

Chapter 4

IMPACT OF DEVELOPMENT ACTIVITIES ON THE HYDROLOGIC CYCLE

4.1 CHANGES IN THE HYDROLOGICAL DATA

The long-term geomorphological development has formed stable, but seasonally variable conditions for the life of typical ecosystems in different parts of the natural environment. A family of these stabilized, local ecosystems forms the regional ecosystem, which is characteristic for the relevant landscape and climatological conditions.

Inputs to and outputs from the ecosystem are moved by the hydrologic cycle. This cycle also serves as the principal vehicle of matter and energy inside the ecosystem. The set of links of the hydrologic cycle, influencing the life and development of ecosystems, is formed by the hydrometeorological regime, which is characterised mainly by precipitation, water quality, groundwater table, runoff, ice and sediment drift data, temperature and sunshine.

Human activities which take place in the framework of the natural environment influence the different components of this system. If this influence on the different components of the ecosystem does not exceed the limits of the homeostasis of the system, the system is able to achieve the original equilibrium again in the long-term. But often human activities also influence the structure of the system. These structural changes, above all the change in the water regime (water quality, runoff, groundwater table, ice and sediment drift), result in sudden or long-term negative changes, i.e. in the degradation of local or regional ecosystems.

The effects of human activities on the hydrologic cycle can be distinguished as

(a) purposeful, i.e. requested consequences of water development projects and measures,

(b) non-requested, i.e. the secondary effects of activities which have another purpose or unintentional effects.

Both these effects can be either desirable or undesirable. Because of the as yet uncoordinated economic development on a global scale, the undesirable effects often prevail. The effects of human activities cause a change in both the quantitative and the qualitative aspects of the hydrologic cycle. The quantitative and qualitative aspects are mutually interconnected. A change in the volume of water in one process of the hydrologic cycle results in a change in the concentration of dissolved and suspended matter as well, i.e. in the water quality. Changes in water quality influence the course of these hydrological processes (water pollution decreases the infiltration and evaporation rate etc.), thus

TABLE 4.1

| Phenomenon Simplified equation | Remarks | Influenced factors and causes of their change |
|---|--|---|
| Rainfall $P = k_c \cdot E$ | k_c - coefficient of condensation E - evaporation | k_c - changes in energy balance changes in the quantity of condensation nuclei changes in air motion E - see evaporation and evapo- transpiration |
| Interception $I = P - P_e$ $P_e = R + S - I_2$ | P - effective rainfall T_e - throughfall S - stemflow I_2 - litter interception loss | I, T, S, D - by changes in the land surface and in the vege- tative canopy and litter |
| Depression and detention storage $D = k_d \cdot A$ | k_d - detention coefficient A - area surface | k_d - changes in the land surface construction of channels and reservoirs, surface drainage A - changes in the area surface |
| Infiltration $v_f = \frac{1}{2} \cdot S \cdot t^{-\frac{1}{2}} + v_k$ | v_f - actual infiltration S - sorptivity v_k - constant infiltra- tion rate t - time from the beginn- ing of the process | S - changes in the hydraulic con- ductivity and in other soil properties including the moisture content and in the overland flow depth v_k - Changes in permeability |
| Subsurface runoff $G_g = A \cdot v_f$ $v_f = k_f^1 \cdot \text{grad} \psi$ $v_f = k_f^1 \cdot I$ | k_f^1 - coefficient of the unsaturated flow k_f - coefficient of hyd- raulic conductivity ψ - soil water potential | I - by changes in the head resulting from water with- drawals, irrigation k_f - by clogging etc. |
| Evaporation and evapotranspiration $ET = k_x \cdot EW$ | k_x - coefficient of the land surface EW - evaporation from free water surface | k_x - changes in the land surface including canopy |
| Overland flow $Q_s = K \cdot H^m$ | K - coefficient of rainfall intensity, slope and roughness H - depth of flow m - coefficient of flow | K - changes in the land roughness and slope m - resulting changes in the flow H - resulting changes in the flow depth |
| Concentrated surface runoff $Q_r = A \cdot v_s$ $v_s = \frac{R^{\frac{2}{3}}}{\sqrt{2gLn}}$ $\cdot [2g\Delta h + k(v_1^2 - v_2^2)]^{\frac{1}{2}}$ | R - hydraulic radius L - length of the stream stretch n - coefficient of channel roughness h - difference in water tables k - reduction coefficient | $v_1, v_2, R, k, \Delta h$ - change in the chan- nel cross section L - changes in the length of the channel stretch n - changes in the channel roughness |

Hydrological processes and factors of their equations, influences of human activities.

influencing the relevant quantity of water (Tab.4.1).

The quantitative influence on the course of the hydrologic cycle is a result of

(a) an acceleration, extension or facilitation of any process of the hydrologic cycle in the particular space,

(b) a retardation, limitation, suppression or discontinuation of any of the hydrologic processes in the particular space.

Such an extension or suppression results in the absorption or release of energy, thus influencing the course of other hydrological processes in situ and/or in another affected space.

The qualitative influence on the course of the hydrologic cycle is a result of

(a) an increase or decrease in the compounds of the hydrologic cycle, which have also previously been its natural component,

(b) the introduction of such new elements and compounds into the cycle and a contingent increase of their content in the cycle.

These compounds or elements may become

(a) an enduring or temporary accessory component of all the processes of the hydrologic cycle, their content being thinned or decomposed during these processes,

(b) an enduring component of water resources, the air mass or the living matter, their content being gradually accumulated.

The change in any value of the hydrological data, including the change in water quality indicators, can be expressed by the equation

$$q_1 = q_0 + \sum_{k=1}^n \Delta_k \quad (m^3, m^3 \cdot s^{-1}, m.a.s.l., g.m^{-3}) \quad (4.1)$$

q_0 - the natural value of any parameter of the hydrologic cycle not influenced by human activities

q_1 - the actual value of the hydrometeorological parameter influenced by human activities

Δ_1, Δ_n - increments/decrements arising from different human activities

1, 2,, n

It is rather difficult to determine the exact values of these increments or decrements. They can be separately measured or assessed by some mathematical method, or by modelling in exceptional cases only. They are provoked by many factors, whose influence is long-term, variable and sometimes also erratic. Their interplay is extremely difficult to follow up in detail and appears to be stochastic. Their usual determination is therefore based on a comparison of the natural and transformed values

$$\sum_{k=1}^n \Delta_k = q_1 - q_0 \quad (m, m^3 \cdot s^{-1}, m.a.s.l., g.m^{-3}) \quad (4.2)$$

The increments/decrements have to be assessed by

- methods of water balance
- research on experimental river basins
- methods of hydrological analogy
- statistical methods
- mathematical or physical modelling
- comparing data of the affected and non-affected period
- comparing data of the affected and non-affected similar catchment.

4.2 CHANGES IN THE HYDROLOGICAL BALANCE

To ascertain the quantitative effects of human activities on the hydrologic cycle, it appears practicable to subdivide the area in question into elements which correspond to, for example, relevant sub-catchments and to separate the atmospheric and lithospheric branch of the hydrologic cycle (Fig. 4.1.).

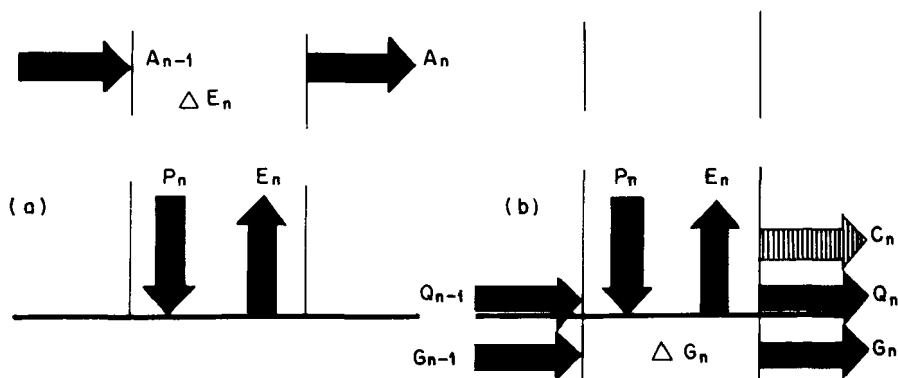


Fig. 4.1. Schematic representation of the atmospheric (a) and terrestrial (b) branch of the water cycle: A - input and output of water vapour, P - precipitation, E - evapotranspiration, Q - surface water discharge, G - groundwater discharge, ΔG , ΔE - storage, C_n - water consumption

Elements of the hydrological balance which represent the deep percolation and storage in flora and fauna can be omitted to simplify the problem. Bearing this in mind, the hydrological balance in the atmospheric branch of the hydrologic cycle can be modelled by the equation

$$A_{n-1} + E_n = A_n + P_n + \Delta E_n$$

$$P_n - E_n = -E_n + A_{n-1} - A_n \quad (4.3)$$

P_n - vertical and horizontal precipitation in the element n

E_n - evaporation in the element n

ΔE_n - increment in the water vapour content in the atmosphere of the element n

A_{n-1} - water vapour input of the element n

A_n - water vapour output of the element n.

The balance of the lithospheric branch of the hydrologic cycle can be expressed as follows:

$$P_n + Q_{n-1} + G_{n-1} = E_n + Q_n + G_n + \Delta G_n + C_n \quad (4.4)$$

Q_{n-1} - surface water inflow

Q_n - surface water outflow

G_{n-1} - groundwater inflow

G_n - groundwater outflow

ΔG_n - increment or decrement in the groundwater content

C_n - water consumption inside the area in question

Depending on the hydrological conditions, the terms of the equation 4.4 G_{n-1} and G_n , which express the groundwater inflow and outflow, can be omitted because their difference is not important. The water consumption C_n may also often be omitted, being mainly the component of the evaporation E_n . In this way, the equation 4.4 can be simplified to

$$P_n - E_n = Q_n - Q_{n-1} + \Delta G_n \quad (4.5)$$

Analysing a long-term period, the increment in the groundwater storage does not change: In this way

$$E_n = P_n - Q_n + Q_{n-1} \quad (4.6)$$

This equation, expressed for the overall catchment area, can be expressed very simply:

$$E_n = P_n - Q_n \quad (4.7)$$

because in this case $Q_{n-1} = 0$.

The exact average value of the evaporation (and also of the soil moisture) cannot be measured and evaluated directly, because it changes considerably during the day and from place to place. They can therefore be derived from the long-term average values of precipitation and surface flow, which are measured daily and are reliable enough.

The equations of the hydrological balance make it possible, therefore, to check the reliability and accuracy of the characteristic averages of the hydro-

logical parameters.

Connecting the equations 4.3 and 4.5 it follows that

$$-E_n + A_{n-1} - A_n = Q_n - Q_{n-1} + G_n \quad (4.8)$$

and for a closed catchment area

$$G_n = -E_n + A_{n-1} + A_n - Q_n \quad (4.9)$$

Bearing in mind the stable water content in the lithosphere and atmosphere over waste areas in the long-term, the direct relation of the long-term averages for a big catchment is

$$Q_n = A_{n-1} - A_n \quad (4.10)$$

Under these conditions, which are not applicable for short-term data, the soil water increment equals the decrease in the humidity in the atmosphere and vice-versa.

Analysing the above equations, the following conditional conclusions can be derived for large catchments:

(a) As a result of an increase in the outflow from the catchment, the water vapour outcome is decreased, causing a decrease in the probability of precipitation occurrence in the area affected, whose position depends on the direction of the prevailing air mass movement. A decrease in the water outflow causes an increase in the mentioned probability (Eq. 4.10).

(b) As a result of an increase in evaporation in the catchment, the probability of precipitation occurrence in this catchment is increased, as far as the conditions for its condensation have not changed, i.e. the increase in evaporation does not necessarily lead to a decrease in outflow (Eq.4.7).

(c) An increase in outflow decreases the average precipitation of the area in question. A decrease in outflow increases the probability of its occurrence.

Equations of the hydrological balance make it possible to define a lot of similar conditioned relations, but the resulting hydrometeorological situation also depends on the influence of the neighbouring areas.

The factors ΔE - the increment in water vapour in the atmosphere - and ΔG - the increment in the soil and groundwater - act as regulators. The increase in the vapour content of the air leads to its oversaturation. The increase in the water content of reservoirs and soil may have the same result when the supply of energy enables an increase in evaporation.

Changes in the hydrologic cycle do not, therefore, depend on the hydrological balance alone. They are also determined by the basic laws of physics. An analysis of the quantitative influence of man on the hydrologic cycle has to be based on the equations of the relevant hydrological processes and on changes in the relevant entry data (Tab. 4.1).

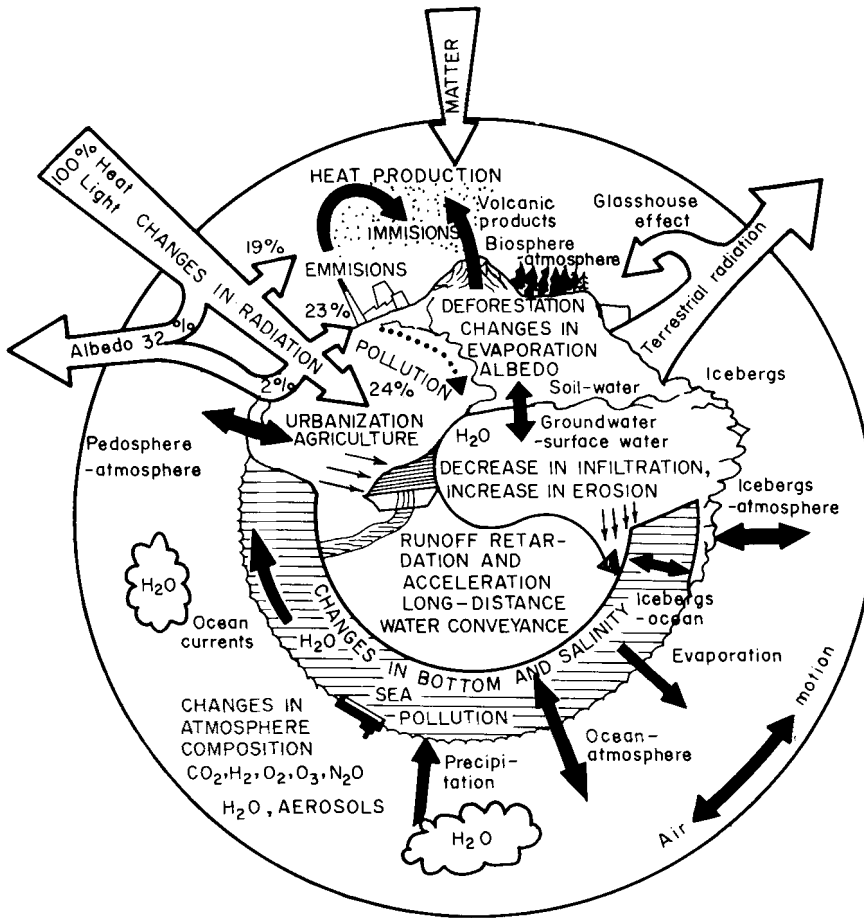


Fig. 4.2. Basic interrelationships of the main processes in the atmospheric, litho (and pedo)spheric and hydrospheric system

The changes which influence the elements of the hydrologic cycle can be categorized into mutually interconnected

- (a) changes in the Earth's surface,
- (b) changes in the energetic balance,
- (c) changes influencing the process of precipitation (Fig.1.2).

The changes in the Earth's surface - as the consequences of clearing, agricultural production, urbanization, industrialization and transport - influence the distribution of the volume of water among the different processes of the hydrologic cycle: interception, depression and detention storage, evaporation, infiltration, groundwater runoff, dispersed and concentrated surface runoff. They also influence their intensity and pace.

The changes in the energy balance as a result of human activities occur with-

in the framework of the natural processes, whose intensity is enormous. In the past there have been fairly regular transitions between warm inter-glacial and glacial years about every 100,000 years. Inter-glacial periods have been relatively shorter, lasting some 10,000 years. The present epoch seems to start in next glacial period. The average global temperature is at present + 14.8°C.

Man's activities increase the energy input into the atmosphere through

(a) the increasing hothouse effect of the atmosphere as a result of the increasing quantity of carbon dioxide in the air and through pollution of the air by other gases and aerosols,

(b) the heat production (Tab. 4.2).

TABLE 4.2

| Mankind' influence | Time period | Estimate of the increment | Relevant surface temperature increment °C | Rate of change towards the end of the time period (°C/decade) |
|--|-------------|---------------------------|--|--|
| Carbon dioxide content of the atmosphere | 2000 AD | + 25% | +0.5 to 2 | 0.2 to 0.8 |
| | 2050 AD | + 100% | +1.5 to 6 | 0.3 to 1.2 |
| Adding chlorofluorocarbons to the troposphere | 2000 AD | 0.8 ppbv | +0.1 to 0.4 | 0.04 to 0.2 |
| | 2050 AD | 2.5 ppbv | 0.25 to 1 | 0.02 to 0.1 |
| Nitrous oxide N ₂ O content of the atmosphere | 2050 AD | + 100% | 0.25 to 1 | 0.02 to 0.1 |
| Direct addition of heat | 2100 AD | 50-fold increase | 0.5 to 2 | 0.05 to 0.2 |
| Adding aerosols, patterns of land use | ? | ? | ? | ? |
| Total expected changes | 2000 AD | - | + 1.2 | + 0.5 |
| | 2050 AD | | + 4.0 | + 0.7 |

Summary of anthropogenetic influences on the global mean surface temperature according to Kellogg (1977).

The changes in the energy balance are interconnected with air mass movement. They influence not only the evaporation rate, but also the water vapour condensation. During this second process, the latent heat of vaporization/fusion

is released . Thus, precipitation is conditioned not only by the presence of condensation nuclei, but also by the transfer of this latent heat to other air masses.

The changes in the energy input also depend on changes on the Earth's surface. Changes in the solar radiation absorbed by the surface have an effect on the heat balance, as well as on the local climate. They are completely heterogeneous, as are their consequences, too, resulting from the influence of other factors.

TABLE 4.3

| Land surface | Albedo (%) | Land surface | Albedo (%) |
|---|------------|--------------------------------|------------|
| Snow: fresh | 85 | Forest: | |
| old | 70 | deciduous in autumn | 33-38 |
| melting | 30-65 | in spring | 16-27 |
| Water (depending on the angle of incidence) | 2-78 | oak in spring & summer | 18 |
| | | pine forest | 6-19 |
| | | spruce | 14 |
| | | fir | 10 |
| Soil and rocks: | | Grassland: | |
| Chalk and limestone (white) | 45 | dry | 16-30 |
| Granit and similar rocks | 12-18 | green | 8-27 |
| Siliceous sand(white,yellow) | | Fields: | |
| dry | 34-25 | Cereals(depending on ripeness) | 10-25 |
| wet | 29 | ploughed dry | 12-20 |
| Clay dry | 29-31 | ploughed wet | 5-14 |
| wet | 16 | | |

Albedo, the coefficient of the reflectance of solar energy according to Lamb (1972).

An increase in the surface moisture and a change in the colour of the earth's surface from bright to dark, for example, causes a decrease in the albedo (Tab. 4.3). Flooding may cause by its water table an increase in the albedo, depending on the angle of dip of the heat rays. Agricultural activities influence the albedo not only through the type of plant, but also through relevant agricultural practices. Thus, man's activities both increase and decrease the value of the albedo. The chain of consequences (Fig.4.4) depends on many local factors, while the resulting consequences may be quite different. In the case of their important influence on the heat balance of the Earth, they may even cause important changes in distant areas.

The third category of changes to affect the hydrologic cycle includes factors which directly influence the process of precipitation, such as:

(a) changes in the soil and air humidity,
 (b) a rise in the number of condensation nuclei, resulting in increased precipitation in the direction of the air mass movement from the entry of the pollution,

(c) radioactive elements (Krypton Kr, Tritium Tr, Radon Rn and other products of Uranium U), entering the atmosphere not only as a result of the generation of nuclear power and enriching the nuclear fuel, but also through the incomplete combustion of low-quality coal.

An ionization of the mentioned elements increases the electrical conductivity of the atmosphere, decreasing its electrical charge. Rain can occur under a strong electrical charge of clouds only. The occurrence of radioactive gases in the atmosphere decreases the probability of rain occurrence and its intensity.

The effect of the mentioned factors may also be contradictory: the air pollution aggravates the condensation of the water vapour by increasing its temperature, but simultaneously forms the condensation nuclei which facilitate this process. Owing to these complicated relationships and feedbacks, the course of hydrological processes and the influence of anthropogenetic factors are remarkably stochastic: Different consequences correspond to identical causes, each of them having a different probability of occurrence, depending on the influence of the other elements of the system.

4.3 INFLUENCE OF FORESTRY AND AGRICULTURE

Vegetative canopy as a component of the structure of the hydrologic system influences the availability of water resources and the negative effects of water occurrence. Different types of vegetation, the density and structure of the growth, the topography of the surface, the quality and quantity of the litter, humus and soil layer have a considerable effect on

(a) the short-term retention, whose consequence is a decrease in flood discharges,

(b) the long-term accumulation, whose consequence is a decreased fluctuation in runoff and increased minimum discharges,

(c) the protection of the land surface against erosion,

(d) the water quality.

This effect consists in

(a) decreasing the concentration of the surface runoff and its velocity,

(b) changing the dispersed surface runoff from the natural recharge of precipitation to groundwater runoff,

(c) slackening the pace of the melting of snow,

(d) causing water losses through high evapotranspiration,

(e) catching the horizontal rainfall in mountainous areas.

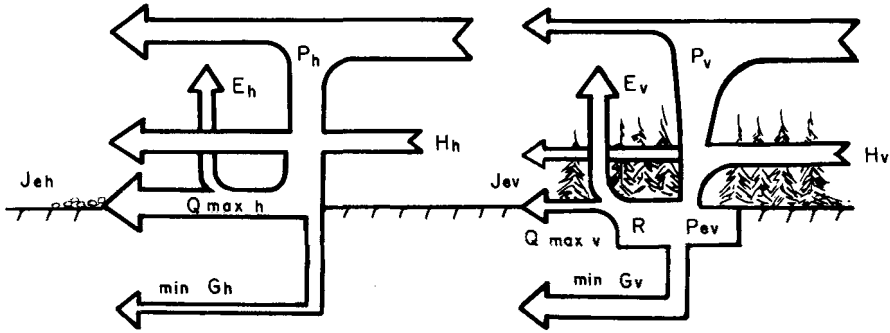


Fig. 4.3. Retention, retardation and anti-erosion effect of the biosphere and its influence on rainfall and evaporation: (a) region with vegetative cover, (b) region without vegetative cover: $P_{ev} < P_h < P_v$; $Q_{max\ v} \ll Q_{max\ h}$; $E_v > E_h$; $I_{ev} < I_{eh}$; $H_v > H_h$; $min\ G_h < min\ G_v$.

In this way vegetative canopy influences, in particular, (Fig.4.4)

- flood discharges Q_{max}
- minimum discharges Q_{min}
- total annual runoff Q_a
- the groundwater regime G_g
- the erosion process and its intensity I_e
- the water quality q_{1-n}
- total annual rainfall P_a
- and the rainfall occurrence p

The interrelationship of these entry data of the runoff process and of the rainfall can be expressed by the equation

$$Q_{max}, Q_{min}, Q_a, G_g, I_e, q_{1-n} = P \cdot f_{1-6} (X_c, X_v, X_s, X_m, X_g, X_x) \quad (4.11)$$

- X_c - climatological factor, including the energy input,
- X_v - factor of the vegetative canopy, depending on its composition, age and state
- X_s - soil factor, depending on the soil type, structure and permeability, characterized by the course of the suction pressure or by the saturation and the coefficient of the hydraulic conductivity,
- X_m - morphological factor, including the shape of the slope and its position, but also the location of erosion rills and channels,
- X_g - geological factor, including the structure and permeability of the geological formations and their communication with the land surface,
- X_x - water management factor, including all other positive and negative influences to arise from human activities, e.g. from the production of heat, land and soil management, mining, thus having an impact on all previous factors.

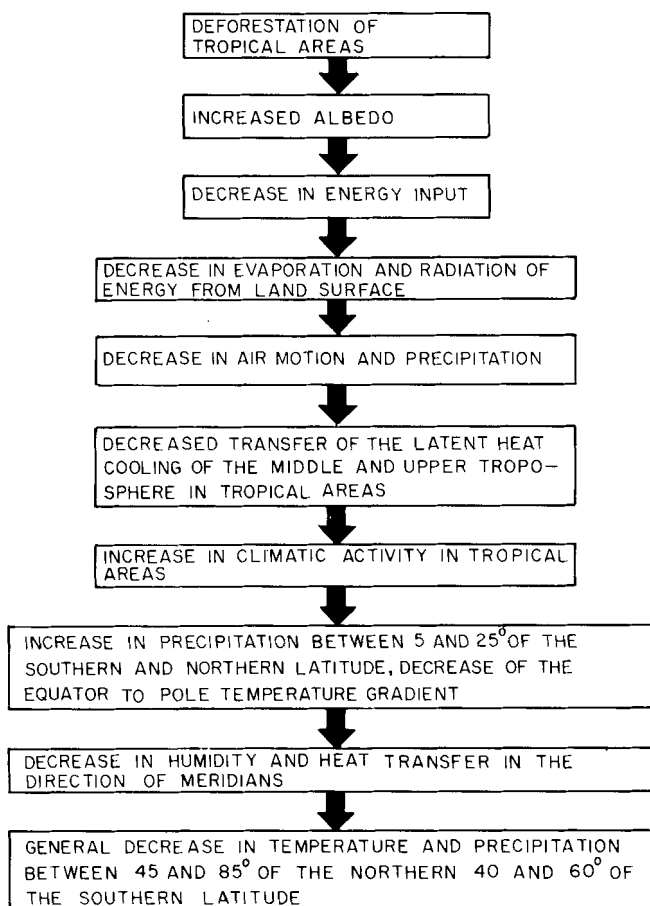


Fig. 4.4. Chain of consequences of deforestation in tropical regions according to Potter et al. (1975).

The intensity of hydrological processes on the boundary of the pedosphere and atmosphere can also be derived from the material and energy balance of the relevant ecosystems. Interception is also important, depending on the composition of the vegetative canopy, its age, density and state and on climatological factors, especially on the rainfall regime. Transpiration, depending on the biomass quantity and also on the characteristics of the vegetative canopy, is far less important.

The influence of the vegetative canopy on the hydrologic cycle can be characterized by simple parameters such as its composition, density, height and volume in the system of the atmosphere and by the density and depth of the root system in the pedosphere. But other interrelated factors, such as pedological, geological and topographical factors, may exceed their importance under specific local conditions of change in the vegetative canopy. Due to these complex inter-

relationships, changes in the vegetative canopy over vast areas may also provoke global consequences (Fig. 4.5).

4.3.1 Interception, Evapotranspiration and Infiltration

The extent of interception depends very much on the characteristics of the vegetation. The difference between the summer and winter values and their averages depends on the type of precipitation, rainfall and snowfall. In forests at low altitudes interception is an important negative component of the water balance. Under conditions of prevailing evaporation, interception decreases the total runoff. At higher altitudes, when horizontal precipitation from mountain fogs prevails, interception increases the total precipitation: drip and stemflow exceeds the value of evaporation of the intercepted water. (Tab. 4.4).

TABLE 4.4

| Precipitation (season) | Interception (%) | | | |
|---------------------------|------------------|--------------|----------------|---------------|
| | Young growth | Pole tree | Timber tree | Noble tree |
| 650 mm (summer) | 12 | 20 | 30 | 39 |
| 550 mm (winter) | 10 | 22 | 26 | 32 |
| Rainfall intensity | Spruce | | Beech | |
| Low | 81.7 | | 71.9 | |
| Medium | 54.8 | | 24.8 | |
| High | 24.1 | | 17.7 | |

Increase in average interception with the age of the vegetative canopy according to Delfs (1956) and values of the actual interception in coniferous and deciduous forests (%) according to Eidman (1968).

The actual transpiration of the vegetation depends on the rainfall, the availability of water in the soil, the energy input, and the quantity and function of the biomass. Different species of vegetation, e.g. agricultural products have different water requirements, depending on their structure, especially on the ratio of their underground and surface parts.

The water requirements of wood species do not differ as much. The difference between the water requirements of hardwood and softwood, of quickly and slowly growing local wood species in Central European conditions is reported to be comparatively small, for water requirements depend on the density and development stage of the relevant wood: they increase noticeably with age. Only some exotic species are reported to have low water requirements, but not exotic industrial wood, which is more likely to be planted in these conditions.

The level of evapotranspiration in forests is, under current climatological conditions, higher than that of other types of vegetative canopy, depending not only on the wood species and the variety of different stories of other plants, but also on forestry practices. Actual evapotranspiration from highly productive agricultural land is lower, under the same climatological conditions, than the evapotranspiration of a forest with little wood production. The evapotranspiration ratio of forest and agricultural land depends to a significant extent on the energy input required to evaporate the total yearly rainfall (Fig. 4.5).

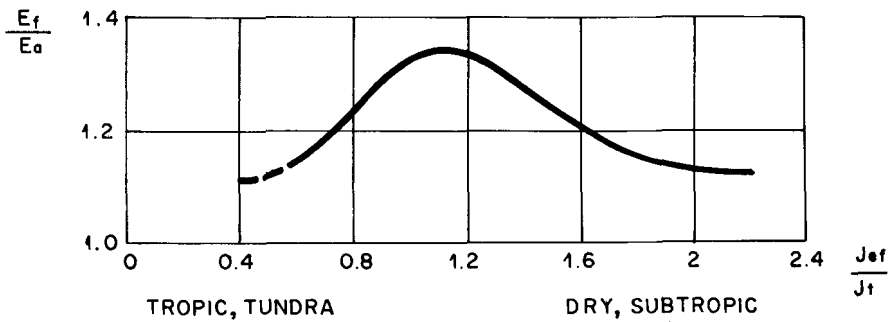


Fig. 4.5. The ratio of evaporation from forests E_f and from fields E_a in relation to the ratio of the energy input J_{ef} and the energy J_t needed to evaporate the total yearly rainfall P according to Budyko (1973).

Two basic theoretical, but contradictory cases of the water management function of soil and vegetative canopy can be distinguished:

- (a) The infiltration increases with the growing accumulation capability of the soil and the vegetative canopy,
- (b) The infiltration rate decreases with the growing accumulation capacity of the soil and vegetative layer.

In the first case of a simultaneous increase in the infiltration and accumulation capacity, the amount of the evaporated rainfall grows with the increasing accumulation capacity, thereby reducing the surface runoff. In such soils the highest groundwater runoff occurs at medium values of infiltration and accumulation, and runoff for both high and low values of infiltration and accumulation decreases to almost zero. In such soils, given sufficient supply of energy, the high infiltration rate enables almost all soil water to be evaporated. The surface runoff, whose values decrease with the increase in evaporation (Fig. 4.6), is supplemented by the groundwater runoff mainly for medium values of infiltration and accumulation.

In the second case, where the infiltration rate of the soil cover is low, although its accumulation capacity is high, most of the rainfall flows away as

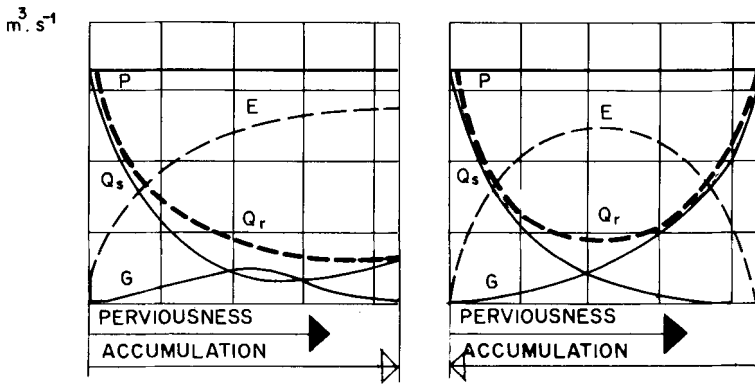


Fig. 4.6. The theoretical impact of perviousness and of the accumulating effect of the soil layer on the distribution of the rainfall P at surface runoff Q_s , groundwater runoff G_g and on the formation of river discharges Q_r and evaporation E according to Lwowitch (1970).

dispersed or concentrated surface runoff. The values of both groundwater runoff and evaporation are low for low infiltration rates. With the growing infiltration rate and simultaneously decreasing accumulation capacity, the dispersed surface runoff decreases and the groundwater runoff increases. Evaporation is low for both high and low values of infiltration: the rainfall changes into surface runoff or percolates into lower geological layers. The highest evaporation values and the lowest values of the concentrated runoff occur at medium values of infiltration and accumulation.

Under conditions of a low infiltration rate of the soil, the surface runoff concentrates without any important influence of the groundwater runoff. Under conditions of a high infiltration rate, the surface runoff concentrates with an important influence of the groundwater: the fluctuation of its values is smaller, provided the accumulation capacity of the soil is sufficient.

The above analysis was based on a theoretical hypothesis of stable physical, chemical and biological properties of the soil layer and the vegetative canopy. In reality, these properties depend on the soil structure and its state, as well as on the development stage of the vegetation and its state. Cultivated agricultural land undergoes comparatively more important and more frequent changes than forest land, which undergoes basic changes during clearing. The changes of the agricultural land are seasonal, depending on the particular cultivation practices.

The infiltration properties of agricultural land are affected especially by ploughing, and depend to a large extent on the duration of the period between ploughing and rainfall. Primitive ploughing loosens the soil till down to a depth of 0.12 m, horse ploughing to 0.16 m, and mechanized ploughing to 0.3 m. Mechanized autumn ploughing slows down the winter runoff, changing a substantial

part of the surface runoff into groundwater runoff, simultaneously increasing the volume of the stored rainfall and snowfall. This positive influence can be reduced or distorted by the weight of tractors packing the lower soil layers.

The extent of the influence of mechanized ploughing on the infiltration rate depends not only on the state of aggregation, but also on the climate and the nature of the precipitation.

It appears to be more important in areas with a low total yearly rainfall and a low soil humidity. Concerning the influence of plant species, the continuous cultivation of cereals decreases the infiltration rate to a minimum value. The effect of the cultivation of cereals in rotation is more favourable from this point of view, and the cultivation of fodder crops in rotation most favourable of all.

The infiltration rate of pastures and forests tends, on average, to exceed this property of agricultural or urbanized land. These lands distinguish themselves from the agricultural land by their extensive and dense root system. In forests, not only species of the lower plant stories and the litter layer contribute to this property, but also the favourable biochemical properties of the forest soil, which generally has a good structure and a high humus content.

The infiltration properties of forest land also depend on the plant species and their age, as well as on cultivation and clearing practices. The highest infiltration rate is produced by the soil of mixed forest cultures. This positive property in comparison with agricultural and pasture land is further helped by the less significant effect of freezing, which penetrates into the upmost soil layer only.

4.3.2 Influence of the Vegetative Canopy on Floods and Erosion

The rate of surface runoff depends especially on the topography, the infiltration rate and, to a lesser degree, also on interception losses. On agricultural lands these properties depend on the agricultural practices, especially on the depth and method of ploughing, as well as on the plant species and their development stage. In forests surface runoff is almost imperceptible, even after heavy rains. In spruce and deciduous forests surface runoff may appear under extreme topographical and soil conditions and during heavy rains, when the soil and litter layer is destroyed by improper clearing practices.

The protective effect of the vegetation canopy form of accumulation and retardation. The accumulation effect, or storage of water, is also aided by the root system and the depth of the soil layer. The retardation of the runoff is caused by the change of the surface runoff into groundwater runoff, by the interception of the plants and litter, and by the roughness of the land surface. This effect also decreases the erosion rate and the concentration of the surface runoff. In forests the concentration of surface runoff into rills and channels occurs later than on pastures and agricultural land (Fig. 4.8).

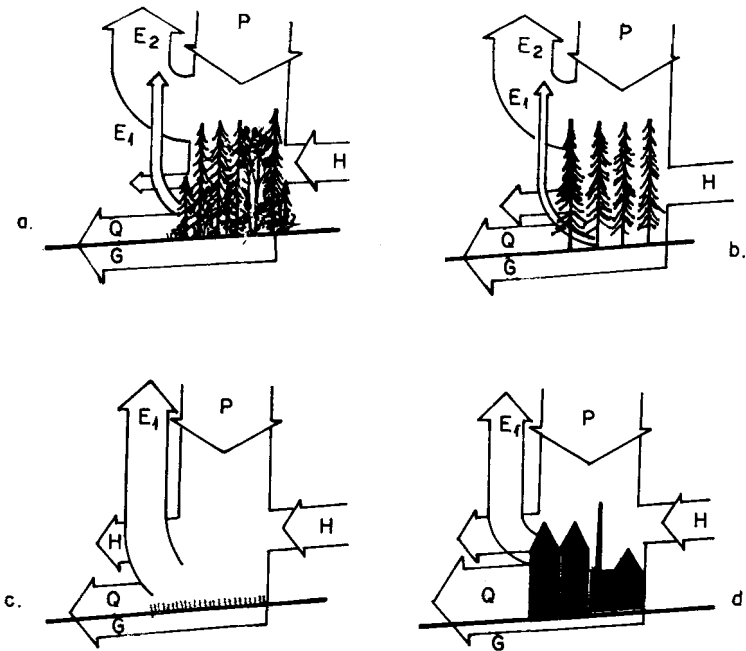


Fig. 4.7. The impact of vegetative canopy on the rainfall-runoff process: (a) multistage forest, (b) single stage forest, (c) grassland and fields, (d) urbanized area. The values of the relevant hydrological phenomena are proportional to the width of relevant arrows:

$$P_a = P_b > P_c < P_d; E_a > E_b > E_c > E_d; Q_{sa} < Q_{sb} < Q_{sc} < Q_{sd}; G_a > G_b > G_c > G_d$$

$$Q_b < Q_a < Q_c < Q_d; H_a > H_b \gg H_c > H_d$$

P - precipitation, H - vapour condensation, E - evaporation, Q_s - surface runoff, G_g - groundwater runoff, Q - total runoff and maximum discharges.

Accumulation on afforested land occurs to a more significant extent during lower rainfall and runoff than during extreme rainfall and maximum floods. Floods with a one year frequency of occurrence may increase after clearing more than ten times and floods with a hundred year frequency of occurrence several times, in inherent dependence on the size of the catchment, the depth of the soil and its moisture before the rainfall. Forests with shallow soils have no important influence on the decrease in discharges in comparison with deforested areas. The accumulation and retardation effect largely depends on the saturation of the soils, i.e. on the frequency of rain occurrences and on the interval between them. If the accumulation capacity is exceeded, this causes an immediate increase in the surface runoff.

The water management function of forests depends considerably on human activities and especially on forest management. Undisturbed forest cultures are character-

ized by their important protection effects against floods and erosion. Multi-storey forests cultures transform floods more effectively than cultivated single storey monocultures, and far more efficiently than pastures or cultivated agricultural land (Fig. 4.8).

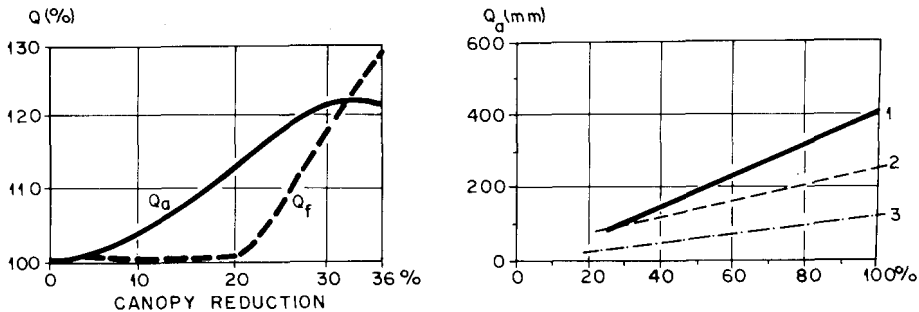


Fig. 4.8. (a) The increase in the total annual surface runoff and in the fluctuation of discharges as a consequence of clearing an afforested catchment according to Zelený, Křeček and Krečmer (1979); p - the decrease in the biomass (%), Q_r - total yearly runoff, Q_f - flood discharges.

(b) The increase in the total annual runoff Q_a as a consequence of clearing according to Bosch and Hewlett (1982): 1 - coniferous, 2 - deciduous, 3 - bush.

Mechanized clearing, the transport of timber and the network of transport communications decrease this positive function. The activities of clearing, harvesting, transport and other machines tend to compact the soil, destroying its structure, which is conducive to infiltration, both in forestry and agriculture. The movement of transport machines, such as for towing logs, form rills, gullies and channels for the concentration of surface runoff, whose increased tractive force accelerates the erosion process.

The direct relationship between the runoff coefficient and soil wash and transport was proved by means of measurement. Murzaev (1977) indicates that the land grading for the mechanized afforestation increases the runoff coefficient of forest land by up to 0.8 (Tab. 4.5).

Vegetative canopy forms an effective protection against erosion for the land surface. The best protection is formed by natural ecosystems. The resistance of cultivated forests without comprehensive anti-erosion measures is relatively smaller, because of their geometrical arrangement, monotonous plant species and human activities during their cultivation. Nevertheless, forests generally form an efficient protection against erosion, if not destroyed by harvesting (Tab. 4.6).

TABLE 4.5

| Group | Characteristics | Water management function | Timber production | Purpose |
|-------|---|---------------------------|-------------------|--|
| I | Forests of catchments used for municipal water supply | superior | inferior | Exclude soil erosion, not to restrict runoff, safeguard the water quality |
| Ia | Forest in zones of sanitary protection of water quality | exceptional | conditioned | |
| II | Forests in upper catchments | | balanced | Balance the runoff fluctuation, protect the land against erosion |
| III | Local protecting canopy | | | Soil protection, river bed stabilization, bank protection, sanitary protection |
| IIIa | Bank canopy | exceptional | conditioned | of local water resources, |
| IIIb | Canopy protecting local water resources | exceptional | conditioned | transformation of surface water into groundwater runoff |
| IIIc | Infiltration forest belts | exceptional | conditioned | |

Categorization of forest canopy as a function of its water management function according to Krežmer and Běle (1975).

Pastures have similar positive effects, if not destroyed by being overgrazed or trampled down by herds. The resistance of cultivated fields against erosion is substantially lower.

The anti-erosion effects of the vegetative canopy have a favourable effect on the quality of the surface water. Its high infiltration capability similarly influences the groundwater quality. The decreased erosion decreases the volume of eroded material in water, thereby reducing the duration of water turbidity in brooks, creeks and rivers. The content of sediments may increase five to seven times due to deforestation. Also important are other changes in water

TABLE 4.6

| Land use | t/ 10 ⁶ km ² /yr | Relative to forest = 1 |
|-------------------------|--|------------------------|
| Forest | 8.5 | 1 |
| Grassland | 85 | 10 |
| Abandoned surface mines | 850 | 100 |
| Cropland | 1700 | 200 |
| Harvested forest | 4250 | 500 |
| Active surface mines | 17 000 | 2000 |
| Construction | 17 000 | 2000 |

Representative rates of erosion from various land uses according to Canter (1983)

quality after clearing, caused by the decay of organic matter and by the increased leaching of nutrients:

- the increase in the concentration of nitrides e.g. from 1mg/l to 60-80 mg/l (Hubbard Brook - USDA Forest Service 1975)
- the increase in the phenol concentration to 0.6 mg/l (Wyoming, Hart et.al., 1981).
- five to thirty fold increase in the calcium, magnesium and potassium content in the outflow (Sopper, 1975).

The influence of agriculture and silviculture on floods, erosion and water quality can be managed, in particular:

(a) by the selection of suitable plants and woods and by the arrangement of relevant cultures and plots, and of the communication and drainage network, by suitable cultivation practices, namely by ploughing along isohyets and horizontal furrows, by sowing without ploughing, by the restriction of land cultivation, by a rational crop rotation, by cultivation in strips, by infiltration strips arranged along water courses, by the protective cultivation of grass, by wind belts, infiltration and overshadowing of forest belts, cultivation of rills, by terraces, dikes, channels and by protecting the destructed land surface to limit erosion,

(b) by measures which limit the compacting of the soil surface and improve the soil quality and humus content so as to increase the rate and the degree of exploitation of mineral fertilizers,

(c) by the cultivation of resistant forest cultures, which remain stable in winds and difficult snow and ice conditions, by preferring selective and partial clearing, and by the immediate recultivation of clearings in vast areas.

4.3.3 Influence of the Vegetative Canopy on Rainfall and Runoff

The roughness of the forest cover, higher in comparison with deforested areas, has an important influence on the precipitation process. It decreases the rate of motion of the lowest layer of the atmosphere and causes turbulence of the air, thus improving the conditions for the condensation of the water vapour. This influence has been proved not only theoretically, but also statistically, however for extremely vast forest areas only. Kalinin (1968) mentions that the influence of large pine forests increases the level of precipitation by about 20% in the summer season and by some 8-10% in winter. The impact of deciduous and mixed forests can be estimated at about one half of the above values. The influence of spruce forests is higher, assessed at a roughly 30% increase in precipitation in the summer season in comparison with deforested areas. This positive influence on rainfall cannot be considered in areas with scattered, relatively small forests.

In addition to this, forests increase horizontal precipitation, depending on the altitude and distance from the sea. Fojt and Krečmer (1976) estimated, for central European conditions and mountainous humid areas, the influence of forests as having a supplement of almost 400 mm to the values of vertical rainfall in comparison with deforested areas. Karpov (1962) estimated the value of annual horizontal precipitation by a 13% increase in the yearly total rainfall (Fig. 4.7).

The influence of forests on air motion has a remarkable effect on snowfall distribution. Snow accumulates in forests to the detriment of deforested plots. Boughton (1970) mentions the following fundamental points:

(a) Snow accumulates mainly in small openings in forests, especially at lower altitudes. The optimum size of opening for snow accumulation is about one to ten times the height of the surrounding forest cover. Large openings do not have such a positive influence because of the wind effect.

(b) The effect of forests on snowfall is more a redistribution of the snow, rather than any overall increase in precipitation. It appears as a positive supplement to the water balance in small catchments only.

(c) The redistribution of snow into deeper falls over smaller areas attenuates the runoff from the melting of the snow, thus decreasing the spring peak discharges.

Forests with intermittent deforested plots have a favourable effect on extending the duration of the snow melt. The decreased rate of melting contributes to the good accumulation and retardation function of forests, manifested by a more stable regime of groundwater, springs and surface water.

The runoff from afforested areas is greatly influenced by the high evapotranspiration of ecosystems, generally exceeding the contribution of the increased

precipitation. The increase in the total yearly runoff from afforested areas in comparison with areas without forest has been statistically determined only for extremely large catchments with moderate evapotranspiration as a consequence of higher vertical and horizontal precipitation.

In the case of small afforested areas a lower yearly runoff has been statistically documented in comparison with areas of the same size and character, but without forests, as a consequence of higher evapotranspiration. Mc Arthur and Cheney (1965) have measured an increase in the total yearly runoff of between 43 and 235 % of the hypothetical runoff of the afforested catchment after a forest fire. Higher values have been measured in the first years after a conflagration.

The values of the increase in the total yearly runoff due to deforestation depend not only on the percentage of the reduction in the forest cover and its type (coniferous, deciduous, bush), but also on the total annual precipitation and its state of aggregation (Fig. 4.9).

The impact of the silvicultural activities on the runoff coefficient c depends on the following groups of factors

$$c = \varphi_s (L, S_1, S_2, B_1, B_2, P) \quad (4.12)$$

L - stable local factors, especially the drainage area shape and slope i , soil depth and type s and geology g ,

S_1 - silvicultural practices and conservation services, namely the stand density, type and density of forest roads, movement and type of transport mechanisms,

S_2 - ratio and type of deforested plots, extending the duration of snow melting,

B_1 - type of culture, its root system and the amount of biomass,

B_2 - the ratio of middle-aged tree classes, which have the highest interception and transpiration losses,

P - the state of aggregation of the precipitation and its coincidence with the season and saturation periods.

The decrease in ratio on the area surface by 30% in dependence on other conditions causes an increase in flood discharges of six times or even more. The fact that rain forests are being destroyed by man at the rate of about 11×10^6 ha every year appears also as a warning in this connection.

But under conditions of an intensive forest exploitation and forest management, the ratio of afforested areas is not the only decisive factor of the water regime. This depends substantially on the depth of the soil, the age, species and condition of the forest, and on cultivation practices (Tab. 4.7). Fully afforested areas may have an insufficient influence to balance the water regime as a consequence of wrong forestry practices which concentrate the runoff.

To increase the total yearly runoff from afforested areas where spruce is the main wood, without increasing the flood discharges, Perina and Krecmer (1973)

TABLE 4.7

| Class | Years | Clearing period 100 years decreased forest density | | | Clearing period 120 years full forest density | | |
|-----------------------------|---------|---|--------------------------|--|--|------------------------------------|--|
| | | Area (%) | Biomass concentration | Annual water consumption ($m^3 \cdot ha^{-1}$) | Area (%) | Biomass concentration factor | Annual water consumption ($m^3 \cdot ha^{-1}$) |
| I. | 0-20 | 20 | 1.0 | 360 | 10 | 1.0 | 180 |
| II. | 20-40 | 20 | 0.8 | 520 | 20 | 1.0 | 560 |
| III. | 40-60 | 20 | 0.8 | 730 | 20 | 1.0 | 800 |
| IV. | 60-80 | 20 | 0.8 | 670 | 20 | 1.0 | 720 |
| V. | 80-100 | 20 | 0.9 | 560 | 20 | 1.0 | 600 |
| VI. | 100-120 | 0 | 0.0 | 0 | 10 | 1.0 | 260 |
| Total annual consumption | | 100 | - | 2840 | 100 | - | 3300 |

The impact of forest density (biomass concentration measured in t per hectare and compared with theoretical values of full density according to Schwabach (1890) on total annual runoff. Pine forest in area with total annual rainfall 1200 mm.

recommend the following biotechnical measures:

(a) The cultivation of forests with a low stand density in areas with low horizontal precipitation in order to decrease the interception losses.

(b) To increase the ratio of younger tree classes and the ratio of clearing (opening) surfaces, and to limit the ratio of the middle-aged tree classes, which have highest interception and transpiration losses, i.e. to shorten or to extend the period of clearing in areas with low horizontal precipitation.

(c) The change of tree species in areas with low horizontal precipitation, i.e. to replace species with high interception and transpiration losses with species which have low interception and transpiration, to substitute deciduous trees for spruces.

(d) A considerable increase in the ratio of the old spruce forests in areas with high horizontal precipitation and high stand density, and a decrease in the ratio of the youngest growth and clearings destined for afforestation.

(e) The deforestation of suitable areas in accordance with the planned extension of the cultivated land, pastures, towns, industry and recreation development.

The runoff coefficient on agricultural lands depends on the cultivated species, their root system: deep, shallow, intermittent, surface etc., their stage of

TABLE 4.8

| Month | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|----------------------------|---|----|----|----|----|----|----|
| Grassland | 6 | 13 | 37 | 11 | 12 | 16 | 16 |
| Winter rye | 2 | 4 | 17 | 25 | 8 | 0 | 0 |
| Spring wheat and barley | 0 | 3 | 10 | 24 | 16 | 0 | 0 |
| Potatoes | 0 | 0 | 2 | 9 | 26 | 30 | 14 |

The impact of field crops on water accumulation in soil (%) according to Bulavko (1971).

growth and on the course of the growth depending on the soil thickness and type, the agricultural practices and the state of aggregation of precipitation. Measurements on agricultural soils document a considerable loss of water accumulation in comparison with grassland, whose value depends on the season (Tab. 4.8). The change of pastures with a deep root system into agricultural fields may result in a 30% increase in the total yearly runoff, when the rainfall occurs mainly in the vegetation period. Also important are agricultural practices: crop rotation, weed removal, the depth and period of ploughing, agricultural conservation services. Lwowitch (1968) shows that deep ploughing can decrease the yearly runoff depending also on the rainfall distribution by some 25 to 75%. Nevertheless compacting of the deeper soil layers by heavy tractors and other agricultural machinery increases the surface runoff.

The intensification of agricultural production, resulting in an increased yield:

- is either accompanied by a growing evapotranspiration, enabled by an increased infiltration rate and higher moisture content in the root zone due to agricultural practices loosening the soil layer, thus limiting the interflow and decreasing the recharge of the groundwater, which results in a decrease in the total annual runoff and a decrease in low discharges in water courses,
- or caused by better utilization of water by plants.

In this second case, the change (increase or even decrease) of the evapotranspiration is less important, because the infiltration rate enables an adequate recharge of groundwater and hence has no significant impact on the total annual runoff.

The impact of agricultural activities on the runoff coefficient depends on four groups of factors

$$c = f_a (L, A, B, P) \quad (4.13)$$

c - runoff coefficient

- L - stable local factors, especially the drainage area shape and slope i , soil depth and type d , geology g ,
- A - agricultural practices and conservation services, e.g. contour or other method of ploughing, its depth and period,
- B - plant species, the depth and type of their root system, the intensity of cultivation, e.g. the yield-biomass ratio,
- P - the precipitation aggregation, occurrence, intensity, duration and coincidence with plant growth, soil processing and saturation periods etc.

TABLE 4.9

| Area | Decrease in total annual runoff |
|--------------------------|---------------------------------|
| Steppe (cultivated land) | 66 - 74 |
| Fields and forests | 40 - 66 |
| Southern edge of forests | 20 - 40 |

The decrease in total annual runoff as a result of deep ploughing of fields, expressed as a percentage of original values, according to Lwowitch (1965).

The selection of the plant species and variety also depends on agricultural practices and on the possibility of conservation services, which have a basic impact on the runoff coefficient.

An evaluation of the influence of the vegetative canopy on runoff leads to the following conclusions:

(a) The consumption of water by plantations, forests and other plant communities depends mainly on the amount available in the soil.

(b) Plant communities of the same ecological order use approximately equal volumes of water. Fast-growing tree species do not use more water than slow-growing ones.

(c) The decrease in the volume of the biomass increases the total yearly runoff in the same way as the change of deep-rooted species into shallow-rooted ones.

(d) The afforestation of grassland or cultivated land decreases both surface runoff and infiltration into the groundwater.

(e) The changes of the water regime as a consequence of the forest and agricultural practices are heterogeneous and depend on soil, geomorphological and climatological conditions.

The vegetative canopy also has a significant influence on the altitude of the groundwater table. A developed forest can cause it to drop to some ten meters

below the land surface. Clearing and thinning results in a rise in the ground-water table, depending on the geomorphological, hydrogeological, climatological and soil conditions. The deep root system of the forest cover takes off the water from the lower soil layers. After clearing a forest the groundwater table may rise over the land surface. Such a rise, in the case of low water quality or if the water rises through salty layers, affects the quality of the soil, increasing its salinity.

4.4 INFLUENCE OF URBANIZATION AND INDUSTRIALIZATION

Urbanization and industrialization influence all the factors in the equation (4.10), determining peak discharges Q_{max} , total runoff Q , minimum discharges Q_{min} , erosion intensity I_e , groundwater regime G , water quality q and the total rainfall P i.e. climatological factors X_c , the factor of the vegetative canopy X_v , soil factor X_s , morphological factor X_m , geological factor X_g , and the water management factor X_x .

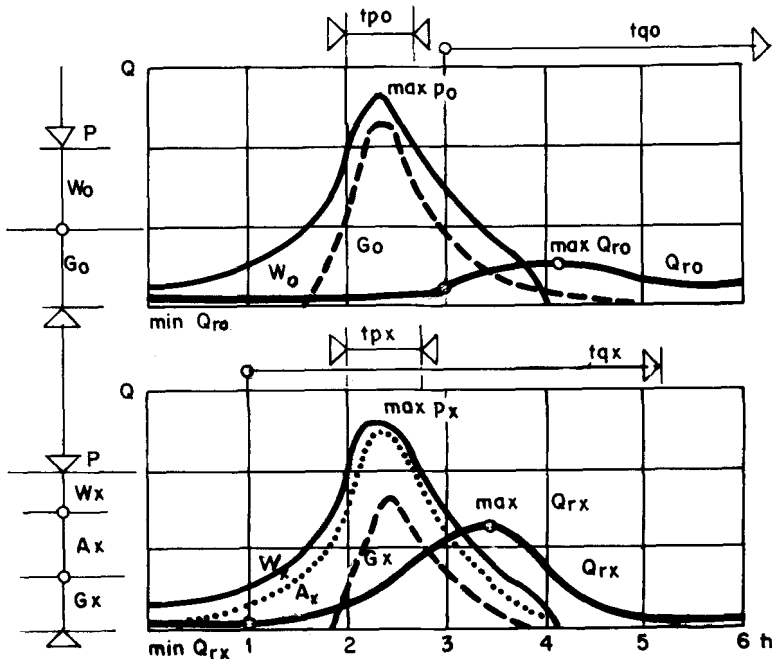


Fig. 4.9. The increase in flood discharges as a consequence of urbanization: P - rainfall curve, Q - river discharge, W - detention storage and water accumulation in the soil layer, G - groundwater accumulation, A - accumulation in the sewerage network. $P = W_0 + G_0 = W_x + A_x + G_x$. $max P_x \neq max P_0$; $t_{px} > t_{p0}$; $min Q_x < min Q_0$; $G_x < G_0$; $t_{qx} < t_{q0}$; $q_{10} \dots q_{n0} < q_{1x} \dots q_{nx}$ (pollution).

The basic hydrological consequences of urbanization and industrialization are as follows:

(a) a rise in water requirements, whose total may exceed the capacity of the water resources of the area in question, necessitating the diversion of water from upstream sources or from external river basins (Fig. 4.11)

(b) a decrease in infiltration on account of the built-up areas

(c) a fall in the groundwater table and a decrease in the natural groundwater outflow

(d) a concentration of and acceleration in the surface runoff as a result of the change in the natural system of drainage, and a concentration of flow in the sewerage system

(e) a rise in peak discharges, and an increase in the yearly total of surface runoff

(f) a rise in erosion on land stripped by construction activities (Tab.4.6)

(g) increased pollution of streams, also caused by waste disposal, which exceeds the capacity of the natural self-purification processes and causes a steady increase in groundwater pollution

(h) a decrease in the natural flow capacity of river beds due to the urbanization of the flood plain and increased sediment transport, thus exacerbating flood damage

(i) a decrease in evapotranspiration owing to the restriction of bare soil and vegetation-covered surfaces by built-up areas, and an increase in evaporation due to industrial production

(j) heat production and a rise in temperature in the urbanized area

(k) change of the albedo, owing to the change of the quality of the landscape surface

(l) an increased probability of rainfall occurrence as a result of the increased number of condensation nuclei, owing to the air pollution

(m) a change in ecosystems as a consequence of the previous changes.

The increase in surface runoff results not only from the decrease in infiltration, especially through the reduced surface permeability of the built-up, communication and other surfaces, but also from the decline in surface roughness. This is caused by the replacement of the original vegetative canopy by the smooth materials of buildings and communication lines. The topography of the area in question also undergoes drastic changes, simplifying the complicated conditions of the original unconcentrated flow by more straight and short ways. The rise in slope increases the velocity of the overland flow and leads to a higher concentration of runoff. Land grading and the increase in velocity reduce the detention storage.

The underground storage has been reduced by the decline in the infiltration rate. Because the surface and underground storage are drastically decreased, this results in an increase in the frequency of flood occurrence and an increase

in the values of relevant peak discharges. In such a way, even rainfalls occurring during dry periods may cause high peak discharges and not sufficiently supplement the groundwater storage.

Urbanization and industrialization increase the total yearly runoff, proportionally with the unpermeability of the land surface and with the concentration of the outflow by the sewerage system. According to Costin and Dooge (1972), peak discharges increase five to ten times with a corresponding reduction in their duration, depending on the frequency of their occurrence. The runoff coefficient also rises three to four times. The average increase in the total runoff (5-15%) is thus comparatively lower than the rise in peak discharges (Fig. (4.7)).

The development of changes in the hydrologic cycle depends on the expansion of the urbanized area, and on its development phase, interconnected with the agricultural development of the adjoining region (Tab. 4.10).

Urbanization and industrialization greatly influence the water regime as well as the values of low discharges. The reduced infiltration leads to a fall in the groundwater table and to a decrease in the volume of the groundwater reserve, occasionally causing terrain settlements. Low discharges in river courses are decreased by water withdrawals and by the reduced water recharge from groundwater resources.

Building and the resultant overshadowing of plots decreases the air motion and hence the evaporation rate. Concerning the total yearly evapotranspiration, it may be either decreased, in areas with low evaporation losses, or increased, especially in industrial areas by evaporation from cooling systems and in tropical and subtropical regions by intensive irrigation of municipal parks and gardens.

The development of vast industrialized and urbanized areas also affects the total yearly rainfall. Costin and Dooge (1973) estimate its increase at some 10%. This rise is a consequence of the higher intensity of air mass motion above the covered area, its increased temperature, caused especially by heat production, air pollution and sometimes by the increased evaporation, especially from industrial production processes. The increase in the total yearly rainfall has been proven statistically, but not the rise of maximum values of precipitation. The increase in the frequency of storm occurrence has also been recorded. The increased rainfall contributes to the frequency of flood occurrence and their duration.

The most threatening effect of urbanization and industrialization is the production of heat energy, which is increasing by some 5% yearly on a global scale. This advancement means an increment of 500% in 35 years. In the year 2000 many huge areas with a surface of some 10^3 to 10^5 sq. km will emerge, where their own artificial heat production will exceed the acceptance of solar energy.

TABLE 4.1C

| Changes in land or water use | Hydrological effect |
|--|---|
| Clearing, removal of vegetation | Decrease in transpiration, increase in evaporation. Increase in overland flow, flood frequency and peak floods. Increased soil erosion and sedimentation of streams. Raised groundwater table. Change in albedo. |
| Ploughing | Change in soil structure. Increased infiltration and evaporation. Escape of carbon dioxide. |
| Large-scale production, mechanization | Liquidation of small streams and dry beds, increase in overland flow and erosion rate, increase in sedimentation of streams, environmental pollution. |
| Irrigation | Stream clogging. Rise in groundwater table. Increase in evapotranspiration rate. Cooling of soil surface and air temperature. Change in albedo. Change in soil structure and quality (increased salinity). |
| Drainage | Drop in groundwater table. Decrease in evapotranspiration warming of area, change in albedo. Increased infiltration. Change of soil structure and quality (decrease in salinity). Impact on the quality of the surface water. |
| Well erection Sewage disposal | Decrease in groundwater table. Local increase in soil moisture. Increasing pollution of wells and streams. |
| Mass construction: Land grading and excavations Communication and storm drainage system construction | Increased erosion and sedimentation of streams. Liquidation of small streams - flooding of land during high rainfall. Decrease in infiltration rate, drop in groundwater table and land surface. Increase in surface runoff and flood occurrence. Lower base flow. Increased pollution of streams. Change in albedo. |
| Construction of the mass water supply and distribution system | Increased water wastage. Rise of the groundwater table around wells of the previous local water supply, lowered water table in location of the mass water withdrawal. Decrease in runoff at point of withdrawal and downstream. Problems of waste water disposal |

TABLE 4.10 (Cont'd)

| Changes in land or water use | Hydrological effect |
|--|--|
| Construction of sewage system | Land drainage, decrease in groundwater recharge. Increased pollution of streams, especially during low discharges and when system also used for the disposal of industrial waste water. Degradation of water for downstream users, loss of aquatic life. |
| Waste water treatment plant construction | Decrease in pollution of streams, improvement of water quality downstream, improved conditions for aquatic life. |
| Late urban stage | Boom in water requirements. Decrease in water quality. |
| Long-distance water transfer | Increased runoff in affected streams. Increased evaporation from the catchment. |
| Deep large capacity wells | Overdraft results in land subsidence. |

Checklist of impact of urbanization activities and of interconnected land and water use on the hydrologic scale and water availabilities.

This will lead to an unproportional increase in the temperature over these scattered areas and also influence the global climate. The rise in temperature in the atmosphere will increase evaporation from the oceans; thus the hydrologic cycle will be more intense. There will be weakened equator-to-pole temperature gradient, so the general atmospheric circulation will be less vigorous, resulting in more precipitation in the region of the present subtropical deserts.

The greatest change may occur in polar regions. The arctic Ocean ice pack, presently highly reflecting, can, after pollution of its surface, absorb more solar energy. It may happen that the warming effect described above might remove this ice pack completely. The relatively fresh water from its melting has a lower density than normal sea water. Wave action and water currents can mix it with sea water, decreasing the probability that this water will freeze again. This will lead to a further intensification of evaporation and precipitation.

Concerning the relatively larger ice sheets of the Antarctic and Greenland, any small change in their immense volume would affect the mean sea level. Their melting has been one of the reasons for the rise in mean sea level of about 0.2 m from the beginning of this century. A complete melting would increase the

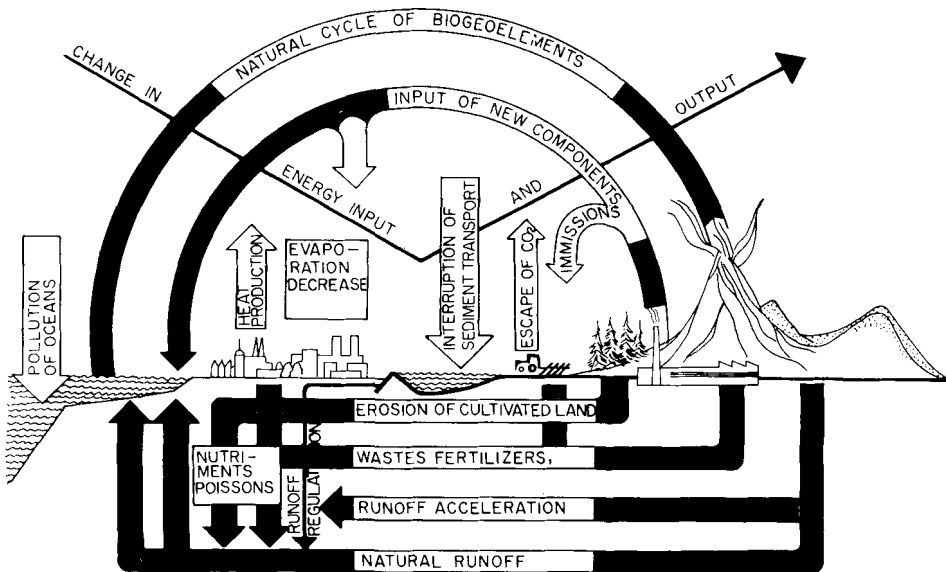


Fig. 4.10. Schematic representation of the impact of human activities on erosion, water quality and selected hydrological processes.

mean sea level by about 70 m. But such an event would appear to be very unlikely during the next 10 to 100 thousand years. The rise in the average global temperature may not even decrease their volume because of the increased rain and snowfall, which will supplement their ice pack.

The changes in the energy balance are likely to increase the temperature in polar regions by about $+10^{\circ}\text{C}$ in the year 2050, also extending the local vegetation period: at the latitude of 50° by about 15 days, at 70° by about some 30 days on average, depending on precipitation occurrence.

4.5 CHANGES IN WATER QUALITY

The physical, chemical and biological characteristics of water are formed not only during its penetration through the atmosphere, soil and rock environment, but also during its contact with the vegetative canopy. Forests and other cultures therefore have an important effect on the bacteriological and chemical quality of water, and on its turbidity. This quality also depends on the plant species, the composition of ecosystems, the stage of growth and season; also important are the impact of pollen and the changes caused by harvesting, ploughing etc. Changes in the ecosystem of the vegetative canopy, i.e. changes in the plant species or cultivation practices, result in a change of water quality.

Waters from afforested areas are generally of good quality, which also depends on the heterogeneity of the ecosystems: the replacement of forest polycultures by monocultures leads to an increase in acidity. But in areas with high rainfall decaying vegetation causes water contamination, depleting the dissolved oxygen and increasing the acidity etc., especially in tropical and subtropical conditions of high temperatures. Water from afforested catchments can also become bacteriologically contaminated by wildlife, and particularly by birds.

The pollution of water resources is a consequence of

- natural processes: erosion, volcanic activities and biological processes, and by human activities, especially by
- increasing erosion owing to deforestation, wrong cultivation practices and urbanization,
- washing of agrochemicals from agricultural and silvicultural production (fertilizers and pesticides),
- accidents during the transport of fuel and other chemicals,
- disposal of gaseous, liquid and solid wastes from industry, thermal and nuclear power generation, agriculture, dwelling areas etc.
- subsequent leaching of wastes deposited on the surface, under the ground or in water,
- infiltration of polluted water from or to groundwater resources etc.

The ratio of these processes to the total water pollution depends on the natural conditions, the development stage and relevant practices. Erosion forms the prevailing part (90% or even more) of pollution in countries with traditional intensive agriculture. The washing of agrochemicals may contribute by more than 50% to the total pollution of surface and groundwater resources, even in highly industrialized countries. Municipal pollution, due to its partly organic origin, is less harmful than the pollution from industry and the stocking of chemicals. Hazardous accidents during the transportation and stocking of fuel and other chemicals can be particularly dangerous, owing to their quantities or chemical properties, as well as accidents in nuclear power plants.

The term pollution refers to undesirable changes in the physical, chemical and biological properties of air, surface water, groundwater and the natural environment which prejudice the living conditions of human beings and desirable biological species and imperil these conditions in future, as well as lead to a deterioration in natural resources and negatively affect production processes, aesthetic or cultural values and endanger them in future.

The atmosphere and the quality of precipitation has been polluted by carbon dioxide CO_2 , nitrous oxide N_2O , sulphur dioxide SO_2 , other gases, sulphates, chlorofluoromethanes and aerosols produced by industry, thermic power generation, transport, space heating, slash-and-burn and other agricultural practices etc. Within the framework of the hydrologic cycle pollution passes from air to water and from one element of the environment to another.

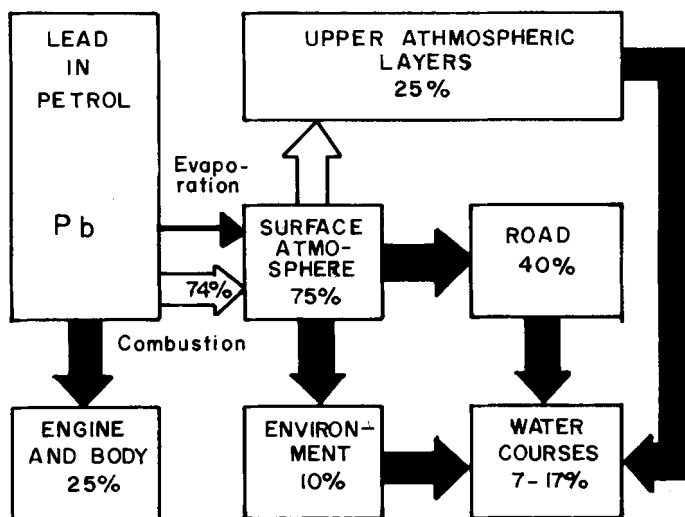


Fig. 4.11. Penetration of lead Pb, produced by combustion engines used in public transport, into the hydrologic cycle according to Fishbein (1976).

Pollutants can be categorized as:

- (a) harmless matter, which can easily be removed from water through filtration and other self-purification processes,
- (b) toxic matter and matter causing sensorial (organoleptic) problems for organisms (Fig. 4.11).
- (c) matter influencing the oxygen demand of water,
- (d) anorganic pollutants, dissolved or insoluble, increasing the salinity of water.

Toxic matter can cause problems or breakdowns in the various biological functions of an organism and its diverse organs (e.g. cancerogens), as well as further physiological and psychical and evolutionary changes (mutagens and teratogens) depending on the concentration and accepted quantity of this matter, the influence of other matter and on the age and health stage of the organism. These problems may occur not only shortly after the contact, but also in the long term over a period exceeding even 40 years (Fig. 4.12).

Research into the impact of different kinds of toxic matter and, especially their synergetic effect, is still in an early stage. This effect can therefore be neither qualitatively nor quantitatively established. The problem is very complicated, especially because of the varying resistance of the same organisms under similar conditions, because of the effect of other factors, and because of

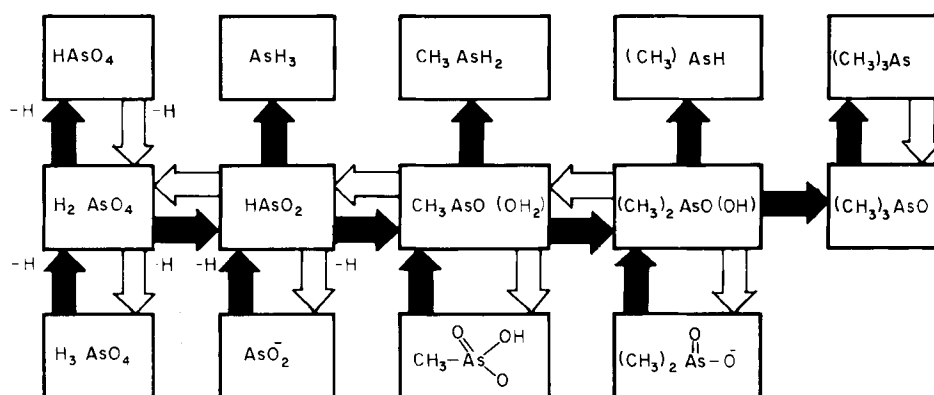


Fig. 4.12. Changes in arsenate compounds during the course of the hydrologic cycle.

the changes in these matters during their passage through the environment.

Some chemicals are chemically stable and pass through various biological and physical processes without change (e.g. DDT - Fig. 4.13), endangering especially higher organisms by their accumulation, i.e. remaining in their organs in a substantially concentrated form in comparison with their concentrations in lower elements in the biological chain.

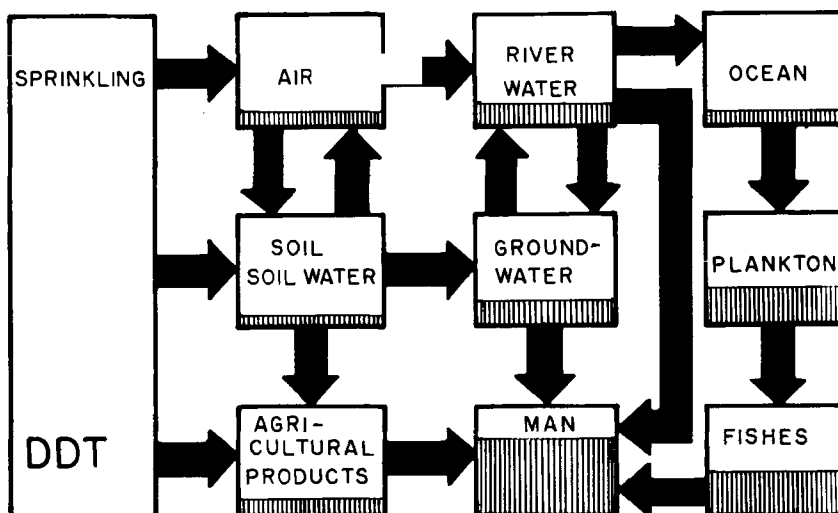


Fig. 4.13. Penetration of the insecticide DDT into the hydrologic cycle and its accumulation in higher organized organic matter according to Woodwell (1965). Concentration is hatched.

The harmfulness or harmless ness of relevant pollutants depend on many factors such as their mutual effect, their duration, the prevailing health standards, individual resistance etc. The general level of knowledge about these factors is still unsatisfactory. It is e.g. presumed that 50 to 90% of the cases of cancer are a consequence of the synergetic influence of cancerogens.

The highest concentration of the matter supposed to have an undesirable effect is the sanitary admissible concentration. These concentrations can be distinguished for

- (a) indirectly harmful consequences,
- (b) sensorial (organoleptic) consequences,
- (c) toxic consequences.

TABLE 4.11

| Categories of waste water | Comments |
|--|--|
| 1. Intensively acid or intensively alkaline | Contain acids or bases in high concentrations. |
| 2. With high degree of mineralization | Not sufficiently suitable for further utilization in industry or agriculture. |
| 3. With high content of suspended matter | Produce secondary pollution by its biological decay. Injurious for fishes. |
| 4. With matter influencing the oxygen input | Tenzids, oil products, grease etc. |
| 5. With high content of biologically degradable matter or matter consuming oxygen chemically | Domestic sewage. The change of aerobic processes to anaerobic ones. The lack of oxygen causes perishing of fishes. |
| 6. With matter influencing the sensorial properties | Chlorphenols, oil products, solvents etc. |
| 7. With toxic matter | Heavy metals, pesticides, nitrogenic and radioactive matter. |
| 8. With pathogenic germs | Water from sanitary services, tanneries etc. |
| 9. With predominant nitrogen and phosphorus compounds | Fertilizers, detergents. Eutrophic influence. |
| 10. Warm waters | Decrease in oxygen content, increase in metabolism of water fauna and its oxygen requirements, resulting in a decrease in the self-purification capacity, providing the aeration is not predominant. |

Categories of waste water depending on the predominant type of pollution according to Pitter (1972).

Waste waters can be categorized on the basis of their main components, which also characterize their prevailing harmful effects (Tab. 4.11). Pollution directly caused by waste disposal is primary pollution. If it does not exterminate all organic life, a development of some undesirable organisms, namely detruments, occurs. The mass decay of these organisms causes secondary pollution.

Human activities draw new, mostly harmful components into natural cycles and thus influence the natural circulation rate of the main biogeoelements. In such a way the volume of the nitrogen circulation is increased, especially by

- (a) gaseous emissions and aerosols from burning and other chemical processes,
- (b) liquid wastes from industrial estates,
- (c) the use of nitrate fertilizers, accelerating the biological production of nitrous oxide.

Nitrides are quickly soluble and therefore mobile, i.e. it is difficult to keep them in the soil and very easy to wash them away. Losses by washing reach some 20 - 40% on average. Only ammonia salts can be bound in the soil, but they are not stable, changing into nitrides in soil.

A direct relation exists, therefore, between the content of nitrogen in surface waters and in the intensity of fertilizing. A substantial part of such contamination comes from the groundwater, polluted by percolation nitrides from fertilized fields.

Five hundred million tons of nitrous oxide N_2O enters the atmosphere annually, mainly by biological decay and denitrification processes taking place in soils and oceans. Human activities presently account for some 10% of this figure. The rate of the denitrification process by soil organisms depends on the soil's acidity. The ratio of N_2 to N_2O produced by soil bacteria increases from 0.05 to 0.2 in acid soil. The rate of nitrogen and nitrous oxide production depends, therefore, on the production of sulphur dioxide and sulphates, i.e. the inter-relationships of the biogeoelements' circulation are complex.

Human activities also change the unbalanced circulation of phosphorus, namely by means of the waste water disposal and by fertilizer wash from agricultural areas. The compounds of phosphorus are difficult to dissolve. They are fixed as ferrum phosphates in acid soils and as calcium phosphates in alkaline soils. Nevertheless, especially through the long-term application of phosphates on light or organic soils with a low absorption capacity, they escape and pollute the groundwater.

The increase in the carbon oxide CO and carbon dioxide CO_2 concentration results mainly from

- (a) agricultural production processes, especially as a consequence of ploughing,
- (b) the continued rise in the burning of fossil fuels.

Six billion tons of carbon oxide enters the atmosphere per annum through in-

TABLE 4.12

| | |
|-----------------------------|---|
| Potential impact (diseases) | |
| Pulmonary | Beryllium Be, Cadmium Cd, Chromium Cr, Selenium Se, Manganese Mn |
| Liver | Selenium Se, Nickel Ni, carbon chloride CCl ₄ , chlorinated phenols |
| Kidney | Lithium Li, Lead Pb, Stroncium Sr, Selenium Se, Nickel Ni, Cadmium Cd - especially cadmium sulphate CdSO ₄ , ethylenglycol |
| Nervous system | Mercury Hg, Stroncium Sr, Manganese Mn, Lead Pb, Calcium Ca, Cadmium Cd |
| Metaheamoglobin-anemia | nitrites and nitrates |
| Fluorosis | Fluorides |
| Canceerogens | tar, asphalt and combustion gases, Chromium Cr, Nickel Ni, Beryllium Be, nitrides and nitrates, nitrosamins, polychlorinated biphenyles, petroleum, triazin, polyuretan, polyvinylchloride, benzene, polynuclear aromatic hydrocarbons, chlorophorm, bromophorm, asbest, pesticides endrine, dieldrine, chlordane, endring, DDT etc.) |

Selected toxic matter, occuring especially in waste water and their possible impact on human health.

complete combustion in conditions of a restricted access of oxygen - the share of combustion engines in transport is more than 75%.

The carbon dioxide in the atmosphere has risen from 0.028% in 1860 to the present 0.033% and may double by the next mid-century. Its content in the atmosphere increases especially as a result of the change of afforested areas into agricultural land. According to Wilson (1975) the percentage of the carbon dioxide in the atmosphere has risen by about 10% in the period 1860-90 by ploughing vast areas in America, South Africa, Australia and Eastern Europe. The burning of fossil fuels increases this content by about 0.0001% yearly, but the combustion of all fuels available would increase this figure almost twenty times.

Obvious additions to the atmosphere, produced by a combination of burning and the photochemical reactions in the presence of ultraviolet radiation, are aerosols, a combination of soot particles, sulphur dioxide SO₂, sulphates and unburned hydrocarbons. An important influence is had here by sulphur dioxide SO₂ and sulphur trioxide SO₃, which occure especially as a product of low quality

fuel burning. The natural volcanic production of sulphur dioxide is some 140 million tons yearly, while power generation, space heating and other human activities add some 50% more to this figure.

Air pollution influences water circulation in an important way, because

(a) carbon dioxide, chlorofluoromethanes, nitrous oxide and other infrared absorbing gases absorb terrestrial infrared radiation in several infrared bands, thereby warming the Earth's surface,

(b) aerosol particles over a dark surface such as oceans increase the net albedo, but lower the albedo over the land, although their overall influence is not known yet,

(c) aerosols produced by burning and industry act as good condensation and freezing nuclei, thus increasing the probability of rainfall occurrence.

The pollution from the air enters the soil and water especially through

(a) washing-out of gases and aerosols from the atmosphere by rainfall,

(b) absorption of gases by the soil, vegetation and water,

(c) settling of solid particles on the vegetation and soil and in the water.

One of the obvious results is an increase in the acidity of rainfall and surface waters including natural lakes. The course of air pollution is uneven, and that of the air motion too, so the acidity of rainfall at one place fluctuates in time. But the overall result on the surface water quality is a rise in its acidity, caused namely by

(a) the inflow of acid rainfall,

(b) the leaching of acid geological layers,

(c) the inflow of acid waste waters,

(d) the supply of salts from the sea water through the atmosphere.

The increased acidity of surface water causes changes in the relevant ecosystems, manifested first by a reduction in their diversity. The decrease of the pH factor below 5.5 is also critical for most fish species, decreasing the overall biological activity and changing the nutrition chains. A similar influence occurs on soils. But the rise in the soil acidity is often artificially neutralized by liming in order to increase yield.

On the whole, the effects of pollution are remarkably negative (Tab. 4.11). The relevant interrelationships are complex, and not yet fully quantified. The result of anthropogenic influences on the climate, environmental quality and the hydrologic cycle, also influencing living conditions and human life, cannot yet be sufficiently quantified.

4.6 ENVIRONMENTAL IMPACTS OF WATER DEVELOPMENT PROJECTS

The exploitation of water resources is inevitably accompanied by a disturbance of the natural balance. The extent of the influence of these projects on the environment depends on the extent of the changes in the water regime in the area concerned (Tab. 4.13).

TABLE 4.13

| Environmental factors (external) | | System factors (internal) | | |
|----------------------------------|------------|---------------------------|----------------|------------|
| Stable | Variable | Stable | Variable | |
| | | | abiotic | biotic |
| climate | weather | project | hydrological | ecosystems |
| geographical position | discharges | size | meteorological | social |
| altitude | ice | purpose | microclimato- | systems |
| morphology | phenomena | operation | logical | |
| geology | | | other physical | |
| soil factors | human | | chemical | |
| natural water quality | activities | | progress of | |
| | | | the project | |

Categorization of basic factors which determine the impact of water development on the environment and on human society.

The identification of environmental impacts should be an early activity in the planning process. Environmental studies are needed to restrict undesirable effects and identify appropriate mitigation measures. An assessment of the environmental impacts requires

- a general knowledge of the impacts of similar water development projects under similar geomorphological and climatological conditions,
- a systematic approach based on the use of checklists, intersection matrices and networks,
- a quantitative approach based on mass balance and environmental dilution calculations,
- the use of mathematical models for multiple environmental factors,
- case studies and pilot projects.

The purposes of constructing water development projects can be classified as

(a) regulating - provision of water for different purposes and safeguarding of its supply, also in periods of low natural discharges and high water requirements, by accumulating water in surface and underground reservoirs during periods of surplus, or by its conveyance.

(b) control - reduction of high discharges and high water tables, runoff retardation, soil conservation, reduction of erosion, control of silt load in streams by conservation storage, river training, water conveyance etc.

(c) distribution and drainage - water supply for municipal, industrial and agricultural use, sewage collection and removal etc.

(d) quality control - pollution abatement, improvement of water quality, prevention of contamination for the protection of the environment and of public health.

(e) beneficial use of land/water space - urbanization, improvement of agricultural and industrial production, transport including inland navigation, water power utilization, recreational use of water and aesthetic enjoyment.

Currently water development projects are planned for several purposes (Tab. 4.14). The sum of all the benefits of a multi-purpose project exceeds the maximum benefit of any one individual function, but the value of any one of its functions is seldom the maximum one. Some of its functions may even be contradictory (Tab. 4.15). These contradictions may occur after the construction of reservoirs, for example because they affect an extensive area and their effects differ

- (a) in the space of the reservoir and its environment (Tab. 4.16),
- (b) along the water course downstream of the dam (Tab. 4.20),
- (c) along the headrace or tailrace (Tab. 4.21),
- (d) in the area under supply (Tab. 4.17).

TABLE 4.14

| | Water supply | Hydropower generation | Navigation | Flood Control | Water quality control | Environmental and aesthetic aspects | Recreation | Fish breeding |
|-------------------------------------|--------------|-----------------------|------------|---------------|-----------------------|-------------------------------------|------------|---------------|
| Water supply | - | 1,2 | 2 | 1,2 | 0 | 2 | 2,3 | 2,3 |
| Hydropower generation | 1,2 | - | 2 | 1,2 | 2 | 2 | 2 | 2 |
| Navigation | 2 | 2 | - | 0 | 3 | 3 | 0 | 0 |
| Flood control | 1,2 | 1,2 | 0 | - | 2 | 0 | 3 | 0 |
| Water quality control | 0 | 2 | 3 | 2 | - | 0 | 3 | 3 |
| Environmental and aesthetic aspects | 2 | 2 | 3 | 0 | 0 | - | 0 | 0 |
| Recreation | 2,3 | 2 | 0 | 3 | 3 | 0 | - | 3 |
| Fish breeding | 2,3 | 2 | 0 | 0 | 3 | 0 | 3 | - |

- 0 - no or non-important variance
- 1 - variance in reservoir volume requirements
- 2 - variance in reservoir operation requirements
- 3 - variance in water quality requirements

Matrix of variances for basic purposes of reservoir construction and operation.

TABLE 4.15

| | Water supply | Hydropower generation | Navigation | Urbanization | Decrease in flood losses | Water table regulation | Landscape formation | Soil erosion | Agriculture | Recreation | Fishery | Environmental protection | Protection of monuments | Number of positive impacts | Number of negative impacts |
|-------------------------------|--------------|-----------------------|------------|--------------|--------------------------|------------------------|---------------------|--------------|-------------|------------|---------|--------------------------|-------------------------|----------------------------|----------------------------|
| Reservoirs in populated areas | 1 | 1 | 1 | 2 | 1 | 3 | 2 | 0 | 2 | 1 | 1 | 0 | 3 | 6 | 3 |
| Reservoir in abandoned areas | 1 | 1 | 1 | 1 | 1 | 3 | 0 | 0 | 2 | 1 | 1 | 2 | 0 | 7 | 2 |
| Flood control dikes | 0 | 0 | 0 | 1 | 1 | 0 | 3 | 0 | 1 | 0 | 0 | 0 | 1 | 4 | 0 |
| River training | 0 | 3 | 3 | 1 | 1 | 2 | 2 | 0 | 1 | 2 | 2 | 2 | 3 | 3 | 5 |
| Bank stabilization | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 5 | 0 |
| Water ways | 0 | 3 | 1 | 1 | 1 | 0 | 2 | 0 | 2 | 2 | 2 | 2 | 3 | 3 | 5 |
| Irrigation projects | | | | | | | | | | | | | | | |
| Irrigation | 0 | 0 | 0 | 1 | 0 | 2 | 2 | 1 | 1 | 2 | 0 | 2 | 0 | 3 | 4 |
| Drainage | 0 | 0 | 0 | 1 | 1 | 3 | 1 | 0 | 1 | 0 | 0 | 3 | 0 | 4 | 0 |
| Fishponds | 1 | 0 | 0 | 1 | 3 | 3 | 1 | 0 | 3 | 1 | 1 | 3 | 3 | 5 | 0 |
| Sanitary eng. projects | | | | | | | | | | | | | | | |
| Waterworks | 1 | 0 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 1 |
| Sewerage | 0 | 0 | 0 | 1 | 0 | 2 ⁺ | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 1 |
| Groundwater development | 1 | 0 | 0 | 1 | 0 | 0 | 3 | 0 | 3 | 0 | 0 | 3 | 0 | 2 | 0 |
| Water recycling | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 |
| Water management measures | 0 | 0 | 0 | 3 | 1 | 1 | 1 | 1 | 2 | 1 | 0 | 1 | 0 | 6 | 1 |
| Afforestation | 0 | 0 | 0 | 3 | 1 | 1 | 1 | 1 | 2 | 1 | 0 | 1 | 0 | 6 | 1 |
| Managed agriculture | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 2 | 0 | 2 | 0 | 4 | 2 |

Divergencies in the impact of selected water projects and measures: 0 - no or unimportant influence, 1 - positive impact 2 - negative impact, 3 - depends on local conditions, + with a waste water treatment plant

4.6.1 Effects of Reservoirs and Irrigation Systems on Climate

The flooding of an area after putting a reservoir into operation changes the character of the landscape. A uniform, compact water table takes the place of diverse surfaces of different character. In such a way the reservoir affects all the natural processes which took place within its area of influence.

The original evapotranspiration of ecosystems and the evaporation from bare soils are replaced by the increased evaporation from the free water surface, whose share was originally far less important. This process is thus released from a dependence on soil, hydrogeological and physiological factors.

TABLE 4.16

| Impact of reservoirs on their surroundings | | | | |
|---|---|--|--|---|
| Flooded land | Flora and Fauna | Water quality | Microclimate | Dwelling value |
| Rise in water table, increased fluctuation | Change in aquatic life | Abrasion | Rise in air humidity | New scenery |
| Loss of agricultural and forest land | Development of plankton organisms | Sedimentation | Equalizing temperature differences | Improvement of living and recreational conditions |
| Flooded mineral resources | New predominant fish species | Production of new organic matter | Increased wind velocity | Increase in insect density |
| Rise in ground water table and increase in infiltration | Change in coastal vegetation | Temperature changes | Change of albedo, energy input and radiation | Increase in population density and in pollution |
| Increased probability of earthquake occurrence | Change in wildlife species including fowl | Mineralization, zones of different water quality | Decrease in local rainfall | Flooding of landmarks and monuments |

Checklist of the probable impact of reservoir construction and operation of the surroundings.

The rise in altitude of the surface at which evaporation occurs, its less protected position and its smoothness all accelerate this process and affect the

air flow. The increased input of solar energy, i.e. the change of the albedo and the increase in the water temperature, may also contribute to the rise in the evaporation rate. The simplification of surface characteristics, the decrease in evapotranspiration, the increase in air humidity change reversely the conditions which influence the run of this process.

Depending on meteorological and other conditions, the evaporation from the free water surface mostly exceeds the evapotranspiration from afforested or cultivated soils. Both evaporation and evapotranspiration from the adjoining shore areas increase, due to the raised groundwater table being sufficiently supplied by the impounded water table of the reservoir. A similar increase in evapotranspiration is recorded along irrigation canals.

The increase in evaporation also influences the water quality, causing non-productive water losses and raising the concentration of suspended and dissolved matter. This fact is extremely important in arid and semi-arid areas because of the extremely high evaporation rate there. The fall in water quality occurs as a consequence of high evaporation, especially in shallow reservoirs. It may result in a drop of water quality below the limits of utilization for the required purpose, or limit the economic feasibility of the relevant project.

The increase in the mean evaporation from an area affected by the construction of a reservoir can be estimated on the basis of the following equation:

$$E \cdot A = EW \cdot A_w + ET \cdot (A - A_w) \quad (m^3) \quad (4.14)$$

$$E = r \cdot EW + ET \cdot (1 - r) \quad (m)$$

$$E = ET + r \cdot (EW - ET) \quad (m) \quad (4.15)$$

$$A - \text{area surface} \quad (m^2)$$

$$A_w - \text{water table surface} \quad (m^2)$$

$$E - \text{total mean evaporation}$$

$$ET - \text{mean evapotranspiration from the soil surface} \quad (m)$$

$$EW - \text{mean evaporation from free water surface} \quad (m)$$

$$r = \frac{A_w}{A} - \text{the ratio of the water table surface } A_w \text{ and the area surface } A$$

Leaving aside the change of the precipitation total and the change of mean evaporation, the decrease in the total yearly runoff from a catchment resulting from the increased evaporation reaches

$$\Delta Q_a = d \cdot (EW - ET) \cdot A \quad (m^3) \quad (4.16)$$

$$d = r_1 - r_0 - \text{the difference between the ratio of the water surface and the surface of the catchment after } (r_1) \text{ and before } (r_0) \text{ the construction of the reservoir}$$

The decrease in the total yearly runoff due to the impact of the construction of an irrigation network can be estimated in a similar way, in accordance with equations 4.14 and 4.16. In this case

TABLE 4.17

| Impact of irrigation (drainage) | | | | |
|---|---|--|--|--|
| Soil profile | Chemical impact | Biological impact | Hydrological impact | Microclimate |
| Rise in the (drop in the) groundwater table | Change in acidity or alkalinity of soil | Increase (decrease) in the root depth | Increase in runoff | Change in the albedo (in both cases) |
| Wetting (aeration) of the soil profile | Increase (decrease) in the salination rate | Increase (decrease) in respiration of roots | Increase in (suppression of) evaporation | Increase (decrease) in the air humidity |
| Change in the soil temperature | (Escape of nutriments, especially nitrogen) | Plant diseases provoked by higher humidity | Decrease (increase) in infiltration | Cooling (warming) |
| Change in the soil structure | | Change in the plant species (in both cases), weed occurrence | | Decrease in the daily fluctuation of temperature |
| | | Increase in (suppression of) insect occurrence | | |

Checklist of the probable impact of irrigation and drainage (in brackets) on the water cycle and the environment.

ET_0 - mean evapotranspiration from the dry-farmed and other non-irrigated land (m)

ET_i - mean evapotranspiration from irrigated land (m)

$r_i = \frac{A_i}{A}$ - the ratio of the irrigated land A_i and the total area surface A

$r_0 = 0$ and therefore

$$\Delta Q_{ai} = r_i \cdot (ET_i - ET_0) \cdot A \quad (m^3) \quad (4.17)$$

The increased yield after irrigation is often achieved less by the growth in the overall evapotranspiration rate, but rather by the different and more efficient evaporation distribution: by its increase in the period of plant growth and by its decrease out of the vegetation season, i.e. by the increase in efficient and

decrease in inefficient evaporation. This phenomenon has been confirmed statistically by long-term measurements, e.g. the water table of the Aral Sea did not change in the period 1910-60, in spite of the extension of the irrigated area from 2 to 4 mill. ha in the catchment of its tributaries. From this point of view an appropriate cropping pattern, correct irrigation timing and appropriate economic irrigation practices are also important. In the step-by-step development of irrigation, therefore, two stages can be distinguished

- stage of evaporation redistribution, not affecting the total annual runoff to a significant extent,
- stage of increased total evaporation, decreasing the total annual runoff.

The increase in the extent of free water surfaces in the catchment owing to the construction of reservoirs often results in a reduction in precipitation. This decrease in precipitation is a consequence of lower temperatures above the water surface in the summer season in comparison with the original temperatures above the non-wetted soil surface. The decrease in the total yearly runoff may, therefore, be higher than the value established according to equation (4.16).

An inversion often occurs above an open water surface: the air temperature does not fall with increasing altitude, but rises. This inversion causes a vertical air motion, decreasing the ratio of its saturation - and hence the probability of rainfall occurrence, too. This probability is also reduced by the reduced roughness of the reservoir surface in comparison with the roughness of the original land surface. The decrease in the total rainfall has been recorded statistically, but only in the case of extremely big reservoir surfaces.

This also signifies a decrease in the water exchange in the total annual runoff of affected water courses, especially in the case of big carry-over storages, which has an important impact on water quality. This effect of the operation of big carry-over storages has already been recorded on a global scale.

The construction and consequent operation of reservoirs and irrigation networks also influences the values of other meteorological phenomena, in comparison with the original state without any reservoir or irrigation. The heat capacity of water is four to five times higher than that of air or soil and rocks, and the latent heat of solidification and evaporation is also comparatively high. Water bodies act, therefore, as a cooler part of the environment during a rapid increase in air temperature, e.g. in spring and during the morning hours. During a fast fall in air temperatures, e.g. in the evening or in autumn, they function as a warmer part of the environment. Likewise, they warm the adjoining air layer during cool summer nights. The heat of the water body limits the fluctuation of the temperature of the surface air layer, also influencing the thermic zonation of the air on the reservoir shore.

This influence can be measured especially in deep valleys, and has a different impact depending on the radiation situation. During radiation back to space,

which occurs particularly during bright nights, the lowest temperatures in a valley without a reservoir are at the foot of the slope, when calm. Lower minimum nightly temperatures also occur in this zone. In the middle part of the slope a warmer zone with higher values of minimum nightly temperatures appears. At the top of the slope, the temperature decreases again (Fig. 4.14 a,b).

In a valley with a reservoir the night temperature decreases upwards to the top of the slope. The difference between day and night temperatures in a valley with a reservoir is higher at the top of the slope, but at its foot in a valley without a reservoir. In a valley with a reservoir, a more intensive wind motion occurs, because warmer air above the water table is replaced by cooler strata which descend from the top of the slope.

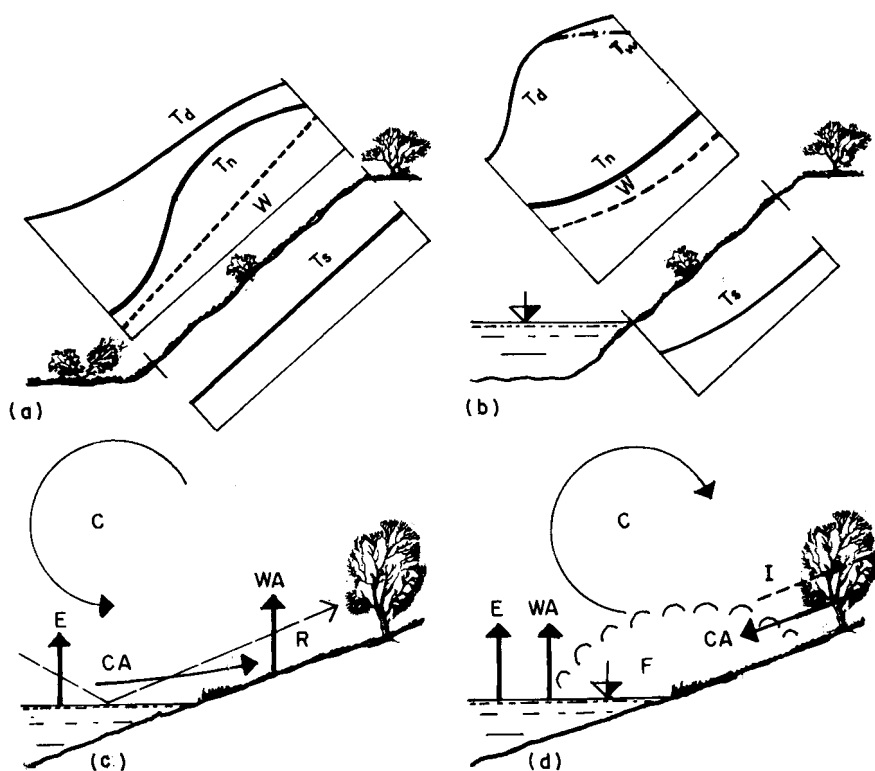


Fig. 4.14. The course of air temperatures (daily T_d , nightly T_n) the temperature of the soil surface T_s and of air humidity W in a valley (a) before and (b) after the construction of a reservoir during radiation situation according to Malý (1979). Air motion above the reservoir shore during calm; (c) clear day, (d) clear night. The occurrence of the inversion I and fog F : R - reflected radiation, CA - cool air, WA - warm air, C - air circulation, E - evaporation.

On a bright day, the highest temperatures occur at the foot of the slope in a valley without a reservoir and decrease upwards to the top of the slope. In a valley with a reservoir, the heat capacity of the water body reduces the morning temperatures. Their decrease to the top of the slope is measurable when windy (T_w), and negligible when calm (T_d).

The air flow depends on the changes of temperature. The lower roughness of the reservoir surface promotes horizontal air movement. The influence of big reservoirs therefore changes the shape of the relevant wind rose, increasing the occurrence of strong winds from the reservoir to the shore, namely along its longest dimension. The wind rose is extended in this direction.

The air movement is more marked in shallow valleys, while in deep valleys this only applies in the case of a coincidence in the direction of the valley and the prevailing strong winds. During calm and during radiation back to space in the spring season in daytime, the warmed air rises above the reservoir's shores, being replaced by the cooler air coming from the expanse of the reservoir itself. This cooler air is replaced by the still cooler air from the upper layer of the atmosphere (Fig. 4.14 c).

The air humidity depends on the evaporation rate. In a flat area an influence of some 10 - 15% of the relative humidity reaches to a distance of some 100 m in the direction of the wind, even in the case of relatively small reservoirs. The highest air humidity is at the reservoir surface, and this decreases towards the top of the slope in deep valleys. The course of the air humidity in valleys without reservoirs is the reverse: its values are about 3% lower at the foot of the slope than at its top.

The high air humidity at the water table and the occurrence of the inversion layer result in fog formation where the cool air flows in, thus increasing the frequency of fog occurrence in valleys with reservoirs - or large headrace, tailrace and diversion canals, especially during periods without winds (Fig. 4.14 d).

The degree of influence of a reservoir on the local climate therefore depends on the frequency of wind occurrence and on its intensity. The change of the microclimate also depends on the change of the solar radiation input and on its reflectance, derived from the change of the area surface. Different species of the vegetative canopy are replaced by the uniform water table, whose reflectance depends on the angle of incidence.

Changes of the absorption and reflectance of solar radiation, together with changes of temperature and humidity, also influence the ecosystems on the shore in question. The energy input increases, producing favourable effects on the relevant canopy, as long as the limits of its heat tolerance are not exceeded.

The extent of the measurable effect of reservoir operation on climatological factors depends on the local conditions. It is a compensating effect, occurring more noticeably in areas with a rough climate than in areas with a mild climate.

The distance of reach of the climatological influence of reservoirs and irrigation networks depends on their size: It does not exceed a few hundred meters in the case of small reservoirs. Big reservoirs influence the climate within a reach of some 1 to 3 km from their shores. The biggest reservoirs in the world, according to Avakyan et al. (1977), can under extraordinary meteorological conditions occasionally influence the climate up to a distance of 30 to 60 km, their average effect generally occurring within a reach of 10 to 15 km. The change of mesoclimate and sanitary hazards caused waterlogging, wrong irrigation practices etc. are more important, because of inhabitants living inside the affected area.

4.6.2 Effect of Reservoirs and Dams on Sediment Transport

Dams, diversion dams and weirs inhibit and disrupt bed-load, suspended and wash load transport. They also change the course of the erosion process both downstream and, within the reach of their swelling effect, upstream. The process of sedimentation in reservoirs occurs as a consequence of the decrease of the velocity and kinetic energy of flow in the estuaries of tributaries running into the reservoir. The increasing depth and extension of the cross section results in a reduction in the sediment transport capacity of the flow. The difference in the original q_0 and the resulting transport capacity, q_r , must be deposited, or

$$\Delta q_r = (q_0 - q_r) \quad (\text{m}^3) \quad (4.18)$$

Δq_r - the difference in the transport capacities,
deposited within the reach (m^3)

This deposition process takes place by affecting the coarse particles of the sediment mixture and those particles with the highest unit mass first, the finest ones with a low unit mass last. This leads to segregation of sediments of different size and density.

The gravel, the boulders and partially also the sand which move as bed load form deltas, sometimes referred to as backwater deposits, at a relatively short distance from the estuary. Deltas extend to the point where the maximum water level intercepts the original river bed. Borland (1971), after investigating the depositional pattern of delta formation, concluded:

- the topset slope approximates one half of the original slope,
- the foreset slope is 6.5 times the topset slope,
- the topset and foreset slopes meet at the normal or mean pool where the reservoir is operated most of the time.

Seasonal drawdown causes the formation of multi-deltas.

Suspended load, mostly sand and other anorganic and organic particles, wash load, i.e. silt, clay, agrochemical particles and colloids, which move predomi-

nantly in suspension and have the kinetic energy of the flowing water, become more and more affected by gravitational forces with the decreasing velocity of flow.

Finer material forms the bottom sediments, spreading throughout the reservoir. The average thickness of the deposition h_{di} per unit time of deposition t_d was specified as:

$$h_{di} = \frac{\Delta q_{ri} \cdot t_d}{A_i} \quad (\text{m}) \quad (4.19)$$

A_i - area between the successive sections, corresponding to the difference in transport capacities Δq_{ri} .

The finest particles of silt, clay, colloids etc. (often flocculated) are also affected by the dynamic viscosity of water and, therefore, sink to the bottom very slowly. They have a tendency to form density currents, which have been found to move towards the spillways, turbines and outlets.

In addition to this, thixotrop gel often forms the mass which acts as a solid when a force is not applied but will flow when a force is applied. Floating debris rest in the zone where the tracting forces are in equilibrium with the resistance of wind. (Fig. 4.18)

The grain size, its unit mass and shape are the basic factors which influence its mobility and determine whether particles will settle or not. The water density in the reservoir is heterogeneous, also depending on temperature. The relevant particles sink until they reach a water layer with the corresponding density or right down to the bottom. Depending on the density, stratification and flow velocity, some particles which are not able to float in the upper layers of the reservoirs, cannot settle near the bottom.

The theoretical distance of deposition L_s for a particle with a settling velocity w , derived for a stable depth and width

$$L_s = H \frac{v}{w} \quad (\text{m}) \quad (4.20)$$

w - vertical sedimentation rate, depending on the unit mass, size and shape of the particle s (see eq. 2.15) $(\text{m} \cdot \text{s}^{-1})$

v - flow rate $(\text{m} \cdot \text{s}^{-1})$

H - depth of the reservoir in a given place (m)

For a reservoir with varying depth and width the distance is

$$L_s = \frac{1}{w} \cdot f(L) \quad (\text{m}) \quad (4.21)$$

because both the depth and the flow rate are functions of the distance of the entry of the sediment particle into the reservoir.

When the flow rate increases, e.g. in the period of the decrease in water table in a reservoir or during floods, particles of the same size settle at greater distances, destroying in this way the homogeneity of the grain-size distribution, which is also influenced by the surf. Only those particles cross the dam profile which happen to be in the reach of the kinetic effect of the outlets, off-takes and spillways (Fig. 4.18)

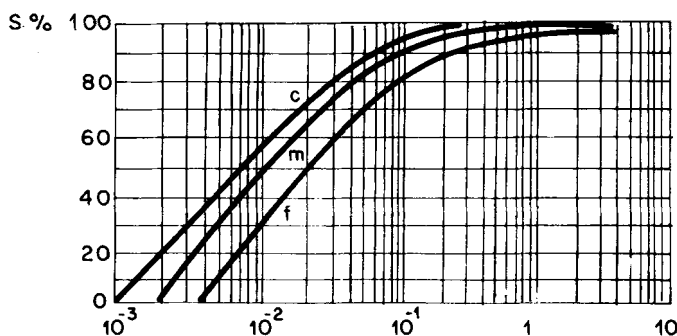


Fig. 4.15. Trap efficiency curve according to Brune (1979): s - sediment trapped as a percentage, r - ratio of reservoir capacity to mean annual flow, v - envelope curves; c - coarse sediment, f - fine sediments, m - medium curve.

The deposition of transported bed-load, suspended load and wash load in reservoirs results in the storage loss. Trap efficiency, the ability of a reservoir to trap and/or retain the sediment which enters it, can be expressed as a percentage of the total load. (Fig. 4.15). For very large reservoirs, the trap efficiency is almost 100 per cent, because only very fine sediments can pass the barrage. To determine the sediment deposit volume Rooseboom (1975) recommends the expression

$$V_t = V_{50} \cdot 0.376 \cdot \ln \frac{t}{3.5} \quad (\text{m}^3) \quad (4.22)$$

for $t > 8$ years.

V_t - the average sediment volume after t years

V_{50} - the arbitrary estimated sediment volume after 50 years.

The reservoir operation also influences the density, i.e. the average unit mass of deposits. The average unit mass for a deposit over a period of t years is given by Pemberton (1980)

$$\delta_t = \delta_i + 0.43 \cdot K \cdot \left[\frac{t}{t-1} \cdot \ln t - 1 \right] \quad (\text{kg/m}^3) \quad (4.23)$$

δ_i - initial unit mass (kg/m^3)

- \mathcal{J}_t - resulting unit mass over a period of t years (kg/m³)
 K - Lane-Koelzer factor (Table 4.18)
 t - period (years)

TABLE 4.18

| Type of reservoir operation | Initial mass, W_i | | | Lane-Koelzer factor K | | |
|-----------------------------------|---------------------|------|------|-----------------------|------|------|
| | clay | silt | sand | clay | silt | sand |
| Sediment submerged | 416 | 1120 | 1550 | 256 | 91 | 0 |
| Moderate to considerable drawdown | 561 | 1140 | 1550 | 135 | 29 | |
| Normally empty | 641 | 1150 | 1550 | | | |
| Rivered sediments | 961 | 1170 | 1550 | | | |

Initial unit mass, W_i and K factors (kg.m³) according to Lane and Koelzer (1975).

Formulas for the estimation of the trap efficiency of reservoirs often have an exponential form, considering that, in the final stage, the arrangement of the reservoir and the flow rate do not allow further sediment deposition. According to Gontcharow (1960)

$$V_t = V_o \cdot \left[1 - \left(1 - \frac{V_y}{V_o} \right) t \right] \quad (m^3) \quad (4.24)$$

V_t - the decrease in reservoir volume through sediment deposit during T years (m³)

V_o - original volume (m³)

V_y - mean annual sediment deposit volume in the reservoir (m³ per year)

t - period (years)

The mean annual sediment deposit V_y in a reservoir is simply

$$V_y = \frac{S \cdot B_{sw}}{\mathcal{J}_s} + \frac{B_b}{\mathcal{J}_b} \quad (m^3/year) \quad (4.25)$$

B_{sw} - medium total annual transport of the suspended and wash load (t per year)

S - coefficient of the trap efficiency

B_b - medium total transport of the bed load (t per year)

γ_s - unit mass of the suspended and wash load ($\sim 0.7 \text{ t.m}^{-3}$)

γ_b - unit mass of the bed load ($\sim 1.7 \text{ t.m}^{-3}$)

The medium total annual transport B_{sw} of the suspended and wash load from a catchment can be derived on the basis of the main catchment characteristics

$$B_{sw} = s_s \cdot A_c \cdot s_e \cdot i_e = 31536 \cdot c_a \cdot Q_a \quad (\text{t/year}) \quad (4.26)$$

A_c - catchment area (m^2)

i_e - annual erosion rate in the catchment area ($\text{t.km}^{-2}/\text{year}$)

c_a - average content of suspended and wash load in the discharge (t.m^{-3})

Q_a - mean annual discharge ($\text{m}^3 \cdot \text{s}^{-1}$)

s_e - share of the eroded matter forming the suspended and wash load (< 1)

s_s - share of the suspended load that has not settle in the mediate river stretch (< 1)

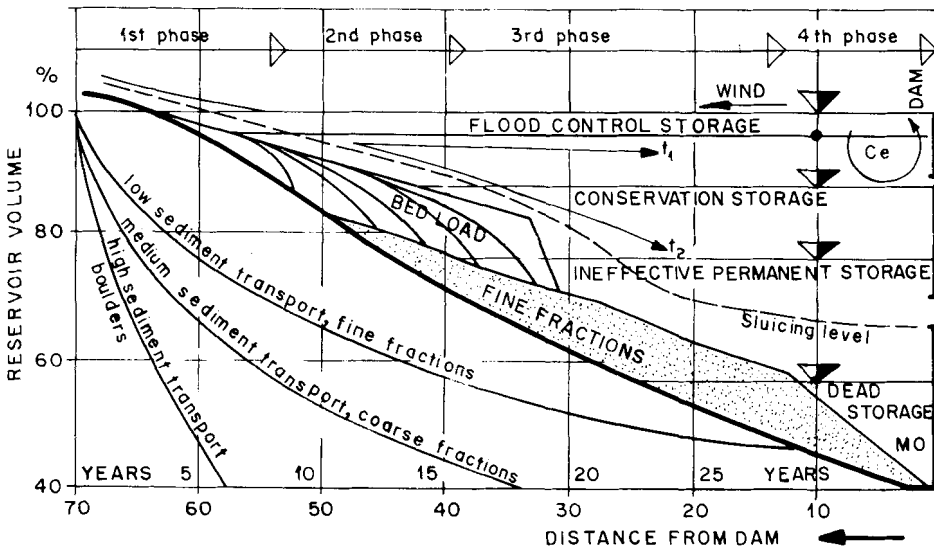


Fig. 4.16 Geographical representation of sediment deposition in reservoirs and the decrease in settling rate. Sediments are built up to an elevation depending on sluicing level, but channel is maintained through these. MO - monolimnion, c_e - circulation in epilimnion.

It is very important from the operational point of view that the rate of storage reduction is higher in the initial period of the reservoir's operation

and depends on the grain size distribution (Fig.4.15). The bed load and coarse fractions of the suspended load at that time enter the upper parts of the storage only, reducing first the volume of the storage zone reserved for flood control and then, in the second stage, also the conservation storage. Under these circumstances only fine fractions are able to reach the ineffective permanent storage. For rivers with a regular sediment transport the course of the decrease in the total storage may be considered as linear:

$$V_t = V_y \cdot t \quad (\text{m}^3) \quad (4.27)$$

In the third phase of the storage reduction process, the movement of the bed load reaches the ineffective permanent storage and then the dead storage, decreasing the rate of reduction in the active (flood control and conservation) storage. In the fourth phase, the sediment transport enters the storage and the space of the dynamic influence of the turbines, outlets and spillways, resulting in a further decrease in the rate of diminuation of the reservoir volume (Fig. 4.16).

The rate of storage reduction by sedimentation depends especially on the proper design of a project. Depending on the sediment transport regime and on the requirements on reservoir and dam operation, an optimum design, i.e.

- the size of the reservoir and
- a lay-out of the project,

can be selected and realized in such a manner that almost no suspended and wash load is kept back, whilst storing water in the reservoir. In such a way only the transport of the bed-load contributes to the storage reduction. The sediment-laden water of the early flood is passed through low-level openings. This condition requires a relatively shallow reservoir and a relatively short reservoir lake, not filled except in late flood, when the flood water contains less sediments. The dynamic influence of relevant spillways and outlets must reach the sediment flow. Their capacity, arrangement and relevant operation with the gates must not permit a division of the streamline, resulting in a reduction in the tracting forces. An appropriate size, lay-out and equipment of the project enables the reservoir to interfere to some 10% with the regime of rivers with a high level of suspended matter transport, thus greatly contributing to the efficiency of the project.

Other control measures can be grouped in

- control of watershed (proper soil conservation, farming and foresting techniques, protection of river banks etc.)
- control of inflow (by settling basins, by-pass canals, provision of vegetative screening, favourable location of intake structures for off-channel reservoirs etc.)

- removal of deposits (flushing, sluicing, dredging, which is economic in exceptional cases only).

The decrease in reservoir volume not only results from the sediment of the reservoir's tributaries, but also from the fall-out from the atmosphere, plankton, washed up soil and agrochemical particles from the adjoining shores and material from the eroded reservoir banks. The abrasion and landsliding of shores is a process of their destruction which is caused by the effect of water, wind, by the fluctuation of the water table, by water flow, by the effect of waves and ice and by the effect of human activities.

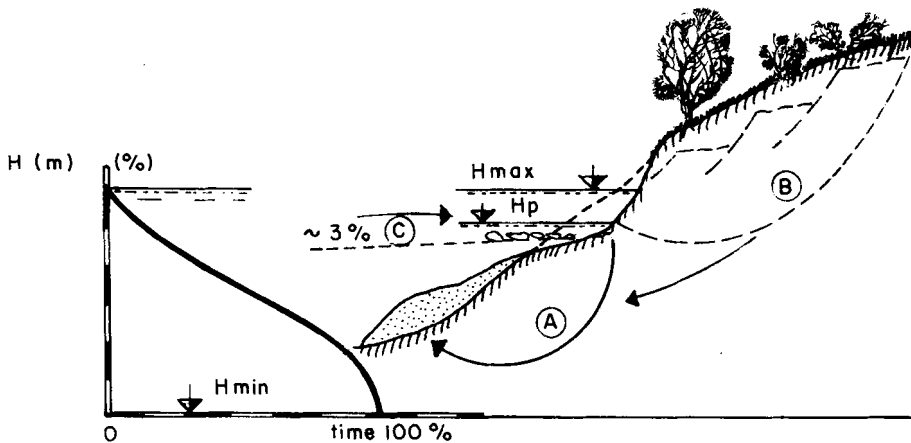


Fig. 4.17. The erosion of reservoir shores in relation to the fluctuation of the storage level. Redrafted according to Bayer (1954), H_p - pond level, H_{max} - maximum water level, A - abrasion shore, B - sliding abrasion shore, C - shore with accumulation of sediments, B+C - abrasion and accumulation shores.

An important destructive effect is exerted especially by variable phenomena. The abrasion of the shores of a reservoir starts shortly after the first filling-up of the reservoir. The rate of this process increases step-by-step in the first years of operation, reaching a peak after some three to five years and then gradually decreasing again. In this phase, the shape of the shores almost reaches a state of geomechanical equilibrium.

The wetting of the shores results in a change in their geomechanical characteristics, especially in their cohesive strength and coefficient of friction. New forces acting on the wetted material destroy the original balance, which may, under unfavourable geomorphological conditions, also result in the sliding of whole rock formations.

Depending on the slope of the shores, their exposure, their geological and soil characteristics and their vegetative canopy, the result of the process on

the shore formation are

- abrasion watersides, generally having a steep slope, whose material is eroded, transported and then deposited (Fig. 4.17 A)
- abrasion and sliding watersides, when the change of geomechanical factors results in landsliding (Fig. 4.17 B)
- accumulation watersides, formed in flat areas, especially in shallow coves, where the material from tributaries was deposited by wave action (Fig. 4.17 C)
- abrasion and accumulation watersides, which are steep, with a platform formed by the eroded material.

Abrasion phenomena do not occur whenever the slope of the shore is below 3° . Under such conditions the acting forces, because of their almost parallel direction, are not able to destroy the surface layer.

4.6.3 Effect of Reservoirs on Water Quality

The sedimentation process in a reservoir is accompanied by many other physical, chemical and biological processes of self-purification, which causes mixing and thinning. The influence of the water level fluctuation on the mean concentration of dissolved matter in the reservoir can be determined on the basis of the following formula

$$q_t = \frac{q_0 \cdot V_0 + Q_t \cdot k_t - Q_t \cdot q_0}{V_t} \quad (\text{g} \cdot \text{l}^{-1}) \quad (4.28)$$

q_t, q_0 - concentration of dissolved matter in the moment 0 and t_0 ($\text{g} \cdot \text{l}^{-1}$)

V_t, V_0 - volume of storage in the moment 0 and t_0 (m^3)

Q_t - water inflow in the period from 0 to $t-1$ (m^3)

k_t - concentration of dissolved matter in the inflow water ($\text{g} \cdot \text{l}^{-1}$)

O_t - outflow from the reservoir in the period from 0 to $t-1$ (m^3)

In this formula a constant concentration of outflow is assumed during the period in question.

Chemical and biological processes, running simultaneously with the physical processes, result in

- (a) the mineralization of organic matter
- (b) the production of new organic matter.

Some chemical substances, e.g. chlorides, do not change during these self-purification processes. Their concentration depends then on the rate of water exchange. The concentration of other matter increases or mostly decreases and can thus be expressed by a dropping exponential function, e.g. in summary by means of the biological oxygen demand BOD.

The course of the physical, chemical and biological processes is influenced

not only by the input of sediments, but also by the input of solar energy and by the oxygen and carbon dioxide from the air. The content of organic matter depends on the rate of the mineralization processes and on the production of organic matter. The dependence of the concentration of organic matter in the outflow on the rate of water exchange is hyperbolic. This concentration depends on the concentration of the organic matter in the inflow, on the average water depth, on the biological oxygen demand BOD₅ in the reservoir and on the rate of the water exchange. According to Straškrabová (1976)

$$q_t = q_r + 0.66 q_o \cdot t_e^{-0.21} + 0.66 \cdot p \cdot h^{-1} \cdot t_e^{0.79} \quad (\text{mg. BOD}_5 \cdot \text{l}^{-1}) \quad (4.29)$$

| | | |
|-------|--|--|
| q_t | - concentration of organic matter in the outflow | (mg. BOD ₅ .l ⁻¹) |
| q_r | - concentration of non-disintegrable matter | (mg. l ⁻¹) |
| q_o | - concentration of organic matter in inflow | (mg. l ⁻¹) |
| t_e | - rate of water exchange in the reservoir | (days) |
| h | - mean depth of the reservoir | (m) |
| p | - BOD ₅ production in the reservoir | (g.m ⁻² per day) |

The rate of mineralization process in reservoirs with a high rate of water exchange is higher than the production of organic matter during the first five days after the inflow of organic matter. In shallow reservoirs, with a depth down to 5 m and a rate of water exchange in excess of 20 days, the production of organic matter exceeds the rate of mineralization. A shorter rate of water exchange results in a higher decomposition rate. The longer rate of water exchange results in an increase in concentration of organic matter in the outflow in comparison with the inflow, especially when the BOD₅ concentration in the inflow is lower.

The concentration of organic matter in the outflow depends on the rate of production of the organic matter in comparison with the rate of the mineralization process:

$$q_p < q_m \longrightarrow q_t < q_o \quad (4.30)$$

$$q_p \cong 0 \longrightarrow q_t \ll q_o$$

$$q_p > q_m \longrightarrow q_t > q_o$$

$$q_p \text{ - rate of organic production} \quad (\text{mg. l}^{-1})$$

$$q_m \text{ - rate of the mineralization process} \quad (\text{mg. l}^{-1})$$

For longer periods of water exchange than 14 to 16 days the share of dis-

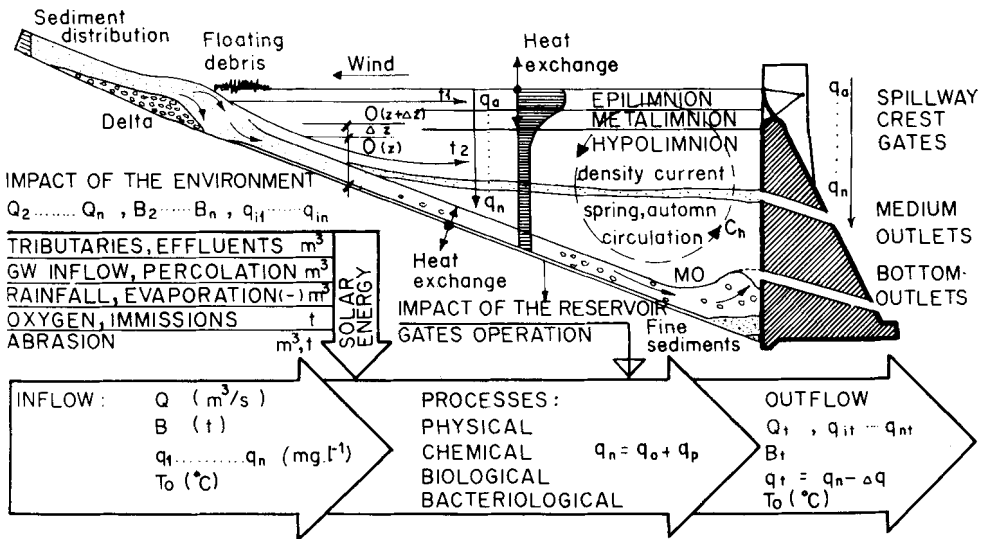


Fig. 4.18. The impact of thermal stratification and operation with spillway gates, bottom and medium outlets on water quality in reservoir. River flow t_1 , t_2 and water circulation c_e during stagnation, circulation c_h during the period of homothermicity is dotted. The seasonal changes in thermal stratification,

integrated organic matter does not depend on the depth of the reservoir. The efficiency of the mineralization process increases with the duration of the water exchange and in reservoirs with a rate of water exchange of 14 to 16 days increases substantially with their average depth.

The upper layers of the reservoir are trophogenic, i.e. nutritive. Assimilation is their prevailing process, while dissimilation occurs only partially. Lower layers are trophylitic, i.e. they support the disintegration of organic matter. The prevailing process there is dissimilation, when destruent disintegrate the dead plankton and other dead organisms. Owing to the water flow a certain development of physical, chemical and biological processes is observed from the estuary of tributaries to the dam.

The rate of the relevant biochemical processes depends largely on the course of water temperatures. The unit mass of water depends on the temperature, chemical composition and content of sediments and results in thermal stratification. The pattern of thermal stratification in reservoirs depends on the

- reservoir depth and geometry
- solar radiation and air temperature
- wind velocity
- reservoir operation, i.e. on the flow to volume ratio.

The degree of stratification depends on the densimetric Froude number Fr which can be approximated by

$$Fr = 320 \frac{L}{H} \cdot \frac{Q}{V} \quad (4.31)$$

| | |
|----------------------------|-------------------------------------|
| L - reservoir length | (m) |
| H - mean reservoir depth | (m) |
| Q - discharge | (m ³ · s ⁻¹) |
| V - reservoir volume | (m ³) |

According to Canter (1983) if Fr is less than $\frac{1}{9L}$, stratification is expected, with the degree of stratification increasing with the decreasing densimetric Froude number.

The thermal stratification in reservoirs is more marked in deeper reservoirs. The difference in temperature between the surface and the bottom layers may exceed 15°C during high summer and 10°C during spring. This difference is about 4-5°C during winter.

Temperature gradients, i.e. the difference of temperature in the vertical direction, are not regular. When the temperature regime is stable, a characteristic zone called the metalimnion or thermoclina occurs at a depth of some 5 to 15 m. Its thickness varies and may even reach 6 m. This layer is characterized by a quick decrease in water temperature with the depth, exceptionally reaching 8°C at 0.3 m. (Fig. 4.18)

The upper layer, above the metalimnion, is the epilimnion, where the effects of solar radiation are intensive, especially in the summer season. This layer extends to a depth of some 4 to 15 m. In this layer, the stock of oxygen is supplemented from the atmosphere by diffusion as well as by the photosynthesis of the water organisms. During the summer season the water temperature of this upper layer is higher, and in winter lower, than the temperature of the lowest layer, the hypolimnion. The temperature of the surface of the epilimnion is decreased from the surface by evaporation, thus causing an upward flow of water. The wind pressure on the water surface results in a turbulent flow, causing together with the water inflow from tributaries a mixing of water and a downward transfer of heat and kinetic energy.

The changes of water quality may result in the creation of a comparatively heavier, cooler layer at the reservoir bottom, enriched by products from the mineralization and decomposition processes. The chemical composition of this layer causes this water to reach its highest density at a temperature slightly above 4°C. This layer, the monolimnion, mostly does not take part in the process of water circulation.

Local circulation flows may occur in any part of the reservoir, but the overall circulation is a result of the destruction of the balance which arises from

stratification by external forces. The probability of the occurrence of an overturn is, therefore, greater at the time of a non-marked stratification. This time occurs mostly in spring or autumn, when the upper and lower layers of the reservoir have the same temperature, i.e. during the period of homothermicity (Fig. 4.19). Such a state occurs once or several times during spring or autumn. During these periods of spring and autumn circulation, the flow caused by the wind effect mixes the whole volume of the reservoir, mostly with the exception of the monolimnion.

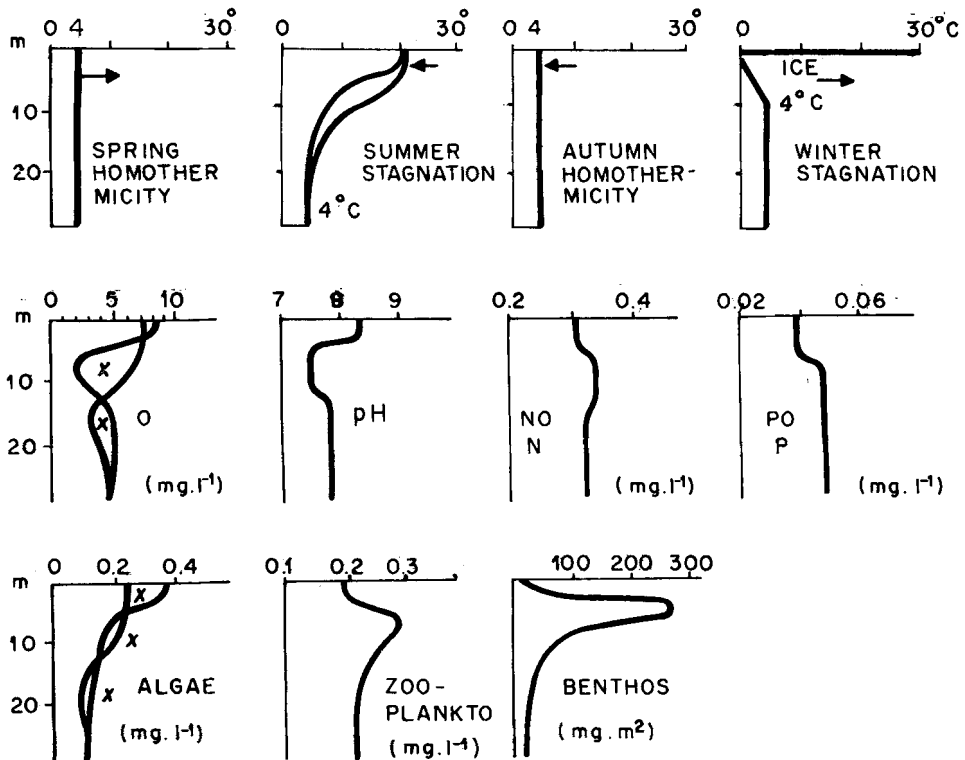


Fig. 4.19. Seasonal changes in thermal stratification in deep reservoirs. Oxygen content and other quality indicators depend on depth and reservoir operation (x). According to Chen and Orlob (1980).

In summer and also during winter, when the reservoir is not covered by ice, winds cause water circulation in the layer of the epilimnion only. During these periods of stagnation, the heat balance of the reservoir is influenced by the heat exchange between the bottom and water and by the heat input or output from the water level or ice cover, i.e. not by overall water circulation. The motion of the suspended matter, their floating and sedimentation, depends on these

circulation phenomena.

In summer water from tributaries, usually cooler than the water in the reservoir, penetrates below the warm epilimnion, following the direction of the original river channel. During this season the water temperature in a single, deep man-made lake is comparatively higher than it would be in a natural lake under the same topographical and climatological conditions. The outflow of the cooler water from the hypolimnion through turbines and bottom outlets results in an increase in the average temperature of the reservoir.

During winter, the bottom outlets and turbines release water which is warmer in comparison with the upper layers, resulting in a decrease in the water temperature. The average water temperature of man-made lakes is, during the winter season, therefore lower than that of natural lakes. Flow conditions resulting from the inflow of tributaries are substantially more complicated as compared with the simple penetration of the cooler inflow below the equilibrium in summer. After the spring circulation a substantially lower flow occurs in the reservoir.

The situation is quite different in a cascade of man-made lakes. The temperature in the second and further reservoirs is greatly influenced by the input of cool water from the upper reservoir. It changes not only vertically, but also in the longitudinal profile. The average of this temperature, and the temperature of the surface layer, is also lower than it would be in a natural lake under similar conditions.

The surface temperatures and often also average temperatures reach their minimum in summer just downstream of the upper dam. The location of a rapid increase in temperature, corresponding to a drop of the streamline and the formation of an epilimnion, changes with the values of inflow from the upper reservoir. Increased discharges upset the upstream zone of the metalimnion in the direction of the flow and extend the zone with low surface temperatures, thus restricting the possibilities of bathing. For similar reasons, the surface temperature decreases in the direction of the main flow downstream of the upper reservoir.

The quality of water in reservoirs is determined by the interplay of

- the water exchange rate,
- the quality of water entering the reservoir,
- the climate and weather,
- the hours of sunshine,
- the resulting water temperature,
- the morphological characteristics of the reservoir, especially its depth,
- the material of the reservoir bottom,
- the aquatic ecosystem and ecosystem of the surroundings
- the impact of human activities.

The quality of the water entering the reservoir varies considerably with the

season, being considerably influenced in dry periods by the quality of effluents from industrial and agricultural enterprises. In arid countries, the salinity of the inflow may increase considerably in this period. In high-flow periods, the quality of the inflow depends to a great extent on the erosion rate, i.e. on the material of the riverbed and wash from cultivated and fertilized land, depending on the season, agricultural practices and on the rainfall intensity.

The self-purification process in reservoirs with the exception of sedimentation is negatively influenced by the greater depth of water, resulting in lower oxygen content and lower temperature in comparison with the original conditions of the riverbed. Reduced flow velocities result in higher sedimentation with a long period of settling, hence reducing the turbidity of water. The increased detention time leads to increased biological activity. A higher nitrogen content, entering the reservoir mainly as a result of wrong cultivation practices, and higher surface temperatures with slower water flow in the epilimnion result in the over-development of algae. The decay of these organisms causes secondary pollution, decreasing the oxygen content, poisoning other organisms and disrupting the biological balance. Serious trouble may be caused by the over-development of weeds in the shallow parts of the reservoir.

The thermal stratification results in the formation of zones of differing water quality (Fig. 4.19). These zones differ not only chemically, but also in the content of various water organisms and can be modelled mathematically (Fig.4.20).

The hypolimnion may be, and the monolimnion certainly is characterized by anaerobic conditions and high concentrations of iron Fe, manganese Mn and sulphides; this causes quality deterioration, especially during the natural autumn overturn or during excessive water withdrawals. This deterioration may occur as a low level of dissolved oxygen, high Fe, Mn and hydrogen sulphide concentration and in organic and inorganic tastes and odours.

When a cool water input or circulation does not destroy the natural thermal stratification, a decrease in the oxygen content of the epilimnion occurs in the summer season. During that period this layer loses, owing to circulation, up to 50% of the oxygen content acquired in spring.

The character of the biochemical changes in the water quality in the epilimnion depends mainly on the course and type of processes, especially those which occur in the summer season. Nutriments enter the free space of the reservoir, also from its bottom, by means of the circulation, thus contributing to the activation of the biological process.

Oxygen losses are balanced by the decrease in temperature in autumn. The hypolimnion, having no contact with the atmosphere, loses its oxygen content as a result of decomposition processes, which occur especially in the bottom sediments. The decrease in oxygen content may result in an oxygen deficit, and in the decay of aerobic organisms. The thermal stratification influences all the

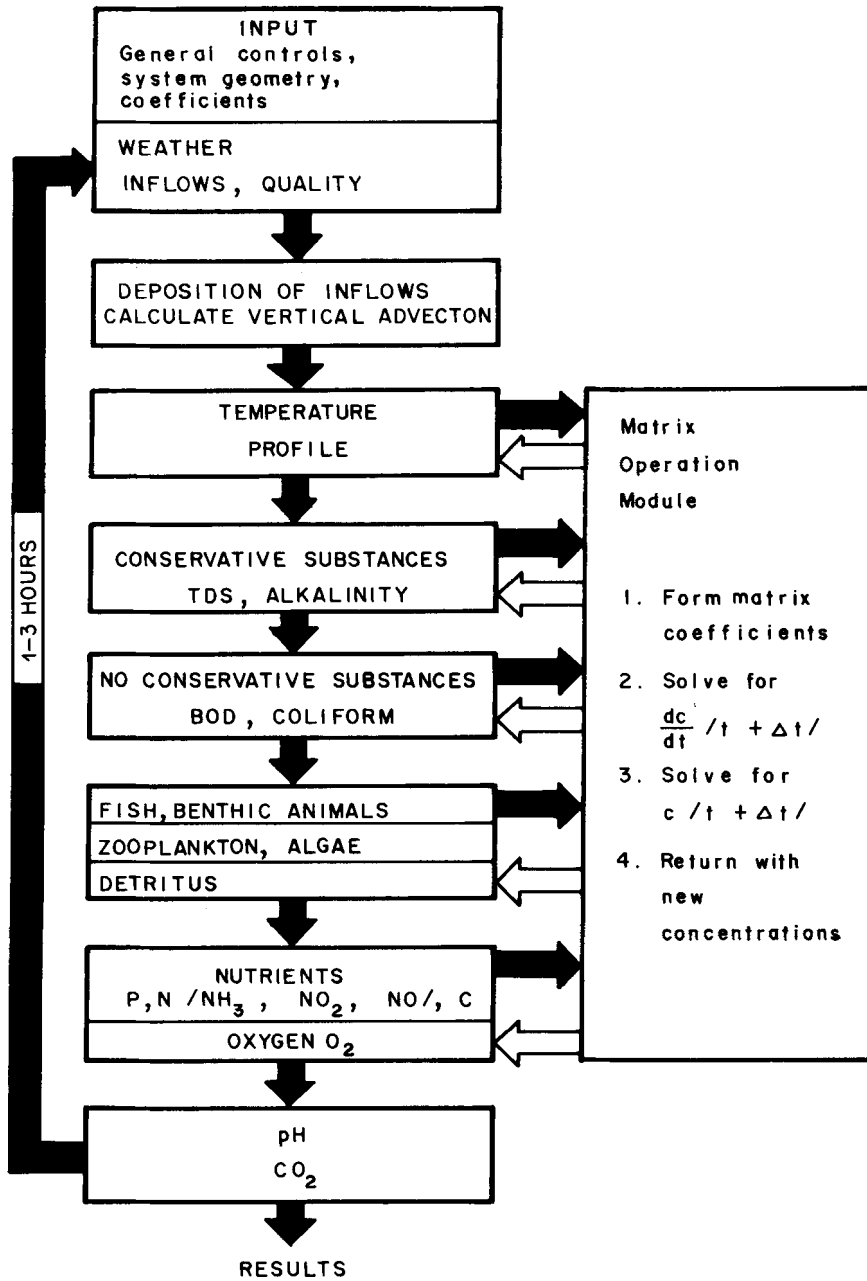


Fig. 4.20. Flowchart diagram (the lake ecological model) for determining the changes in water quality and the biomass production according to Chen and Orlob (1973).

chemical and biological processes, determining the water quality and the rate of biological production (Fig. 4.20).

Human activities also contribute to the occurrence of zones with an oxygen deficit, especially effluents, pits and dikes at the bottom of the reservoir, impeding the water circulation. Similar effect has the inexpediency of the reservoir operation, e.g. its emptying by upper outlets and spillways, which is required not only during floods but also to increase the water temperature in summer for bathing downstreams.

The thermal stratification is less significant, or does not occur at all, in shallow reservoirs (see Eq. 4.31). The cooler water is generally at the end of the backwater. The temperature increases in the direction of the main flow, i.e. to the dam, spillweir or outlet. The heat inertia of shallow reservoirs is low. The decrease in temperature at night may result in the formation of homothermicity, enabling intensive water circulation.

The higher day temperatures result in the formation of an inexpressive metalimnion. As it grows in size, the metalimnion reaches the bottom, and gradually disappears. The resulting homothermicity permits frequent circulation, thereby increasing the biological production of shallow reservoirs.

An improvement in water quality in reservoirs can be achieved by mechanical destratification, by the use of air and mechanical pumps or by treatment with copper sulphate CuSO_4 with or without citric acid, lime and alum. The control of algae growth can also be achieved by limiting the nutrient input in the major tributaries, especially by limiting the input of phosphorus.

4.6.4 Influence of Man-made Lakes on the Biosphere and Society

The development of aquatic life in a new reservoir is greatly influenced, and the water quality is determined, by the following factors:

- topographical, geological and soil conditions of the locality and its vegetative canopy
- climatological conditions of the site, especially the duration of sunshine
- water quality of its tributaries and the resulting water temperature
- the original ecosystems in the river and on the shore
- clearing, removing of stumps, litter, humus, cleaning and other measures undertaken by man to decrease sanitary hazards
- measures taken by man to accelerate the development of desirable species in the ecosystem of the new reservoir
- operation of the reservoir, often causing a periodic daily, weekly and seasonal draw-down and rise of the water table
- appropriate human activities during the reservoir's operation, namely those resulting in water pollution. (Tab. 4.19).

TABLE 4.19

| Category | Factor | Category | Factor |
|----------------------------------|---|----------------------------------|---|
| Terrestrial: | | Aquatic: | |
| Population | Crops Natural vegetation Herbivorous mammals Carnivorous mammals Upland game birds Predatory birds | Populations | Natural vegetation Wetland vegetation Zooplankton Phytoplankton Sport fish Commercial fisheries Intertidal organisms Benthos/Epibenthos Waterfowl |
| Habitat/land use | Bottomland forest(a) Upland forest (b) Open (non-forest)lands(c) Drawdown zone Land use | Habitats | Stream (d) Freshwater lake (e) River Swamp (f) Non-river Swamp (g) |
| Land quality/ soil erosion | Soil erosion Soil chemistry Mineral extraction | Water quality | pH levels Turbidity Suspended solids Water temperature Dissolved oxygen Biochemical oxygen demand Dissolved solids Inorganic nitrogen Inorganic phosphate Salinity Iron and manganese Toxic substances Pesticides Faecal coliforms Stream assimilative capacity |
| Critical community relationships | Species diversity | | |
| Air: | | | |
| Quality | Carbon monoxide Hydrocarbons Oxides of nitrogen Particulates | | |
| Climatology | Diffusion factor | | |
| Human Interface: | | | |
| Noise | Noise | Water quantity | Stream flow variation Basin hydrologic loss |
| Aesthetics | Width and alignment Variety within vegetation type Animals-domestic Native Fauna Appearance of water Odor and floating materials Odor and visual quality Sound | Critical community relationships | Species diversity |
| Historical | Internal & external sites | | |
| Archaeological | Internal & external sites | | |

Checklist of bio-physical and cultural environment factors for impoundment projects according to Canter (1983). Explications follow.

(a) A composite of the species associations; percentage mast-bearing trees; percentage covered by understory; diversity of understory; percentage covered by groundcover; diversity of groundcover; number of trees ≥ 0.5 m diameter per ha; percentage of trees ≥ 0.5 m diameter; frequency of inundation; edge (quantity) and edge (quality).

(b) A composite of the following: species associations; percentage mast-bearing trees; percentage coverage of understory; diversity of understory; percentage coverage of groundcover; diversity of groundcover; number of trees 0.5 m diameter/ha; percentage of trees ≥ 0.5 m diameter; quantity of edge; and, mean distance to edge.

(c) A composite of the following: land use; diversity of land use; quantity of edge; and, mean distance to edge.

(d) A composite of the following: sinuosity; dominant centarchids; mean low water width; turbidity; total dissolved solids; chemical type; diversity of fishes; and diversity of benthos.

(e) A composite of the following mean depth; turbidity; total dissolved solids; chemical type; shore development; spring flooding above vegetation line; standing crop of fish; standing crop of sport fish; diversity of fish; and, diversity of benthos.

(f) A composite of the following: species associations; percentage forest cover; percentage flooded annually; groundcover diversity; percentage of groundcover; and, days subject to river overflow.

(g) A composite of the following: species associations; percentage forest cover; percentage flooded annually; groundcover diversity and percentage of groundcover.

Non-influenced ecosystems in the man-made reservoir tend in the long term to achieve biological equilibrium, corresponding to a natural lake under similar conditions. Man-made reservoirs can therefore be categorized in the same way as natural lakes (Tab. 1.31).

As soon as the filling up of a reservoir begins, the original ecosystem of flowing river water changes, gradually being replaced by a new ecosystem of stagnant water. Within a period of several weeks, an over-development of some plankton species usually occurs. This boom affects the species, which do not encounter important life concurrence and first find the rich stock of nutriment in the newly flooded soil layers and their partly removed vegetation canopy.

The development boom of this species is interrupted in the next stage by an overdraw of the original nutriment, leading to the development of other species. This situation gradually tends towards a biological equilibrium, with a more rich aquatic life in the area of the estuaries of the reservoir tributaries, where the nutriment input is more intensive.

The aquatic life of man-made lakes is greatly influenced by a frequent draw-down and rise of the water level. This results in the poorer heterogeneity of ecosystems in the upper littoral zones of man-made reservoirs in comparison with natural ones: these ecosystems do not include species which are not resistant to the fluctuation of the water level and which cannot follow the water level or find a temporary shelter in the denuded surface cover.

This is the reason why a number of current species are disappearing as a result of the action of the fluctuating water level, including weed, rush etc., and there only remain some unwanted species of insects (some midges and gnats) and worms (e.g. leeches). The occurrence of mosquitos can be significantly reduced by a managed draw-down and rising up of the water level.

The occurrence of aquatic species depends mainly on

(a) critical physical and chemical factors, i.e. on the occurrence of nutrients which are indispensable for the relevant species in quantities exceeding the necessary minimum,

(b) the ecological valency, i.e. on the extent of the tolerance of the relevant organisms to these factors and to the occurrence of other unwanted components of their living environment. Critical limits and optimum conditions are specific for the species in question. Approaching these limits, living phenomena become more demanding, especially energetically. Under favourable conditions, less energy is required, leaving aquatic animals the necessary reserve for finding and consuming food. A sufficiency of food and energy supply and an appropriate environment form the optimum living conditions for the species in question.

The existence of relevant fish species depends on the water quality, - mainly on its temperature and oxygen content, on the water depth, rate of flow, morphology and material of the bottom and the banks, and on the occurrence of aquatic flora. The construction and operation of a reservoir changes all these conditions. A dam or a weir forms an invincible obstacle for the draw of migratory fishes, e.g. eels, salmon.

Fish traps, elevators and other equipment constructed to enable the migration of fishes do not form an adequate substitute for such a purpose. There are also problems with the optimum location of such equipment and their capacity, especially in the period of the draw, is often not sufficient. The migration of fishes is already restricted during the construction period. The development of some fish species is even curtailed. Fish species that are not able to accept the changed conditions die out, changing in this way the structure of the ecosystem and conditions for the development of other herbivores, carnivores and detritivores. The conditions for fish occurrence in fish-ponds differ completely from those in reservoirs used for water supply and flow control. High inflow and outflow result in a high rate of water exchange and in water quality which is characterized by a lack of nutrient content. Fresh water fishes usually live

near shores, and not in the free space, where a lack of nutrition occurs. This results, together with the lack of solar radiation, low temperature and lack of oxygen, in a substantial drop in productivity in reservoirs deeper than fifteen meters.

The water level fluctuation reduces the production surface and destroys zooplankton, the basic component of the fishes' food. The productivity of a reservoir does not depend on the extent and frequency of the water level fluctuation only, but also on the period of its occurrence. Shores covered by a dense vegetative canopy form favourable conditions for fish shelters, spawn deposition and foetus development. The decrease in the water level usually destroys spawn and foetus, especially in its early stage of development. The drop in the water table also has certain positive effects on fish production, forming suitable conditions for fauna development in the uncovered surface. The inundated grasses create a favourable environment for the development of some fish species, as well as offering them food.

The population boom of some fish species, e.g. of pike, after the first filling of the reservoir is also caused by the abundance of nutrients in the newly inundated soil surface and by the number of shelters. This population boom lasts several years, then gradually diminishes.

Ichthyofauna of man-made lakes can be categorized as follows:

(a) fishes which occur in the reservoir from the original ecosystem of the stream and which are able to adapt to the changed environment and breed naturally,

(b) fishes which have extremely favourable conditions for their natural breeding and development and are able to exterminate other fish species,

(c) fishes of the original ecosystem which are able to adapt to the changed conditions only in restricted areas of stream estuaries, where conditions have not been changed drastically,

(d) fishes which are able to live in the reservoir, but do not have the ability to breed naturally, thus requiring artificial breeding for replenishment of their occurrence,

(e) fishes which are imported artificially from other ecosystems and, being adaptable to the reservoir conditions, are able to fulfill the required function in the reservoir ecosystem: weed reduction, maintenance of ecosystem equilibrium, meat production etc.

The ecosystem of a reservoir includes

(a) fishes intended for breeding,

(b) supplementary fishes, using food which is not utilized by the raised fishes.

The extent and intensity of changes in the landscape caused by the reservoir depend not only on the topography, character and accessibility of the area and on the density of population and communication lines, but also on the size of the

reservoir, especially on its surface area. The following occurs after the construction and operation of a reservoir:

(a) changes in the inundated area:

- flooding of forests, cultivated and urbanized land, communications, buildings and other engineering works, landmarks and historic places,
- flooding of mines and mineral deposits etc.,
- the extinction of the original ecosystems, the destruction of dry land species of flora and fauna, including the rare ones,
- the inception of aquatic flora and fauna, as well as the extension and change of its environment, including that for fowl and insects.

(b) changes in the reservoir environment

- creation of new scenery, influenced by the water level fluctuation,
- changes in the hydrogeological and hydrogeological conditions, new ballast of the Earth's crust,
- changes in the groundwater level, soil moisture and air humidity, changes in temperature, resulting in a change of ecosystems,
- changes in the living environment of man; change in dwelling environment, in health and recreational conditions, and a severing of communication lines,
- change in the conditions for economic development: the economic impact of the dam construction and reservoir operation causes a construction boom, as the equipment used on the building site offers possibilities for further utilization, and the construction of new communications increases the accessibility of the area and its consequent utilization for recreation purposes, which leads to a modernization of the life style of the population.

The reservoir's environment is negatively affected by the water level fluctuation, especially at the end of backwater and in flat areas. When the banks are steep, landsliding may occur. The negative consequences of the water level fluctuation should be restricted by overflow dams, dikes, banks, ramparts, and by excavation in shallow flooded areas etc.

Dry land ecosystems are affected not only by the rise in the groundwater level and by an increase in soil moisture and air humidity, but also by the flooding of pastures and dens, by complications associated with the access of shy animals to water, by the worsening in the living conditions, especially of rare species, through the increase in population density and economic activities. In sparsely populated areas reservoir shores form favourable conditions for nesting and resting places for migratory birds.

The social, group and personal interests of the population are affected by the creation of new shores, by the increase in soil moisture, by changes in the microclimate etc. The increase in dwelling value of areas not adversely affected by water level fluctuation waterlogging or other negative effects results in an increased density of habitation. The change in the dwelling value has an impor-

tant impact on the life style, supporting its recreational aspects. The reservoir creates or supports favourable conditions for fishing, camping, hunting, and other types of weekend and vacational recreation. The space for water tourism increases, but the recreational value is sometimes prejudiced by the change of the flowing water into stagnant water.

The increased density of habitation has as a secondary effect a breaking down of the natural vegetative canopy, an increase in the erosion rate, a rise in the transport density, an increase in noise density, a gradual pollution of the environment, with the concomitant need for a mass water supply, organized waste and waste water removal.

Depending on the water quality and prevailing sanitary conditions, the reservoir operation can create or strengthen the conditions for the dissemination of germs or their bearers, especially in tropical and subtropical areas. Negative circumstances may result in economic, cultural and social losses, either permanent or temporary, especially in the period during and shortly after the construction.

Some of the expected economic effects may be not achieved due to various planning, financial and organizational obstacles or due to the unexpected reaction of the population. This mainly concerns the immediate surroundings of the reservoir, which sometimes fail to attract sufficient interest among potential investors.

Uncoordinated planning and lack of investment in further construction activity or institutional gaps may cause discrepancies in the area in question, restricting or even cancelling the positive impact of the reservoir in the border areas, or even altogether.

4.6.5 Effect of Flow Control and Water Withdrawals

Downstream of the dam profile the reservoir operation and water withdrawals affect, especially,

- the water and ice regime, the transport of sediments, and the water quality,
- the aquatic flora and the riverside canopy,
- the aquatic fauna including fishes,
- the dwelling value of the relevant area (Tab. 4.20).

Changes in the water regime are manifested mainly by changes in discharges, dependent on the reservoir operation, and on the time distribution of water withdrawals and effluents. These changes result especially in

- (a) a decline in peak discharges and relevant water levels downstream, usually with the exception of superfloods and floods of long duration, because these often exceed the capacity of the reservoir,
- (b) an increase in low discharges,
- (c) a water deficiency in the case of excessive water withdrawals.

TABLE 4.20

| Impact of reservoir operation and water withdrawal on downstream water course | | | | | |
|--|--|--|---|--|------------------------------------|
| Water quantity | | Water quality | | Flora/Fishes | Dwelling |
| Decrease in higher discharges | Increase in low discharges | Decrease in sediment transport | Decreased salinity of low discharges | Change in water table and ground-water table | |
| Restricted flooding | Improved water supply | Decrease in water table of floods | Increase in salinity by evaporation | Change in aquatic flora | Improved flood control |
| Restricted natural fertilization | Improved navigation and power generation | Decrease in sedimentation flooded land | Increase in nitrogen, iron and mangan content | Change in coastal flora | Restricted soil re-generation |
| Restricted erosion | Decrease in sedimentation | | Decrease in oxygen content | Increase in yield | Changes in pattern of watertourism |
| Restricted groundwater recharge | Increase in infiltration | Decrease in clogging | Decrease in water temperature in summer | Interrupted draw of fishes | Restricted summer recreation |
| Restricted waste disposal | Improved sanitary conditions | | Increase in water temperature in winter | Restricted migration of fishes | Restricted skating in winter |
| Decrease in evaporation | Slight increase in evaporation | Extended period of high turbidity | Change in ince formation and flow | Change in zones of fish occurrence | |
| Decrease in water table and discharge fluctuation | | | | | |
| Periodic fluctuation of water table and discharges in case of hydro-power generation | | | | | |

Checklist of the probable impact of reservoir operation and water withdrawal on downstream water course.

Water withdrawals do not generally result in a substantial decrease in flood discharges, as they are usually comparatively small. Big withdrawals, such as those used for irrigation purposes, reduce the value of low discharges in the summer season, thus causing an increase in these discharges in the winter season on account of the greater groundwater outflow from irrigated land at that time. Irrigation may also increase flood discharges, because watered land has a limited infiltration capacity, thus causing an intensive outflow of the rainwater.

The flood control effect of the reservoir results in

- (a) a decline in the flooded area,
- (b) a decline in the extent and frequency of irrigation by flood water spreading and soil regeneration by silt sediments,
- (c) a decline in the rate of natural riverside infiltration,
- (d) a decline in the erosion rate, and an increase in the sedimentation rate.

The decline in the flooded area results in a reduction in flood losses. Nevertheless, irrigation by flood water spreading is restricted, thus reducing the regeneration rate of the soil profile. In this case, the natural watering and soil regeneration process has to be replaced by artificial irrigation and fertilizing, which results in high operation costs and also requires appropriate operation skill, as well as being connected with a change in irrigation methods and in the cropping pattern.

The necessary measures for this purpose require the supply of artificial fertilizers, energy for their production, manpower and skill and may appear to be operationally, financially or organizationally unsuitable, especially in developing countries. They are feasible for intensive production, but are not satisfactory from the environmental point of view, as they may supply the requested quantity of anorganic nutrients, but not the necessary volume of organic matter.

Flood control results in the decline in the natural riverside infiltration, reduction in the groundwater recharge and subsequent negative influence on agricultural production, especially in flat river valleys. In the case of the low quality of river water, the drop in the infiltration rate results in an improvement of the groundwater quality.

The decline in the erosion rate and interrupting of the sediment transport which result from the flood control functions of the reservoir serve the maintenance of riverbeds. As a consequence of the reduction in high discharges, an increase in the sedimentation rate may occur resulting in a decrease in the channel capacity downstream of the dam profile and thus influencing water level hydrographs, navigation conditions etc. As a result of the decreased discharges and attendant higher sedimentation, the rate of the self-purification processes falls, thus causing a deterioration in the water quality. The decrease in the erosion, and increase in the sedimentation rate negatively influence the occurrence of fish shelters, thus limiting the fish population.

Depending on the given conditions, the reservoir with a low impact on flood discharges may on the contrary, owing to its trap efficiency depriving the downstream flow of its sediment content, increase the erosion rate downstream.

The increase in low discharges is caused not only by the reservoir operation, but also by the influence of water utilization processes between the water withdrawal and effluent, the second process having a negative effect on the water quality.

The increase in low discharges, being accompanied by a raising of minimum water levels, creates more favourable conditions for water withdrawals, navigation and water power generation, as well as having a favourable impact on the groundwater regime, and therefore also on agriculture and forestry. Such a raising of the water table may sometimes result in advancing percolation and evaporation, i.e. in growing water losses. The flow rate increases, augmenting sediment transport and the rate of self-purification processes, and thereby improving the sanitary conditions and the aesthetic value. Under certain circumstances the flow rate may exceed the relevant limiting values of the river bottom stability, thus causing erosion.

Water withdrawals and subsequent utilization frequently increase the concentration of dissolved or suspended matter in the remaining discharges. Water utilization decreases the oxygen content especially and increases the nitrogen content. The regulating effect of the reservoir with a longer rate of water exchange mostly reduces the level of water pollution. The augmentation of low discharges also dilutes the pollution in water from tributaries and effluents.

The sedimentation and self-purification processes in the reservoir generally have a favourable effect on the quality of the water outflow, even in the case of a low quality inflow. In semi-arid and arid areas the concentration of dissolved and suspended matter can nevertheless be increased by passing through the reservoir with a high evaporation rate.

The value of the water pollution downstream of the reservoir, at the confluence or at the estuary of effluents, can be determined or its course modelled on the basis of the mixing formula

$$i_{q_3} = \frac{Q_1 i_{q_1} + Q_2 i_{q_2}}{Q_1 + Q_2}$$

i_{q_1}, i_{q_2} - the concentration of relevant indicators before the confluence or before the estuary of effluent
 resulting concentration downstream

i_{q_3} - resulting concentration downstream

$i = 1, 2, 3, \dots, n$ order of water quality indicators

$Q_1 - Q_2$ - discharges upstream of the confluence.

The real course of the water pollution in the longitudinal profile of the water course differs from the computed on account of the self-purification process including sedimentation. The relevant computed values should, therefore, be checked and corrected in the sequence from the upper profile to the estuary. On this basis, the course of the water quality can also be controlled and its improvement during critical periods achieved by reservoir operation. Such an emptying of the storage is to the detriment of the water supply. The feasibility of such operation depends on the course of the decomposition processes and on the evaporation rate in the reservoir, and resulting water quality.

The changes in water temperature downstream of the dam site arise from the reservoir operation. With the power generation or with the bottom outlet open, the deep water layers, i.e. the hypolimnion, are emptied, which results in a cooling of the river water in the summer season and its warming during winter, in comparison with the original state before the reservoir operation. This water also contains more nitrogen and iron and less oxygen. The difference in water quality, including temperature, is substantial, especially in the case of a cascade of reservoirs. The water of the epilimnion, whose temperature does not differ as much from the original one, enters the river channel downstream of the reservoir by means of spillways, mainly during floods, i.e. not so frequently.

Temperature changes have an influence on, especially,

- (a) water utilization after its withdrawal
- (b) fish occurrence and fish breeding
- (c) other in-stream water uses, especially water sports, recreation, navigation, and also waste disposal.

The decrease in water temperature is favourable for both municipal and industrial water supply, namely for cooling purposes. For irrigation purposes, warmer water is more convenient. Changes in water temperature and water quality also influence the ichthyofauna. They may cause a change in the zones of fish occurrence. The changes in water temperature mostly have a negative effect on recreation and water sports; the cool water in summer spoils the conditions for bathing and other water sports; while the increase in winter temperature restricts the freezing of the water pool and skating in winter, but tempers the ice bound regime, thus creating more favourable conditions for water transport.

Water temperatures are also affected directly by water withdrawals, decreasing water discharges, water depth and flow rates with consequent temperature increase, also caused by the high temperature of effluents from cooling systems. These temperature changes depend to a great extent on the ratio of discharges and withdrawals and on the quantity and temperature of effluents. Water withdrawals also increase the concentration of sediments in the remaining discharge, aggravated by material input from effluents, increasing the sedimentation rate and causing the filling of riverbeds.

The drop in the sediment content in discharges caused by the sedimentation in the reservoir reduces the course of water levels in comparison with the state prior to the reservoir operation. The fall in the water table reduces the potential energy, and augments the kinetic energy of water. This intensifies the erosion process, entailing a gradual increase in sediment and bed-load transport downstream, where, depending on the conditions, the water level may gradually approach the original one of the same discharge. Downstream of the reservoir, the period of turbid water discharges is usually longer because of the gentle sedimentation of fine particles in the reservoir.

The natural river channel downstream of the reservoir is also affected by the construction of many offtake and outlet structures, some stretches being regulated or paved in this connection. The natural riverside canopy, whose development and state depends on climatological conditions, altitude, soil and geomorphological conditions, bank slopes, exposition of the location and the water regime changes under the long-term influence of the water level alterations and consequent changes in groundwater table. Vegetation species which are not adaptable to the new conditions gradually expire, affecting the scenery and the relevant dwelling and recreational conditions.

The living conditions for fishes in the stretch which is affected by the operation of the reservoir and especially by

- changes in water quality, including temperature
- increase in the minimum and decrease in the maximum flood discharges and their occurrence,
- changes in the riverbed and associated flora,
- construction of obstacles for the movement of fishes upstream,

are drastically changed. These consequences include a decrease in the heterogeneity of the prevailing ecosystems, including the expiring of migratory fishes. The improvement of the water quality and the decrease in water temperature may result in the formation of a trout zone in the stretch downstream of the dam site. Intensive sport fishing is often recorded in these stretches, especially when this activity is not permitted on the reservoir, e.g. because its water is used for drinking purposes.

The flood control, water supply or multi-purpose effect of the reservoir operation increases the dwelling value of the affected area. But, downstream of the reservoir, there obtains the risk of a possible dam destruction. The probability of such an event is very low, but its consequences may be catastrophic, destroying economic values and threatening the population.

The effects of very large reservoirs appear even as far down as the estuary of the river into the sea, or where it expires in an area without outflow. The drop in the nutriment input and possible deterioration in water quality by human activity may limit the extent and heterogeneity of the quatic fauna including

fishes, as well as restricting fish production in the coastal zone. The decrease in sediment transport may result in erosion, deepening the estuary and aggravating sea-wave action.

The decrease in discharges caused by the reservoir operation or by water withdrawals results in an increased penetration of seawater upstream, with a consequent increase in soil salinity, also leading to a degradation of salt-resistant plant species including e.g. date palms. The saline effluents from irrigation schemes may also contribute to this degradation, a process which is more evident in the dry period of low river discharges.

The resulting stage in the estuary largely depends on the operation both of the reservoir and the associated water users. The increase in low discharges may cause a decrease in the average salinity, i.e. it may shorten the period of upstream penetration of the salty back water, which reduces the acreage of the affected area. Another consequence may be the raising of tracting forces, and the intensification of the self-purification process. In this way, a balanced reservoir operation can also improve the conditions for coastal flora, thereby augmenting both agricultural and fish production.

4.6.6 Effect of River Training and Open Channel Water Conveyance

The formation of riverbeds depends on hydrometeorological, hydrogeological, geomorphological and soil conditions. It is also affected by the occurrence and species of the vegetative canopy on the river banks. The basic natural functions of streams consist of

- (a) drainage and water conveyance
- (b) ice transport during the winter and spring season,
- (c) sediment and bed-load transport, soil quality regeneration,
- (d) groundwater table and soil moisture regulation, i.e. maintenance of conditions for the riverside vegetation,
- (e) maintenance of conditions for aquatic life and of environmental balance.

Incidental phenomena of these natural functions, such as floods, restrict the possibilities of utilizing the adjacent area for the various activities of human society, e.g. for intensive settlement, industrial and intensive agricultural production, mining, uninterrupted in-stream water utilization e.g. navigation and water power generation. The variability of the channels of natural water courses, their fluctuating water levels, changing discharges and also ice phenomena negatively influence the socioeconomic functions of water. For this reason water courses are trained and canals for water conveyance constructed with the aim of

- (a) improving the conditions of water supply and drainage, in-stream and on-side water use,
- (b) restricting inundations and consequent economic losses,

- (c) adapting the riverbed to the changing discharges, inland water transport requirements, power generation, sediment transport or ice regime phenomena,
- (d) increasing the dwelling value of the adjacent area,
- (e) stabilizing the river banks and river bottom, achieving directional stabilization, restricting the erosion process and removing its consequences,
- (f) improving the groundwater regime,
- (g) adapting the riverbed to the consequences of diversion dams and weir construction, as well as of the construction of communication lines, urban, industrial and agricultural development,
- (h) improving the water quality, safeguarding the desired sanitary conditions and the requirements of aesthetic enjoyment (Tab. 4.21).

The unavoidable precondition for ensuring the desirable effect of river training is that natural functions of the stream must not come into conflict with the desired goals. The flow of natural rivers and streams is frequently almost steady, i.e. changes very slowly with time. Unsteady flow occurs as flood waves or travelling surges. In natural riverbeds, this flow is non-uniform, changing slowly or suddenly in the magnitude and direction of the velocity along the streamline. Strictly uniform flow rarely exists in such channels. The cross section of a trained stream usually has a simple geometric shape. The flow in such a canal is generally considered to be uniform, only having slow changes of direction and no changes with distance in the value of the velocity along a streamline, with the exception of stretches upstream of drops, weirs and diversion dams, where non-uniform flow occurs.

The natural riverbed, though often not sufficiently stable in the short-term, is a result of the activities of external natural forces, and may be considered to be in long-term equilibrium with them. The prismatic channel of a trained river with a uniform flow cannot correspond to the complicated conditions of the original state and, destroying this long-term balance, frequently has a negative effect on some of the basic natural functions of the stream or river.

The biological equilibrium in the original ecosystems on the banks is a result of an interplay of the original groundwater level and corresponding soil moisture fluctuation. The conditions for the equilibrium of aquatic ecosystems depend on the interplay of water depth, flow rates, the morphology and material of the channel, and on the aquatic flora. Ecosystems, both aquatic and on the banks, generally need heterogeneous conditions for their development or survival. These conditions are unified by river training, or newly and uniformly established by the headrace or tailrace construction. Unified conditions are not acceptable for many relevant species. This results in a decline in their heterogeneity, signaling the disturbed biological balance. These changes occur gradually from the beginning of the construction work.

River training, if not accompanied by the construction of weirs and dams to

TABLE 4.21

| Hydraulic parameters | Discharges | Impact of river training | | Flora and Fauna | Dwelling value |
|--------------------------------|--|-------------------------------------|---------------------------|--|---|
| | | Increase | Decrease | | |
| Increased slope of the channel | Limited flooding | Change of sedimentation and erosion | | Change in water quality | Increased flood control |
| Extended cross section | Restricted natural fertilization | Change in water temperature | | Change in water flora | Improved agriculture |
| Increased velocity of flow | Restricted groundwater recharge | Increase in infiltration | Decrease in infiltration | Change in water fauna including fish species | Deteriorated soil regeneration |
| Increased drainage rate | Decrease in base flow during vegetation period | Rise in groundwater table | Drop in groundwater table | Change of riparian vegetation | Improved navigation and hydro-power generation |
| | Increase in winter discharges | Waterlogging | Excessive drainage | | Improved accessibility. Negative impact of water tourism |

Checklist of the probable impact of river training on the water cycle and riparian environment.

swell the water table, results in a substantial drainage effect. Such an effect may be supported by the associated irrigation network and result in a 10-20% increase in annual outflow in the first 4-5 years after construction. In the next period, the drainage impact on the annual outflow is not as substantial and mainly occurs as a regulating effect, increasing low discharges. Its effect on flood occurrence is controversial. Decreased moisture content in the upper soil layer increases the infiltration capacity, thus lowering the surface runoff. The increased flow capacity of the riverbed, and especially of the associated drainage network, increases the flow velocity and contributes to the increase in flood discharges. The drainage effect of river training and associated network increases the probability of flood occurrence and the value of flood discharges, depending on the soil and moisture conditions, i.e. depending on the share of the balancing effect of the increased infiltration capacity of the drained soil layer.

River training drastically changes the conditions for sediment transport. This can also be analyzed on the basis of the following simple formula, derived from the water depth, the flow rate and the grain size of the bed-load mixture

$$d_e = \frac{v_x^3}{K \cdot h} \quad (4.33)$$

- d_e - characteristic grain size of the bed-load mixture (m)
 h - water depth (m)
 v_x - minimum flow rate causing the onset of bed-load transport ($m \cdot s^{-1}$)
 K - coefficient of the sediment transport ($m^{1.5} \cdot s^{-3}$)
 (almost stable and = 216 according to Schamow)

River training influences both the water depth and the flow rates, and in this way changes also the characteristic size of the bed-load mixture and the intensity of the bed-load transport. This change in the bed-load transport may result in demands for further river training in the stretch downstream. River training usually has a positive influence on the ice regime in the regulated stretch, but due to its accelerating effect has negative impact on unregulated stretches downstream;

The negative impacts of river regulation result mainly from the reduction of the stream length, from the extension of the cross section and from the removal of the riverside vegetative canopy. This augments the drainage effect, increases the flow rates, accelerates the outflow and, limiting groundwater recharge, results in the reduction of evaporation and evapotranspiration.

River training may result in curtailing the duration of runoff from the source to the estuary, even to the extent of reducing it to half the original duration. The decrease in groundwater recharge limits the regulating effect of groundwater on surface water discharges, resulting in a decrease in average discharges during the summer period and in an increase in discharges in winter, thus causing a drop in agricultural production in the adjacent area.

The impact of headrace, tailrace and feeder, link and other conveyance canals is more drastic: They change the groundwater regime and associated ecosystems, they may cause waterlogging with associated salinity hazards in vast areas, they change the infrastructure of the area - severing the communication network and restricting the accessibility of certain areas both for the population and the wildlife. Their construction restricts wildlife occurrence, worsening the living conditions, especially of rare species, and permits fish to escape from reservoirs and rivers.

Conveyance canals enable the transfer of pollution and under certain circumstances form favourable conditions for the occurrence of insects and for disease dissemination. Nevertheless, an improvement in the conditions for water trans-

port, power generation, other multi-purpose utilization of water, settlement, agricultural and industrial production, recreation form the precondition for a development boom in the adjacent area (Tab. 4.20).

River training has to be realized only as an integral part of an improvement in the water regime in the adjacent area. It is, therefore, indispensable

(a) to simultaneously accept measures for changing the surface runoff into groundwater runoff, especially on the forest and agricultural lands,

(b) to simultaneously accept measures for achieving a biological equilibrium in the ecosystems of the river valley and the catchment, especially by determining the ecologically optimum ratio of arable land,

(c) to solve river training problems not only hydraulically, technically and economically, but also from an environmental point of view.

Streams and river channels are formed by the long-term impact of hydrometeorological, geological and biological processes. Substantial changes in the original river bed, in its route and in the accompanying vegetative canopy during river training may disrupt the balance which has been established by natural forces and endanger the course of natural functions.

Only when the construction respects the original state, the main natural functions and basic interrelationships, as occurs after minor amendments to the original river bed and through the construction of protection dykes adapted to the topography of the terrain, can the consequent state be predicted with satisfactory accuracy and therefore be managed to offer maximum benefits with minimized environmental losses.