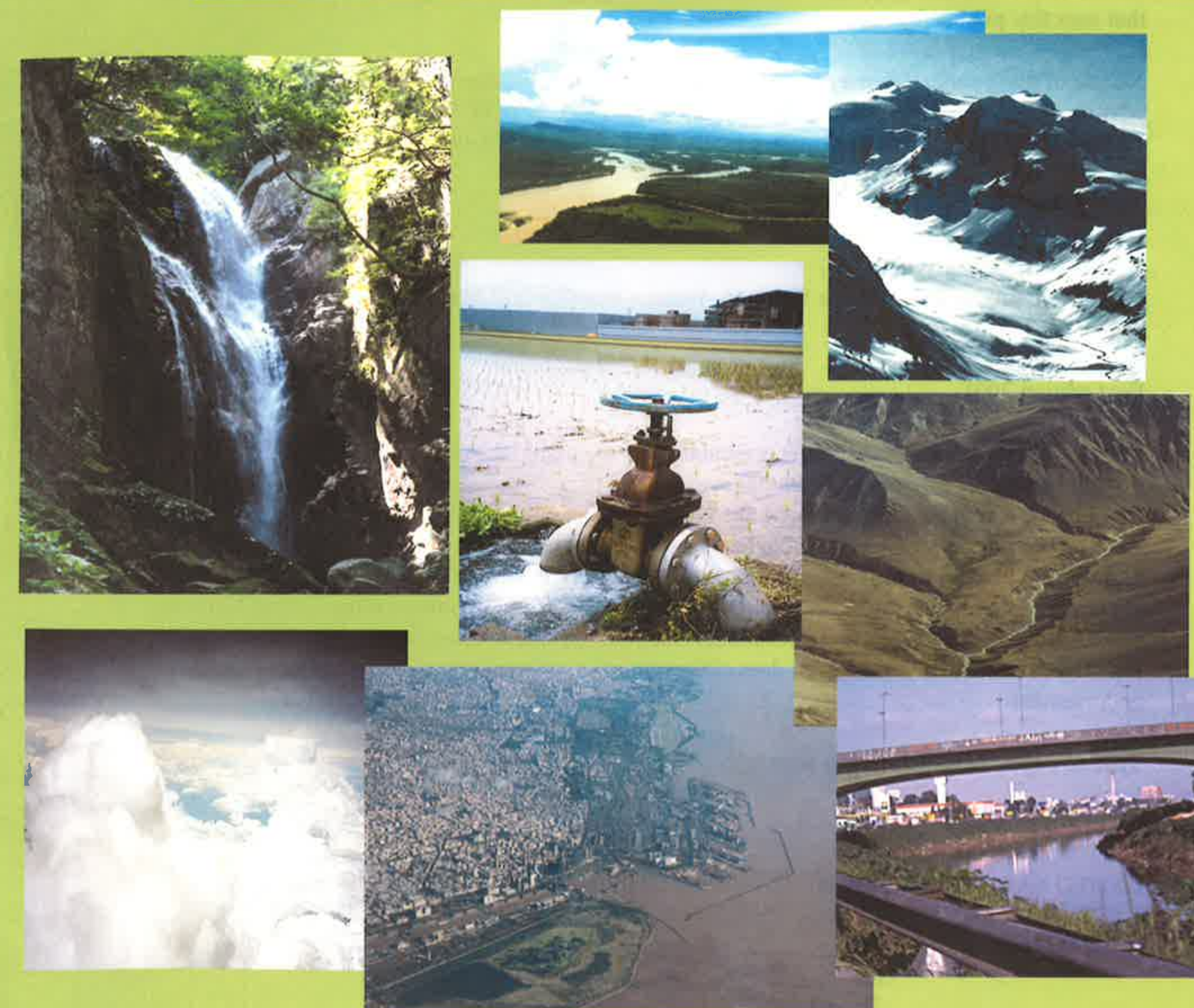
Lakes and Reservoirs

The Watershed: Water from the Mountains into the Sea



International Lake Environment Committee Foundation
United Nations Environment Programme - Division of Technology, Industry and Economics - International Environmental Technology Centre

UNEP
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Vol. 2

The UNEP-International Environment Technology Centre (IETC) and
the International Lake Environment Committee Foundation (ILEC)
Lakes and Reservoirs: The Watershed: Water from the Mountains into the Sea
(UNEP-IETC/ILEC Vol. 2)

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First edition 2001

Type of paper: Non-wood pulp paper

UNITED NATIONS ENVIRONMENT PROGRAMME-INTERNATIONAL ENVIRONMENTAL TECHNOLOGY CENTRE and INTERNATIONAL LAKE ENVIRONMENT COMMITTEE FOUNDATION PUBLICATION

UNEP-IETC/ILEC Vol. 2
ISBN4-906356-29-X

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The Watershed:
Water from the Mountains into the Sea

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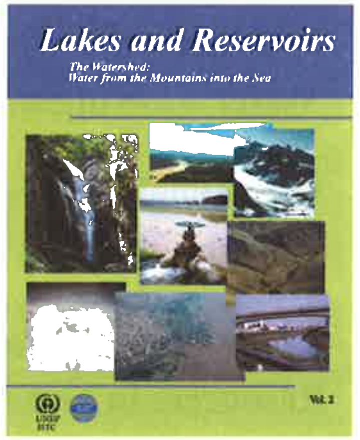

Cover:
(Clockwise)
Yatsubuchi cascade, Japan
River Ucayali, Peru
Mountain glacier, Argentina
Upstream river basin, Chile
River Tiete, Brazil
Ketelmeer, The Netherlands
Cumulus clouds
(Centre)Rice field irrigation faucet, Japan

CONTENTS

Foreword

We are pleased to introduce Volume 2 of the Short Series about the management of lakes and reservoirs. The present volume entitled "The Watershed: Water from the Mountains into the Sea" looks at the different components of the Watershed and explains in general terms how they function as well as their characteristics. The Watershed is one of the most important physical, environmental and administrative structures considered by planners for the sound management of river basins together with the surrounding rainfall catchment areas and land use practices.

When referring to the Watershed it is important to realize that we are talking about the whole of the hydrological cycle from rain to water vapor as well as to snow, ice caps, streams, rivers, lakes, reservoirs, wetlands and swamps, ground water as well as river mouths or estuaries. The interaction between the components is fundamental as changes in any of them may have important negative impacts on each other as well as the fauna, flora and the society.

Unfortunately the impacts produced by direct or indirect activities of man in the Watershed can be seen all over the world; rivers which used to have large flows of water into the sea now only have few cubic meters per year during the rainy season; ground water is constantly being degraded due to surface contamination and it is also overexploited causing in many places the ground to sink; wetlands are continuously destroyed reducing the number of habitats hence the possibilities for reproduction of many species of waterfowl and fish; coastal areas suffer heavily from pollution originating from upstream agricultural, industrial and domestic activities; water quality of streams and rivers is also undergoing degradation resulting in health problems of riverine populations. The list of environmental impacts is enormous, therefore there is a need to understand what the watershed is, how it works and the way to look after it.

This volume provides to the reader an overview of the Watershed with the idea of facilitating its understanding and importance. Following the same design of Volume 1 it is written in simple language trying to avoid technical or sophisticated words as far as possible. Volume 2 also includes numerous photographs to illustrate the referred information in the text with additional figures and tables providing comprehensive and easy to read information.

The intrinsic value of the Watershed with its components and the efforts to preserve it are larger than we think and as citizens we have to join efforts with the authorities, industries, agricultural and forestry sectors to ensure its preservation and appropriate or sustainable use either for us or for future generations. We hope you enjoy it.

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What this Booklet is All About

Introduction

Adequate supplies of fresh water are the single most important natural resource for human well-being, survival and socioeconomic development. It is no accident that early human settlements developed near rivers, lakes and other freshwater sources. Fresh water also is a fundamental feature of the global landscape. Indeed, as seen from space, the Earth largely appears as a globe with an expansive blue mass of water *(Photo 1)*. From the perspective of human water needs, however, this picture is very misleading. Most of this water resides in the world's oceans and is too salty for human use. Or else it is locked up in glaciers and ice caps, or situated deep under the land surface, essentially beyond easy human reach.

Why is fresh water so important for human existence? The most obvious answer is that humans are composed largely of water. Without adequate supplies of clean, safe fresh water, we would all die within a relatively short time. The plants and animals we eat as food also require water. Further, our socioeconomic development depends on adequate supplies of this natural resource. We use fresh water for a myriad of purposes, including growing food and livestock, cleaning, cooking, industry, commercial and sports fisheries, aquaculture, recreation, aesthetics, hydro-power production and transport of commercial goods. It is no surprise, therefore, that areas with scarce supplies of fresh water typically have limited socioeconomic development.

In view of its importance to human existence, water has been characterized by some as precious, finite and irreplaceable. This description is certainly valid. It is precious in that we need it to satisfy our physiological needs and to fuel economic growth. It is finite in that our planet only has a fixed quantity of it. It is irreplaceable in that we have no substitutes for it. Unfortunately, it is also very sensitive to human activities, and can easily become over-exploited and/or polluted because of such activities.

Photo 1: Earth from space; a blue planet.

It is the intention of this publication to follow water from the time it falls on the land surface as precipitation, through the various water systems and water-bodies it encounters on its overland journey back to the oceans, and the myriad of hydrologic and physical components that can affect it on its journey. This booklet also provides a description of the overall cycle of water on the planet Earth, as well as an indication of the availability and characteristics of our global water resources.

The Hydrologic Cycle: How Water Moves around the World

Comprised simply of two atoms of hydrogen and one of oxygen, water is a remarkable substance in many ways. Water covers nearly three-fourths of the surface of our planet, and it is present in the Earth's atmosphere and in its crust. It also comprises a large part of all plant and animal matter. It is the only natural resource that exists naturally in three forms: liquid, solid (snow, ice) and gas (clouds). Unlike most mineral resources, it is renewable – it exists in an endless cycle, moving between its gaseous, liquid and solid forms. This "hydrologic cycle" comprises nature's method of replenishing, redistributing and purifying the world's natural water resources.

To understand how water moves in our world, attention must be directed to the hydrologic cycle. The hydrologic cycle is essentially a water continuum, representing the different paths through which water circulates and is transformed in the natural environment *(Fig. 1)*. Being a cycle, it has no specific beginning or ending. Rather, liquid water from the Earth's surface, particularly the oceans, is evaporated into a gaseous form and enters the atmosphere as water vapor (clouds). The atmospheric moisture is eventually returned to the Earth's surface in the form of rain or snow. It is estimated that approximately 100,000 cubic kilometres (about 20% of the total global annual precipitation) falls onto the land surface of the continents. The liquid fresh water moves over the land surface on its journey back to the ocean. During its overland journey, it creates rivers, lakes, wetlands and/or groundwater aquifers. Further, a portion (so-called endorheic water-bodies) have no direct access to the oceans. As discussed in a later section,

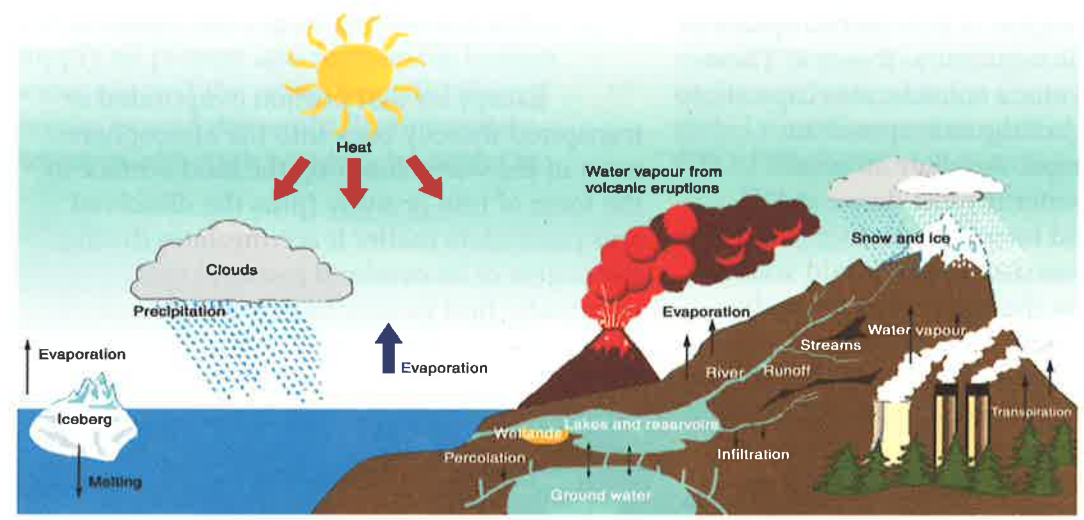


Fig. 1: The hydrologic cycle.

examples of the latter include the Caspian Sea in eastern Europe, the Aral Sea in south-central Asia, and Pyramid Lake in the western United States.

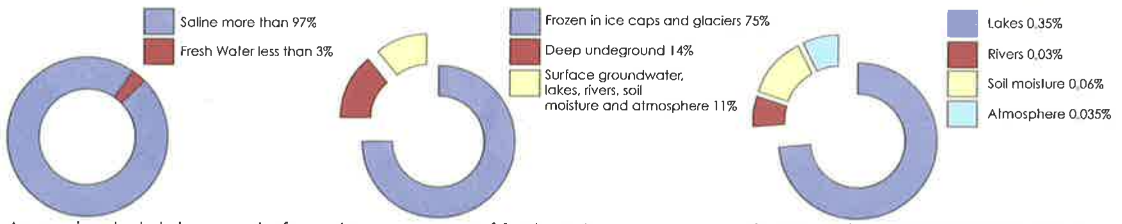
It is estimated that approximately 42,000 cubic kilometres of precipitation flows back to the oceans through the world's rivers each year. Some of the precipitation will seep down into the Earth's surface and become groundwater. Some of it will be taken up by plants and subsequently released in gaseous form back into the atmosphere via a process called transpiration. A substantial quantity of water is returned to the atmosphere in this manner, thereby short-circuiting the full hydrologic cycle. It is estimated, for example, that a hectare of corn can transpire about 30-40 cubic metres of water back into the atmosphere each day. Nevertheless, because of their enormous surface area, the most important source of water in the atmosphere is evaporation from the oceans, which comprises nearly 90% of the total global evaporation. Indeed, it is the fact that more water evaporates from the oceans than is directly precipitated back, thus creating the driving force for the hydrologic cycle.

A substantial input of heat energy is required to melt ice into liquid water, and to boil it into water vapor. A substantial uptake of heat energy also is required to freeze it. These properties give water a considerable capacity to resist freezing or boiling in response to temperature changes. Another unusual property is that water is most dense at 4°C, when still in liquid form. Because ice (solid water at 0°C) is less dense than liquid water at 4°C, it will float on the top of a water-body, with the liquid water below it *(Photo 2)*. Otherwise, lakes would freeze from the bottom up, freezing all life contained within it.

There are several basic features of water that fundamentally influence how humans interact with and use it. The first is that water naturally flows downhill in response to gravity. Further, water can dissolve materials in its flow over the land surface and carry the materials as it moves. If the water volume and velocity are sufficiently large, flowing water also can pick up and carry materials that it cannot readily dissolve. A small mountain stream, for example, will not be able to carry large rocks along the stream channel, while a large, swiftly-flowing river can readily carry rocks, soil and other materials in its flow. A third factor is that humans can control the movement of water, including such measures as pumping it upstream against the force of gravity, pooling or storing it in different locations, and even moving it over long distances.

Photo 2: Floating ice on Lake Argentino.

Except for that portion evaporated or transpired directly back into the atmosphere, most of the water reaching the land surface in the form of rain or snow (plus the dissolved and particulate matter it accumulates during the course of its overland journey) will eventually find its way back to the oceans via transport in streams, rivers, lakes, reservoirs, wetlands and groundwater aquifers, to begin its cycle anew.



Approximate total amount of fresh water (35 million Km3) compared as percentage of that of the approximate total amount of water on Earth (1.3-1.4 billion Km3)

Large sources of fresh water and its approximate comparative percentage amount of that of the total on Earth(35 million Km3)

Comparative approximation of the amount of fresh water found in lakes, rivers, soil moisture and atmosphere as percentage of that of the total on Earth (35 million Km3)

Fig. 2: Fresh water availability on Earth.

Although it is impossible to get an exact figure, it is estimated that the oceans contain approximately 1.3-1.4 billion cubic kilometres of water, comprising about 97% of all the water on Earth. Of this global total, the volume of fresh water is estimated to be about 35 million cubic kilometres. It is estimated that about 75% of the world's freshwater volume is locked up in frozen form in polar ice caps and glaciers, 14% is located deep underground beyond easy human reach, 11% is in groundwater at depths accessible to human use, 0.35% is in lakes, 0.03% is in rivers, 0.06% exists as soil moisture, and 0.035% is in the atmosphere *(Fig. 2)*. To illustrate the relative volumes, if all the water on Earth could be put into a gallon jug (about 3.85 liters), the quantity readily available for human use would be equal to about one tablespoon.

Atmospheric deposition is the primary means by which water is distributed over the Earth's surface. Ironically, it is estimated that there is a sufficient quantity of fresh water to supply all present and foreseeable human water needs if the water were distributed evenly around the world. Unfortunately, however, although nature is bountiful in supplying fresh water, it also displays a confounding fickleness in not distributing the water equitably around the world. This observation applies to both location and timing. Some areas receive large quantities of precipitation each year. In contrast, semi-arid and arid regions are characterized by a limited or scarce water supply *(Photo 3)*. The world's water resources are also unequally distributed in regard to the water flows in different regions.

Photo 3: Mojave Desert, an arid region, USA.

The Parama River *(Photo 4)*, is the second largest river in South America after the Amazon River. The latter carries 16% of the world's water runoff *(Photo 5)*. In contrast, arid and semi-arid regions only account for about 2% of the total global runoff, even though they comprise about 40% of the Earth's land surface.

Photo 4: Parana River and city of Posadas, Argentina.

Photo 5: River Ucayali which gives birth to the Amazon River, Peru.

Nature is also inconsistent with regard to the timing of the precipitation. Some regions receive the bulk of their annual precipitation at one time of the year, while the primary human water needs may occur at a different time during the year. This is a major impetus for the construction of artificial lakes or impoundments, thereby allowing humans to store water for use at a time of their choosing *(Photo 6)*.

Whatever its distribution and timing, adequate supplies of fresh water are an obvious and fundamental requirement for socioeconomic development. This is readily evident in the limited economic development that characterizes most semi-arid and arid regions in the absence of major human intervention to overcome the water deficit.

Rivers are a very most important component of the hydrologic cycle, being a primary determinant of human settlement patterns and economic development. They also represent the major portion of the world's water withdrawals and water consumption. Water runoff over the land surface is the primary interface between human activities and their impacts on water supplies. Thus, human actions in a watershed are the primary factor determining the quantity and quality of water available for human water uses, as well as for maintaining natural ecosystems. One can even characterize human water use as a type of "anthropogenic hydrologic cycle", in that humans typically extract water, use and degrade it, discharge it, extract and treat it when needed again, and then re-use it in a continuing cycle. Unfortunately, the cycle can become increasingly expensive and difficult to maintain as humans continue to pollute and/or otherwise abuse their water resources.

Photo 6: Takayama Dam on the Nabari River, Japan.

The Watershed: The Water Collector

The quantity and quality of water on the land surface depends to a large degree on land usage and human actions within watersheds (or catchments, drainage basins) *(Photo 7)*. In much the same manner as a drop of water along the lip of a cup will flow into the cup, all the water in a watershed will flow down to its lowest part, which is usually a river, lake or other water-body. Within this context, the Earth's land surface can be viewed as a series of irregularly-shaped watersheds contiguous to one another. The characteristics of an individual watershed depends on the cumulative effects of all the water, land and land-based activities, people, plants, animals, farms, cities, factories, etc., contained within it. Further, other than where water is artificially transferred from one watershed to another, each watershed is independent of all others, even those lying adjacent to it.

Photo 7: Section of the Amazon Watershed; satellite image, Brazil.

Land use typically refers to the specific use or purpose for which humans use the land surface, examples being agricultural fields, urban areas, roads, forests, etc. Human actions on different land uses further dictate the quantity and quality of fresh water within a given watershed. Agricultural land, for example, can be used for a number of different purposes, including row crop production, livestock raising, orchards, pastures, etc. As discussed below, land use and land-use activities are primary determinants of water pollution.

Nature largely dictates the absolute quantity of available water (in the form of precipitation) in a given watershed via the hydrologic cycle. However, human water demands fundamentally influence the relative quantity of available water within a given watershed. Arid and semi-arid regions, for example, do not receive a large quantity of precipitation over the annual cycle and may cause excessive demands on existing water supplies. The result is water scarcity *(Photo 8)*.

Photo 8: Yemeni Desert in the South Arabian Peninsula.

The converse is true for watersheds receiving large quantities of precipitation and/or having fewer water demands. Thus, the availability (or scarcity) of water in a watershed represents a balance between the water supply (the volume of water supplied by nature) and the water demand (the volumes of water needed by humans for different land-based activities).

Human settlement of a watershed involves the building of cities, industrial complexes, farms, streets, etc., the use of raw materials and chemicals used in industrial activities, fertilizers and pesticides used in agriculture, and alterations in land cover vegetation, natural drainage networks, etc. These types of activities invariably result in the production of liquid, solid and gaseous wastes of various types and quantities, which can subsequently find their way into rivers, lakes and groundwater aquifers in the watershed. This phenomenon is called "pollution" which, depending on the types and quantities of materials, can fundamentally define the quality of water *(Photo 9)*.

Specific human water uses require adequate supplies of water of acceptable quality for its intended use. Drinking water, for example, requires the highest quality in order to be safe for human consumption. In contrast, water used for irrigation or to generate hydro-

Photo 9: Water pollution in an urban lake, Jakarta, Indonesia.

Photo 10: Pipeline discharges; a point source of pollution.

Photos 11, 12 and 13: Non-point source of pollution originating from storm run-off water entering Lake Biwa, Japan.

power does not have to be of the same high quality. Within this context, water pollution also constitutes a type of water "scarcity" in that it decreases the range of potential water uses for a given water supply without some degree of pre-treatment prior to its use.

Pollutants can be characterized as point or non-point (or diffuse) in origin. Point sources comprise "pipeline" discharges of wastes or other pollutants to rivers or lakes draining a given region, examples being municipal wastewater treatment plant and factory effluents *(Photo 10)*. Non-point sources represent storm-induced water drainage or runoff over the land surface in which the flowing water dissolves or picks up pollutants and other materials and carries them to rivers and other water systems draining the region *(Photos 11, 12 and 13)*. Accordingly, non-point source pollutant loads are closely tied to precipitation or snowmelt events. Further, the quantities and types of non-point pollutants are a function of the characteristics of the land surface over which the water passes, as well as of human activities on the land surface. Agricultural and urban areas typically produce large non-point pollutant loads, and are the major pollutant sources in many regions of the world *(Photos 14 and 15)*.

Photo 14: Mixed urban and agricultural lands causing point and non-point pollution in rivers and streams.

Photo 15: Polluted stream with urban waste and agricultural run-off.

Ice and Snow: Water in a Frozen Form

Humans generally do not extensively use water in the form of ice as a water supply. Ironically, however, about three-fourths of the world's fresh water exists in polar ice caps and massive, slow-moving glaciers. Frozen lakes and rivers comprise a tiny additional fraction of fresh water. The existence of water in frozen form has the effect of withdrawing vast quantities of water from its movement through the hydrologic cycle. With some variability, most of the world's ice remains in frozen form over very long periods of time. This is significant within the context of predicted global warming, which can potentially give a significant rise in sea level.

Photo 16: North Pole ice sheet and Greenland. Satellite image.

Permanent ice cover exists as polar ice caps in the Arctic and Antarctic, and in Greenland *(Photo 16)*. It also exists at high altitudes and latitudes in the form of glaciers. It is estimated that the Antarctic ice cap is equivalent to about 30 million cubic kilometres of water. Ironically, the polar regions receive extremely small quantities of precipitation annually. Thus, even though polar ice caps contain a massive quantity of frozen water, the areas are characterized as arid because of their very limited precipitation.

Glaciers are slow-moving ice masses in areas where snow or ice has accumulated in large quantities, typically in mountainous areas *(Photo 17)*. Some glaciers contain massive quantities of ice, ranging in size up to continental ice sheets. Many lake basins were formed by the slow movement of huge glacial ice masses ("glacial scour") *(Photo 18)*, over the land surface over geologic time scales. The Laurentian Great Lakes of North America were formed in this manner, and provide an excellent example of the almost unbelievable power of water in frozen form fundamentally to change the character of the land surface.

Photo 17: Mountain glacier in the Andean region.

Photo 18: Glacier valley carved by ice flow during the last ice age, Argentina.

Another form of perennial ice is permafrost *(Photo 19)*, particularly in the northern, sub-Arctic region of the Northern Hemisphere. Although perennially-frozen soils can interfere with both land use and land-based activities, this type of frozen water is of no major significance in regard to human water supplies.

Snow represents a transient form of water. Although it can begin its descent from the atmosphere in the form of raindrops or droplets, it can freeze into snow if the air temperature is sufficiently low. At the same time, snow is more sensitive to elevated temperature than are massive ice caps and glaciers. Accordingly, although snow falls in many temperate regions, it usually does not stay on the ground for any appreciable time. In fact, streamflow in some regions consists mainly of snow that has subsequently melted as the temperature increased in the spring, resulting in significant runoff from the land surface, so called snowmelt. In some parts of the world, the winter snow cover in a watershed can fundamentally control both the quantity and quality of the runoff likely to be expected during the subsequent spring and summer period. In fact, some watersheds can exhibit wide variations in water supply, as a function of the precipitation and snowfall variability from season to season and from year to year.

Mountainous areas are characterized by limited or no human settlement or land-based activities. The water originating from snowmelt in mountainous regions, therefore, is typically the water of best quality within the context of the hydrologic cycle. Because their high altitudes define the physical boundaries of some watersheds, some have suggested that mountain-tops can be said to represent the point from which water begins its journey to the sea.

Photo 19: Permafrost in the Russsian tundra.

Streams and Rivers: Water Flowing over the Land Surface

Rivers, cascades and streams are major hydrologic features of the global landscape *(Photo 20)*. They are the primary means by which precipitation and snowmelt flow over the land surface to the oceans to begin the hydrologic cycle anew. Water flow or drainage over the land surface also represents the part of the hydrologic cycle of most concern to humans because it represents the primary interface between water resources in nature and human use of this resource. In fact, no other natural resource has been more tightly tied to the degree of human settlement in different regions of the world.

Photo 20: Yatsubuchi cascade in the Kamo River, Japan.

The primary factor determining whether precipitation will seep underground into the soil, or flow over it to streams and rivers, is the type of soil and the extent to which it is already saturated with moisture. One way to envisage this phenomenon is to consider a dry land surface onto which precipitation begins falling. The dry soil will absorb the initial precipitation, thereby "wetting" the soil. If the precipitation volume and duration is sufficiently large, the spaces between the particles comprising the soil will become filled with water, thereby "saturating" the soil *(photo 21)*. Once the soil becomes saturated, any additional precipitation will begin flowing over the land surface, rather than seeping into it, eventually entering rivers, lakes, wetlands, etc. Thus, the flow regime of rivers is directly dependent on the precipitation patterns in their watersheds. In semi-arid and arid regions, rivers like wadies *(Photos 22 and 23)*, may only flow intermittently. Low flows in humid areas may be considerable, presenting frequent flood events. River flows can vary significantly between these extremes, in both volume and timing.

Photo 21: Water saturated soil.

Photo 22 and 23: Wadi in the wet and dry season, Syria.

Precipitation that does not seep into the ground will flow downhill, eventually draining into streams that increase in size downstream. The streams can eventually become large rivers transporting large volumes of water (as well as dissolved and particulate material collected in its passage over the land surface). The drainage channels (streams, rivers, etc.) typically occupy the lowest part of the landscape. Thus, both the depth of the drainage channels and the volume of water carried in them generally increases downstream in a watershed. Other factors being equal, the volume of water carried in drainage channels usually increases with increasing size and development of the contributing watershed area.

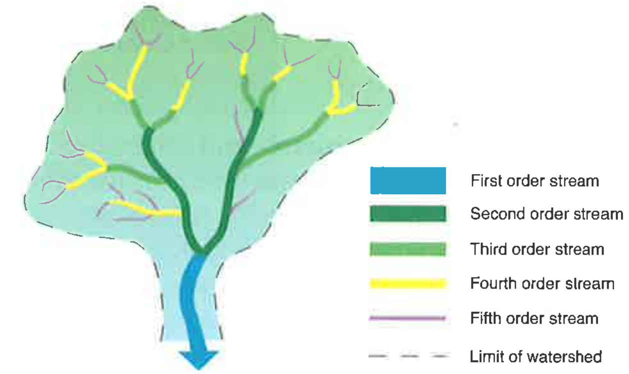


Fig. 3: Dendritic shape of a river in a watershed.

Because most rivers are part of a branched or dendritic drainage pattern, small creeks join to form larger streams downstream, much in the same manner represented by branches in a tree or blood vessels in the human body *(Fig. 3 and Photo 24)*. Because flowing

Photo 24: Mountain streams; originators of rivers.

Photo 25: Colorado River and Grand Canyon, USA.

water can dissolve minerals and otherwise erode water channels in the land surface, river flows have produced dramatic modifications of the land surface over time. In fact, viewed from above the land surface, rivers are never straight. Rather, because of the turbulent nature of flowing water and the variability of land surface geology, many rivers tend to form meandering channels. A prominent example is the Grand Canyon in the western United States. This was carved out of the natural landscape over geologic time as a result of erosion by the meandering Colorado River *(Photo 25)*.

Fig. 4 summarizes data on the availability of river water resources on the various continents. It is noted that six countries (Brazil, Russia, Canada, United States, China and India) contribute nearly half of the world's total river runoff to the oceans. The annual discharge of selected rivers from different continents, comprising about 40% of the total global river runoff volume, is given in Table 1.

The volume of river water discharges generally reflects both the watershed size and the prevailing patterns of the discharge as well as the land surface patterns. Panama and Surinam, for example, have the world's largest water availability per square kilometre of land surface (1,870,000 and 1,411,000 cubic kilometres of water/year, respectively). In contrast, Mauritania and Libya exhibit the minimum water availability per square kilometre (390 and 3,010 cubic kilometres of water/year, respectively). Per capita water availability also varies widely around the world, being a function of the quantity of river flow and the number of persons using the water.

Fig. 4: Availability of river water resources on the various continents (figures in cubic kilometres per year).

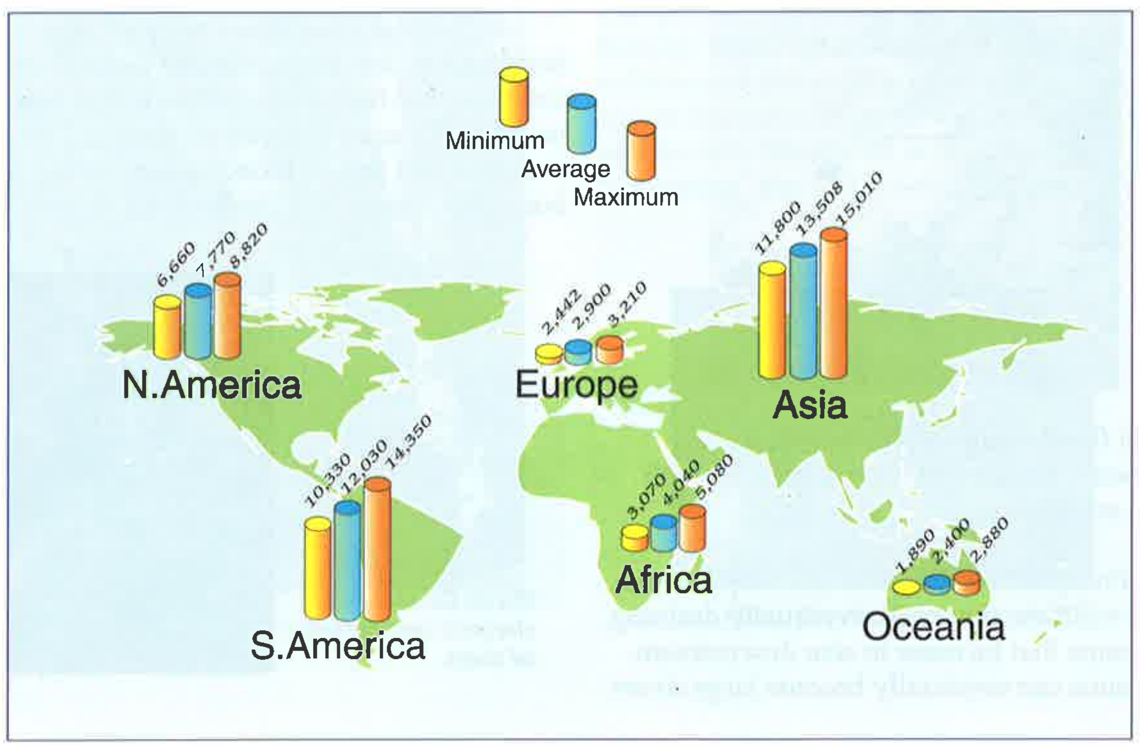


Table 1: Runoff of major rivers in the world, watershed population and Watershed land area.

River	Water runoff volume (km^3/year)	Watershed population (million people)	Watershed land area (million km^2)		
			Minimum	Maximum	Average
Amazon	6.92	14.3	6,920	8,510	5,790
Ganges (incl. Brahmapulre & Meghna Rivers)	1.75	439	1,389	1,690	1,220
Congo	3.50	48.3	1,300	1,775	1,050
Orinoco	1.00	22.4	1,010	1,380	706
Yangtze	1.81	346	1,003	1,410	700
La Plata	3.10	98.4	811	1,860	453
Yenisei	2.58	4.77	618	729	531
Mississippi	3.21	72.5	573	880	280
Lena	2.49	1.87	539	670	424
Ob	2.99	22.5	404	567	270
Mekong	0.79	75.0	505	610	376
Mackenzie	1.75	0.35	333	420	281
Amur	1.86	4.46	328	483	187
Niger	2.09	131	303	482	163
Volga	1.38	43.3	255	390	161
Danube	0.82	85.1	225	321	137
Indus	0.96	150	220	359	126
Nile	2.87	89.0	161	248	94.8
Amu Darya	0.31	15.5	77.1	118	56.7
Yellow	0.75	82.0	66.1	97	22.1
Dneiper	0.50	36.6	53.3	95	21.7
Syr Darya	0.22	13.4	38.3	75	26.2
Don	0.42	17.5	26.9	52	11.9
Murray	1.07	2.1	24	129	1.16

Photo27: Downstream turbulance after the water passing through the turbines causing environmental impacts. Yaserita Dam, Argentina and Paraguay.

Most of the world's major rivers are now impounded at some points in their watersheds, primarily to counter the vagaries of their flows *(Photo 26)*, and/or to utilize their water to maximum human benefit although some environmental impacts may occur *(Photo 27)*. In some countries, virtually every feasible dam site has been exploited, and the only remaining large, free-flowing rivers are found in the North American and Russian tundra regions and in parts of Africa and South America. River modifications have changed the natural flows of some rivers to the extent that they no longer flow to the oceans during their dry seasons *(Photo 28)*. Prominent examples include the Yellow, Indus, Ganges, Nile, and Colorado. In some cases, a watershed can become a closed or terminal water system, in which no water flows from it to the oceans.

Photo 26: River impoundment to control flooding.

Photo 28: River bed during the dry season, Brazil.

Lakes and Reservoirs: Water Pools on the Land Surface

Lakes are some of the most picturesque features of the natural landscape *(Photo 29)*. They range from pond-sized water-bodies to those stretching for hundreds of kilometres and containing vast quantities of fresh water. Lakes are water-bodies formed when natural depressions or basins in the land surface become filled with water over time. In contrast to flowing streams and rivers, lakes provide a means for pooling or storing water for varying periods of time.

Lakes are of both natural and human origin. Many natural lake basins were formed by massive glaciers creating depressions in the land surface ("glacial scour") as they slowly moved over it during the past glacial periods. Other formative processes for lake basins include volcanic activity and the slow movement of different portions of the land surface ("tectonic movements"). Whatever their origin, the basins subsequently became filled with runoff over time, producing the familiar water-bodies known as lakes.

There are millions of small natural lakes around the world. Most of the world's great lakes are also natural. Prominent examples include Lake Baikal in Russia, containing about 23,000 cubic kilometres of water (equivalent to about 20% of the world's liquid fresh water), and the Laurentian Great Lakes of North

Photo 29: Lake Poso, one of the most beautiful and deepest lakes in Indonesia.

No.	Lake Name
1	L.Tanganyika
2	L.Eyre
3	L.Urmia
4	L.Geneva
5	L.Khanka
6	L.Huron
7	L.Michigan
8	L.Koko Nor
9	L.Baikal
10	L.Superior
11	L.Jerid
12	L.Biwa

No.	Lake Name
13	L.Balkhash
14	L.Tonle Sap
15	L.Nicaragua
16	Beloye Lake
17	L.Har Us
18	L.Victoria
19	L.Malawi
20	L.Titicaca
21	L.Beyschir
22	L.Sevan
23	L.Toba

These lakes are drawn on the same reduced scale

Fig. 5: Comparative size of some lakes in the World.

America (Superior, Huron, Michigan, Erie and Ontario), comprising the world's largest contiguous freshwater volume (containing 24,600 cubic kilometres of water, also equivalent to about 20% of the world's freshwater), Lakes Victoria and Tanganyika in Africa, and Lake Titicaca in Latin America. Interestingly, most natural lakes are relatively shallow geologic features and even some of the largest lakes have maximum depths of less than 30 m. However, a few natural lakes have maximum depths of up to 1.5 km at their deepest parts (e.g., Lakes Baikal and Tanganyika). A relative comparison of the surface area of many of the world's larger lakes is provided in Fig. 5.

Arid and semi-arid regions are characterized by having low annual rainfall, high evaporation and sparse vegetation. Nevertheless, these regions also can have large waterbodies seasonally or unpredictably. They can range in size from shallow lakes which contain water only intermittently, to large, permanent and deep lakes. Most are relatively shallow. As discussed in a following section, many arid and semi-arid watersheds may contain "terminal lakes", which have no natural drainage outlets to the oceans. They are found on all continents and often have more saline (salty) water than lakes in temperate regions.

The total volume of freshwater lakes comprises about 0.009% of the world's liquid freshwater.

Photo 30: View of the Dead Sea, Jordan side.

The equivalent value for saline lakes is about 0.008%. Interestingly, some of the world's largest natural lakes exist in dry areas. For example, the Caspian Sea alone contains about 70% of the world's inland saline water. Other large saline lakes include the Aral Sea, Great Salt Lake, and Lake Chinghai. Saline lakes also exist at the highest and lowest altitudes (e.g., Tibetan Plateau lakes and the Dead Sea *Photo 30*, respectively).

Lakes also can be artificially constructed. Human-made lakes, also known as reservoirs or impoundments, typically are constructed by erecting a dam structure across a flowing river, thereby trapping or pooling the previously flowing water *(Photo 6)*. They are normally constructed to address situations of water scarcity or water excess. In regard to water scarcity, reservoirs store precipitation received during one time of the year for subsequent human use during other times of the year when it is more needed. For areas subject to excessive precipitation and runoff, reservoirs temporarily store the excess water, thereby alleviating downstream flooding problems. As might be expected, reservoirs are more prominent in areas with relatively few natural lakes.

Because they are of human construction, reservoirs are not of a geologic age. The first small reservoirs were constructed about 4,000 years ago in China, Egypt and Mesopotamia, primarily for drinking water supply and irrigation purposes. The total volume of impounded water increased about 12-fold around the world after World War II, including a 40-fold increase in Latin America and a 100-fold increase in Africa and Asia. On a global scale, the building of reservoirs peaked in the late 1960s, and since then construction of new reservoirs has essentially ceased in North America and Europe. More than one-half of the world's reservoirs (including most of the largest ones) are located in the United States, Canada, Mexico, Brazil, China and India. Nearly all the new reservoirs scheduled to come into operation in the 21st century are located in Asia, Africa and Latin America.

A few comments on the similarities and differences of lakes and reservoirs are relevant. Natural lakes are generally more or less circular, bowl-shaped, natural depressions in the land surface. The center of the lake water basin is usually the deepest part, and the lake usually has one inflowing and outflowing river channel. In contrast, reservoir basins usually have multiple tributary inputs ("arms") along their lengths, and are more irregular and dendritic in shape *(Figure 6)*. The depth increases from the upstream end to the dam end of the water basin. Because the dams are the physical

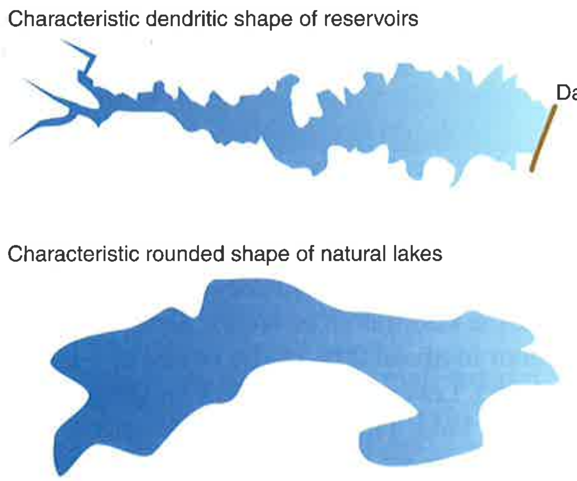


Fig. 6: Characteristic shape of reservoirs and natural lakes.

structures that facilitate the pooling of the inflowing water, they also offer increased management options. Many dams contain water-discharge outlets at multiple depths, for example, allowing for the selective discharge of water from specific layers in a reservoir *(Fig. 7)*.

Volume I of this UNEP/ILEC Short Series discusses the similarities and differences of natural lakes and reservoirs, as well as their management implications, and the reader may refer to it for additional information.

The fact that the velocity of inflowing river water decreases as the water enters lake and reservoir basins can have both positive and negative impacts on water quality. The water quality will typically increase, for example, when the inflowing tributary water enters the

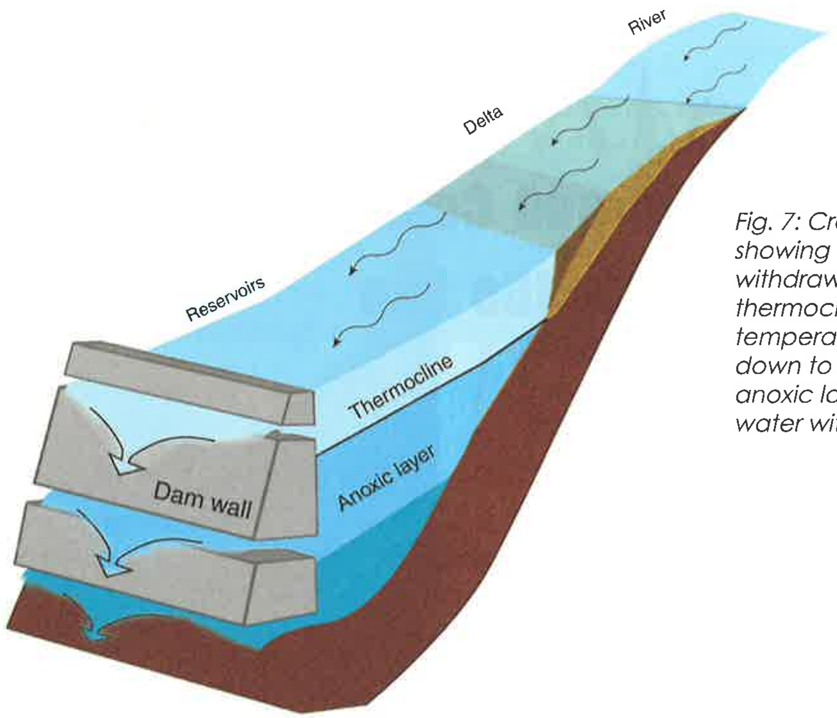


Fig. 7: Cross sectional dam wall showing multiple water withdrawal possibilities. The thermocline shows the drop of temperature from the surface down to deeper layers. The anoxic layer is a volume of water without oxygen.

deeper, pool-like environment of a lake or reservoir, mainly because the decreased water velocity will allow the sediments and sediment-associated materials (e.g. nutrients) in the water column to settle to the bottom of the lake/reservoir basin. This will also typically result in increased water clarity. At the same time, however, decreased water velocity enhances natural processes that flourish in non-flowing or pooled water systems. An example is the growth of microscopic, free-floating algae (phytoplankton). Lakes and reservoirs enhance the possibility for phytoplankton to accumulate to nuisance levels that interfere with beneficial human water uses (i.e., algal blooms *Photo 31)*. The phytoplankton can also grow in flowing waters, but are subsequently swept downstream before they can accumulate to visible nuisance levels. Thus, the cumulative positive and negative effects of pooled water environments must be balanced in evaluating the water quality of lakes and reservoirs. The increased potential for controlling water quality in reservoirs, via selective water withdrawal, is another factor to be considered in developing water-quality management programs for these water-bodies.

Because sediments and other materials carried in inflowing waters will typically settle to the bottom as they enter the more pool-like environment of natural lakes and reservoirs into which they drain, lakes and reservoirs are essentially transitory features of the Earth's surface. They will slowly cease to exist over time as they continue to fill with sediment and other materials.

Photo 31: Characteristic algal blooms during summer time in a polluted reservoir.

Estuaries, Deltas and Coastal Areas: Water Gateways to the Sea

Typically, estuaries are semi-enclosed areas along the coastal shoreline where fresh water enters the oceans *(Photo 32)*, at the end of its journey over the land surface via rivers, lakes and/or wetlands. Fresh water can also enter the oceans via underground water flows (groundwater) although it is difficult to determine the extent of this phenomenon in a given situation. As a result, the salinity or saltiness of estuaries typically is intermediate between that of the freshwater inflows and the ocean waters into which they drain, dependent on the relative amounts of both. Accordingly, the quality of estuarine waters limits their beneficial human uses, particularly compared to freshwater resources.

Photo 32: Portion of the Parana River Delta entering the La Plata River, Argentina and Uruguay.

There are several physical types of estuaries. The sinking or drowning of rivermouths, for example, can form coastal-plain estuaries. These estuaries can result from a lowering of the land surface and/or a rising sea-level, resulting in an elongated indenture along the coastline. Coastal-plain estuaries are typically shallow, with a river flowing into the upstream end. A second type of estuary is formed when an offshore bar develops along a relatively flat shoreline. In contrast to the shoreline indenture structure of coastal-plain estuaries, these estuaries are usually elongated embayments parallel to the shoreline, with a relatively narrow connection to the open sea. They often develop between offshore barrier island chains and the main coastline, an example being the barrier island system along the coastline of Texas in the United States. Deep-basin estuaries are usually significantly elongated coastline indentures, with a relatively deep basin and a shallow rivermouth area. The fjords of Norway, Canada and New Zealand *(Photo 33)*, are prominent examples of this latter type of estuary.

Estuaries can sometimes be separated from the open ocean by islands or other land barriers. The hydrologic boundary of an estuary is usually controlled by the interplay of outflowing river water and incoming tidally influenced coastal waters. The upper limits of an estuary often move up and down the rivermouth as a function of the advancing and retreating tides. Winds can also influence the upper limit of the estuarine water, resulting in

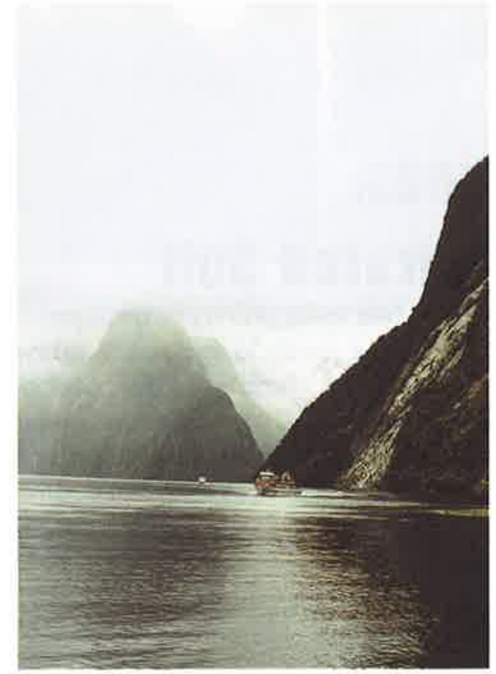


Photo 33: Milford Sound Fjord, New Zealand.

complex estuarine water mixing patterns. Estuaries also represent chemical and biological buffer zones between fresh water and the ocean. Shallower estuaries typically have a more uniform salinity from the surface to the bottom than do deeper estuaries. When the river outflow is large compared to the tidal flow, seawater can move a few kilometres inland as a saltwater "plume" along the bottom of the river channel. In contrast, the freshwater discharge from some large rivers can extend many tens of kilometres into the ocean. Because the density of the freshwater is less than that of ocean water, this can result in a surface fresh water layer extending over the more dense saline water for a considerable distance offshore of the rivermouth.

Because estuaries are the hydrologic connection between freshwater inputs and the open oceans, they often receive large pollutant loads, with accompanying water-quality impacts. Estuarine fishery nursery grounds are especially sensitive to upstream point and non-point pollutant sources. Because large rivers can carry huge volumes of soils and suspended sediments, estuaries are typically turbid. Further, when the inflowing sediment load becomes large, rivermouth deltas can form as the sediment drops out of the water column with the reduction in water velocity as the river enters the coastal waters. Prominent examples of this phenomenon are the major deltas located at the mouth of the Mississippi River *(Photo 34)*, in the Gulf of Mexico and the mouth of the Nile River in the Mediterranean Sea.

Estuaries are highly variable and complex aquatic ecosystems. They are also highly productive ecosystems, containing abundant plant and animal life. As an example, estuaries are major spawning or nursery grounds for many commercially important fisheries, as well as being a magnet for sport-fishers of all types.

In addition to being major nursery systems for many fisheries, estuaries are also a physical buffer zone between inflowing rivers and the open ocean. Because they are located along coastal areas, estuarine components can include coastal wetlands, marshes and mangrove swamps. Unfortunately, continued human development and exploitation of coastal areas is seriously threatening the physical as well as the ecological integrity of many estuaries. Consequently, their ability to function as a buffer against the effects of such phenomenon as typhoons, cyclones, wave surges, etc., is being seriously jeopardized in many places.

Photo 34: Mississippi River delta dischrging large amounts of sediments into the Gulf of Mexico, USA. Satellite image.

Wetlands and Flooded Areas: Water on Perpetually-Saturated Soil

Another important component of the hydrologic cycle is wetlands, which comprise the land areas that are partially or permanently saturated with water during some or all of the annual cycle. The international Ramsar Convention defines wetlands broadly as "areas of marsh, fen, peatland or water; whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine waters, the depth of which at low tide does not exceed six metres" and may include "riparian and coastal zones adjacent to the wetlands or island or bodies of marine water deeper than six metres at low tide lying within". For the purposes of this booklet, however, wetlands comprise marshes, swamps and other heavily vegetated areas (bogs, peatlands, fens, etc.) saturated with water.

Photo 35: Wetland in Lake Biwa, Japan.

A major wetland characteristic is the continuing presence of water either at the land surface or within the root zone of plants. Wetlands *(Photo 35)*, are found throughout the world, ranging in size from a few hectares to thousands of square kilometres. They are often located along the edges of lake basins, on river floodplains and on rivermouth deltas. It is estimated that approximately 6% of the Earth's surface is covered with wetlands, equivalent to about 8.6 million square kilometres. Wetland vegetation can be quite varied and dense and include substantial accumulations of dead and partially decayed trees and plants. Wetlands also hold a large variety of plants and animals *(Photos 36, 37, 38 and 39)*. Some types of wetlands are specific to certain regions, an example being the mangrove swamps associated with coastal areas *(Photo 40)*. The latter are especially important as a buffer zone between the land and coastal waters.

The most important factor controlling the structure and function of a wetland is its hydrology. Wetlands are highly dependent on the upstream conditions in their watershed, in regard to both water quantity and quality. The degree of soil saturation of a wetland will obviously depend on the magnitude and consistency of its freshwater inflows. As with upstream rivers and lakes, the quality of the inflowing water to a wetland is a function of the point and non-point pollutant sources in the watershed, and water pollution can readily modify the natural flora and fauna of a wetland.

Photos 36, 37, 38 and 39: Biodiversity in wetlands.

Compared to rivers, lakes and groundwater, the range of direct human water uses associated with wetlands is limited. Nevertheless, wetlands are a vital life support system for many biological communities. They also provide a range of ecological and hydrological functions for human benefit, as well as goods and services for human health and well-being. In addition to providing fish, shellfish and other food resources, wetlands also perform ecosystem services of direct economic benefit to humans, including groundwater recharge and discharge, flood storage, dissipation of natural erosion forces, sediment and nutrient retention and removal, wildlife and fishery habitat, and water purification. In fact, some of the ecosystem services provided by wetlands are not found elsewhere.

Photo 40: View of the mouths of the Irrawaddy River, Myanmar, taken from a satellite. The pinkish colour in the photograph shows mangrove forest.

Among the ecosystem services, flood control and water purification warrant further mention. In regard to flood control, wetlands act as temporary storage systems for water discharges from flood events. Wetland vegetation also retards surface water flows, thereby hindering the downstream passage of flood waters. This property can both reduce flood flows and peaks, and increase the duration of reduced floodwater flows. In regard to water quality, wetlands have a significant capacity to maintain and/or purify water passing through them. Virtually all water-quality parameters can be altered by the passage of water through a wetland; hence, their characterization by some as the "kidneys" of the landscape. Improved water quality can result from sediment deposition, as suspended sediments and sediment-associated pollutants drop out of the water column with reduced stream velocities in a wetland. A variety of biological and chemical reactions in wetlands, as well as dense vegetation, can also transform and/or remove certain chemicals from the water.

Because of their ability to remove or minimize pollutants, wetlands have been used to purify domestic and industrial wastewater, either as a primary treatment for untreated waters or as a supplemental "polishing" treatment for partially treated wastewaters. Both natural and artificially constructed wetlands *(Photo 41)*, have been used for this purpose, with the primary constraint being the need to insure that a wetland's water-purification capabilities are not overloaded. The latter consideration includes the types and quantities of water pollutants, as well as the timing of their introduction into the wetland system.

Photo 41: Artificial wetland constructed to treat organic liquid waste, Kenya.

Groundwater:
Water Flowing under the Land Surface

Groundwater comprises water that flows under the land surface *(Fig. 8)*. Most people only encounter groundwater within the context of water wells and, accordingly, it has been characterized by some as being "out of sight, out of mind". Nothing is further from the truth. Groundwater represents the largest single source of fresh water in the hydrological cycle available for beneficial human uses, being greater in volume than all the water in rivers, lakes and wetlands combined. The groundwater in the United States alone, for example, exceeds the total water volume contained in all its lakes, reservoirs, rivers and wetlands. On the other hand, approximately half of the world's groundwater resources are located underground at depths too deep to be economically exploited for human use.

Groundwater represents the portion of precipitation that seeps ("infiltrates") into the land surface, entering the empty spaces between soil particles. The larger the soil particles *(Fig. 9)*, the larger the empty spaces, and the greater the potential for water infiltration. Soils composed of large soil particles are more permeable than soils composed of small particles. Thus, they can hold more water than the latter. The infiltrating water sources include natural precipitation or snowmelt, streams, lakes, reservoirs and wetlands.

There are several groundwater properties that fundamentally affect how and where humans interact with it. Water exists under the land surface in permeable geological

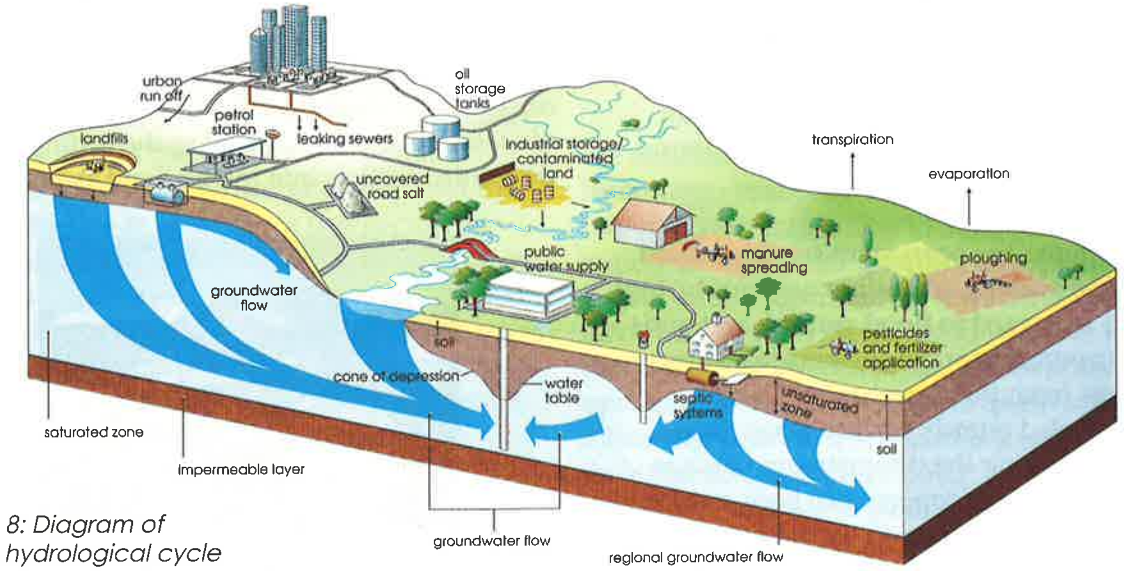


Fig. 8: Diagram of the hydrological cycle showing groundwater and surface water relationships along with and groundwater pollution risks.

a) b) c)

Fig. 9: Some types of unconsolidated materials in the soil: a)sand, b)rocks and c)limestone. The last can hold more water than the others.

formations known as aquifers. In some geographic settings (e.g., valleys between mountain ranges), the physical boundaries of an aquifer can closely coincide with the surface stream watershed. However, in limestone and sandhill areas, the physical boundaries of aquifers and surface watersheds can have very different configurations and can be completely unrelated.

If a person digs a well to a depth where water is encountered, the depth at which the water is first encountered identifies the uppermost boundary of the water-saturated soil. Stated another way, it is the upper boundary at which all the spaces between the soil particles are filled with water. Thus, all the soil below this depth comprises the "saturated" soil zone. The water surface in the well coincides with the upper boundary of the groundwater, and is commonly called the "water table".

In contrast to the saturated zone, the spaces between the soil particles above the water-table contain no water. This upper soil layer represents the unsaturated zone. The water-table will rise as more water enters the saturated zone (e.g., during periods of precipitation), and it will fall as water is withdrawn from the aquifer (e.g., via wells and pumps) faster than it can be replenished by natural precipitation or other water inputs. Thus, the bottom boundary of the unsaturated zone rises or falls, conversely to the dynamics of the saturated zone. As previously noted, wetlands constitute areas in which the water-table is at, or higher than, the land surface, resulting in a perpetually water-saturated soil condition. Springs *(Photos 42 and 43)*, and artesian wells represent hydrologic conduits or discharge areas through which groundwater can reach the land surface.

Photos 42 and 43: Figeh Spring in Syria which provides water to Damascus, and a typical Oasis in Oman.

Groundwater is constantly in motion *(Fig. 10)*. However, its velocity is highly variable, ranging from as little as a few metres per year to as much as a few metres per day. During periods of little precipitation or land surface runoff, groundwater can seep into overlying stream and river channels, thereby providing most or all of the streamflow during such periods (so-called "base flow", or dry-weather flow of perennial streams). In fact, groundwater comprises the only readily available natural freshwater supplies in semi-arid and arid regions. This reality has water supply implications in that excessive water withdrawal from a groundwater aquifer can directly affect water availability throughout an overlying watershed. It is noted that the replenishment of groundwater supplies in arid and semi-arid regions is very slow, even though these water resources are the most important and critical in such regions.

Only about half of the world's groundwater resources is located sufficiently close to the land surface to allow its withdrawal to be economically feasible *(Photo 44)*. Some have identified this limit as being no more than about 800 m below the land surface, although the ease of underground water extraction also depends on other factors. The majority of drinking water supplies on a global scale is from groundwater sources. Agricultural production also uses large quantities of groundwater. This latter water use is of special significance in that large quantities of water used for agricultural irrigation undergo transpiration back into the atmosphere via irrigated crops, thereby short-circuiting its passage through the hydrologic cycle. This water "consumption" is in contrast to water used for drinking water supply and industry. The latter is eventually discharged back into streams, rivers and other receiving water systems, thereby allowing its reuse, usually after pre-treatment of some type.

The present volume of water being withdrawn annually from aquifers around the world is approximately 600-700 cubic kilometres. Unfortunately, many aquifers are currently being overexploited to meet human water demands. A prominent example is the Ogallala Aquifer, which underlies much of the central part of the United States. Continuing over-exploitation of this massive aquifer over many years, primarily for agricultural irrigation, has caused its water table to sink to hundreds of metre below the land surface. In some cases, artificial recharge efforts have been used to attempt to augment the replenishment rate of groundwater aquifers. These comprise constructions or other methods of enhancing the infiltration of surface water into aquifer recharge zones, including water spreading, flood areas, permeable surfaces, pits, wells, etc. An important part of aquifer recharge in arid and semi-arid regions is provided by river losses and underground seepage during floods.

Groundwater use in Germany, Belgium, France and Sweden has been relatively constant over the years, while groundwater withdrawals have decreased in Canada and the United States over the last 20 years. In contrast, groundwater use has increased significantly in many developing countries, including China, India, Mexico, Iran and Pakistan. The greatest increases are in developing countries in arid and semi-arid regions with increasing populations.

Because of its relatively slow movement below the land surface, groundwater is especially susceptible to water pollution. The volume and flow of surface waters allows for the possibility of rapid flushing rates for pollutants contained in them. In contrast, the typically slow movement of groundwater insures that a much longer time is required for a groundwater aquifer to flush or otherwise wash-out pollutants contained in its water. The extent of pollution of an individual groundwater aquifer will obviously depend on the types and quantities of the pollutants contained in the water entering the aquifer via its recharge zone. The major pollutant sources include runoff from different types of land use and waste disposal practices, including excessive agricultural fertilizer use, deep well

How groundwater flows

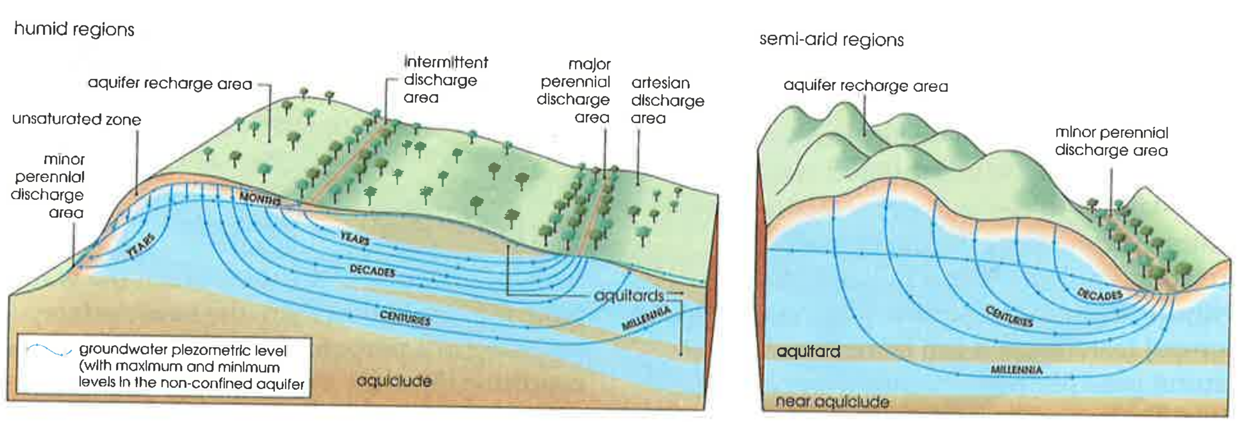


Fig. 10: Basic elements of groundwater flow in humid regions (left) and semi-arid regions (right).

Photo 44: Caves and Cenotes originating from near surface groundwater flowing through limestone, Mexico.

injection of pollutants, etc. The polluted groundwater can result in significant health problems if it is subsequently consumed by humans and/or livestock.

Land subsidence from excessive groundwater withdrawal is also a problem, particularly in coastal-plain regions. Areas of significant land subsidence have been observed in Mediterranean coastal-plains, the Texas High Plains in the United States, Libya, Saudi Arabia, and the Chinese Hebei Plain. The water table in some coastal plains has dropped below sea-level, including areas in Germany, Denmark, Netherlands, Italy, Spain and the United Kingdom. Major cities experiencing varying degrees of subsidence include Venice, Milan, Berlin, London, Denver, Houston, Las Vegas, San Francisco, Mexico City *(Photo 45)*, Shanghai and Hanoi. Major effects include negative impacts on the base flows of rivers and springs, changes in the freshwater/sea water balance in some cases, and enhanced salt water intrusion in some coastal rivers and groundwater aquifers.

Photo 45: Tilted churches in Mexico City as a result of ground water overexploitation resulting in subsidence.

Endorheic Lakes: Waterbodies that Don't Flow to the Sea

The vast majority of the precipitation falling onto the land surface will eventually find its way back to the oceans via rivers, lakes or wetlands, or else be evaporated or transpired back into the atmosphere. There is one class of water-bodies, however, for which this journey is terminated prior to its surface water reaching the oceans. Such water-bodies exist in closed or endorheic watersheds, which contain rivers or lakes that do not drain to the oceans. This interruption of surface water flow results from a balance between inputs (precipitation + surface flows) and outputs (evaporation and seepage). Lakes in endorheic watersheds are often called "terminal" or sink lakes.

Photo 46: Size of the Aral Sea in 1985.

Although most of the millions of freshwater rivers and lakes drain to the ocean, endorheic water-bodies represent a special class of water-body like the Aral and Caspian Seas. Most are located far inland from the sea. Their watersheds often are contained within a mountain range or other natural geologic feature that has severed their direct hydrologic connection to the ocean. Because their inflowing waters subsequently flow into dry watercourses or are evaporated, minerals and other inflow erosion products concentrate within these water-bodies. With a continuing mineral input, some water-bodies typically become saline compared to water-bodies that drain to the oceans. Because evaporation plus seepage are the major water outflow pathway, endorheic water-bodies also tend to be more sensitive to pollutant inputs than water-bodies that drain to the oceans.

Endorheic water-bodies exist in belts between the northern and southern margins of desert zones in both the Northern and Southern Hemisphere. Although endorheic water-bodies usually contain water of lower quality than that of water-bodies draining to the oceans, they often are of great importance to their watershed inhabitants.

Photo 47: Size of the Aral Sea in 1992 after water diversions for irrigation had begun.

Surprisingly, endorheic water-bodies include some of the largest lakes in the world. One major endorheic lake, for example, is the Aral Sea *(Photos 46 and 47)*, in south-central Asia. Considered by many to be an "inland sea", it actually is a large terminal lake. Its two major inflow rivers, Amu Darya and Syr Darya, previously maintained the lake within acceptable boundaries of water quantity and quality for many beneficial human water uses. A thriving commercial fishery of economic importance to the watershed inhabitants also existed. However, the two river inflows were more or less completely diverted beginning in the middle of the last century for agricultural irrigation.

The diversion of its tributary inflows completely changed the character of the Aral Sea and its watershed as well as the socioeconomic status of the watershed inhabitants. Prior to diversion of its major tributaries, the lake had a surface area of about 62,000 square kilometres and a water volume of 970 cubic kilometres. Once large enough to be visible from spacecraft circling the Earth, the lake has since shrunk to about one-third of its original size, and its water has become more saline than ocean water. A once-thriving commercial fishery has been completely destroyed, and the Aral Sea watershed is now beset with excessive fertilizer and pesticide use, as well as salinized soils, which are believed to be responsible for significant human health impacts. What makes this situation noteworthy is that this devastation of the Aral Sea ecosystem occurred essentially within the space of a single human generation, an extremely short period for the extent of the ecosystem degradation that has occurred. It provides a sobering example of unsustainable socioeconomic development of a watershed, and the serious environmental, ecosystem, human health and social consequences that can arise from such actions.

Other major endorheic water-bodies include the Caspian Sea *(Photo 48)*, of eastern Europe and Pyramid Lake in the western United States. The Caspian Sea has the largest surface area of any lake in the world (more than 436,000 square kilometres), and was originally connected hydrologically to the Atlantic Ocean to the west and the Indo-Pacific Ocean to the east. With its hydrologic connections subsequently terminated over geologic time by mountain formation, etc., a vast isolated inland water basin was formed. The Caspian Sea remains the largest saline water-body in the world cut off from the ocean. Its major river inflow is the Volga River. Thus, the flow and quality of the Volga River, as influenced by its watershed population, land use and human activities, can also significantly affect both the water-level and quality of the Caspian Sea. Pyramid Lake is a large lake located in the desert region of the western United States, containing relatively salty water. It is also very sensitive to the quantity and quality of its inflowing tributaries.

Photo 48: View of the Caspian Sea from space.

How Can We Manage and Use our Freshwater Resources in an Environmentally-Sustainable Manner?

As noted in the previous chapters, fresh water passes over and through a myriad of natural landscapes in its journey to the sea. It also reacts to a range of natural and human-induced activities and obstacles in its journey, many of which can fundamentally change both its flow, volume and character. Thus, in concluding this discussion of the movement of water from the time it falls as precipitation and snowfall onto the land surface, and through the various water systems and water-bodies it may encounter on its journey back to the sea, the central question is: how we can effectively manage and use this precious resource in a manner that insures us a continuing supply in the future. It is of particular interest to consider its sustainable supply and use within the context of its role as a basic component and driving force for socioeconomic development.

As previously noted, liquid freshwater resources comprise only about 2% of the world's total water volume. All life as we know it depends on this relatively small fraction. Nevertheless, even this quantity is thought to be adequate to meet our current and foreseeable water needs, *if it were managed and used in a sustainable manner.* At the same time, we must also not forget the fundamental water needs of nature. Terrestrial and aquatic ecosystems, for example, require a minimum inflow of water to maintain their structure and function (i.e., a wetland cannot remain a wetland if it does not receive a certain minimum inflow of water). Flowing water also moves minerals, nutrients and other materials through ecosystems, and drives many biogeochemical cycles. Unfortunately, however, as we allocate our available water resource between competing human users, we seldom consider the water requirements of natural ecosystems, even though many are vital for our own existence.

The organizations of the United Nations, together with Governments and non-governmental organizations met in Rio de Janeiro, Brazil, in 1992 at the United Nations Conference on Environment and Development (UNCED). This international conference, also referred to by some as the World Summit and the Rio Conference, gave birth to what is known as Agenda 21, which recognizes and provides a framework and guidance for addressing human and ecosystem water needs in a rationale and sustainable manner. Agenda 21 promulgated the view that sustainable use of scarce water resources requires humans to consider water and its related environmental linkages in an integrated manner ("integration" refers to the process of making a whole from the parts), and within the context of an entire watershed or groundwater aquifer.

Previous chapters of this document described the various components of the natural landscape through which water passes on its journey to the sea. If the goal is to insure sustainable water resources, other important factors that must be considered include the quantity of available water and its condition, the geology, type of soil and character of the landscape over which it flows, the types of

Photo 49: Over exploitation of ground water during irrigation.

vegetation in the watershed, the watershed flora and fauna, the numbers, types and locations of pollution sources, the population centers and the extent of agricultural production, where the water is located in the watershed and where and how it is used, etc. These largely scientific and technical concerns define the quantity, location and condition of our existing water resources, as well as providing us with a picture of human and ecosystem demands on these resources.

Just as important, however, are socioeconomic issues, which are as diverse as the scientific and technical components. They include such components as the institutional structures that exist within a country and/or watershed, the existing laws and legal framework, the population patterns, the economic development characteristics and trends, the educational status of the watershed inhabitants, the existing social and cultural structures and beliefs, the state of public awareness, economic capabilities and political realities. Sustainable water management also involves integrating users and stakeholder interests in a participatory manner when allocating available water resources among competing uses and users (including ecosystem water needs). To this end, the watershed appears to be the fundamental water planning and management unit. In fact, experience suggests that these various social and economic elements are as important as the scientific and technical factors in addressing sustainable water resources, primarily because they fundamentally define how humans manage and use (and abuse) their available water resources *(Photo 49)*.

Accordingly, and although not an exhaustive listing, an integrated and environmentally-sustainable management plan for freshwater resources should ideally incorporate the elements identified in Table 2.

Water systems that cross international boundaries bring an additional dimension into the equation. It is estimated, for example, that there are more than 300 international river basins, most with considerable potential for fueling economic development. An undetermined, but equally important, number of groundwater aquifers is shared and used by more than one country. Because aquifers are the subterranean equivalent to watersheds, many of the same principles described above in regard to surface watersheds are equally applicable to groundwater systems. Unfortunately, because they are often viewed as politically-sensitive issues, many Governments and international organizations have shied away from resolution of international surface and groundwater problems. As a result, international water systems have not received the management attention they need, with predictions of future "water wars" being heard in some circles.

As a concluding observation, it might be said that many of the observations contained in this report are simply commonsense to most individuals. Indeed, most have been reiterated in some form in many regional and international water-related fora during the last decade. Nevertheless, the unfortunate reality is that humans generally continue to treat freshwater resources as a cheap, abundant and perpetually available resource. As a result, we continue to accord these resources a relatively low priority in our national and international political arenas. Accordingly, many already-serious environmental issues continue to worsen around the globe, with the supply and quality of water resources being especially sensitive to such problems.

- ***Accurate assessment of water problems*** - as the basis of an accurate knowledge base for developing realistic and defensible water management programs; further, it is important that the knowledge and information gained in such assessments be conveyed and described to decision-makers in such a manner that the latter can readily understand and use it;
- ***Maximizing water-related benefits*** - the overall goal should be to maximize the benefits of water resources on a watershed scale for the greatest number of people in both this and subsequent generations, while at the same time ensuring basic social needs and maintenance of beneficial ecosystem services;
- ***Incorporating appropriate technologies*** - this consideration includes determining whether advanced technology or simpler indigenous approaches are more appropriate for individual watershed situations, especially for developing countries; non-traditional methods (e.g., rainwater and fog harvesting) may merit consideration for these latter situations;
- ***Public awareness, education and participation*** - there is a fundamental need to inform the public of their role in both causing, and helping to solve, water-related problems; the media can be especially helpful in this regard as a means of providing information and guidance to enhance human attitudes to protecting and wisely using available water resources;
- ***Considering nature's water needs*** - because of their fundamental importance to human existence, humans must develop the means for accurately identifying and assessing the water needs of aquatic ecosystems, as well as guidance in incorporating these natural water needs into watershed development plans and programs at an early stage; and
- ***Proactive approach to water issues*** - because prevention is typically less expensive than remediation, humans should strive to consider water-related problems at the earliest possible stage; the increasing population and growth of mega-cities and their associated water needs provide a sobering example of a major emerging issue requiring proactive attention.

Table 2: Relevant elements of an integrated environmentally sustainable freshwater management plan.

Increasing population growth and urbanization *(photo 50)*, particularly in the developing world, and the resulting increased poverty and competition for limited natural resources, including fresh water, are paramount among the causative factors for environmental degradation. Escalating costs, lack of investment funds, increasing technical complexities and lack of understanding of fundamental water issues also work to impede development and implementation of necessary remedial programs and projects for addressing the issue of sustainable supplies of clean, safe freshwater resources. Nevertheless, human recognition that water is **precious**, **finite** and **irreplaceable** will hopefully provide humanity with the impetus for a proactive approach to insuring its sustainable management and use on a watershed scale, both within and between countries.

Photo 50: Tiete River, a highly polluted river crossing Sao Paulo, Brazil.

GLOSSARY:

Anthropogenic: originated by humans
Aquifer: naturally stored underground water
Artesian well: a well made by a perpendicular boring into a confined aquifer
Brackish: having a somewhat salty taste, especially from containing a mixture of seawater and fresh water
Catchment: the physical or surface area from which rainfall flows into a river, lake or reservoir
Dendritic: “tree branch-like” shape
Drainage basin: region surrounding a lake, reservoir and rivers from which water is drained into
Ecosystem: functional natural component consisting of plants, animals and microorganisms together with the surroundings
Estuary: the part of the wide lower course of a river where its current is met by the sea
Fauna: animals
Fjord: a long, narrow, deep inlet of the sea between steep slopes in a coastal area
Flora: plants
Hydrologic cycle: cycle of water
Impoundment: a confined body of water
Oasis: a green patch of vegetation in dry areas or deserts where water is found on the surface
Perennial Ice: ice in glaciers, high mountains and polar areas which always present throughout the year
Permafrost: frozen underground water
Phytoplankton: a community of microscopic plants found in the majority of surface water-bodies
Runoff: water which flows on the ground surface after rainfall
Sedimentation: process in which suspended particles settle to the bottom
Socioeconomic: of or involving both social and economic factors
Subsidence: sinking of the ground
Subterranean: situated or operating beneath the earth’s surface; underground
Wadi: a name given in the Arab region to an ephemeral watercourse
Water quality: a description of how good (adequate) a water is for a particular purpose
Watershed: either the dividing line between two water catchments or the catchment itself
Water table: the level below which the ground is completely saturated with water

Figure and table credits

Adapted from a figure in the homepage of World Meteorological Organization <http://www.wmo.ch/web-en/wmofact.html>: Fig.1
From the homepage of “Friends of Chapala”, Mexico <http://www.lermachapala.com.mx/art9.htm>: Fig.3
W. Rast: Fig.4/ Table 1,2
Adapted from the brochure of the “9th International Conference on the Conservation and Management of Lakes”: Fig.5
UNEP Environment Library No. 15 (Groundwater: A Threatened Resource) 1996: Fig.8, 9, 10

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