GROUNDWATER RECHARGE FROM RUN-OFF, INFILTRATION AND PERCOLATION

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GROUNDWATER RECHARGE FROM RUN-OFF, INFILTRATION AND PERCOLATION

by

K.-P. SEILER

GSF National Research Centre, Neuherberg, Germany

and

J.R. GAT

Weizmann Institute of Science, Rehovot, Israel

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Cover Graph:
Discharge is generated by precipitation excess and transforms along interfaces into flow components with different turn-over-times and flow directions;. Overland- and inter-flow move both in lateral surface, respectively subsurface directions and have short turn-over-times. In contrast, groundwater recharge percolates vertical down and reappears very delayed in the surface water. The quantitative influence of the above mentioned interfaces on discharge depends from many factors changing with seasons, wet and dry cycles, rain intersities and even during individual rain events.

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PREFACE

Life on continents depends on the availability of fresh-water. Hence, preferred sites for human settlements were situated close to springs, rivers, or shallow groundwater resources, and it was accepted at the dawn of mankind that the local social and economic development was limited by the natural available water resources in a quantity and quality sense; any shortage in the availability of water stimulated people to migrate.

With the growing earth population and during the industrial age, water availability reached a new dimension: By technical means, water became everywhere available by drilling and piping and in more recent times also by low cost desalination methods. This seemingly ubiquitous water availability let in many areas of the world to an overexploitation of water resources often with the consequence of a deterioration of fresh-water quality by salt water intrusions from deep aquifers and in coastal areas from the sea, or by subsidence, which changed hydraulic properties of aquifer systems. These adverse developments have always a transient character; this means the hydraulic system responds with a more or less long delay time till reaching new steady-state conditions and often create new situations that—when ever—can only be managed with high costs.

In humid areas of the world, the limiting factor for groundwater development became mostly water quality, in semi-arid and arid areas, it is both water quantity and quality. To overcome these problems, safe-yield concepts in terms of water quantity and water quality have been developed. Simplistically,

- The quantity safe-yield concept is based on the replenishment of surface/subsurface systems either by natural or artificial (groundwater) recharge; this concept has not only to consider average inputs and outputs, but also the year to year meteorological fluctuations, droughts, floods and socio-economic facts.
- The quality concept is based either on the natural, good water quality or on threshold concentrations to protect health and life of beings and ecosystems.

It is often overlooked that the amount of water extraction, according to the needs of the urban and industrial, agricultural and recreational development of a region, changes not only the local water cycle, but can also introduce new boundary conditions for recharge and discharge pathways. This is often also accompanied by a deterioration of water quality, which cannot be completely governed by respective water treatment measures. Finally, the local water demand has often been satisfied by water imports without considering seriously, if such measures exceed the water drainage and natural attenuation capacity of the respective region and aquifer system.

A new challenge raises with climate changes, in particular a change in the precipitation amount and pattern, which will modify the water cycle, specially the water availability on continents. The groundwater response to such climate changes will not be instantaneous, but transient; therefore, any prediction on respective changes in the fresh-water resources will not persuade at present water users, because negative effects do not appear instantaneously, but it will in a remote time, when deterioration of water resources already proceeded so far that it may have become irreversible.

This book focuses on the present global and local water cycle, especially how precipitation changes water fluxes at the interface atmosphere/lithosphere/biosphere, within the weathering zone of sediments/rocks and in the subsurface. The detailed understanding of these processes allow a better estimate and assessment of the components of the water cycle and a better prediction of the impact of men's activities on the water cycle. These facts are documented by some examples from the main climate zones of the globe. In contrast, this book does not consider the wide field of fresh-water quality.

Klaus-Peter Seiler
Joel R. Gat

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ABBREVIATIONS AND DIMENSIONS

A	Area	m^2 or km^2
BBM	Black-box models	–
b.g.s.	Below ground surface	–
C	Concentration	mg/L or g/m^3
dpm	Decays per minute	–
D'	Dispersion coefficient	m^2/s
D'_L	Longitudinal dispersion coefficient (x-direction)	m^2/s
D'_T	Transverse dispersion coefficient (z- or y-direction)	m^2/s
D	Specific run-off	mm/year or L/(s km^2); 1 L/(s km^2) = 31,536 mm/a
D_G	Specific groundwater run-off	mm/year or L/(s km^2)
D_I	Specific inter-flow run-off	mm/year or L/(s km^2)
D_M	Molecular dispersion	m^2/s
D_O	Specific overland-run-off	mm/year or L/(s km^2)
D_T	Specific discharge transfer	mm/year or L/(s km^2)
D_{SF}	Specific surface run-off	mm/year or L/(s km^2)
DM	Dispersion Model	–
e	Vapor pressure	mbar
eq.	Equation	–
EM	Exponential Model	–
EP	Evaporation	mm/year or L/(s km^2)
ET	Evapo-transpiration	mm/year or L/(s km^2)
g	Gravity acceleration	m/s^2
GMWL	Global Meteoric Water Line	–
h	Height	m
h'	Relative humidity	– or %
H	Hydraulic head at water saturation	
	Volumetric related	*Pa*
	Weight related	*m*

H_c	Capillary head	m
H_g	Gravity head	m
H_o	Osmotic head	m
I	Activity concentration	Bq/L
IN	Infiltration	mm/year or L/(s km^2)
K	Hydraulic conductivity	m/s
LAI	Leave area index	–
LMWL	Local Meteoric Water Line	–
m	Empirical parameter	–
M	Mass	kg
MTT	Mean-turn-over-time, Mean-transit-time Mean residence time	day, year
MTT_W	Mean-turn-over-time of the water	day, year
n	Empirical parameter	–
N		mol/m^3
p	Pressure	mbar
p'	Porosity	– or %
pmc	Percent modern ^{14}C	%
P	Precipitation	mm/year or L/(s km^2)
Pa	Pascal	kgm^{-1}s^{-2}
PFM	Piston Flow Model	–
q	Specific flow rate	m^3/(s m^2)
Q	Discharge/flux	m^3/s
r	Capillary equivalent radius	cm
R'	Groundwater recharge	mm/year or L/(s km^2)
R	Isotope ratio, e.g., $^2H/^1H$	–
S	Storage	% or mm/year
S'	Water saturation	– or %
S_c	Storage coefficient	–
S_e	Effective saturation	%
T	Time	second, hour, day, year
T'	Thickness	m
$T_{0.5}$	Half live	year
T	Temperature	°C
TBT	Tracer break through curve	–
TP	Transpiration	mm/year or L/(s km^2)
TU	Tritium unit	–
WMO	World Meteorological Organization	–
v_f	Filter velocity	m^3/(m^2 year) or m/year
v_a	Apparent flow velocity	m/year
V_T	Total volume	m^3
V_V	Void volume	m^3

V_W	Water volume	m^3
x, y, z	Distances and Cartesian co-ordinates	m
α	Separation factor	–
α^*	Thermodynamic separation factor	–
α'	Dispersivity	m
β	Water-solid contact angle	degrees
γ	Constant parameter	–
δ	Deviation of stable isotope contents from a standard	‰
ε	$(1-\alpha)$	–
ε^*	$(1-\alpha^*)$	–
λ'	Tortuosity	–
λ	Decay constant	time^{-1}
θ	Water content	%
θ_s	Water content at saturation	%
θ_{fc}	Water content at field capacity	%
θ_r	Residual water content	%
θ_w	Water content at wilting point	%
σ	Surface tension	g/s^2
ρ_W	Density of water	g/cm^3
Ψ	Suction	
	volumetric related	*hPa*
	weight related	*mm*
Φ	Hydraulic head as the Sum of $(\Psi + H)$	
	volumetric related	*Pa*
	weight related	*m*

DEFINITIONS

Active groundwater recharge zone: Aquifer zone, which hosts groundwater recharge with mean turnover times of <100years. Groundwater in this zone is also named shallow groundwater (section 2.4, Fig. 2.10).

Base-flow: Surface discharge fed by groundwater (section 2.3, Fig. 4.3). Under dry weather conditions, groundwater is the only discharge component in rivers.

Capillary fringe: The capillary fringe is the transition zone from water unsaturated to water saturated conditions in the subsurface. In it, capillary forces still play a role, but gravity forces increasingly dominate, when approaching the groundwater table/surface (section 2.3).

Connate water: Water entrapped in sediments, which was not in contact with the biosphere since sedimentation time (section 2.4, Fig. 2.11).

Deep groundwater: Groundwater in the passive groundwater recharge zone with mean turnover times exceeding 100 years (section 2.4), but being by far younger than connate water (Fig. 2.11).

Direct run-off: Surface run-off, which immediately responds to rain events. Direct run-off consists of the components overland- and inter-flow (section 2.3).

Discharge: Discharge is made up of the residuals, produced by precipitation in excess to evapo-transpiration and to water retention in the unsaturated zone. It can take the form of base-flow, inter-flow or overland-flow (Fig. 4.3).

DOC: Organic carbon in water with particle sizes <0.45 μm (**D**issolved **O**rganic **C**arbon). In contrast, the sum of all organic matter in water is called **T**otal **O**rganic **C**arbon (TOC).

Epizone of consolidated rocks: Zone of decompression and weathering upon consolidated rocks. The epizone collects infiltration, may create perched groundwater and distributes the infiltration flux between the flow paths of inter-flow and groundwater recharge (section 2.3, Fig. 2.7).

Groundwater recharge: Component of infiltration into the subsurface that joins groundwater through the unsaturated zone, the river bed or lake ground.

Groundwater: Underground water that completely fills the pores of an aquifer, following only gravity forces. Groundwater discharges to rivers, lakes or directly to the ocean.

Indirect run-off: Surface run-off, which responds delayed to rain events. Base-flow or groundwater discharge to rivers is synonymous with indirect discharge (section 2.3, Fig. 4.3).

Infiltration: Infiltration is the process of transition of precipitation or surface water into the lithosphere; strictly spoken, it describes the process of how the dimensions of unsaturated flux and storage are influenced by the entry of water into the lithosphere. Infiltration contributes to inter-flow and groundwater recharge (section 3.3, Fig. 4.2).

Infiltration capacity: Maximum amount of water that can infiltrate into the subsurface. Water in excess of the infiltration capacity produces either overland-flow or excessive ponding at the infiltration surface. Infiltration capacities depend on actual fabrics and water contents of the sediment.

Inter-flow: Run-off component that follows in the subsurface approximately the morphology of the landscape (Fig. 4.2) and was in exchange with stored water of the unsaturated zone, but not necessarily with groundwater (section 3.3). Inter-flow joins on its flow path surface run-off either directly or mixed with overland-flow.

Overland-flow: Run-off component that did not infiltrate (Fig. 4.2) or infiltration excess discharge. It follows flow paths along the land surface and joins surface run-off in rivers (section 3.3).

Passive groundwater recharge zone: Aquifer zone, which hosts groundwater recharge with mean turnover times of >100 years. Groundwater in this zone is also named deep groundwater (section 2.4, Fig. 2.11).

Perched groundwater: Local groundwater accumulation upon low hydraulic conductivity interfaces within the vadose zone; perched groundwater is over- and underlain by unsaturated zones (section 2.3, Fig. 2.7).

Percolation: Flow in the unsaturated zone. In contrast to groundwater flow, percolation can follow all directions, even against gravity, because it is driven by both gravity and capillary gradients (section 2.3).

Regional groundwater: Groundwater of large extent, forming a hydraulic continuum and discharging close to the water table to local and at depth to distant receiving rivers (section 2.3).

Run-off: Components of discharge like direct (overland- + inter-flow) and indirect run-off (base-flow or groundwater discharge), overland-flow, inter-flow, groundwater recharge (Fig. 4.3).

Saturated zone: Groundwater zone.

Shallow groundwater: Groundwater of the active groundwater recharge zone with mean turnover times of <100 years (section 2.4, Fig. 2.11).

Surface discharge: Discharge in a river, representing one or a mix of different run-off components (section 2.3, Fig. 4.3).

Unsaturated zone: The unsaturated zone contains water and air with sharp interfaces, in which flow is governed by both capillary and gravitation forces and in which most of the time capillary forces are dominant (section 2.3).

Vadose zone: The vadose zone stretches from the ground surface to the regional groundwater table/surface and consists of maximum three distinguishable elements: the unsaturated zone, perched groundwater and capillary fringes (section 2.3).

CHAPTER 1

INTRODUCTION

Fresh-water on continents is made up by two-third of ice and one-third of non-solid water. Groundwater accounts for 96.3% of all non-solid fresh-water resources (8,000,000 km^3), followed by lake water (2.7%), soil water (0.8%), and river water (0.01%); the rest belongs to atmospheric water vapor. Most lakes are interrelated with groundwater; more than 45% of the surface discharge of rivers in humid and semi-arid climates originates from groundwater, whereas in arid (dry-land) and cold climates surface discharge contributes to groundwater. Hence, this subsurface resource is associated with altogether 8,300,000 km^3 of water. Less than 50% of this water was recharged within the last 100 years through the present water cycle, the rest was renewed in the historic and geological past under climate conditions, which are not precisely known; hence, groundwater hydrology is faced with various water storage forms and run-off systems, changing with time.

At present, groundwater is the major resource of water supply for about half of the nations. Approximately 40% of the world's population uses groundwater and about 50% of the world's food production depends on irrigated agriculture linked to groundwater. During the 20th century, the water demand of human beings increased 6 times while population tripled; it is expected that this trend will continue into the 21st century.

Apart from human needs, water plays an important role in distributing energy and matter over the globe, in the functioning of ecosystems and in natural attenuation processes. Fortunately and in contrast to other geological deposits of economic value, the water cycle results in the renewal of water resources and triggers together with local or regional, orographic, tectonic, and ocean level settings groundwater flow. In humid temperate and tropical climates, natural groundwater flow is mostly at steady-state, in permafrost and arid (dry-land) areas (Lloyd 1980) often transient. Groundwater management and land use, however, often add a man-made transient behavior to groundwater flow, which, however, is usually not immediately discernible.

It is evident from the data on water withdrawal and consumption (Table 1.1) and water availability (Table 2.2) that in some areas of the globe, water demand is close to or already exceeds the availability of the present rechargeable water. Thus, the social and economic welfare depends today and even more in the future

Table 1.1. Water withdrawal and consumption in the 20th century and the extrapolated development to the beginning of the 21st century

	Withdrawal (km^3)	Consumption (km^3)	Agriculture (%)	Industry (%)	Private sector (%)	Others (%)
1900	579	331	88.6	7.5	3.7	0.2
1950	1,382	768	78.1	14.8	6.3	0.8
1980	3,174	1,686	66.5	22.5	6.9	4.1
2000	3,975	2,182	65.6	19.5	9.7	5.2
2025	5,236	2,764	60.9	22.3	11.6	5.2

Water consumption is detailed according to the main sectors of water use (UNESCO, 1999).

on rechargeable, treated, and imported water. But all options of water import, if realized, may have various economic and environmental consequences, which have not yet been studied in sufficient detail.

In recent years, the possible diminution of water resources as a consequence of man-made global climate changes is drawing additional attention of the scientific community. Although the extent of such changes is still difficult to predict, new strategic approaches have to be developed to provide more flexible answers to both new and existing challenges.

Groundwater resource development is based on the concept of groundwater yield, which turns out to be difficult; it has to meet a set of hydrologic, social, and economic objectives and may be defined as the balance between the benefits of maximum allowed extraction rates and undesired changes by pumping and pollution. In this concept groundwater recharge is one important component, which is mostly determined under special steady-state initial and boundary conditions; however, groundwater development may change these conditions throughout the recharge–discharge regime with time. Therefore, the development of sustainable groundwater management strategies cannot refer to single numbers but needs an integrated concept within a specific timeframe.

The management of groundwater resources involves, among others, the following subjects:

- Determination of the range of groundwater recharge with appropriate methods,
- Manipulation of groundwater recharge according to local needs and possibilities,
- Protection of the recharge pathways to safeguard natural attenuation,
- Monitoring aquifer exploitation,
- The development of special control (early warning) systems to recognize, assess, and prevent groundwater degradation in time.

The paramount importance of the recharge process in this scheme is clear. Therefore, this book is devoted to groundwater recharge.

Groundwater recharge in humid temperate and tropical climates typically accounts for more than 10% and in arid (dry-land) areas for less than 5% of the precipitation; in semi-arid and cold climates the values lie in between these numbers.

There are six general approaches to determine groundwater recharge:

- Bulk mass balance methods,
- Methods based on outflow characteristics,
- Mixing approaches,
- Numerical/hydraulic,
- Tracer flux, and
- Mean-transit-time methods.

The precision in determining groundwater recharge depends significantly on

- The conceptual model, based on which percolation has been evaluated,
- The precision in determining the source (precipitation, snowmelt, dew formation, and infiltration) and loss functions (evapo-transpiration, overland-flow, interflow),
- The time span, to which groundwater recharge refers to.

According to the precision and the time increment for which groundwater recharge has to be determined, lots of modifications of these six basic approaches have been established.

The results of these various methods to determine groundwater recharge have different scale relations. Flux methods, are based on artificial tracing, refer to the smallest, bulk mass balance methods to the largest scale and inverse calculations as well as many discharge analysis often deal with an intermediate scale of groundwater recharge.

In contrast to infiltration, percolation is a rather slow process and both change with boundary conditions mostly in a non-linear way: therefore, only average values of groundwater recharge result from most studies. Nowadays, however, there is also a strong interest to obtain short-term information on infiltration, discharge, and the storage of subsurface water for agriculture and irrigation planning as well as for early-warning systems to improve flood control.

Long-term information on the water balance refers mostly to precipitation and discharge measurements on a catchment scale; this needs a minimum of 10 years to more than 25 years of observation in humid temperate, respectively tropical and arid (dry-land) climates. Such long-term observations

- smoothen the short-term variability of precipitation and evapo-transpiration, which govern the input function of discharge and
- reduce errors related to delayed responses of the subsurface system in connection with water storage and release and slow percolation velocities.

In developed countries, such long-term observations on discharge and groundwater level fluctuation exist continuously since the end of the 19th and beginning of the 20th century and are still operating. In many developing countries and areas with a small population, such measurements mostly started in the second half of the 20th century by the initiative of the WMO; however, these observations often stopped after some years or decades, because of logistic problems. Because of these circumstances it is important to apply complementary methods, which also act in support of the long-term observations, that deliver time- and space-integrated information on groundwater recharge. For the last 60 years, this was step by step realized with artificial and environmental tracer techniques that have been developed since the 1940s using chlorides (Schoeller, 1941) and environmental isotopes (Münnich, 1968) or analyzing in rivers the hydraulic (Natermann, 1951) or environmental tracer response (Sklash et al., 1976) to storm events.

Groundwater recharge on continents has an uneven horizontal and vertical distribution;

- Horizontally, it depends
  - on climate and weather trajectories (section 2.2.2),
  - transformations of precipitation and air humidity at the interface atmosphere/ biosphere/lithosphere (section 3.2),
  - topographic factors and lithology (section 3.3),
  - hydraulic interfaces in the effective root zone (section 3.5);
- Vertically, it depends on the depth-related sequence of hydraulic parameters and the thickness of aquifer systems (section 2.4).

In all climate zones, old (>100 years) and fossil groundwater (>10,000 years) are more abundant than the presently recharged groundwater (<100 years old); these old (historic) and fossil groundwater should not be wasted, in order to keep operational a buffer system for variable natural, man-made recharge, the many ecological functions of water and emergency situations (Vrba & Verhagen, 2006).

Groundwater recharge can be manipulated by selecting an appropriate vegetation cover, by forced gradient river-infiltration (section 3.6) and by artificial recharge through basins, ponds, artificial lakes, and wells (section 3.7).

Both the quality and the quantity of the recharged waters are significantly influenced by the plant cover and land use, especially by irrigation practice, urbanization, industrialization, traffic, and in more recent times also by the import of blue water from distant areas.

Considering the above-mentioned general facts, this book intends to

- describe the factors that influence groundwater recharge,
- describe methods to measure groundwater recharge,
- draw attention to possibilities and limitations of manipulation of groundwater recharge.

CHAPTER 2

THE WATER CYCLE

The lithosphere, oceans and the atmosphere form the largest reservoirs on earth. The main link between these reservoirs is the hydrological cycle, which provides fresh-water for humans, continental ecosystem functions, weathering, and sediment transport and is co-responsible for the temperature equilibration on earth. The driving force of the water cycle is solar radiation, contributing with an average of 10^{24} J/year to water evaporation; for comparison, the European Community consumes about 7×10^{19} J/year of energy.

Annually, about 1 km^3 of water enters the water cycle from both the earth's interior and the space. The escape of water into the space and the return of water either to the earth's interior through plate-tectonics or by binding water through the weathering of feldspars and others (about 0.7 km^3/year) are estimated to be of the same order of magnitude. As compared to the yearly turn over of 577,000 km^3 of water through the water cycle on continents and oceans (Fig. 2.1), uncertainties in determining this 1 km^3 are negligible on a long and short run of time.

2.1. DISTRIBUTION OF WATER ON EARTH

Water on earth accounts for about 1.386×10^9 km^3: most of it is liquid, some occurs as ice and very little is in the form of vapor (about 13,000 km^3). Ocean water constitutes about 97.5 vol.% and fresh-water the remaining 2.5 vol.%. The distribution pattern of solid, liquid and vapor water is temperature dependent and accounts for the difference between conditions on earth as compared with other known planets within the solar system.

Except for sea-ice at the North Pole, all fresh-water is found on the continents:

- 68.9 vol.% is fixed in ice shields, glaciers (27,000,000 km^3) and permafrost (about 300,000 km^3, Shiklomanov, 1990); glaciers and perennial snow cover an area of about 680,000 km^2);
- 29.9 vol.% belongs to groundwater,
- 0.9 vol.% to soil moisture and atmospheric water vapor and
- 0.3 vol.% appears as surface water.

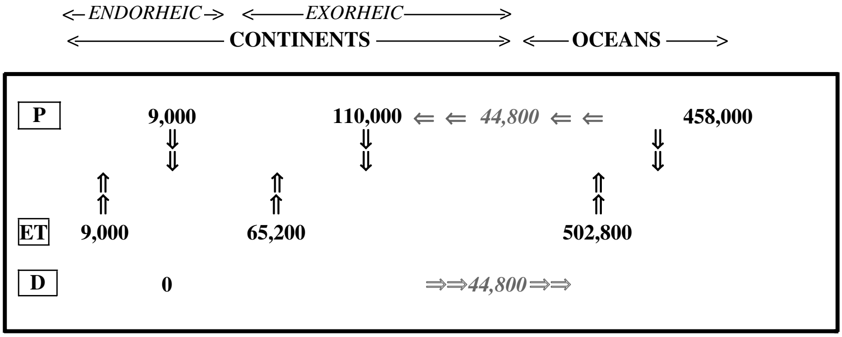

Figure 2.1. The global water cycle. All numbers in km^3 (UNESCO, 1999)

Groundwater represents the most important resource for continental ecosystems. This is especially not only true for semi-arid and arid areas but also for all rock formations in other climates with unlimited infiltration capacities (karst, gravels).

On the time scale of a century, the hydrologic water cycle is to a first approximation balanced; however, on different time scales it appears imbalanced according to the reservoirs through-flown by the different run-off components. To better understand the importance of such reservoirs for the fresh-water balance, mean-turn-over-times (MTT) are considered (Table 2.1). From these it becomes evident that connate water represents a non-renewable resource within geologic time scales (section 2.4); in contrast, atmospheric water vapor, shallow groundwater, lakes and rivers are significantly recharged by the present water cycle. In between renewable and non-renewable groundwater occurs an intermediate zone, named deep groundwater by Seiler and Lindner (1995), which received its groundwater recharge in geologic or historical times and is little fed by the present groundwater recharge.

All glaciers and perennial snow represent these days a long-term water reserve, contributing to water supply; ice shields do not in the same extent, because they are too remote from consumers. With global warming they are expected to reduce in

Table 2.1. Average mean-turn-over-times for waters in different reservoirs

Ocean	~2,500 years
Cold glaciers	>100,000 years
Temperate glaciers	<500 years
Connate water	>1,000,000 years
Deep groundwater	>>100 years
Shallow groundwater	<100 years
Lakes	~15 years
Rivers	~16 days
Atmospheric water vapor	~10 days

volume, which may hide for a long period the real consequences of climate changes on fresh-water availability in the respective areas (section 6.3).

Continental water resources have an unequal latitude distribution. This is due to the uneven distribution of solar radiation on earth, the global atmospheric circulation pattern and its modifications by heat capacities and albedo, the size and topography of continental masses and interactions between the atmosphere and warm or cold ocean currents (section 2.2.1).

According to the most recent world water balance (UNESCO, 1999), the yearly discharge from all continents amounts to 44,800 km^3 (Fig. 2.1), and the distribution of average discharge from the different continents to the oceans is summarized in Table 2.2. In the time span 1921–1985, discharges did not show a marked tendency of increase or decrease (UNESCO, 1999); this may either be interpreted in terms of

- Steady-state conditions in the water cycle over this run of time or
- Changes in temperatures, precipitation and evapo-transpiration do not show up instantaneously, because of long mean residence times in the respective reservoirs, hence, of a transient character of discharge.

Based on world population census in 1985, discharges are related in Table 2.2 to the capita of the respective area. These numbers should be assessed relative to the demand per capita, which approaches

- an average of 1,000–1,500 m^3/year (maximum 2,500 m^3/year in the USA); this quantity includes
- about 50 m^3/year for the private sector and
- about 5–10 m^3/year for survival.

The numbers in Table 2.2, however, do not consider that any use of blue water produces gray water; empirically, 1 m^3 of untreated gray water needs for the restoration of natural attenuation before reaching the ocean in exorheic or terminal areas in endorheic systems (Fig. 2.2)

- About 9 m^3 of blue water if rejected untreated and
- About 3 m^3 of blue water if rejected after physical, chemical and biological treatment.

The numbers in Table 2.2 show on the average that

Table 2.2. Relative distribution of renewable water resources in world regions (1921–1985) as related to a discharge of 44,800 km^3 and the availability of rechargeable water in m^3 per capita and year (UNESCO, 1999)

Continent	Percentage of discharge	Rechargeable water in m^3/(capita and year)
Asia	31.5	3,920
Europe	6.7	4,200
Africa	9.8	5,720
North America	18.4	17,400
South America	28.0	38,200
Australia and Oceania	5.6	83,700

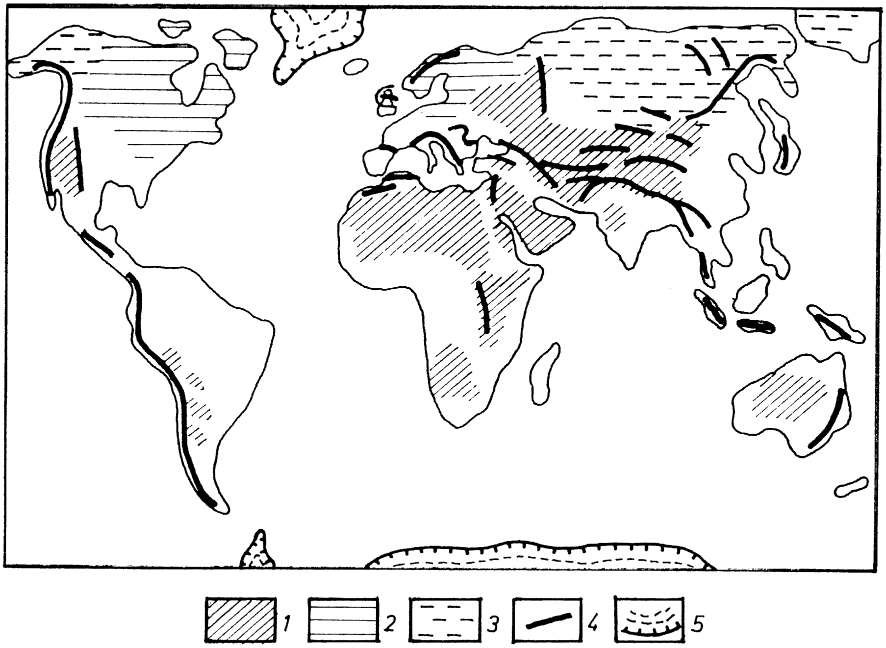

Figure 2.2. The influence of morphologic and geologic factors on discharge. 1 = endorheic areas, 2 = ice melt areas, 3 = permafrost, 4 = mountains, 5 = ice sheets (Starkel, 1995)

- Australia, Oceania and the American continent have a significant excess of fresh-water,
- Europe, parts of Asia and Africa might soon or already do reach limits in using rechargeable water of the present water cycle.
- The Near East and North Africa are so short in water recharge that most of the nations in this area are already over-exploiting their water resources; as an example Kuwait has only 0.2 m^3/(capita and year).

Shortening of available water by means of a non-adapted management or an excessive demand becomes evident in many parts of the world; the Aral Lake and the Dead Sea are shrinking in size; since 1972, the Yellow River (China) runs dry over increasing periods of time a year (Fig. 2.3); water follies are known in North America (Glennon, 2002) and in many areas of India groundwater levels decline continuously. Under these circumstances, renewable fresh-water resources can no longer be considered as a free-of-charge-gift of nature.

2.2. THE CONTINENTAL WATER CYCLE

By means of water quantities, the main present source and sink area of the water cycle are oceans. No doubt, on a long time scale, the naturally waxing and waning ice shields and permafrost areas, which exist on earth since the Miocene period, also act as a significant source and sink term of the water cycle, producing ocean

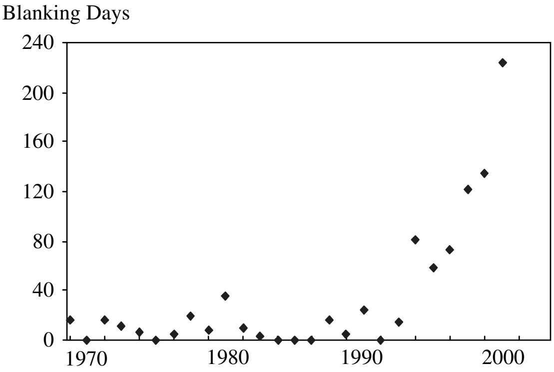

Figure 2.3. Days without surface discharge (blanking days) in the Yellow river in the period 1972–2000

level fluctuation of 150–200 m compared with the present ocean level; however, on a short time scale, this sources or sinks are not too appreciable.

One can distinguish between a continental and an oceanic branch of the water cycle (Table 2.3, Fig. 2.1), which are interconnected. Most of the water evaporates over oceans and falls back as precipitation to the ocean; however, 9% (44,800 of 502,800 km^3) of the water vapor of the oceanic evaporation joins air humidity of continental evaporation, precipitates on continents and returns as surface or subsurface run-off to the oceans (exorheic areas). There is also an endorheic water cycle branch on continents, which has no outflow to the oceans (endorheic areas, Fig. 2.2), but operates an intra-continental run-off evaporation mechanisms (such as the catchments of the Aral Lake, Baikal Lake and Dead Sea).

Strictly speaking, any safe water use in quasi-equilibrium with the present water cycle is limited to the present run-off, discharging from the continents to the ocean either as river water or as groundwater. Any potential use of ancient water, stored in deep aquifers, beneath permafrost or in glaciers as well as of waters, which are

Table 2.3. World water balance (UNESCO, 1999) and the distribution of exorheic discharge to the oceans

		Oceans	Exor. areas	Endor. areas	Σ
Evapo-transpiration	mm/a	1,393	548	300	
	km^3	502,800	65,200	9,000	577,000
Precipitation	mm/a	1,269	924	300	
	km^3	458,000	110, 000	9,000	577,000
Discharge	mm/a		124	0	
	km^3	–	44,800	0	
					44,800
Discharge in % of 44,800 km^3 into the					
Atlantic			46.9		
Pacific			29.9		
Arctic			11.4		
Indic			11.2		

unproductively consumed by evaporation in endorheic areas, must be approached with caution to ensure that no negative feedback is produced, affecting delicately balanced ecosystem functions and, hence, may lead to severe supply and ecological problems on a long run of time.

2.2.1 The Components of the Water Cycle

The motors of the water cycle are *evaporation* and gravity; evaporation occurs along ocean and continental surfaces (Fig. 2.4) and is enhanced by the transpiration of continental plants.

This EP-/ET-flux amounts to:

- Oceans (502,800 km^3/year or 1,393 mm/year),
- Exorheic areas of the continents (65,200 km^3/year or 548 mm/year),
- Endorheic areas of the continents (9,000 km^3/year or 300 mm/year).

Ocean areas with an excess of evaporation are the central and south Atlantic, the south Indic and the central and south Pacific oceans, all at low latitudes (Fig. 2.4). Depending on the distribution of land and ocean surfaces, these regions of preferential evaporation reach up to 40° in the south-hemisphere and to 30–35° in the north-hemisphere (Fig. 2.4).

The limited availability of water at continental surfaces is the one reason that the evaporation rate on continents is less than 40% of that on oceans. The other factor is the low net solar radiation received by the land surface compared with the ocean surface; this is mainly caused by the albedo—the reflection of solar radiation – which is only 3–10% for oceans and ranges on continents from 7%

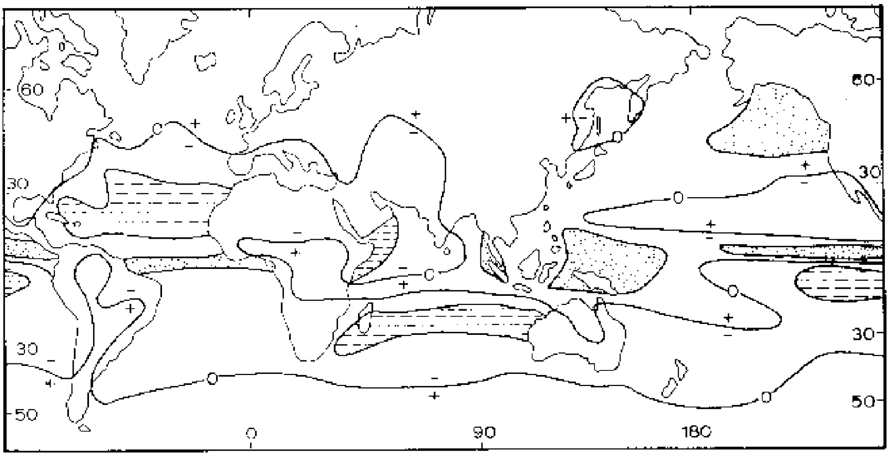

Figure 2.4. Precipitation/evaporation ratios exceeding (+) or remaining below (−) mean global ratio. Stippled areas: precipitation excess >100 mm/year; dashed areas: evaporation excess >100 mm/year (Lisitzin, 1971)

Table 2.4. Albedo of different surfaces without and with vegetation covers (List, 1951)

Surface	Albedo in %	Surface	Albedo in %
Fresh-water lake	6–10	Humic soil, dry	14
Forest, green	3–10	Humic soil, wet	8
Forest, snow covered	10–25	Wheat field	7
Sand, dry	18	Grassland, dry	15–25
Sand, wet	8	Grassland, wet	11–33
Death Valley desert	25	Snow, fresh	80–90
Bare soil	10–20	Snow, old	70
		Glacier with few snow	46

The albedo is the ratio of reflected/incoming short wave radiation.

(tropical rain forests) to about 25% (dry, white sands). Some albedo values are indicated in Table 2.4.

The evaporation (EP) from an open water surface under given environmental conditions is termed 'the potential evaporation' and is a measure of the to-be-expected EP-flux. The magnitude depends inter-alias on the surface temperature, which determines together with the saturated vapor pressure at the water surface the energy supply that balances the cooling of the surface because of a loss of the latent heat, the humidity gradient across the atmospheric boundary layer and the turbulent air exchange, related to the wind speed (section 4.1.1).

Evaporation from a land surface is enhanced by transpiration of plants that pump water from beneath the evaporating front in the subsurface (Fig. 4.30) to be evaporated at the plant surface. As a result, the ET depends on a combination of

- the energy and moisture balance at a specific surface,
- the aerodynamic conditions, which involve considerations of the effect of the surface roughness and
- physiological parameters related to the plants.

The best-known energy balance/aerodynamic method to calculate EP (section 4.1.1) was developed by Penman (1948). Haude (1954) simplified and Monteith (1965) modified Penman's formula so as to make it applicable to vegetation surfaces, by introducing monthly constants for different types of vegetations (Haude, 1955) (Table 4.5) or by introducing biological and plant aerodynamic resistance factors, expressing development and respective physiology characteristics of the vegetation cover (Monteith, 1965). With the Haude (1955) method an ET close to the present one originates, but reliable data can only be achieved for periods of months or longer although calculated on the base of daily data. On the contrary, Monteith (1965) refers predominantly to a potential ET and with some restrictions can be applied on a daily, better on a weekly base.

On green areas of continents, TP amounts in the vegetation period to more than 65% and evaporation to less than 35% of the total ET; during the cold seasons of mid- and high latitudes, evaporation accounts more or less only for water losses; in this cold season also some sublimation from the snow covers can play a role (Moser & Stichler, 1975; Stichler et al., 2001), albeit very little.

Precipitation: The average annual vapor content in the atmosphere reaches about 50 mm of water equivalent in-low latitude regions and decreases to less than 5 mm over high-latitude areas; air humidity generally travels from the warm, low latitudes to the cold, high latitudes, and precipitates out along this trajectory.

Precipitation is caused by condensation of water vapor when air is cooled below its dew point. This cooling is caused by the interaction of air masses, by adiabatic expansion of uplifted air, because of the decrease in atmospheric pressure with elevation. This process releases heat, which can provide additional energy for a further rise of air masses, resulting occasionally in convective thunderstorms (section 3.1).

The rising air along the equatorial convergence zone produces the high rainfall of the tropical areas, whereas the high pressure belt in mid latitudes with its heating of the descending air by compression lacks relative humidity and is responsible for the desert areas of North Africa. In contrast, the low relative humidity of the inner Asian deserts results from continental and topographic effects (Fig. 2.2) on rain-out of air moisture.

On the continents, annual rainfall exceeds continental ET in exorheic areas, because ocean evaporation contributes 44,800 km^3 to continental precipitation; this contribution is in equilibrium with the present run-off of fresh-waters to the ocean.

According to the main source areas of excessive marine evaporation (Fig. 2.4) as well as the mechanisms and influencing factors on rain-out of air humidity (section 3.1), precipitation is very unevenly distributed on the continents (Fig. 2.5); this results together with the uneven heat distribution on earth in cold, temperate, tropical, subtropical and arid (dry-land) climate zones (section 2.2.2); these climate zones are further subdivided according to the local conditions.

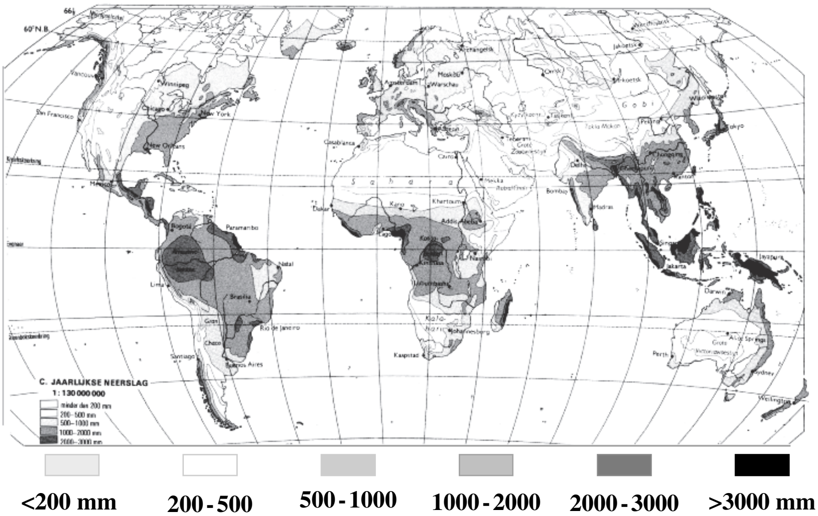

Figure 2.5. The global pattern of annual precipitation