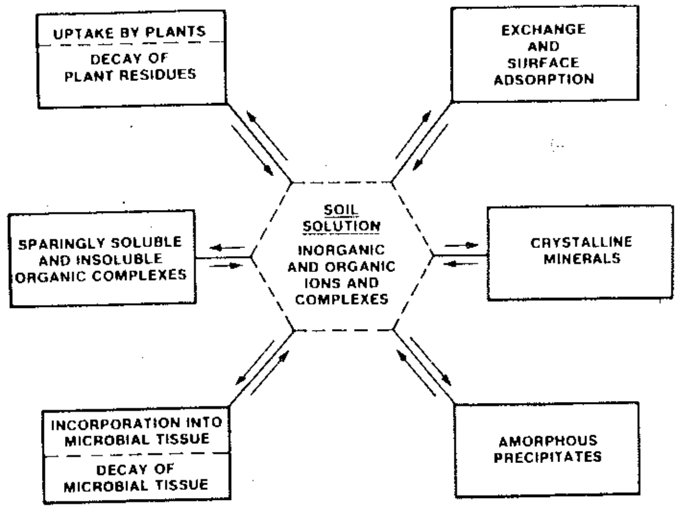


Fig. 3.21 Possible pathways of trace elements in soils (Page et al. 1981)

Source: Feigin et al. 1991

Fig. 3-18 b

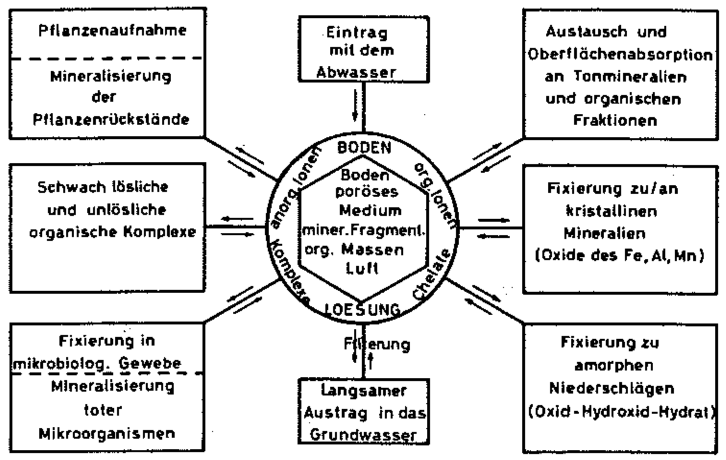


Abb. 2.5.4/1: Mögliche Reaktionswege der Stoffe im offenen, dynamischen System der Böden (aus ISKANDAR, 1981, erweitert.

Source: Blue et al. 1992

3.6.2 Wastewater and Irrigation

An indirect use of wastewaters is always practiced - in the form of water extraction from rivers or groundwater aquifers receiving upstream wastewater effluents. Salinity problems from saline waters are related to this indirect usage.

The type and magnitude of impacts on soils varies with sewage effluent and soil characteristics. Important reactions and transformations in the soil phase are shown in Figure 3-18a/b. Wastewater changes its constitution for example by filtration of solids, precipitation (eg phosphates, heavy metals), ion-exchange reactions, adsorption at colloidal surfaces, biological oxidation and reduction, and organic decomposition. Hence, as water quality changes (usually improves) in the soil-water phase during percolation, soil properties also change. Some changes are beneficial for agricultural soils and some are detrimental. The processes are complex and interrelated which makes impossible the practical use of any model for simple prediction of soil behaviour under wastewater applications.

Typical wastewaters are composed of 99.5 to 99.9% of water. The remaining percentage is composed of inorganic and organic solids, colloids, and dissolved solids. These contain major plant nutrients (N,P,K) and some trace elements (Table 3-19). Treated wastewater contains less N and P, depending on the processes used. Average annual applications may correspond to about 300 and 60 kg/ha of N and P respectively (Table 3-20a-b), although higher rates can be achieved especially for N:

assuming 800 mm/ha/a = 8 000 m^3/ha/a

N = 70 μg/l = 70 g/m^3 * 8 000 = 560 kg N/ha/a

P = 6 μg/l = 6 g/m^3 * 8 000 = 40 kg P/ha/a

Supplementary fertiliser requirements can thus be reduced by wastewater applications.

Sources: Shuval et al. 1986; Biswas/Arar 1988; Blume et al. 1990

3.6.3 Impact of Wastewater on Soils

The maintenance of favourable physical soil properties can be promoted by organic manure applications or green manuring. Similar effects can be attributed to most wastewaters which contain suspended microorganisms (excluding pathogens) and to the use of sludge (solid waste). Aggregation can be enhanced and the formation of macropores improves rather infiltration and soil aeration (Burn/Rawitz 1981). The net results are site-specific and can be modified by crop- and water management practices. High concentrations or application rates as well as anaerobic processes (stagnant water, often associated with odour impacts) may result in surface pore clogging and surface crust formation and, hence, reduced intiltration which is beneficial in earth canals and paddy fields due to seepage losses. Surface clogging by accumulating sludge is also undesireable in rapid-infiltration installations, eg in ponding (land treatment) of wastewater for groundwater recharge.

Tillage and intermittent drying promote aerobic decomposition and, hence control unwanted clogging and odour impacts. Suspended solid particles may add appreciable amounts of fine material to soils which can be especially important with regard to improving fertility of sandy soils. Significant increases of silt and clay fractions have been observed (Noy/Feinmesser 1977).

Applications for over 100 years in Berlin/Germany with a mixture of treated domestic and industrial wastewater resulted in the following soil modifications (conditions: humid, cool climate; appliation rate 1 600 mm/a; applied on sandy soils and using basin irrigation).

i) slight morphological changes:

- increase in morphological evidence (Mn-concretions; mottling) of hydromorphic properties resulting from reduction processes (temporary waterlogging and anaerobic conditions)
- thin organic layers in the upper subsoil horizons (caused by filtration)
- increased mobilisation of clay minerals; evidence of illuvial layer-lattice clays in the subsoil, especially around subsurface drains
- lack of Ca-accumulations (mycelia) in the subsoil due to leaching

ii) moderate changes in soil composition and chemical properties:

- increased soil humus content
- nitrogen and phophorus status is higher than in traditionally fertilised soils
- soil reaction is less acid (pH 5-6) than under natural conditions (< 5); development of high CO_2, HNO_3, H_2SO_4 concentrations under temporarily anaerobic conditions hampered the development of strongly alkakine reactions (wastewater: 8 - 8.5 pH)
- strong accumulation of Na, Zn, Pb, Cu, Cd, and Cr within the rootzone
- no accumulation of Fe and Mn despite high inputs from wastewaters

iii) growth conditions changed and hence altered the composition of grasses:

- improved nutritional and soil-moisture status
- high application rates (200-400 mm) produced temporary poor aeration
- plant societies (eg grasses) adapted to temporary poor aeration in the main root zone and tolerant to high N-status become predominant, however there is no significant loss of species (Sukopp et al. 1980)
- anaerobic soil microorganisms prevail over aerobic ones (with high water applications (ie in wastewater systems meant primarily for safe disposal of excessive water)
- ammonium-fixing bacteria increased and nitrification intensified
- bulk of soil fauna is concentrated in the continuously wet topsoil; worm activitiy increases with smaller applications
- buffer capacity decreases at time, eg as a result of temporarily low redox potential which increases mobility of heavy metals, eg Fe, Mn
- NH_4 ions compete with remove K, Mg and Ca on the exchange complex
- Na, NO_3, Fe, Mn, Cl are present in soil solution

iv) microbiological activity increases due to ample supply of material for decomposition and favourable moisture conditions:

- formation of various highly mobile organic complexes with possible positive symbiotic side-effects in the rhizosphere of crops
- enzymatic activities are considerably increased
- formation of CO_2 during decomposition of organic constituents may enhance photosysnthesis,
- the mineralisation of organic compounds continuously delivers nutrients
- negative impacts are associated only with long-lasting anaerobic conditions (reduction phase) and the possibility of formation of sulfidic complexes
- soil fauna may change considerably due to changed conditions as described above. There is no significant change in the number of individuals but there is a change in species. New species are characterised by higher tolerances to higher salinity, hydromorphic and decaying conditions.

Source: Blume/Horn 1982; Aurand 1981; Kretzschmar in: Blume et al. 1990

Fig. 3-19

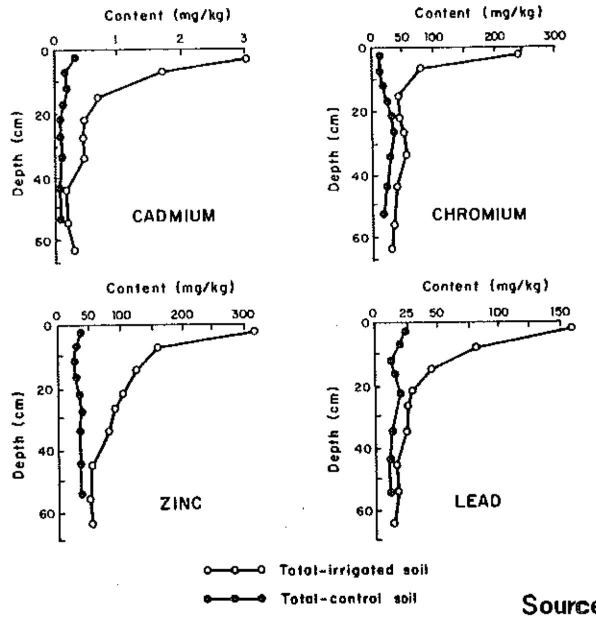
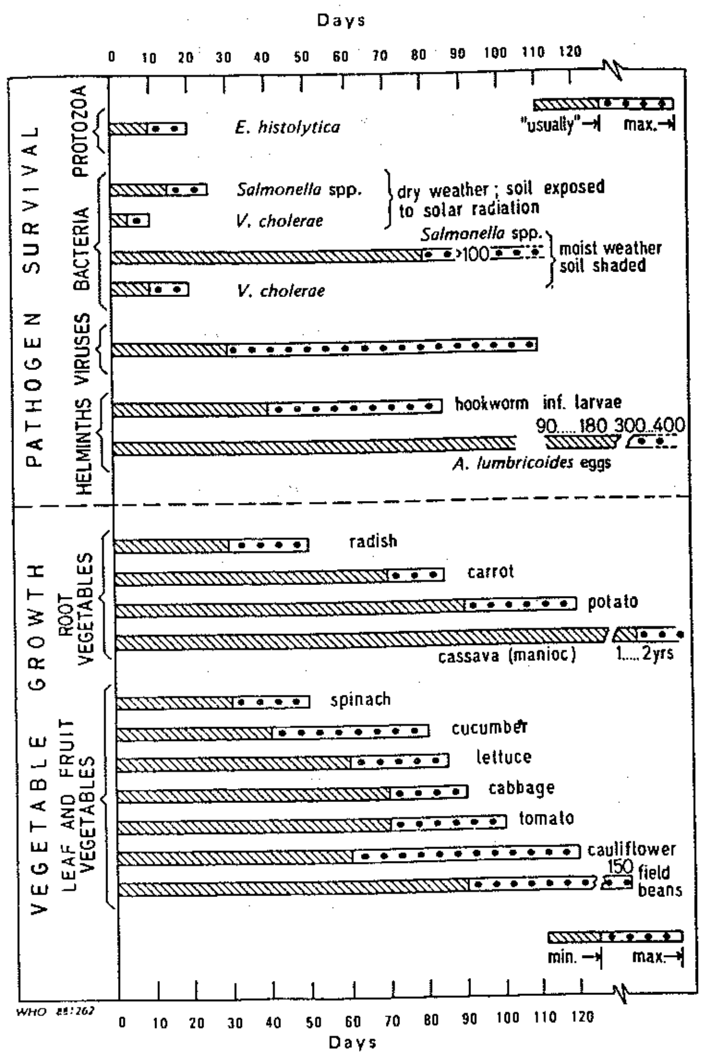


Fig. 23

Heavy metal content of the soil profile after 80 years of irrigation with wastewater
(Evans, Mitchell and Salau 1979)

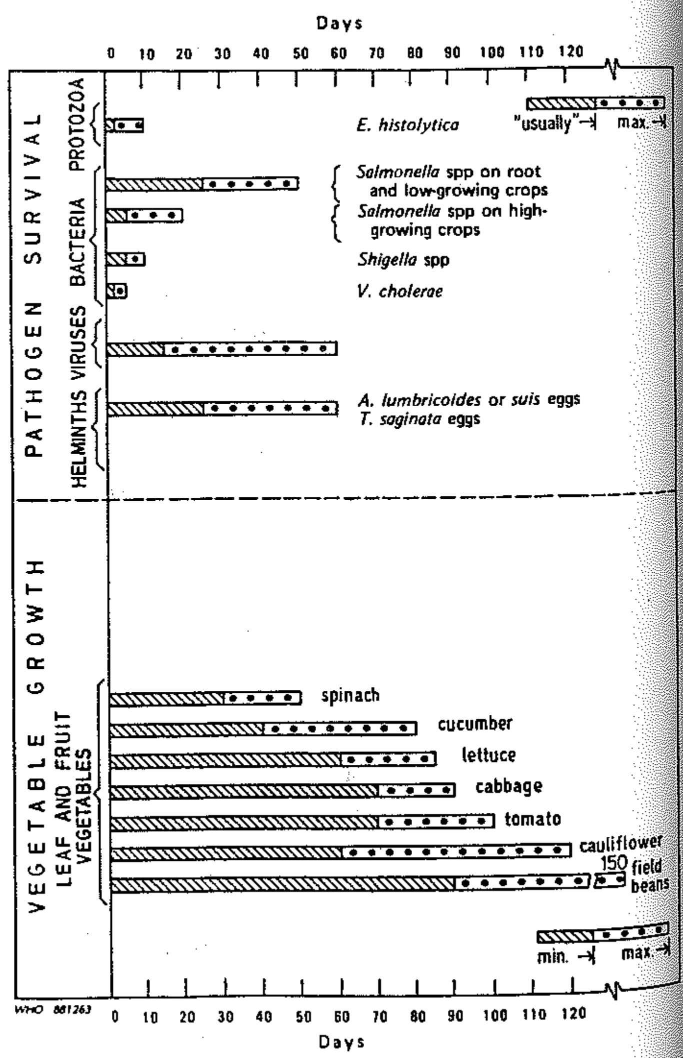
Source: Ayers/Westcot (FAO) 1985

Fig. 3-20
(Figure 4.2) Pathogen survival in soil compared with vegetable growth periods in warm climates



Reproduced by permission from Strauss (1985).

Fig. 3-21
(Figure 4.3) Pathogen survival on crops compared with vegetable growth periods in warm climates



Reproduced by permission from Strauss (1985).

Source: Mara/Cairngross (WHO) 1989

Soil fertility related problems may occur if secondary treatment of sewage occurs (eg chlorination), or if water has been previously treated chemically to lower the hardness of Ca and Mg-rich waters for domestic purposes. The addition of amendments or ion exchange processes usually replaces calcium with sodium ions. Such water may require additional treatment giving exactly the reverse effect to be suitable for alkaline soils or to reduce the sodicity risk in soils (see section 3.2).

In addition to beneficial nutrients wastewaters also may contain

- **toxins**, ie trace heavy metals which include Ag, Al, As, Ba, Cd, Cr, Cu, Co, Fe, Fl, Hg, Li, Mn, Mo, Ni, Se, Pb, and Zn,
- **contaminants**, ie disease causing organisms (pathogenic microorganisms): viruses, bacteria, protozoa and helminths,
- high contents of soluble **salts**, excessive concentrations of nutrients; unfavourable ionic composition,
- persistent organic synthetic **organic compounds**.

High concentrations of heavy metals are ususually not present in treated domestic wastewaters (they precipitate as hydroxides or oxides during treatment) but may be present in untreated wastewaters, excreta and especially in industrial wastewaters (Tables 3-21a and b). Under average conditions in developing countries, such chemicals are not present at dangerous concentrations (Shuval et al. 1986, Biswas/Arar 1988). However, precise data and systematic surveys in developing countries are rare.

Trace metals sources can pose significant health hazards, especially Cd, Co, Mo, Ni,, Zn, and Se. They tend to accumulate in soils and plants and in animals consuming the contaminated plants (Fig. 3-19). Immediate phytotoxicity is relatively rare because of low concentrations in wastewaters, except for boron which may be present in concentrations well above 1 ppm. Provided that the quality of the wastewater conforms to that recommended by FAO (Ayers/Westcot 1984) or others (see Part II section 2.1), it may be used safely in agriculture.

For a qualified risk assessment of wastewater uses the typical uptake rates or transfer coefficients between plant and soil water should be known and subsequently, the actual wastewater quality can be evaluated for its agricultural use. Tables 3-22a and b may be used, although they have been developed for hunid European conditions.

Enteric pathogens are of special interest because they are always present in wastewater sewage effluents and they can survive in soils at considerable concentrations for some time, and some, especially bacteria, may multiply in suitable environments. Furthermore, they can be mobile in soil-water solutions (Tables 3-23 and 3-24). Migration of bacteria, ova of intestinal worms or protozoa cysts occurs as transport through soils and depends on straining, sedimentation and adsorption rates. The mobility of viruses depends onthe degree of adsorption to soil components. Generally, low flow rates in soils (ie most medium to fine textured, unstructured soils) favour retention and most faecal organism (>90%) are usually concentrated in the surface layers (Pescod/Arar 1988).

Mobility and persistence of pathogens at ambient temperatures in various environments and factors affecting survival time are shown in Tables 3-25 to 3-28 and Figs. 3-20 and 3-21. In hot and arid climates survival of pathogens is limited to 2-3 months at most, whereas in cool and moist soils and those rich in organic matter survival is longer (Table 3-29). Adsorption onto solids can protect viruses from envrionmental factors and thus extend average survival also in warm climates up to 3 months.

Heat, sunshine (UV-radiation) and low humidity promote pathogen death. Average survival times are significantly shorter than in water or soils (Tables 3-25 and 3-26). Whereas bacteria and viruses cannot penetrate undamaged vegetable skins they may survive on crop surfaces that have been irrigated (mainly relevant to sprinkler irrigation). Pathogens may survive harvesting and marketing and eventually they may reach the consumer. Pathogen removal by wastewater treatment is covered in Part II sections 2.5 and 4.

Soluble salts concentrations are always higher in wastewaters compared with original water quality. Therefore, all criteria for the use of saline waters and the control of soil salinity are applicable to wastewaters, too. This applies also for wastewater with an unbalanced ionic composition which have potential detrimental effects on soil fertility status and physical conditions (section 3.1).

Complex synthetic organic compounds are not common in domestic wastewaters produced in developing countries. Some of them are highly toxic and are discussed in section 2.7 as they are commonly derived from pesticides.

Organic compounds (colloids) in wastewaters are usually not harmful to crop production, since there is only insignificant - if any - direct uptake from the soil. Most organic compounds contribute to improvement soil physical conditions.

In arid climates there may exist a potential danger of over-fertilisation and/or imbalanced supply of nutrients if all water requirements are met by wastewater over long periods. An application of 800 mm wastewater would result in 640 kg N/ha/season if the wastewater contained 80 g N/m^3. It should be realized, however, that nutrient concentrations of wastewaters are usually lower in developing countries than in industrialized countries, eg in India the average N-concentration is in the range of 30 to 60 mg/l.

Summarising, wastewater and excreta reuse may have beneficial or detrimental impacts on soils, depending on the quality and quantity of effluents, use of remedial measures to optimise beneficial and minimise detrimental effects and adequate soil and water management practices (see Part II sections 2.5 and 4).

Wastewater and excreta use schemes can have several direct or indirect positive environmental impacts:

- using effluents to substitute for other fertiliser sources
- use of wastewater in areas with limited water resources
- avoidance of groundwater pollution which would occur if wastewater drained untreated into rivers or lakes. Major problems associated with surface water pollution can be minimised: eutrophication, depletion of dissolved oxygen, foaming
- contribution to soil conservation through the enhancement of soil aggregation to prevent soil erosion and the additional supply of water for shelterbelts/ windbreaks in arid regions
- enhancement of biological diversity (species, number of individuals) especially in arid areas by the supply of water, nutrients and microorganisms.

Potential hazards - except health-related hazards (see section 8) - are associated with:

- increased salinity from saline effluents
- effluents with high ESP-values with associated damage to soil structure
- over-irrigation causing waterlogging and prolonged anaerobic conditions
- overloading with nutrients and microorganisms beyond the capacity of the soil as filter, adsorbant and transformer, thus, contaminating the soil which serves as a natural filter to prevent groundwater pollution.

In practice, however, contamination of soils by wastewater reuse under irrigation not widespread and in most cases soil fertility is maintained or improved over decades of irrigation (eg Mexico City). Most treated wastewaters usually have low concentrations of industrial or other chemicals (toxants, organic compounds, heavy metals). Nevertheless, careful control is required during project planning and operation. Safety standards can on-

Fig. 3-22

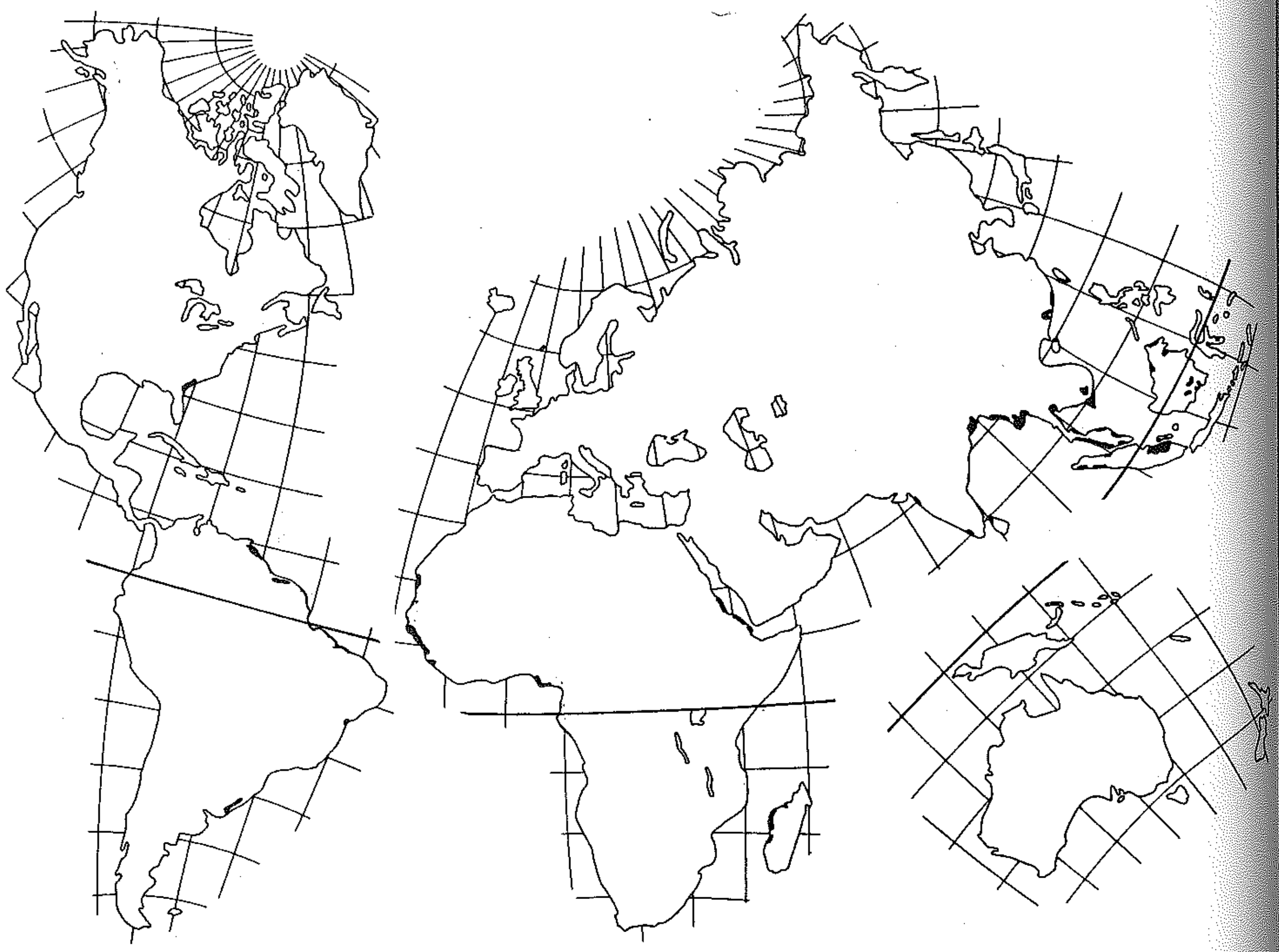


Table 3.
Regional distribution of acid sulphate soils (based on data from FAO/UNESCO Soil Map of the World; length of growing periods according to FAO Agro-Ecological Zones Project, Rome).

Region	Area(10^6 ha)	Area (million ha) per length of growing period			
		<90 days	90–180 days	180–300 days	> 300 days
Africa	3.7	0.4	0.7	1.5	1.1
Near and Middle East	–	–	–	–	–
Asia and Far East	6.7	–	0.2	5.1	1.4
Latin America	2.1	–	0.1	0.8	1.2
Australia	–	–	–	–	–
N. America	0.1	–	–	–	–
Europe	–	–	–	–	–
World total	12.6				

Source: ILRI 1980

ly be met with continuous monitoring of effluents and soils by qualified personnel (see Part II sections 2.5 and 4).

Souces: Feigin et al. 1990; Biswas/Arar ed. 1988; Cairncross/Mara 1988; Shuval et al.1986; Pescod/Arar ed. 1988

3.7 Other Chemical Soil Degradation Processes

3.7.1 Acid Sulphate Soils

Acid sulphate soils are formed from both river and estuarine alluvial soils that become exceptionally acid on drainage and oxidation, either as a result of natural processes (land upheaval, regression of the sea) or of human-made drainage or empoldering. They develop from sulfidic materials (>0.75% S), are waterlogged (gleyic) and rich in organic matter (>1%). They are found in brackish coastal environments, usually formerly under mangrove. The total area of actual and potential acid sulphate soils (Thionic Fluvisols) comprises some 10 M ha in the tropics (Fig. 3-22) and another 20 M ha of coastal peat are underlain by potential acid sulphatic soils (Histosols, mainly in Indonesia and Thailand).

The use of acid sulphate soils for irrigation has a long tradition in some Asian regions. Acid sulphate soils developed where apparently promising coastal plains were reclaimed for rice cultivation. However, the rapid expansion during the last century occured on areas, unsuitable for permanent use with traditional methods. Meanwhile, thousands of hectares of injudiciously reclamed land in coastal swamps have been degradated or abandoned and mangrove areas destroyed. Time consuming and costly technical solutions for large scale reclamations exist but their economic feasibility is questionable and the destruction of mangrove areas may be hardly justifiable. Costly engineering works such as dikes and weirs/sluices, designed for preventing salt water intrusion, have been abandoned.

> *Background Information:*
>
> The most important properties of acid sulphate soils are pH-values of below 3.5, frequently in the range of 2 to 3, associated with Al- and Fe(III)-, Mn(II)-toxicity and limited nutrient availability, eg P. On submerged soils with pH 6 to 8 in the topsoil Fe(II)-toxicity may occur. The profile is usually a clay (cat-clays), but sandy loamy soils may also become acid sulphatic. When submerged, colours are grey to blueish black with pH values of above 5 and a smell of hydrogen sulphide. If such soils are reclaimed by drainage, yellow jarosite mottles develop and the pH decreases within 1.25 m from the surface. Vertical cracking results in coarse prismatic structures to the mottled horizons, whilst the subsoil remains structureless and relatively impermeable. Apart from actual or potential acidity most soils are also affected by salinity because they are located in active tidal areas.
>
> The cause of acidification is the oxidation of pyrites, FeS2, with the formation of sulphuric acid. Sulphates from the seawater are deposited during mud sedimentation and later reduced by bacteria under anaerobic conditions to form hydrogen sulphide (H2S). The presence of organic matter is required for bacterial growth. H2S reacts with iron compounds in the soil to form ferrous iron sulphide (FeS2). Oxidation on contact with air causes the formation of ferric sulphate, which produces the mottles and staining, and sulphuric acid. Further reaction with clay minerals forms aluminium sulphate at toxic concentrations (further details in Mohr et al. 1972).

Most potential acid sulphate soils are under natural vegetation, while some are used for fishponds or salt extraction. Extensive delta areas, for example the Bangkok plain, Mekong delta, Ganges delta and estuaries in West Africa (Sierra Leone, Gambia), are under irrigation with paddy rice, sometimes with vegetables, fruit trees or oil palms. Preference is given to areas with low tidal movements, passive sectors of old channels, or deltas where saline intrusions are blocked off by flood embankments, port schemes or estuary barrages.

Best possibilities for sustainable cultivation exist on older and deeply developed Thionic Fluvisols with low pyrite contents in the topsoil. They may be traditionally used under rice cultivation. Yields are generally low to moderate which can be attributed to a relatively low fertility, to deficiency levels of micronutrients (Zn, Cu, Mn, Mb) or to toxic concentrations of B, Mn, Al and Fe (Pagel 1974), and reduced activity of microorganisms responsible for decomposition.

There are several approaches for sustainable use of acid-sulphate soils under cultivation; the key lies in controlling acidity.

- Keeping soil subsurface horizons saturated to prevent oxidation of pyrites. This condition is often met in some plains where deep water rice is grown on older, well developed Thionic Fluvisols (in Thailand) which are subject to seasonal flooding; in Malaysia oil palms are grown with carefully maintained groundwaters at shallow depths (60 to 90 cm); the crucial factor with this method is the availability of freshwater (rain or irrigation) for seasonal leaching.
- Submerging with freshwater when under paddy cultivation and seawater during the dry season. Acidity during the growing season will be reduced and pH-values will increase in the topsoil layers; soils are almost permanently submerged (Sierra Leone Research Station).
- Neutralise the soil with lime. Theoretically, large quantities of lime in the range of 30 to 300 (average 100) t/ha or more are usually required for 1 to 5% of pyrite, which usually make reclamation uneconomic. Recent research, however, has indicated that beneficial effects may be achieved by smaller applications (3 to 6 t/ha) applied over a period of some years.
- Drain, aerate and leach the soil with freshwater. This approach is applicable only if the pyritic substratum occurs at greater depths. Leaching efficiency in Thionic Fluvisols is usually limited due to the relative immobility of sulfidic material and low permeability. A special method has been successfully used in Vietnam where deep ditches are excavated to make 3 to 5m wide ridges; after some years of pyrite oxidation and leaching the soils are suitable for crops, eg pineapple; negative impacts are associated with strong drainage water acidity (pH 2 to 3).
- Leaching may be sucessful if carried out with saline seawater which provides bases to substitute the exchange acidity; subsequently fresh water is needed for desalinisation; this method requires permeable soils.

The leaching method may have detrimental impacts at other places receiving the leachate which may contain toxic concentrations of Al (eg reports from Kalimantan, Vietnam).

Large engineering schemes for the reclamation of potentially acid sulphate soils are rarely economically feasible, and in most cases young, strongly acid sulphate soils should not be reclaimed for irrigation. Possibilities for reclamation and sustainable crop production exist on older, deeper developed acid sulphate soils and sucessful development is usually attributed to the availability of sufficient fresh water, a combination of fertilization and liming, good water management, and skilled farmers (eg Muda project, Malaysia). Hydrological research and numerical modelling for large river regulation schemes which aim to control seasonal saline intrusions in deltas in order to permit irrigation, have been conducted by Hydraulic Research (Overseas Development Unit) on the Gambia estuary, Guayas estuary (Ecuador), Abary river (Guayana) and the Irrawaddy delta (Burma). (Overview in ODA Bulletin 1987).

Preconditions for future development activities should be: adequate soil surveys with selection of suitable sites; detailed hydrological surveys including models for long-term prediction of saline intrusion; seasonal availability of sufficient freshwater (rain or irrigation);

adequately trained farmers who will use good soil and water management practices; establishment of research trials and trained extension service; adequate supply of and access to lime amendments and fertilisers (especially phosphorus).

Sources: Seiler 1989; Beek et al. in ILRI 1980; Spaargaren et al. (ISM) 1981; Mohr et al. 1972

Further readings: Dost ed. (ILRI) 1986; Dent 1986. Dost/van Breemen ed. (ILRI) 1973; Bloomfield/Coulter 1973; van Beers (ILRI) 1962

3.7.2 Others

Occasionally, high concentrations of trace elements and metals are found in irrigation waters which may lead to unfavourable enrichment in soils (or plants) or to subsequent groundwater contamination. Groundwaters may contain high concentrations of boron and iron.

High **boron** concentration are found in some Southern Libyan groundwaters which restrict the continuous use for irrigation (see water quality Part II section 2.1).

High **iron** concentrations occur in groundwater of some districts in Bangladesh (Khan 1988). The precipitation of iron in the subsoils resulted in the formation of hardpans which are relatively impermeable and restrict root penetration. Growth is restricted due to waterlogging and poor soil aeration.

3.8 Physical Changes in Soils under Irrigation

Changes in soil physical properties induced by irrigation and drainage are manifold and many of them already have been treated in separate sections dealing with salinity, erosion and sodicity. Soil compaction which is mainly caused by tillage practices under prevailing conditions in developing countries is treated in section 9.

Irrigation and subsequent drainage modify the natural soil-moisture regime in qualitative and quantitative terms. These changes may be either temporary or permanent and most impacts are due to changes induced by soil tillage practices and cropping pattern. The most important irrigation-induced changes are modifications of the soil-air-water system with subsequent impacts on soil structure, soil temperature and biotic activities. The response of soils influenced by continuous and intensive farming, however, may vary with the soil type including their biotic activities, and generalisations from isolated observations should be carefully examined.

For sustainable irrigated farming, the most important factors are the **creation or maintenance** of favourable soil structure and aeration status for the specific crops to be grown. These conditions may vary with type of crops and cropping pattern, but also with types of irrigation (see Part II sections 2.3 and 3.2).

The prominent changes and features of irrigated soils are

i) in arid and semi-arid regions the introduction and intensification of wetting-drying cycles respectively

ii) in semiarid or subhumid regions the extension of wet cycles by water applications in addition to the natural humid phases of the rainy season.

Hence, soil structure forming processes can be either intensified or a loss of favourable structure can occur under situations of prolonged wetting. Indirect effects of irrigation on soil structure occur with modifications of soil temperature and enhancement of microbiological life, especially in arid and semiarid areas. This, in combination with wetting-drying cycles, typically improves the formations of micro-aggregation and macropores which provides favourable conditions for crop growth. Extreme drying (a typical feature of arid and semiarid regions under natural moisture conditions) is usually avoided under irrigation and favourable conditions for microorganism and soil fauna is provided throughout most parts of the year.

Indicators of physical soil conditions and typical influences of agricultural and irrigation practices are briefly summarised below.

- **bulk density** and total porosity: there is a tendency for both to increase under cultivation but tillage practices may exert a large influence; observed changes range from large decreases to moderate increases; irrigation typically enhances intensification of cultivation and mechanisation and may result in increased negative impacts (see also section 9 under soil compaction)
- **hydraulic conductivity** and infiltration rate: there is a tendency for these to decrease under cultivation, but tillage practices, reclamation measures and drainage may exert large effects; observed changes range from decreases to increases; irrigation with non-sodic water may be neutral or a positive modifier,
- **pore size distribution** and moisture retention characteristics: there is a tendency to decrease available water holding capacity under cultivation but tillage and drainage practices may exert a moderately large influence; observed changes range from moderate increases to large decreases; irrigation and drainage may be positive modifiers or neutral,
- **aggregate stability** and water stable aggregates: there is a tendency for these to decrease under cultivation, but tillage practices, agronomic measures and cropping pattern exert large influences: observed changes range from large decreases to moderate increases; irrigation with sodic water may enhance deterioration; irrigation with non-sodic water may be a positive modifier,
- **organic matter content** and organic matter composition: there is a tendency for these to decrease under cultivation (except in arid regions) but tillage practices and agronomic measures exert a large influence; observed changes range from large decreases to large increases. Irrigation may contribute to increased crop growth and, hence, increases in organic matter; on the other hand, additional soil moisture and lower temperatures in arid areas may enhance decomposition,
- **soil texture**: there is a tendency for fine particles and organic matter to be lost from topsoils due to accelerated soil erosion under cultivation; tillage practices and other agronomic measures exert a large influence; observed changes range from slight to heavy losses of fine particle. Irrigation may be a neutral, a positive or a negative modifier. For example, irrigation in arid and semiarid regions may enhance soil weathering and the formation of fine clay and silt particle sizes. Irrigation can reduce both wind erosion losses and - under good management - water erosion losses from irrigated lands compared with non-irrigated croplands; however, poor water management can increase runoff and enhance fine partile losses in topsoils,
- **shrinking-swelling processes** can be intensified under intermittent irrigation practices; this may result in heavy textured soils in the development of unfavourable macro-aggregation.

Sources: Lal 1987; Sanchez 1976

Further readings: Lal/Greenland ed. 1979; Hillel ed. 1972; Taylor/Ashcroft 1972

3.9 Special Problems in Rice Soils

Rice (paddy) soils are continuously or intermittently flooded. This flooding sets a series of physical, chemical and microbiological processes in operation. These include retardation of gaseous exchange between soil and air, anaerobic soil conditions, and the chemical and electrochemical processes accompanied with reduction. There is a decrease in redox potential, increase in pH under acid conditions, and decrease under alkaline conditions, and an increase of conductivity. Flooding causes denitrification, accumulation of ammonia, release of methane, reduction of magnesia, iron (ferric iron), and sulphates, accumulation of the products of anaerobic organisms and other secondary effects of reduction. Aluminium hydroxides are precipitated and ferrous iron is absorbed by clay minerals.

Impacts of paddy cultivation

Paddy soils undergo chemical and physical changes that differ from other irrigated soils and are caused by permanent or intermittent submergence. The flooded soil-rice ecosystem consists of five major subsystems: floodwater, surface oxidised layer, reduced puddled layer, subsoil alternatively oxidised and reduced, and the rice plant, its phyllosphere and rhizosphere. Most important for soil processes are sequential changes of several soil redox systems.

Common problems in paddy soils are related to iron toxicity in acid and extremely alkaline soils, phosphorus deficiencies in ultisols, oxisols, vertisols and andepts, zinc deficiencies in sodic, calcareous, and peat soils (see also acid sulphate soils).

Important chemical changes that have implications for soil degradation, agricultural productivity and soil fauna are:

- Change in **pH**: a few weeks' submergence causes the pH of acid and alkaline soils to converge between 6 and 7. The rate and degree of changes depends on soil properties (eg organic matter, active iron) and temperature. The effect may be positive by eliminating extreme pH-values.
- Changes in **salinity**: EC of the soil solution increases with time after submergence, reaches a peak and eventually decreases. Most submerged soils, regardless of their initial salinity level, have values of EC > 2dS/m during most of the growing season. Changes are correlated with iron and manganese concentrations in acid soils and with calcium and magnesium bicarbonate in alkaline soils.
- **Reduction** of Fe(III) to Fe(II): Fe(III)-oxide hydrates are reduced to Fe(II) -compounds and Fe-concentration in the soil solution may increase to toxic levels; manganese and aluminium toxicity may subsequently occur for dryland crops. These resultin negative effects on crop production and soil fauna.
- Increase in supply and availability of **nitrogen**; the turnover of available N is faster in tropical paddy soils than in temperate zones. The effect is positive.
- Increase in availability of **phosphorus, silicon, molybdenum**. This may benefit nitrogen-fixing algae at the surface, anaerobic bacteria in reduced soils, and aerobic bacteria on the roots.
- Decrease in concentrations of water-soluble **zinc** and copper, especially on continuously wet and peat soils. Deficiencies are not acute for subsequent dryland crops. The effect is negative for rice production, but almost neutral to soil fauna and dryland crops.
- Production of **toxins**, organic acids, ethylene and hydrogen sulphide by reduction and anaerobic decomposition. These hamper productivity in sulphate soils and soils with high organic matter. The effect on crop productivity and soil fauna is negative.
- Total **algae biomass** production increases sharply during the crop cycle.

In addition, rice soils are exposed to changes in physical properties through **puddling**. This is the process of breaking down soil aggregates into a uniform mud, accomplished by applying mechanical force to the saturated soil. Whereas puddling in other cropping systems is the unintentional outcome of tilling at too high moisture contents, it is an important practice in lowland rice cultivation aimed at minimising the percolation of water.

Puddling decreases pore volume, increases bulk density, eliminates aggregates and macropores, reduces hydraulic conductivity and infiltration, creates anaerobic conditions, and effects pH and Eh (redox potential). Rice shoot and root growth, nutrient uptake and water use are typically favourably affected by moderate compaction unless soil strength remains low. The effects of traditional puddling on medium textured soils are often less significant for increasing rice yields and water use efficiency but require more energy and time (Ghildyal in: IRRI 1978).

The anaerobic conditions typically hasten the anaerobic microbial degradation and detoxication of most pesticides in paddy soils. This is in contrast to the increase in stability of natural organic compounds, but chemical compounds with reductive and hydrolytic pathways seem to undergo rapid decomposition:

> Important pesticide transformations stimulated by flooding are reductive dechlorination (PCP, DDT), dehydrochlorination (HC), hydrolysis (organophosphates), and reduction (fensulfothion, parathion). Epodixation (aldrin, heptachlor) and ring cleavage are inhibited. Anaerobic microorganism are particular implicated in these transformations, but chemical degradation catalysed by redox reactions such as the iron redox system may also be common.
>
> Anaerobic metabolism of pesticides leads to the formation of easily soil-bound residues. The alternate oxidation and reduction processes may assist in more extensive degradation of pesticides than will either system alone.
>
> The persistence of insecticides in non-flooded soils usually follow the order chlorinated HC > organophosphates = carbamates. In flooded soils, certain chlorinated HC (DDT, BHC, endrin, heptachlor) are readily destroyed; in contrast, cyclodienes (aldrin, dieldrin) persist in both flooded and non-flooded fields (see Table 3-30)
>
> Source: Sethunathan/Siddaramappa in: IRRI 1978

Sources: Watanabe/Roger in: IRRI 1985; Mohrmann/van Breemen (IRRI) 1978; Ghildyal in: IRRI 1978; Patrick/Reddy in: IRRI 1978; Yoschida in: IRRI 1978; Sanchez 1976; Russel 1973

Further reading: IRRI 1978

4 Impacts on Land Use and Biological Resources

4.1 Introduction

Biological resources include ecosystems and their biotic components fauna and flora. The term resources implies their value for human use and their contribution to ecosystem functioning and utilisation values but also non-tangible values such as aethetic, leisure and scientific value.

Human impacts on land use and biological resources derived from irrigation are manifold:

- **utilising land** for irrigation, thus destroying habitats of current natural fauna and flora and genetic resources in these ecosystems which are often precious wetland ecotones (ie transitional ecosystems at the boundary of aquatic-terrestrial habitats). New habitats for terrestrial species, adapted to cropland ecosystems, are developed. Irrigation in arid areas may lead to the creation of new ecosystems along drainage canals and evaporation lakes, thus contributing to an increase in the diversity and population of soil microfauna,

- abstraction of **water** from rivers, lakes or groundwater aquifers modifies, and sometimes degrades (but seldom destroys unless total abstraction takes place) the habitat of aquatic and terrestrial ecosystems and species in downstream river sections or in adjacent areas with a groundwater drawdown,

- chemical **residues** from intensified agricultural production accumulate in soils and groundwater, eventually polluting downstream river sections and aquifers at a further distance, thus, modifying or degrading terrestrial and aquatic species along downstream river sections,

- **erosion** may occur, which affects river water quality (turbidity), thus modifying and degrading auatic habitat in downstream sections

- **reservoirs** have manifold impacts on land occupancy and the hydrological regime of rivers with potential impacts on marine (deltaic) ecosystems. Habitats in the reservoir zone are destroyed while habitats of aquatic and terrestrial species along downstream sections are modified, degraded or destroyed, depending on reservoir size and operation.

When land is developed for agricultural use, almost all types of natural flora and wildlife resources are changed. Often a degradation of aquatic and terrestrial ecosystems results from these changes, affecting breeding and migration, but also basic habitat functions such as shelter and food supply. Impacts related to land occupancy result from all agricultural systems and they cannot be attributed to irrigation alone unless development takes place in environments which are otherwise not suitable for arable farming. Such areas which are especially affected by irrigated agriculture are wetlands. In other areas, only impacts related to the abstraction or storage of water can be attributed to irrigation, whereas other impacts, related to soil and water resources degradation and pollution may occur under other agricultural uses, too.

> Note: The boundaries of an ecosystem can be identified by changes in vegetation, soils , topography, water status, and animal habitat. The scale of an ecosystem depends on the purpose of the analysis: an irrigation canal with its adjacent impoundments may constitute a small ecosystem, whereas the entire irrigation scheme is a medium scale ecosystem with its distinct functions and structures, while a lower watershed of a large river system may constitute a third scale of ecosystem. All ecosystems are connected with others of various scales through exchanges of energy and biotic or abiotic material.

4.2 Human Impact on Ecosystems

The continuing progress of evolutionary change and adaption have led to the development of the enormously diverse community of aquatic and terrestrial organisms on earth. The collective impact of humans on this process was on a global scale for long time hardly perceptible. But as humans increased in number and particularly after the development of urbanisation, industrialisation, and intensive agriculture and forestry, the impacts on selection and evolution have became progressively more important. Over the last century, increasing pressure has been put on the natural ecosystems which are used as a resource for human goods and services (see section 3.1). This pressure has resulted in widespread changes or destruction of habitat for many species and biotic communities. Such changes result from various classes of stress factors that affect the health, productivity, species composition, genetic diversity, geographic distribution, and survival of ecosystems and their components. Natural stresses or growth limitations include competition, climatic, biological and chemical classes. Agriculture and irrigation may exert the following stresses on ecosystems and organisms (taxa) living in them:

- **human competitional stresses** occur when humans compete with other sepcies in the same ecological niche for a limited supply of growing space, food, solar radiation, water, and essential nutrients. These also include interactions among organisms which result from injurious chemicals produced by man which adversely affect the survival and development of fauna and flora in the same environment,

- **human disturbances stresses**: these are imposed by various deliberate or inadvertent human activities including waterlogging, drainage, burning, physical disturbance of soils, erosion, leaching of nutrients, accumulation of toxic substance; eg the disturbance of mosquito breeding sites is a human stress factor on disease vectors as is the drainage of wetlands which may be used by wildlife or plant communities,

- **air pollution stresses** may occur whenever ecosystems are exposed to injurious concentratons of toxic gases, toxic aerosol particles or coarse particles in air or precipitation, eg from erosion, sprinkler application of toxins, fertilisers, etc.,

- **water pollution stresses** may occur whenever aquatic communities are exposed to injurous concentrations of toxic chemicals, temperature changes or turbidity changes which affect the thermal stratification and light penetration of aquatic systems,

- **global climate stresses** may occur as a result of increased accumulation of radiatively active gases (greenhouse gases) in the atmosphere, such as methane from rice fields.

Sources: Cowling in: Mathy ed. (CEC) 1986; see also: Freedman 1989; Westman 1984

As a result of stress, the following consequences, apart from sheer physical destruction, may occur to ecosystems and their fauna and flora when they are transformed from natural ecosystems or rainfed croplands to irrigated lands.

- **energetics**: for example, primary production increases under irrigation (compared with rainfed); respiration increases (eg from increased water supply under irrigation); the ratio between production-respiration (P/R) becomes unbalanced.

- **nutrient cycling**: nutrient turnover increases under irrigation; horizontal-vertical transport ratio changes under irrigation to any direction, depending on water management; nutrient input increases with fertilisation; nutrient export increases without fertilisation and green manuring

- **community structure**: proportion of "R-Strategists" may increase (in non-equilibrium, early successional habitats, species with short generation times and large reproductive efforts are selected); size of organisms may increase or decrease under irrigation; life spans of organisms may decrease; food chains may be shorter because of reduced energy flow at higher trophic levels and greater sensitivity of predators to stress; species diversity decreases and dominance increases; if original diversity is low (eg in most arid soil habitats) the reverse may occur; redundancy of parallel processes declines

- general **system-level trends**: system becomes more open, ie inputs and outputs become more important as internal cycling is reduced; efficiency of resource use may decrease; parasitism and other negative interactions increase, and mutualism and other positive interactions decrease; functional properties (community metabolism) may be more robust than are species composition and other structural properties.

Source: Freedman 1989, modified from Odum

The intensity of human stress varies in time and space. After some time, the affected ecosystems and its taxa will either recover after **alleviation** of the stress (eg reduced pollution in affected downstream river sections) or, more likely under irrigation, **succession** occurs associated with changes in ecosystems structure and function. This is with changed composition of the biota and the predominance of particular taxa which are better adapted to the emerging irrigated field habitats. This may ultimately lead to an increase in biodiversity and species number in arid and in semiarid regions due to higher moisture levels in irrigated soils and increased nutrient supply, since water usually provides a medium of transfer and storage of energy and materials used by living organisms within the ecosystem.

Essentially, there are two issues which are to be addressed: (i) identification of current predominant species and ecosystems which are to be preserved or protected, and (ii) definition of the maximum allowable stress (directly or indirectly induced by human activities) for such species, taxa or ecosystems without affecting the integrity of the biotic communities. Such aspects are treated in Part II section 1 where environmental performance standards are defined. In the following sections stresses induced by land occupancy, ie the direct competition for space are treated. Further aspects of disturbances (air, soil and water pollution) are treated under separate sections, eg 2, 4 and 5.

4.3 Structured Evaluation for Ecosystem Impact Analysis

Ecosystems are complex and varied, multiscaled and multitiered, and subject to continual change and adaption. Hence, the practical characterisation of ecosystem disturbances induced by anthropogenic stress is a rather complex process and many concepts exist. Recovery and succession of ecosystems are dependent in part upon the characteristics of the impact/stress and in part upon the characterisation and history of the ecosystem. The difficulties of characterisations of ecosystems, responses and recovery (or succession) require adoption of points of view, operational definitions, and choices on how to simplify and what scales to emphasise. All of these have influences on what and how to measure, and simple models and extrapolations are simply inadequate because ecosystems are 'individualistic'. Ultimately, site specific concerns need consideration in every case. However, the qualitites of measurements may be considered more generally.

The most useful single criterion to apply in order to reduce the measures of ecosystem health down to a manageable level is the relevance to issues of concern to humans (see section 3.1). That means, a change in an ecosystem is only considered of importance if it relates to something of concern to humans. By focusing on such generic ecological endpoints, a structured way of evaluating ecological effects can be developed. Such a framework of **ecological endpoints** can be divided into a hierarchy of levels:

i) Human Health: vectors for exposure to humans

ii) Species-level endpoints:

direct interest: economic, aesthetic, recreational, nuisance, species

indirect interest: biospecies effect (predation, competition, pollination), habitat role ecological role: trophic role, functional relationship, critical species

iii) Community-level endpoints: food-web structure, species and biotic diversity

iv) Ecosystem-level endpoints: ecologically or economically important processes, water quality, soil quality, air quality (habitat quality).

Source: Kelly/Harwell 1989

These endpoints provide an initial base for deciding what indicators should be significant for a given or predicted disturbance. Indicators are not mutually exclusive and, indeed, they may strongly complement each other, and multiple indicators of several qualities may be required. Categories of **indicators** include:

i) intrinsic indicator: economic species, endangered species, other species of importance; key: indicator is the endpoint

ii) early warning indicators: use when the endpoint is slow in response; key: rapid indication of effect

iii) sensitive indicator: use when endpoint is relatively insensitive; key: reliability in predicting

iv) process indicator: monitoring other than biota: decomposition rate; complement structure; key: endpoint is the process

v) indicator of ecosystem sensitivity/vulnerability: abiotic indicators (soil/water/air); key: system attributes

Source: Kelly/Harwell 1989

Critieria for such indicators include:

i) reliability of response: specific to a given stress

ii) rapid response: early exposure, quick dynamics

iii) signal-to-noise ratio: sensitivity to stress

iv) ease/economy of monitoring: field sampling, lab expertise, data base

v) relevance to endpoint: intrinsic, string of ecological connections

vi) feedback to regulations or management: adaptive management potential

vii) relevance to recovery process

Source: Kelly/Harwell 1989

A multitude of criteria can be used to identify and evaluate the significance of natural areas (further details in: Smith/Theberge 1986); they include:

rarity, uniqueness	biotic, abiotic type
diversity	biotic, abiotic
size	biotic, abiotic, planning and management
naturalness	biotic, abiotic
productivity	biotic
fragility	biotic, abiotic
representativeness	biotic, abiotic
importance to wildlife	abundance of biotic, abiotic types
threat	planning and management
educational value	cultural
cultural resource	cultural
research investment	cultural, economic
recreational value	cultural
level of significance	planning and management

consideration as buffer	planning and management
geographic location	planning and management
shape	planning and management, biotic.

Source: Smith/Theberge 1986

General references: Kaule 1992; Freedman 1989; Kelly/Harwell 1989; Cowling in: Mathy ed. (ECE) 1986; FAO (EEP 6, EEP 7, EEP 8) 1986; Westman 1986

Review of literature relevant to ecological assessments:

Duinker 1989: Ecological effects monitoring. Monitoring can be used as a check on changes over time. For prediction, implicit, process-based, quantitative forecasting models are favoured.

Wakeley 1988: Simplified versions of existing Habitat Suitability Index (HSI) for Habitat Evaluation Procedures (HEP) which determine the impact on fish and wildlife habitat (US-models)

Herricks/Schaeffer 1985: Optimisation of Biomonitoring as an element of environmental management

Gassner/Siederer: Definitions of terms Gestaltsänderung, Nutzungsänderung, Beeinträchtigung des Naturhaushaltes und Landschaftsbildes; Erheblichkeit und Nachhaltigkeit der Beeinträchtigungen (German)

see also under: wetlands section 4.7.

4.4 Socio-Economic Background: Human Land Occupation

Increases in human population have meant an increase in the demand for food, which, in turn, has resulted in conversion of bushland/forests into cropland. Whereas population growth remained rather low in most developing countries (except Latin America) until the 19th century, there has been an accelerated rate of cropland expansion in the 20th century and especially over the past 30 years. Between 1850 and 1950, cropland in Asia increased at an annual rate of 1.2 M ha, resulting in an increase of cropland from 70 to 200 M ha in South Asia, and from 10 to 60 million ha in Southeast Asia. Currently, in Asia are some 374 M ha under cultivation.

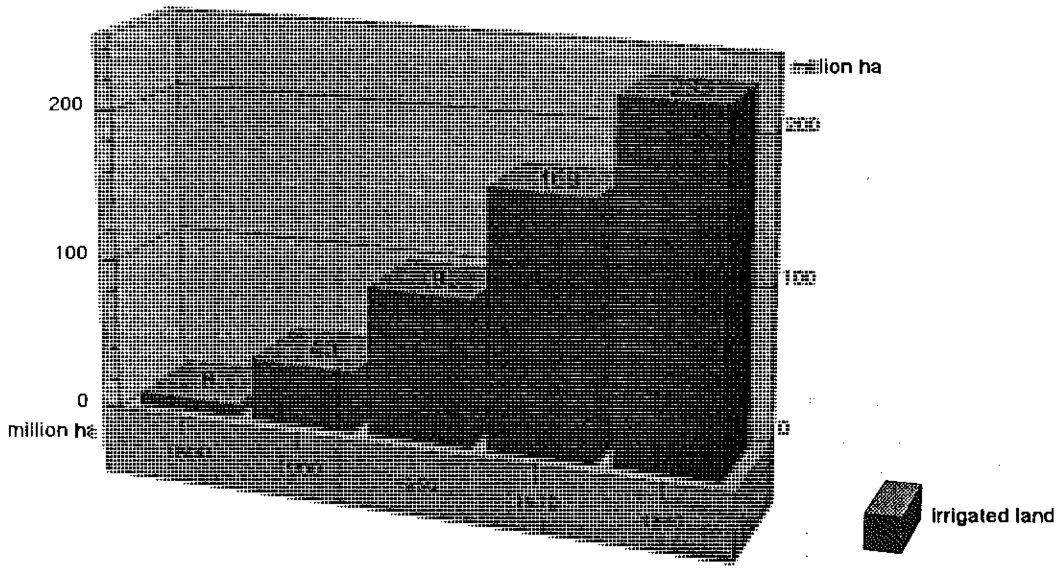
The situation differs from country to country, for example, in China, cropland area has almost tripled in this century, whereas in Bangladesh increases were small because most arable lands were already under cultivation at the beginning of this century. However, cropland expansion slowed down in recent years and expansion in some countries is expected to come to a halt as the land frontier is exhausted and structural changes of economies reduces the absolute size of agricultural populations. In some Asian countries the total cropland area decreased over the decade 1976 to 1986 (eg in China -2.9%), and only in Southeast Asia and Pakistan are growth rates in the range of 3 to 8% over that decade. It is projected that these expansions will level off in the early 1990s.

Over the past two decades agricultural growth without arable land extension was made possible by the application of <u>land-use saving technologies</u> such as **irrigation** and **modern farm technologies** (agricultural imputs such as fertilisers, pesticides, improved seeds, high yielding varieties, mechanisation, improved tillage) in most Asian and OECD countries (ADB 1991).

However, the situation is different in **Africa**, where only 2% of the world's irrigated areas are located and food production per capita has declined by some 17% although conversion of land to cropland had been increased over the last 20 years. By 1985, only 15% of the irrigation potential is developed in Sub-Saharan Africa (FAO 1987). The irrigation needs for crop production in Africa are high, because many areas suitable for rainfed production outside the rainforests require, irrigation for secured and increased yields, due to temporary or permanent water deficits.

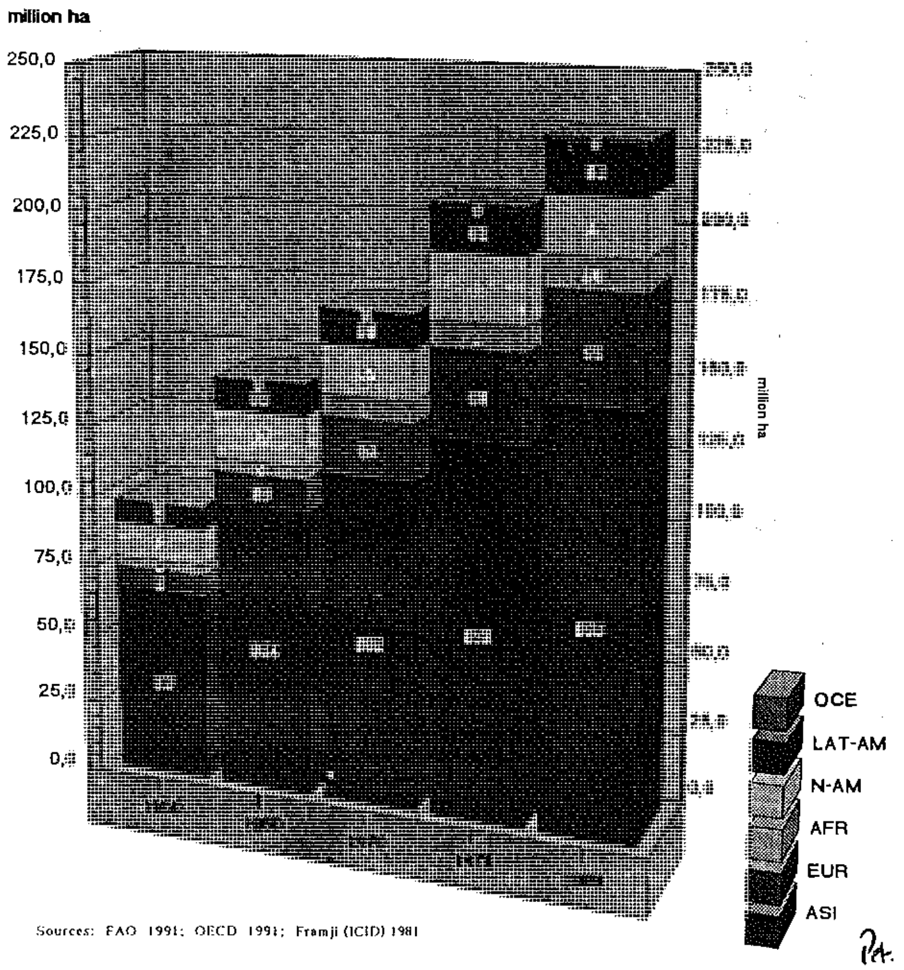
Fig. 4-1 a, b

Total Irrigated Areas in the World 1800 to 1990



Sources: Framji (ICID) 1981; FAO 1991

Irrigated Areas in the World by Continents



Sources: FAO 1991; OECD 1991; Framji (ICID) 1981

The land resources for arable farming in Africa are assessed by FAO as follows:

good rainfall areas	244	M ha	38% of arable land (120-270 growing days)
low rainfall areas	62	M ha	10% of arable land (<120 growing days)
problem areas	288	M ha	45% of arable land (>270 growing days)
flooded areas	44	M ha	7% of arable land (naturally flooded)
desert	1	M ha	currently under irrigation
total arable areas		639 M ha	100%

It is estimated that in Africa about 115 M ha are suitable for irrigation (18% of the arable land). The water resources are sufficient for irrigating some 40 M ha of which probably 20-25 M ha match with land suitable for irrigation (without consideration of large scale water transfer schemes). Water reuse increase the water resources in some areas.

Source: Seckler in: Barghouti/Le Moigne (WB) 1990; FAO (EEP 6) 1986

There is no reason to assume that the rapidly growing **demand** for food can be met in Africa without future **expansion** and **intensification** of agriculture. It cannot be that Africa needs less irrigation or fertilisers or other agronomic inputs than Asia does, nor that Africa has a surplus of agricultural land and therefore requires a low-input, low-yield form of agricultural production. There are still vast savanna and forest areas which could be converted to cropland, but land use saving technologies are also applicable, such as irrigation and other means to improve rainfed productivity or a combination of irrigation and new agricultural technologies.

Sources: Seckler in: Barghouti/Le Moigne ed (WB) 1990; FAO 1987; FAO (EEP 6) 1986
Further readings: Barghouti/Le Moigne ed. (WB) 1990; FAO (EEP 6, EEP 7, EEP 8) 1986

4.5 Irrigation and Competition in Land Use

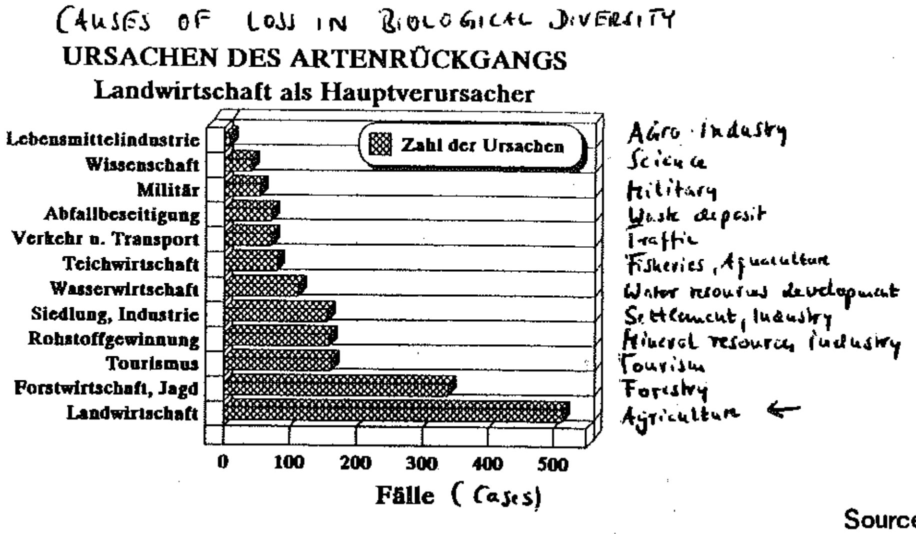
A major 'environmental cost' of agriculture is related to land occupancy in relation to natural ecosystems. Irrigation competes, like any other human land use system, with natural ecosystems. Figure 4-1 shows the increase in irrigated area. Per unit area, irrigated agriculture produces considerably more food than any other agricultural cropland system, and, thus, irrigation may also be understand as a land-saving cropland technology (Further details related to the productivity of agricultural systems are compiled in Table 4-1; but: see also: section 4.7). For example, in a semiarid region, irrigated farming produces about 3.5 times more grains than rainfed farming (Sub-Saharan Africa, FAO 1987) and irrigation improvements in Asia (namely India and China) contributed to the decrease in the per capita agricultural land area.

On the other hand, irrigation tends to use the most fertile agricultural lands, areas which are ecologically sensitive, or areas of a high natural biotic potential or diversity. Irrigation is, independent of agro-climatic zones, mainly practiced in riverine areas, floodplains and along seasonal or perennial wetlands and lakes. These, in turn, belong to natural ecosystems with the highest productivity and degree of diversity: riverine or riparian woodlands, wetlands, alluvial savanna (scrub or grassland) plains.

Losses of natural ecosystems or disturbances may occur within and outside the irrigation command area:

- the irrigated area itself (command area) is converted to agricultural land,
- upstream areas: if dams are built then the reservoir zone may submerge vast areas of land (land losses to large reservoirs are shown in Table 4.2.),

Fig. 4-2



Source: Boesel 1990

Fig. 4-3

Table 2: Wetland Values

	Estuaries (without mangroves)	Mangroves	Open coasts	Floodplains	Freshwater marshes	Lakes	Peatlands	Swamp forest
Functions								
1. Groundwater recharge	○	○	○	■	■	■	●	●
2. Groundwater discharge	●	●	●	●	■	●	●	■
3. Flood control	●	■	○	■	■	■	●	■
4. Shoreline stabilisation/Erosion control	●	■	●	●	■	○	○	○
5. Sediment/toxicant retention	●	■	●	■	■	■	■	■
6. Nutrient retention	●	■	●	■	■	●	■	■
7. Biomass export	●	■	●	■	●	●	○	●
8. Storm protection/windbreak	●	■	●	○	○	○	○	●
9. Micro-climate stabilisation	○	●	○	●	●	●	○	●
10. Water Transport	●	●	○	●	○	●	○	○
11. Recreation/Tourism	●	●	■	●	●	●	●	●
Products								
1. Forest resources	○	■	○	●	○	○	○	■
2. Wildlife resources	■	●	●	■	■	●	●	●
3. Fisheries	■	■	●	■	■	■	○	●
4. Forage resources	●	●	○	■	■	○	○	○
5. Agricultural resources	○	○	○	■	●	●	●	○
6. Water supply	○	○	○	●	●	■	●	●
Attributes								
1. Biological diversity	■	●	●	■	●	■	●	●
2. Uniqueness to culture/heritage	●	●	●	●	●	●	●	●

Key: ○ = Absent or exceptional; ● = present; ■ = common and important value of that wetland type.

Source: Dugan (IUNC) 1990

- downstream areas: loss or deterioration of seasonal or perennial wetlands due to shifts or substantial changes in hydrological regimes, eg reservoir operations for flood control will reduce the downstream flooded areas.

4.6 Impacts on Biological Diversity

Biodiversity is an important feature of an ecosystem's function and structure. The extinction of a species represents an irrevocable and regretable loss of a portion of the biological richness (Fig. 4-2; Tables 4-3, 4-4). Anthropogenic habitat destruction, eg by large-scale conversion of wetlands in irrigated agriculture, is an increasingly dominant cause of extinction, although other conversions may contribute to extinction at much higher levels, for example tropical forest conversions with the extinction of endemic taxa with local distributions.

Biodiversity can be interpreted from agricultural, floral or faunal perspectives, or from environmental or economic views. **Perceptions** may vary with different socio-cultural backgrounds. For example, in African societies maintaining biodiversity is currently often seen as an alternative, rather than a complement to economic development. In contrast, biodiversity in modern 'environmental economics' is, amongst others, an important feature (or indicator) of the natural capital **stock**. This stock is an indicator of sustainability, with the presupposition that maintaining environmental quality is a condition for sustainability.

Important criteria for such analysis includes 'intergenerational equity' and 'risk minimising'. In this respect, biodiversity may be related to risks and irreversibilities of human interference in ecosystems. A major problem arises with the fact that the environmental consequences of development projects are often unknown and hence impacts emerge from natural resource degradation over time. The problems stem from the lack of comprehensive understanding of (1.) ecosystem functions, structures and interactions and (2.) how ecological systems assist certain economic activities. Irreversible losses of environmental functions and structures are difficult to identify and to evaluate in economic terms.

Thus, sustainability includes avoiding, as far as possible, irreversable changes due to human interference and, hence, moves towards the preservation of integrity of biological communities (see also section 3.1). Any change in biodiversity, however, must be interpreted in the context of human basic needs (eg for food production) and the need for the development of human ecosystems such as irrigated agriculture.

Further readings: McNeely et al. (IUCN) 1990; Risser in: Naiman/Dechamps ed. (UNESCO) 1990; Pearce et al. 1989; Freedman 1989; Barbier 1989

4.7 Wetland Degradation

In the past, **wetlands** were often seen as **wastelands** or as places which should be avoided or at least be reclaimed because they carry diseases or were of little human use unless drained. Only recently has their value been re-assessed in industrialized countries (Figure 4-3); natural wetlands help to control floods, they produce various types of food, serve as a resource for materials, help to stabilise wildlife population, remove bacteria, viruses, organic and inorganic toxicants/pollutants and suspended solids, and serve as a genetic resource for precious fauna and flora (Hemond/Benoit 1988).

Since 1900, over half of the world's wetlands disappeared (Figure 4-4, Tables 4-5, 4-6). Originally, some 6% of the land was classified as wetlands (Dugan IUCN 1990). In the USA alone, some 87 M ha were lost, of which 87% are accounted for by agricultural development, 8% by urban development, and 5% by other conversions (Maltby 1986).

Fig. 4-4a

The Causes of Wetland Loss

Human Actions	Estuaries	Open coasts	Floodplains	Freshwater marshes	Lakes	Peatlands	Swamp forest
Direct							
Drainage for agriculture, forestry, and mosquito control.	■	■	■	■	●	■	■
Dredging and stream channelization for navigation and flood protection.	■	○	○	●	○	○	○
Filling for solid waste disposal, roads, and commercial, residential and industrial development.	■	■	■	■	●	○	○
Conversion for aquaculture/mariculture	■	●	●	●	●	○	○
Construction of dykes, dams, levees, and seawalls for flood control, water supply, irrigation and storm protection.	■	■	■	■	●	○	○
Discharges of pesticides, herbicides, nutrients from domestic sewage and agricultural runoff, and sediment.	■	■	■	■	■	○	○
Mining of wetland soils for peat, coal, gravel, phosphate and other materials.	●	●	●	○	■	■	■
Groundwater abstraction	○	○	●	■	○	○	○
Indirect							
Sediment diversion by dams, deep channels and other structures.	■	■	■	■	○	○	○
Hydrological alterations by canals, roads and other structures.	■	■	■	■	■	○	○
Subsidence due to extraction of ground-water, oil, gas and other minerals.	■	●	■	■	○	○	○
Natural Causes							
Subsidence	●	●	○	○	●	●	●
Sea-level rise	■	■	○	○	○	○	■
Drought	■	■	■	■	●	●	●
Hurricanes and other storms	■	■	○	○	○	●	●
Erosion	■	■	●	○	○	●	○
Biotic effects	○	○	■	■	■	○	○

Key: ○ = Absent or exceptional; ● = present, but not a major cause of loss; ■ = common and important cause of wetland degradation and loss.

Source: Dugan (IUNC) 1990

Case studies

Many river basins in Africa contain large floodplains that are of outstanding ecological importance. Among those are the Sudd and White Nile region, Lake Chad (Logone-Chari system), Inner Delta of Niger, and the Okavango Delta in Botswana. Major riverine plains exist along the rivers Senegal, Gambia, Nile, and Zambesi. These areas help to control floods, stabilise river flow, trap sediment, and are highly productive for natural ecosystems, ie for plants and migratory wildlife, such as mammals and birds.

But, considering the productivity per unit of water in the Inner Delta of the Niger and the Office du Niger irrigated rice schemes, the former produces some 10 000 t meat, 120,000 t milk, 100,000 t fish, and 80,000 t rice (traditional) whereas the latter produces 100 000 t of rice. When computed per unit of water, irrigated rice produces almost 10 times as many calories and almost twice as many grams of protein as the swamp, although the swamp's produce is much more varied in type and nutritional value (Le Moigne/Barghouti in: Barghouti/Le Moigne (WB) 1990). This is illustrated in Table 4-7a (from: Hollis et al. 1988). Whilst both systems (traditional and modern rice schemes) produce about the same gross profit margin, the high interest charges arising from the modern irrigation scheme turns the net profit of irrigated rice into a loss of $0.65 per 100 m^3 of water.

In West Africa there are 114 dam projects, which are likely to have an impact on wetlands, with 51 percent operational at present (Ketel et al. 1987, cit. in: Hollis et al. 1988). Modern medium and large scale irrigation projects in West Africa are shown in Fig. 4-4b.

In northern Nigeria, the Bokolori dam was built in the mid-1970s to supply a 30,000-ha irrigation scheme. The dam reduced the magnitude of the wet-season floods which supported an extensive agriculturral system and a fishery upon which some 50,000 people depended. Reducing flooding caused a shift from rice to lower-value millet and sorghum crops in the wet season and a significant reduction in the extent of dry season cultivation. Fish population declined, and fishing decreased (Adams 1985, cit. in Hollis et al. 1988). Other case studies in: Goldsmith/Hildyard 1984.

Inland wetlands, ie marshes and swamps, in the world equal about 2 M km^2, of which 75% are located in the tropics (Crutzen cit. in: Lal 1987). In South and Southeast Asia most of these swamps have been utilised intensively. In fact the Asian lowland rice culture is a sustainable system that has supported the high population density in these regions without causing far reaching ecological imbalances and soil degradation problems that have limited the intensive utilisation of tropical uplands.

Also tidal marsh vegetation is under serious threat and vegetation changes result from tidal restriction. Restrictions are imposed by tide gates and associated structures to protect agricultural (including irrigated) land from flooding by seawater and from discharge regulation devices imposed by dams across larger rivers, eg. Senegal River, River Volta, etc.

The characteristics of wetlands are influenced primarily by hydrological regimes which affect many abiotic factors, including salinity, nutrient availability and soil anaerobiosis (Holland et al.). Many wetland-uplands support relatively high biological diversity, but species diversity for a particular wetland system may be affected by a variety of factors. Some upland ecosystems have few species due to sharp boundaries. Often the primary production is high in wetland-open water systems but conditions can be stressful for less adapted plants, especially in wetland-upland ecosystems which are only occasionally flooded. On the other hand, such periodically or seasonally flooded plains provide sufficient moisture for prolonged plant growth periods in semiarid and arid areas, and distinct community structures exist, adapted to both flooded and upland conditions. Human interference in such plant communities often reduces productivity and homeostasis and stability of the wetland as well as adjacent systems can be disrupted.

Fig. 4-4b

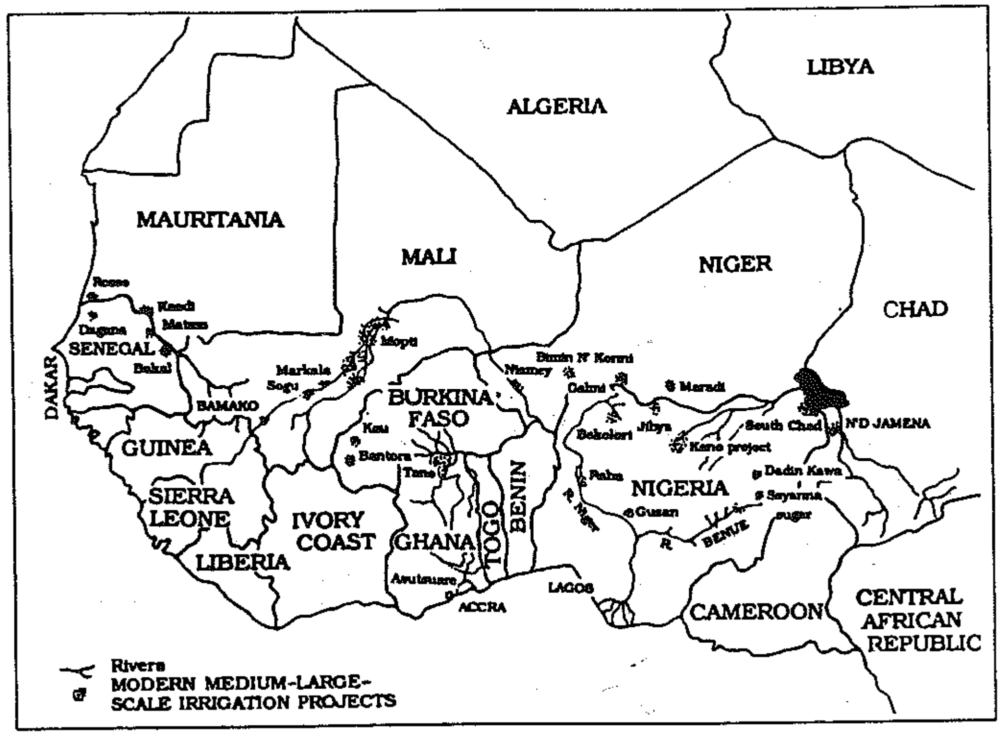
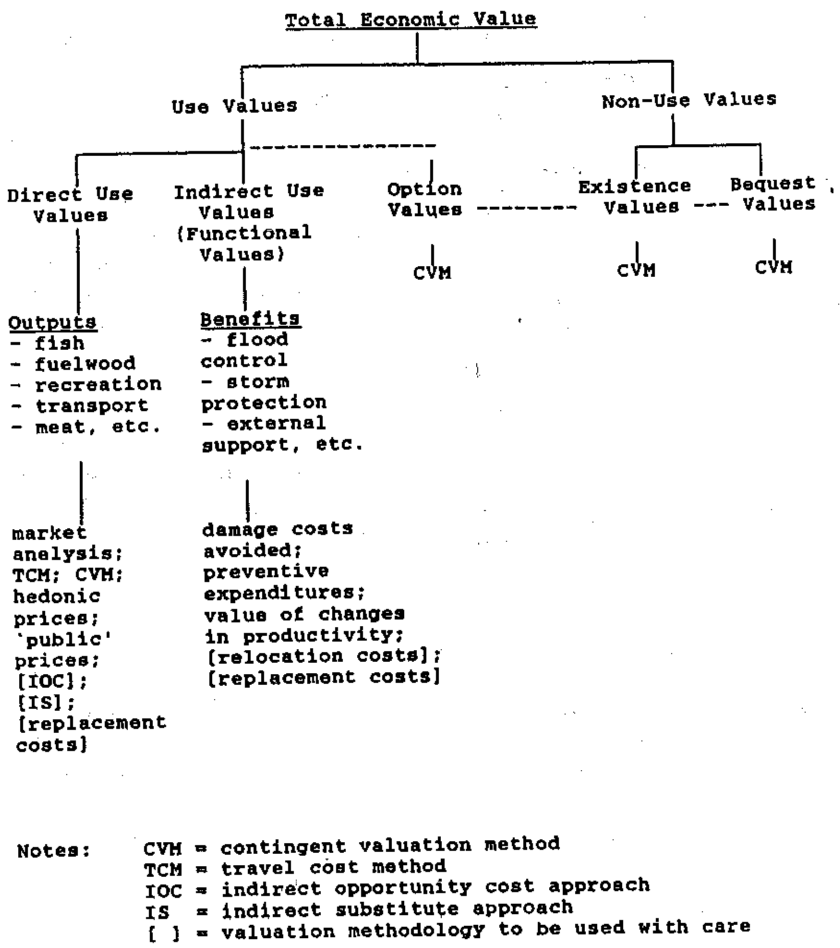


Figure 1. Map of West Africa showing modern medium- and large-scale irrigation projects.

Source: Maurya in IIMI 1990

Fig. 4-5

Figure 1. Valuing Wetland Benefits



Source: Barbier o.J.

Source: Holland/Whigham/Gopal in: Naiman/Dechamps ed. (UNESCO) 1990; Roman/Niering/Warren 1984; Dugan (IUCN) 1990

Further reading regarding cumulative impacts on wetlands and their assessment: Hemond/Benoit 1988

The characteristics of wetlands with value to humans include (details see Table 4-8)

Components (direct harvest or use of structural ecosystem components; resource stocks)

1. Water Resources
2. Fisheries Resources
3. Forest Resources
4. Wildlife Resources
5. Agricultural Resources (germplasm collection)
6. Forage Resources
7. Medicinal Plants Resource, Herbs
8. Ornamentals Resource

Attributes

1. Biological diversity
2. Uniqueness to culture, heritage
3. Aesthetic views

Functions (ecosystems flows and services which may assist or support human activities)

1. Groundwater discharge and recharge
2. Flood and flow control
3. Shoreline stabilisation
4. Sediment retention
5. Nutrient retention and decomposition
6. Retention and decomposition of toxins
7. Water quality maintenance (general)
8. Storm protection (shelterbelt)
9. External support
10 Micro-climatic stabilization
11. Recreation/Tourism
12. Water Transport

Sources: modfied after Barbier 1989, see also OECD 1985; ADB 1988, Westman 1985]

The **economic** values of these components, attributes and values may be **direct** (value derived from economic uses), **indirect** (through services) or related to preservation or non-human **uses** (typically the attributes). The magnitude of importance is subject to the specific valuation. An approach to the valuation of wetland benefits is shown in Fig. 4-5.

Further details on economic evaluation are given in Barbier o.J. ; Pearce/Barbier/Markandya 1988

The impacts of irrigation on wetlands may include:

- direct conversion to agricultural land under irrigation,
- hydrological interference by up- or downstream water abstractions,
- pumping of groundwater with subsequent lowering of watertables,
- land filling and drainage for new land uses or for eliminating vector habitats,
- alteration or complete removal of vegetation,
- pollutant inputs: fertilisers, xenobiotic organic chemicals

- peat harvesting,
- wildlife management (through 'pest' control, or by neighbouring population)
- drainage effluents (these may have negative or beneficial overall effects).

Further readings on general wetland degradation: Hemon/Benoit 1988; Winter 1988; Preston/Bedford 1988; Bedford/Preston 1988; Hirsch 1988; Stakhiv 1988; Harris 1988; Cable/Brack/Holmes 1988

In addition, the conversion or alteration of wetlands may have impacts on downstream water resources, eg water quality, which, in turn, may affect other downstream users.

Further reading: Brinson 1988; Dugan 1990

The development of irrigation and drainage projects has typically had detrimental impacts on wetland ecosystems. In semiarid to subhumid regions irrigation areas, especially for **paddy** cultivation are those areas around lakes or low lying depressions. In other places, wetland zones are dispersed within riverine floodplains which generally offer the best potential for irrigation because of fertile alluvial soils and ample availability of water for irrigation. To meet the increasing demand for food production, additional wetlands will have to be brought under irrigation, especially under paddy production. In fact, the area sown to rice is expected to increase from 98 to 126 M ha by the year 2000 (Dudal cit. in: Lal 1987).

Wetlands in tropical **Africa** constitute a huge potential useful land resource for intensive cropping. Wetlands and hydromorphic soils can often be utilized for double or triple cropping provided that environmentally sound agricultural and soil/water resource management practices are applied. In humid to subhumid areas of West Africa the total wetland area ranges from 13 to 28% of the total land area of various countries. One third of this is in streamflow valleys which are the likely targets for development to meet future land use demands in tropical Africa. Most of these areas also offer great potential for irrigation. However, their use in large-scale irrigation would jeopardise or destroy wildlife and plant diversity and would be detrimental to indigenous populations and/or traditional land use systems which rely on fish, collection of plants or fruits and rainfed crops.

Indirect impacts of irrigation on surface water resources are of similar importance. Changes in quality and quantity of stream flow typically result in a deterioration of habitat quality for wildlife and aquatic life.

It is obvious that more precise information needs to be obtained on the environmental and economic costs and benefits associated with large scale irrigation development to determine whether water diverted from swamps (or further upstream) will indeed find more worthwhile use elsewhere. This however, also implies that development or conservation priorities must be set in the social, cultural and economic context of the area under concern. Technical and ecological information may contribute towards formulating alternative solutions if conflicts between various actual or potential future users arise.

Case Studies:

USA. San Joaquin Valley in California: An increased concentration of selenium from drainage effluents has caused reproduction failures and death in some species of aquatic organisms and waterfowl in the Kesterton National Wildlife Refuge. (Tanji/Hanson in: Stewart ed. 1990).

USA. Central Valley in California: This area once contained some of the finest bird and fish habitats in the world. As the valley was developed and land was converted to agricultural (irrigation) use, fish and wildlife habitats declined. Today only 120,000 to 170,000 ha of natural wetlands remain out of an estimated 1.6 M. In addition, 10,000 km of productive stream and river habitat habe been reduced to about 1,500 km, as a result of construction of dams and other major water developments. Reduction of habitat area has resulted in corresponding reductions in fish and wildlife populations. (Hoffman in: Lesaffre ed. 1990).

USA. Arid Western States: Many wildlife refuges are, in essence, terminal points for irrigation schemes. These areas are often closed basins with no outlet to the sea, and so water quality problems can become severe. In all cases, the reduction of stream flow and the deterioration of water quality have been stressful for fish and wildlife. (Hoffman in: Lesaffre 1990)

Australia. Central Murray River Catchment: Large scale flood irrigation of pasture lands and associated infrastructure works without adequate drainage has lead to a rise in watertables and the build-up of soil, groundwater and streamflow salinity. Most of the stream systems have been degraded by works intended to upgrade their water carrying capacity, including dredging, channelisation and levee banking. Dredging of low-lying natural streams has led to the interception of saline groundwater and consequently more saline streamflow. All wetlands have undergone major changes affecting the water regime, water quality and the vegetation. None of the wetlands can be classified as pristine. 21 out of 40 wetlands in the area have declined in rating in the past 15 years. Increasing salinity has reduced the value of many wetlands for waterbird breeding to the extent that some wetlands no longer meet the Ramsar Convention criteria. Salinity can reach high levels during the non-irrigation season and dramatic changes can occur in some areas as saline slugs are flushed through the system during the early part of the following irrigation season. These slugs are particularly detrimental to the aquatic environment and to high value horticulture enterprises. Stratification in lakes and streams due to salinity and the associated deoxygenation of the lower, more saline layer, can result in significant loss of habitat and the development of potentially toxic conditions for instream fauna (Lakey in: Lefeffre ed. 1990)

Sources: Lakey in: Lesaffre ed. 1990; Hoffman in: Lesaffre ed. 1990; Tanji/Hanson in: Stewart 1990; Holland/Whigham/Gopal in: Naiman/Dechamps ed. (UNESCO) 1990

Further readings: UNESCO/UNEP/FAO 1979; Dugan IUCN 1990

Further reading: Assessments and Regulatory Alternatives for Management: Lee/Gosselink 1988

4.8 Riparian Habitat Degradation

Riparian habitats support some of the richest terrestrial vertebrate faunas of semiarid and arid areas. These composite terrestrial-aquatic ecosystems are ecotones (ecosystem transitional zones) which have not only the highest densities of bird populations but also contribute significantly to the distribution of birds in adjacent areas. They also contain numerous habitats for large and small mammals in dryland regions. Changes in ecotones thus affect the diversity of adjacent ecological communities. For example, 95% fewer birds and 32% fewer species were recorded on agricultural lands along the Sacramento River, USA), from which the adjacent riparian vegetation had been removed. Such removals may also reduce invertebrate and fish production due to a loss of energy inputs into adjacent streams. Generally, riparian forest can affect the flow of water, nutrients and other materials from uplands into streams. They may capture (filter) significant portions of N, Ca, P, and Mg which otherwise would have been washed into the river. Each riparian ecotone has unique features which reflect different hydrological regimes and positions.

Source: Risser in: Naiman/Dechamps ed. (UNESCO) 1990

Irrigation development typically contributes to the clearing of riverine forests, especially in semiarid regions. Often, they consist of fertile strips of land which are brought under cultivation. But the construction and operation of intake structures may also result in portions of riparian rivers being destroyed. Riparian habitat degradation may occur due to human health or other pest control activities because riparian forests may be sources of agricultural pests or provide habitats for water-related vectors.

4.9 Impacts on Aquatic Fauna

Aquatic fauna is affected twofold by impacts resulting from irrigation and irrigated agricultural activities:

- Changes in **hydrological regimes** of rivers by water abstractions: typically seasonal variations and total flow volume may be changed by irrigation projects. The magnitude of impacts on aquatic life varies from negligible to significant. Changes and impacts induced by large dams are treated in section 11.
- Changes in **water quality**, namely increased salinisation and other water pollution from agro-chemicals from washed or leached from agricultural areas into the river systems (especially persistent pesticides and toxic metals, see sections 3, 4 and 9).

Any significant impact on the hydrological regime of a river has effects on fish populations and indirectly on fishery. Irrigation projects may have direct and indirect impacts:

- **Direct** impacts are related to (i) the total reduction of downstream water flow, (ii) changes in seasonal flow regimes, and (iii) changes in downstream water quality, namely increasing salinity and introduction of toxic chemicals.
- **Indirect** influences include changes in river regime caused by large-scale water development schemes such as reservoirs. These impacts can become a serious threat to migratory fishes and may result in a reduction of breeding habitats.

Case Studies

In Thailand dams have impacts on marine and fresh-water fisheries; the daming of main inflows caused a serious decline of fishery productivity, since dams trapped nutritious sediment loads; in several cases the dams interupted the life cycle of fish or crustaceans (Tuntawiroon in: Goldsmith/Hildyard ed. 1986).

In Egypt, after the construction of the Aswan High Dam, both downstream fishery and marine declined.

On the other hand, favourable fish habitats may be developed in reservoirs, with new fish populations adapted to lacustrine conditions and typically higher fish catches compared with the average fish catches in such rivers:

In Egypt, the Aswan High Dam reservoir exhibits high rates of biological production in the range of 8-15 g $O^2/m^2/d$ in some favourable habitats (khores).

The actual impacts from changes in water quality differ greatly and may vary from insignificant to acutely toxic. Fish kills as a direct impact from irrigation projects are rarely observed because toxic concentrations from drainage effluents may only occur incidentally. In large resevoirs the development of aquatic weeds may become a threat to fish populations. For example, blue-green algae (Cyanophyta) in reservoirs or swamps are impoundment organisms which deplete the oxygen in water, fix nitrogen, cause taste and odour problems, are toxic to certain fish and represent the dead end in the food chain.

More important are indirect effects from changes in fish breeding habitats in downstream reaches which may be affected by siltation or changes in seasonal water level fluctuations. However, the most serious impacts are where reservoirs across larger streams hamper the migration of fish populations. In addition, some fish species may not adapt to lake or reservoir conditions and fish numbers may fall unless new species are introduced. Indirect impacts also occur from an increase in sediment loads in rivers caused by increased farming and soil erosion on farmland. Irrigation practices may increase or decrease runoff but poor farming practices will increase runoff and hence increase turbidity in downstream reaches of rivers.

The concentration of a pesticide is rarely distributed evenly through the aquatic phase. Soon after introduction (or application) there is a high concentration close to the surface or the emitter (eg drainage pipes) where it may kill fish, and thereafter, it tends to become absorbed on to particulates or dead organisms and become depostied on the bottom.

Most planktonic organisms tend to be extremely susceptible to pesticides in solution. However, there is much less difference in susceptibility between different groups of aquatic invertebrates belonging to different taxa than there is between organsim of different taxa that inhibit the soil. Invertebrates used in laboratory bioassay tests provide evidence of this comparatively uniform susceptibility to pesticides, eg water fleas, ostracods and stoneflies.

Most **insecticides**, including the organochlorines, organophosphates and pyrethroids are very toxic to aquatic arthropods with relatively little difference in relative toxicity between them. The greatest kill occurs within a few hours of a pesticide reaching the system. Usually, the effects of several successive incidential exposures are catastrophic.

Although aquatic systems are often polluted with herbicides, most of these chemicals have little direct toxicity to aquatic invertebrates, although they have drastic effects on the availability of food. The use of herbicides can decrease the amount of floating phytoplankton but, when they are killed and sink to the bottom, detritus-feeding invertebrates in the bottom sediment may be favoured. The greatest reduction in aquatic invertebrate populations resulting from herbicide use reported to date is 50% (Edwards 1987).

After the aquatic invertebrate fauna population has been affected by pesticides, the time taken for repopulation depends mainly on how long it takes for the residues to disappear. Populations tend to take longer to recover in isolated ponds or streams than in faster flowing systems where contamination is soon removed (dilution effect). Usually, repopulation is relatively rapid and direct effects on fish populations feeding on invertebrates are relatively small. Many invertebrates, however, accumulate pesticides in their tissues without being killed, so that fish that feed on them are exposed to the residues. Fish may contain concentrations of residues many thousand times greater than the water. However, although it is common for animals at higher trophic levels to contain greater concentrations of residues, such bioconcentrations, induced by typical pesticide pollutions from agricultural lands, have not been demonstrated in food chains at significant levels. Thus, pesticides certainly have the potential to affect all the functions of aquatic systems and fish productivity. Care should therefore always be taken to minimise or eliminate such pollution even if direct killings are not encountered.

Source: Edwards 1987

Further readings regarding changes in reservoirs: Baumann et al. (BMZ) 1984, Zauke/Niemeyer/Gilles 1992