Urbanization: A Hydrological Headache
Author(s): Gunnar Lindh
Source: *Ambio*, Vol. 1, No. 6 (Dec., 1972), pp. 185-201
Published by: Allen Press on behalf of Royal Swedish Academy of Sciences
Stable URL: http://www.jstor.org/stable/4311983
Accessed: 03/02/2010 10:19

Urbanization: A Hydrological Headache

BY GUNNAR LINDH

Urbanization disrupts the natural hydrologic cycle and creates problems concerning the quantity, quality and distribution of water. The problems are myriad and range from the higher frequency of thunderstorms in cities to the need to negotiate bilateral water transfer treaties.

The science of hydrology deals with the occurrence, circulation and distribution of the waters of the earth. It is also concerned with their chemical and physical properties and their reactions with the environment, including living things. The development and management of water as a natural resource is also part of hydrology.

THE HYDROLOGIC CYCLE

The water of the hydrosphere is continually in motion between the ocean, the atmosphere and the continents and the process that describes its movement is called the hydrologic cycle. Hydrology is involved with the study of the hydrologic cycle.

Fig 1 presents a schematic diagram of the hydrologic cycle. The sun supplies the energy that causes evaporation from the ocean surface. The rising water vapor is then cooled and condensed, producing precipitation in the form of rain, hail, snow, etc. Most of the precipitation falls into the oceans, lakes and watercourses, but part of this is re-evaporated to the atmosphere. Fig 2 illustrates this process.

Some of the precipitation that falls over land is intercepted by vegetation. Some precipitation reaches the ground and infiltrates to the upper, aerated zone of the soil. A portion of the infiltrated precipitation percolates down to ground water reservoirs. Another portion is taken up by plants and then released into the atmosphere in a process called transpiration. Some of the infiltrated water is evaporated to the atmosphere directly from the upper part of the ground. That part of the infiltrated water which is not returned to the atmosphere seeks its way through the soil and finally empties into the groundwater reservoirs and some returns to streams which ultimately flow into the oceans.

The cycle can be regarded as a series of storage and transfer parts. Water is stored in the atmosphere, lakes and the oceans, and it is transferred between storages through the processes of precipitation, evaporation and transpiration. The renewal period for different storages is an important concept in the study of the hydrologic cycle, theoretically and also when estimating available water resources. The mean renewal period for a stored volume of water can be calculated as the quotient of storage volume and annual rate of removal. Table 1 shows calculations made by the Soviet researchers Kalinin and Bykow (1).

From Table 1 it is evident that the renewal time for the different storages varies between nine days and 16,000 years. The mean value for the total hydrosphere is about 2,800 years. Thus a renewal that started in the days of Homer is just now nearing completion. In comparison, the renewal time of the blood transport through the human body is about one minute.

In many respects the concept of the hydrologic cycle is a very important one. Yet the cycle is a very simplified way of describing a very complicated process. The diagram gives an incomplete picture of reality because it depicts a perfect cycle completely unaffected by man. This ideal hydrologic cycle is often called the pre-urban system.

A mathematical study of the schematic representation of the process will result in a formal description of the interactions occurring in that system. The goal of such a study is the identification of influences caused by human activity in the mathematical model. This is one example of what is called systems analysis, an important aspect of modern hydrology.

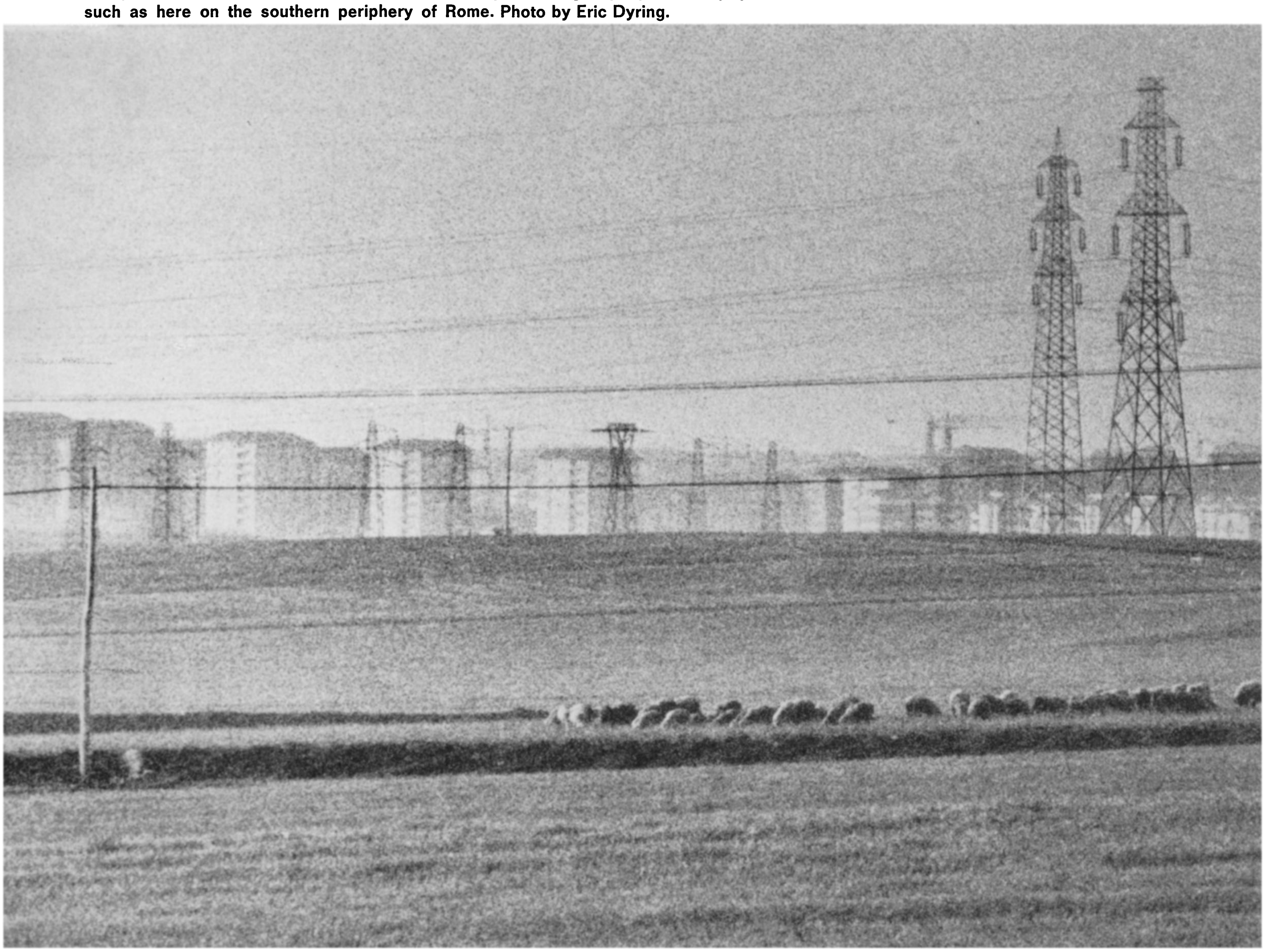
THE URBANIZATION PROCESS

Urbanization may be considered to be the change in land occupancy and use brought about by the conversion of rural lands to urban, suburban and industrial communities. The obvious effects are increasing population density and the concentration of residential, industrial and commercial buildings and facilities with the resultant increase in areas that are impervious (impermeable to infiltration).

From a hydrologic point of view, urbanization gives rise to several problems; namely (a) an increased demand for water for municipal, industrial and recreational purposes, (b) changes in the physical environment that alter the natural water balance and (c) waste disposal that may contaminate streams and aquifers (ground water reserves).

The effect of urbanization on the hydrosphere may also be defined in a broader sense. According to American geologists Savini and Kammerer (2) there are certain distinct phases of urbanization that might affect the hydrologic cycle or the water balance.

Competition for land. The urbanization process is proceeding rapidly in many parts of the world, such as here on the southern periphery of Rome. Photo by Eric Dyring.



The authors describe a first phase which includes such measures as deforestation, the initial use of wells, and to some extent the erection of dwelling houses with the attendant use of septic tanks and sewers.

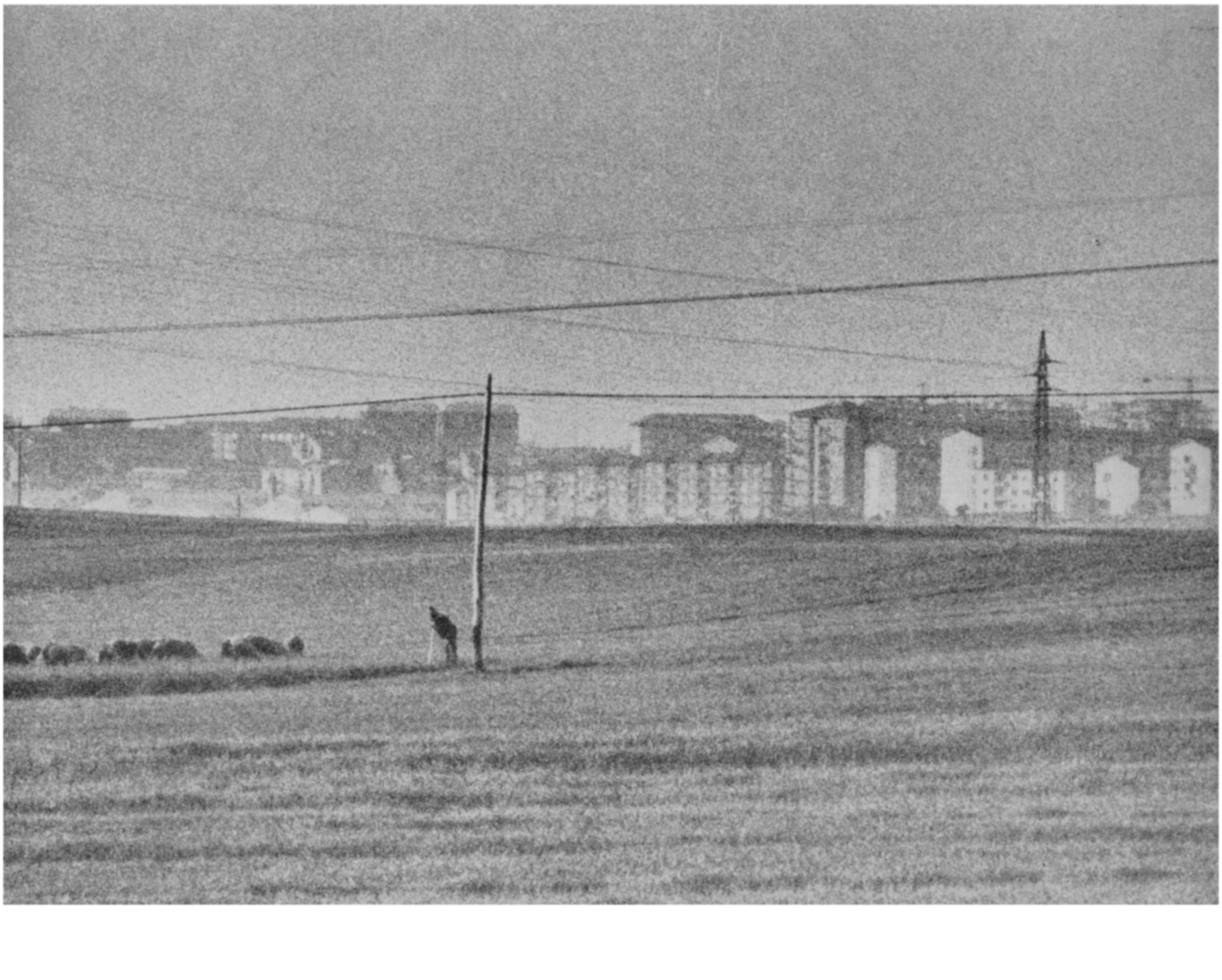
The second phase of urbanization comprises such activities as excavation for housing, erection of housing, paving of streets, construction of culverts, etc. Waste water, purified or not, is diverted to water courses or lakes.

The third and last phase of urbanization includes, among other things, the completion of the housing areas. Increasing quantities of waste water and solid wastes are disposed of in receiving waters. Existing wells are abandoned, mainly because of severe pollution. The increasing population leads to the enlarging of the existing water supply system. Sewage treatment plants are erected. Urban storm runoff is conveyed by a system separate from or combined with the municipal sewage system. New, high-capacity wells are planned. Artificial infiltration is used.

The effect of urbanization on the hydrologic cycle can be represented schematically in a cyclical process designated as the urban hydrologic system. Such a system can show how different external demands can affect the original hydrologic cycle. It also illustrates the changes brought about by the change in land use and the creation of artificial draining systems (Fig 3).

CHANGES IN THE MICROCLIMATE

One starting point for the study of the hydrologic effects of urbanization is the investigation of the microscale



climate and how it is influenced by the urban area. Microclimate is generally understood to be the climate within the layer of air nearest the earth's surface, usually up to 10—20 m, although in some cases the upper limit may extend up to 100 m near the earth's surface. In this particular case the term is used to refer to the climate caused by the city, or climate on a yet smaller scale. Unfortunately, little is known about this subject.

However, Landsberg (3) says there is a very substantial change in the composition of the atmosphere around cities and that an increase in precipitation is a characteristic feature of cities. He says there was an increase of ten percent or more in the number of days per year having thunderstorms at Nuremberg.

It has been generally observed that the mean annual temperature is higher for cities than for the country. Humidity, however, seems to be lower in cities than in the countryside. This could be because there is much less water available for evaporation in the cities, since natural vegetation has been removed.

Increased cloudiness is also observed in cities, probably caused by pollutants from municipal heating and from industries in or near the city.

Wind turbulence is increased in some parts of the city due to increased surface roughness. Mean wind velocity however is said to decrease.

A similar opinion about microclimate is expressed by the Canadian meteorologist Munn (4) in his now-classic book on micrometeorology.

The Swedish meteorologist Högström (5) points out that

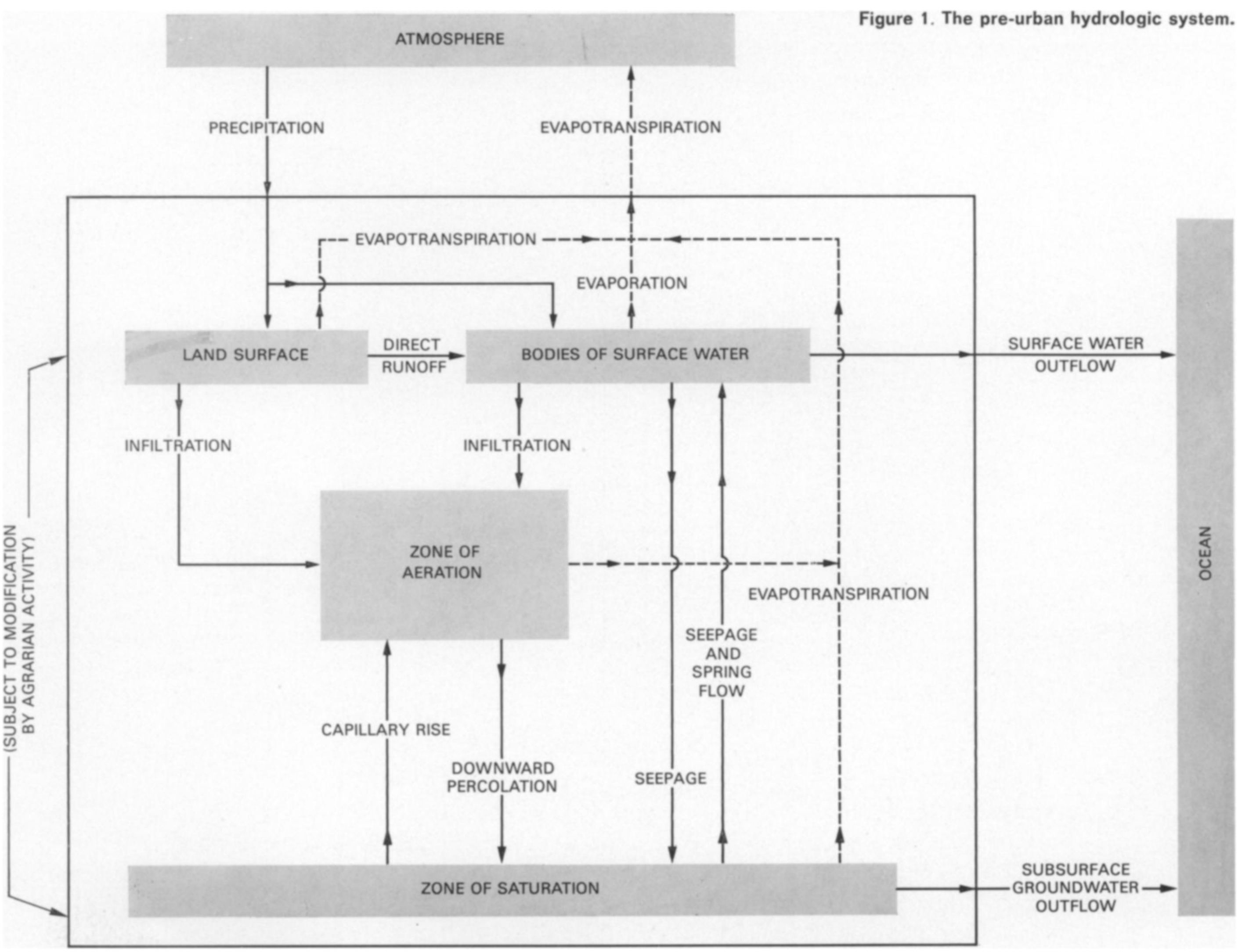


Figure 1. The pre-urban hydrologic system.

several investigations show increased precipitation in cities.

Reports from France have shown that more precipitation occurs on weekdays than on Saturdays or Sundays, an effect that could be due to differences in air pollution emissions.

THE GROUND'S HYDROLOGICAL RESPONSE

Some of the most pronounced hydrological effects of urbanization are the changes in the runoff of precipitation water from the urban region. These changes are due to the fact that the natural drainage process, in which precipitation is converted to runoff, is completely changed in the urbanization process. The infiltration possibilities are reduced when the natural ground surface is replaced by pavements, roofs etc. Simultaneously, the draining efficiency is increased heavily by the introduction of a dense network of artificial drains. It can be said that the urbanization of a rural area brings about a total change in the area's response to precipitation.

The response of the ground to precipitation can be visualized with a hydrograph, which is a graph on which time is scaled on the horizontal axis and the amount of runoff is scaled on the vertical axis. The urban runoff hydrograph is strikingly different from that of rural runoff (Fig 4). It shows a much more concentrated time history of runoff, with a sharp peak. The peak flow is substantially higher than when the area was in its rural state.

Not only is there a substantial increase in the flood runoff when an area is urbanized but there is also an increase in the total volume of runoff. This volume increase

Figure 2. The hydrologic cycle.

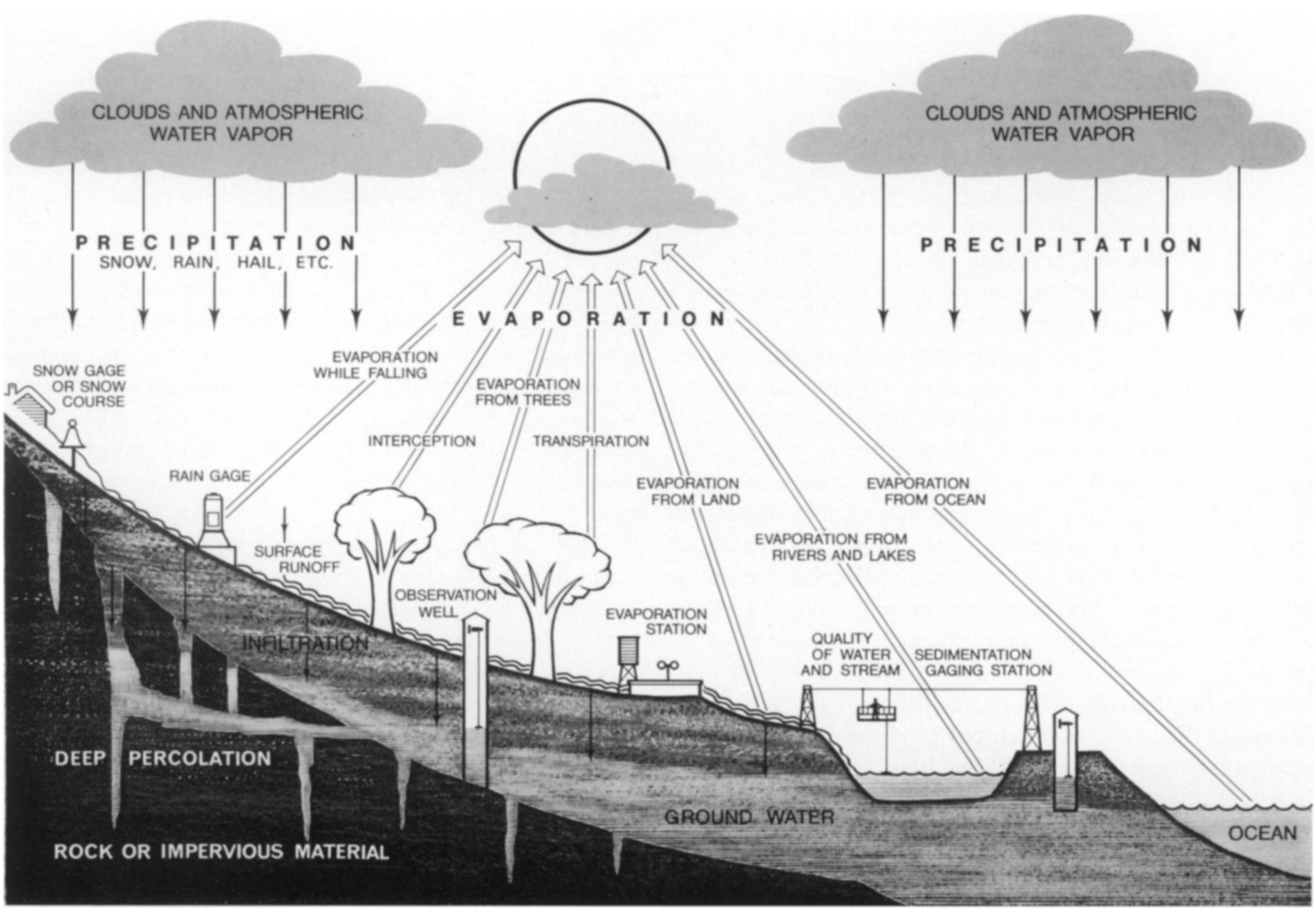


Table 1. World's water resources

Resource	Volume (W) in thousands of km^3	Annual rate of removal (Q) in thousands of km^3 and process		Renewal period (T = W/Q)
Total water on earth	1,460,000	520	evaporation	2,800 years
Total water in the oceans	1,370,000	449	evaporation	3,100 years
Free gravitational waters in the earth's crust (to a depth of 5 km)	60,000	13	underground runoff	4,600 years
(Of which, in the zone of active water exchange	4,000	13	underground runoff	300 years
Lakes	750		— —	
Glaciers and permanent snow	29,000	1.8	runoff	16,000 years
Soil and subsoil moisture	65	85	evaporation and underground runoff	280 days
Atmospheric moisture	14	520	precipitation	9 days
River waters	1.2	36.3*	runoff	12 (20) days

* Not counting the melting of Antarctic and Arctic glaciers.

which is equivalent to an increase in the mean runoff, implies that a higher percentage of the precipitation leaves the area as runoff. This fact is generally attributed to the reduction of infiltration, evaporation and transpiration that occurs when an area is urbanized.

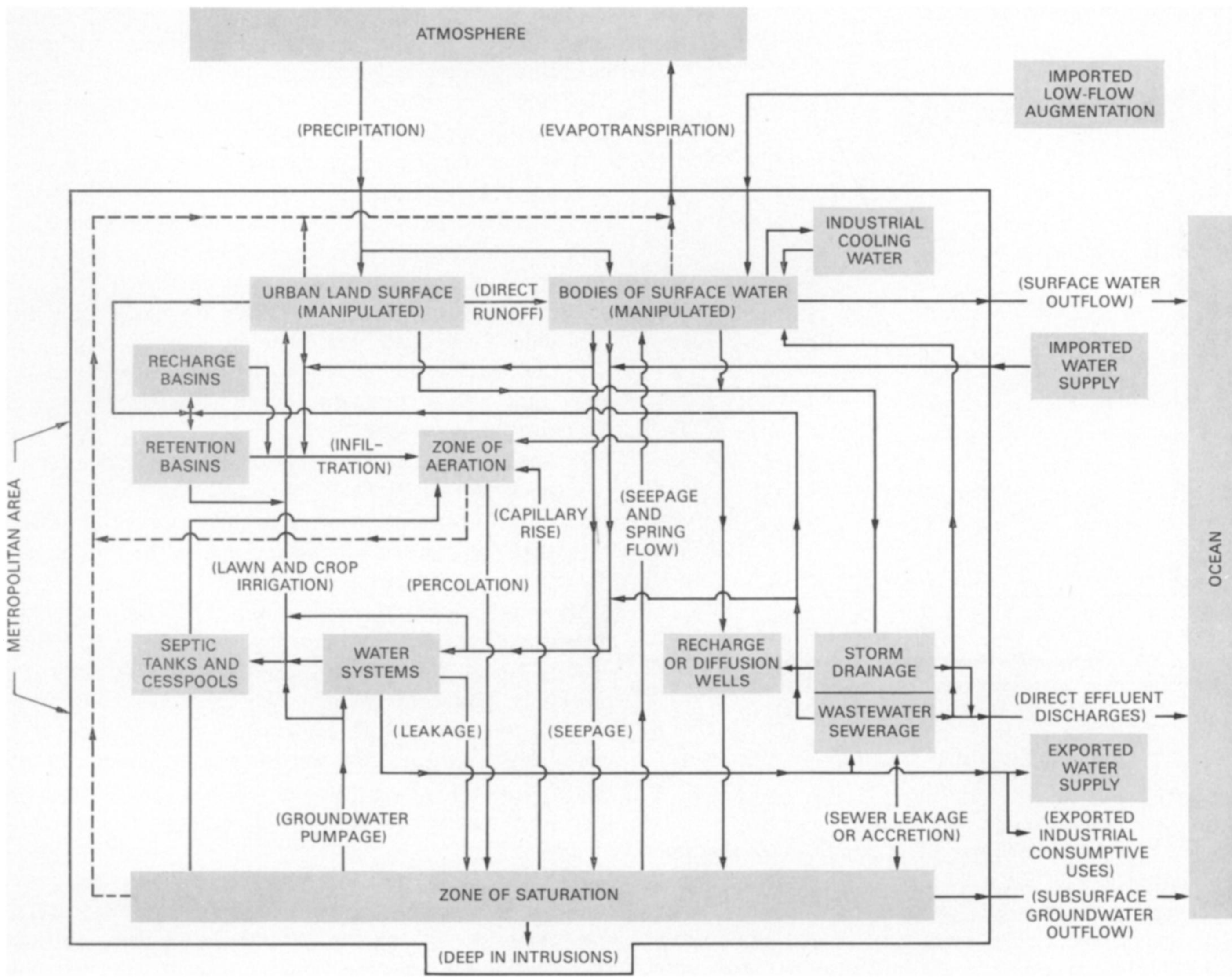
As it has been observed that the peak runoff reaches higher values when the percentage of impervious areas such as paved streets, parking places etc is increased, much interest has been devoted to the possible connection between increases in impervious area and increases in urban runoff. In analyzing urban storm runoff, the opinion is still expressed that there could be a more or less direct relation between these two factors. Considering the urban hydrologic system, however, it becomes clear that looking at the urban runoff in this oversimplified way would be wrong.

Very often the opinion is expressed, mainly by practicing engineers, that impervious areas produce a hundred percent runoff, a statement that has been proved to be quite incorrect. Some of the water does not run off the impervious area; it is stored in holes and cavities formed in the surface. Viessman et al report that about 0.2 cm has to be immediately abstracted from the precipitation in order to take this storage into account in paved areas (6). Thus the surface water storage has an important influence on the runoff. A simple analysis performed by Lindh (7) resulted in a time distribution of runoff as shown in Fig 5. Note: this analysis assumes that the intensity of precipitation is constant while it is raining and that no infiltration occurs. If infiltration is incorporated into the analysis the runoff history will change. Infiltration plays an important role in urban runoff. A city generally shows a variety of ground surfaces, such as streets, lawns, parks etc.

Many confusing observations have been made on the connection between runoff and infiltration. Investigations have been published showing that overall infiltration increases during dry periods in certain urbanized areas. This fact has been shown to be a consequence of increased lawn sprinkling and importation of water from other basins.

Several research workers have reported that the widespread opinion that there ought to be a high infiltration capacity of lawns, urban green areas etc, is not always right. Investigators in one case (8) recorded an infiltration capacity rate of about 0.25 cm/min, a figure found to be $^1/_6$ that of the infiltration rate of forest in the case studied.

Figure 3. The urban hydrologic system.



Later it was explained that the low infiltration rate of urban green areas resulted from bulldozing, soil mixing and other technical procedures involved in the building of a city (9).

Infiltration studies refer mainly to point infiltration observations. Measurements of this type cannot give precise information about the real relationship between such values and ground layer infiltration values which are needed in practical calculations.

These few examples may serve to show that the details of the urban runoff process, in spite of all the experimental work and theoretical studies that have been conducted, are not very well known. An attempt to explain the runoff process must account for all factors involved in the hydrologic cycle: precipitation, infiltration, evapotranspiration and surface detention storage.

It is important to remember that the prediction of the magnitude and the time distribution of urban runoff is still an unsolved problem. Not only the urban hydrological conditions, but also the intensity, duration and frequency of precipitation must be known in order to be able to calculate urban runoff. In many countries extensive studies are being conducted on these problems.

The runoff from land areas empties into nearby water

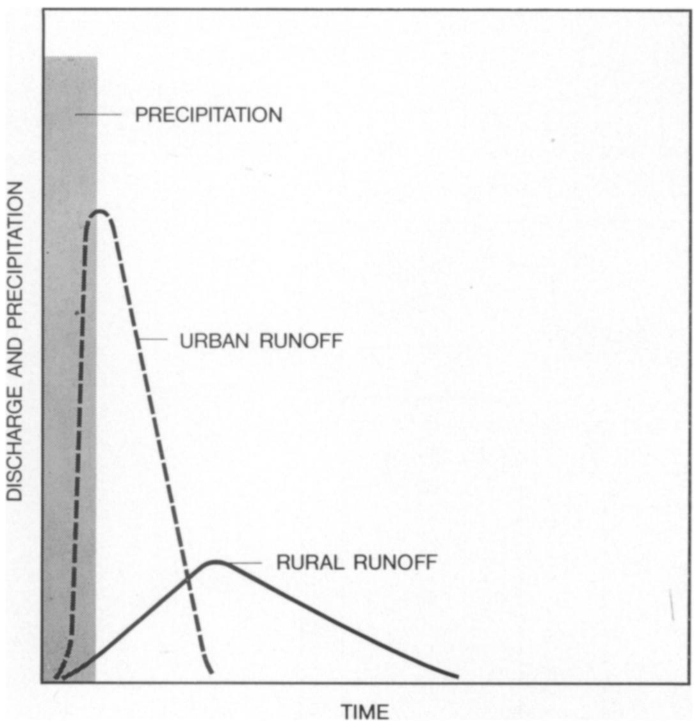


Figure 4. This hydrograph shows how the time history of urban runoff differs from that of rural runoff.

courses. Changes in the runoff of urban areas therefore imply alterations of the natural seasonal variation of river discharge (river regime). These variations can be changes in the mean flow, in the mean maxima and minima, and in the absolute maximum and minimum flow. Many natural factors affect river regimes. Seasonal variation in the natural runoff of a drainage basin depends primarily on the relation between climate, vegetation, soils and rock structure, basin morphometry and hydraulic geometry. However, the important fact is that man's activities can alter the regime.

LOWERING THE GROUNDWATER LEVEL

Both quantitative and qualitative groundwater changes have been observed as a consequence of urbanization. The reduced infiltration caused by the transformation of rural lands into urban areas has in many cases been responsible for a lowering of the groundwater table. The reason for this is that reduced infiltration results in a reduction of the rate of replenishment of the groundwater body. Such a lowering of the water table may also be caused by construction work in an urban area. In some cases areas must be drained to prepare land for the construction of housing. The digging of subways and other types of tunnèls may also result in the lowering of the water table.

A serious problem is the damage to buildings that accompanies the subsidence brought about by a lowering of the water table in certain soils. One classical example of such a settlement is that reported from Mexico City (10). Subsidence of from about five to seven m was recorded in the central part of the city (1960). Because of this the Guadalupe Cathedral is now inclining.

In the San Joaquin Valley in California, subsidences of about nine m have been caused by groundwater withdrawal for irrigation purposes (11).

Perhaps the most well known example of subsidence due to groundwater withdrawal is the sinking of Venice. However, other factors are involved in this case: the extensive withdrawal of gas, tectonic movements in the Po district, the influence of tidal water, etc.

Many other cities throughout the world have reported instances of subsidence. Authorities report that subsidences of 0.5—1.0 m have been observed in Swedish cities. In Stockholm there are extensive clay areas in certain parts of the city, and ground settlement resulting from clay consolidation occurs. One way to prevent subsidence of this kind would be to provide for sufficient infiltration so that the groundwater body could be recharged (see pictures pp 194—196).

A special problem concerning groundwater depletion has been reported by the German hydrologist Zayc (12). This has to do with mining activities in the Ruhr district. In order for the mines to function properly, the groundwater must be drained. In an area 50 km long and 15 km wide, the water table is said to have been lowered to 300 m below the surface.

A ca 20 m thick layer of loess has prevented severe damage to vegetation. But other hydrological problems have resulted. About 35 m^3 per second of drained water has to be discharged into a river where the natural flow is only 5 m^3/s. This situation results in a constant, high water state and therefore it has been necessary to create an artificial waterway which leads directly into the Rhine. Since the drained groundwater is sometimes warm (deep groundwater), this may cause changes in the local climate.

Zayc also stresses the fact that if some water courses rise to a higher water level, other water courses will sink to a reduced water level when deprived of a considerable

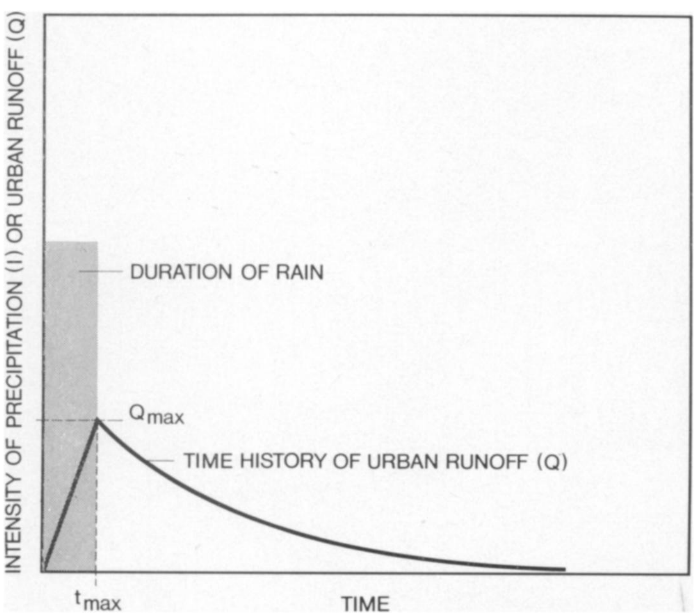


Figure 5. Time history of runoff in impervious areas at a period of constant precipitation. Water is stored on the surface and the runoff first reaches a peak value and then decreases exponentially.

amount of natural discharge. This in turn affects the purifying ability of the water courses, since the diluting effect is reduced.

The problem as described by Zayc may be regarded as a special case, although many such special but important cases are reported in the hydrological literature, describing negative effects on the hydrologic cycle and the biosphere.

One class of groundwater problem which appears in many countries is the well-known one caused by heavy groundwater withdrawal from wells near the coast which is followed by salt water intrusion into the wells.

The sinking of the groundwater level is a result of a changed balance between recharge, natural discharge and artificial withdrawal. Determining the balance of the groundwater bodies beneath urban areas is complicated by the fact that a certain recharge takes place by means of water leaking from water distribution pipes.

The American economist Howe (13) reports that he collected information from 91 cities in the USA, and that it appears the mean loss of water from distribution systems was 12 percent of production. In certain areas the loss was near 20 percent. By means of this leakage a recharge to a local groundwater storage may occur, depending on the geological and urban conditions.

POLLUTION OF GROUNDWATER

In addition to quantitative changes of the groundwater storage, many cases of qualitative deterioration have also been reported. The leaking of water from or into underground systems (pipes or tunnels) has been reported from many countries. Depending to some extent on the geological environment, groundwater may also be contaminated by leakage from cesspools, septic tanks and industrial oxidation lagoons.

Judging from a Swedish investigation (14) where samples of percolating water were taken from the bedrock of a tunnel roof, it appears that the groundwater in urbanized areas is contaminated by waste water from discharge pipes and infiltration plants. Therefore small communities that for economical reasons are forced to use groundwater from reservoirs situated near these sources of waste water should be warned of the contamination risks.

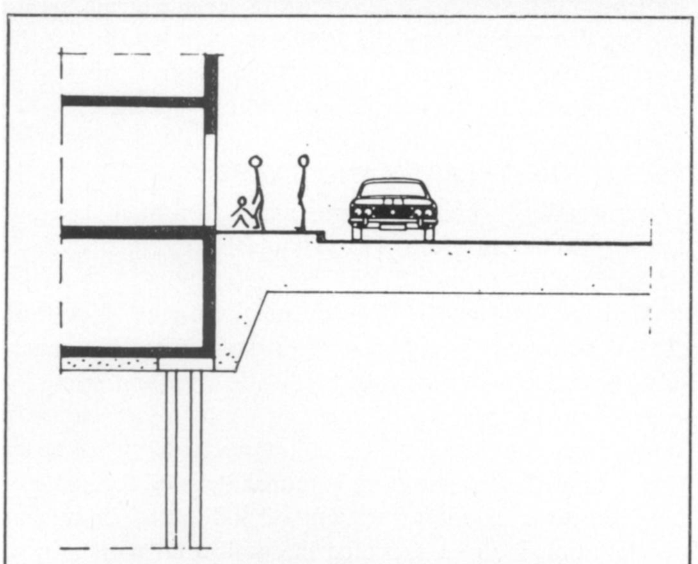
A rather special case in Stockholm shows clearly how urbanization can affect hydrologic processes (15). When the subway was built in Stockholm immense quantities of water were pumped away from the region under construction. Of course, this pumping contributed very much to settlement. In addition a large quantity of water is constantly withdrawn from the ground supply and is used for the cooling of air condition units and electric plants. At least 8,000 m^3 is used daily during periods of maximum cooling demand. During the 1960's the temperature of the groundwater rose from 1 to 1.5°C in central Stockholm and at present the temperature is about 10.5—11°C.

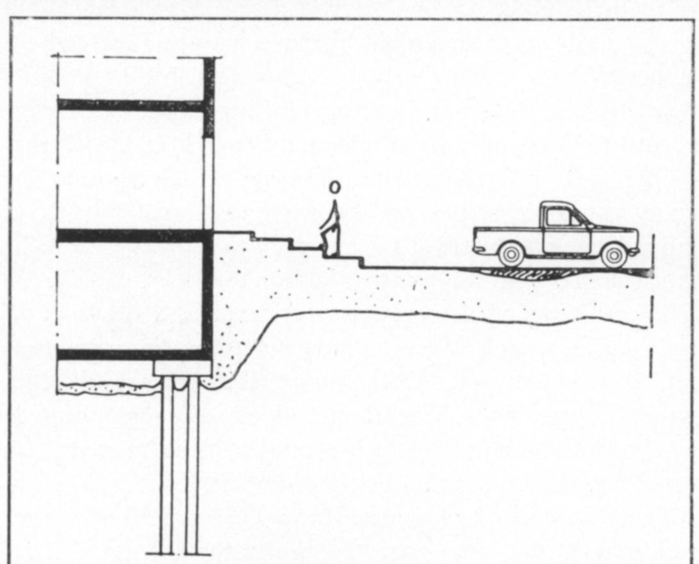
POLLUTION OF LAKES AND RIVERS

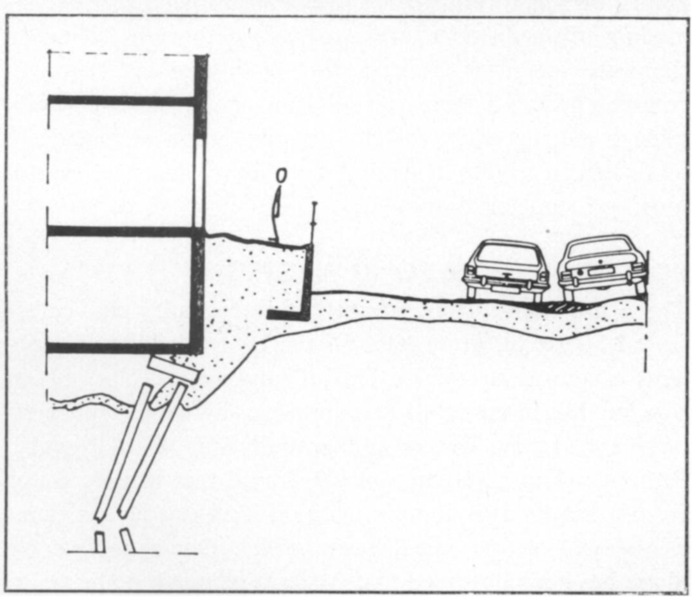
Water quality is certainly as important a problem as water quantity in urban areas. Urban runoff contain pollutants which have to be treated.

Analyses by the Swedish chemist Gunnar Söderlund (16) of pollutants in urban storm runoff show that generally the amount of suspended solids is high and seems to depend on the intensity of the rain. A high-intensity rain causes high concentrations of pollutants. Since it is known that a rain of short duration is more intensive than one of long duration, a greater amount of pollutants per mm of precipitation is to be expected in connection with rain of short duration.


Kodak
OKHANDEL







The scarcity of available land for the rapid expansion of Stockholm has in several cases resulted in the exploitation of swamp areas. At Huddinge, a suburb south of Stockholm, a shopping center was constructed in the middle of a swamp. The soil originally consisted of a 1—2 m layer of peat moss on top of a bed of soft and compressible clay with a depth of up to 20 m.

The whole building area was filled in with heavy soil, immediately causing the peat to be compressed to a fraction of its original thickness. This augmented the load on the clay by about 40 MN/m^2. In addition, it was decided that the finished level would be slightly above the original swamp level. Finally, the drainage caused a lowering of the ground water level, which is also a kind of load increase. The total load increase on the clay then amounted to approximately 60 MN/m^2 when the shopping center was inaugurated about ten years ago.

The pressure on the clay started a subsidence process which caused serious damage to most of the surfaces in the shopping center. The subsequent repairs included refilling in order to keep the original level of the communication surfaces and to maintain access to the store entrances.

The subsidence also took place under the buildings.

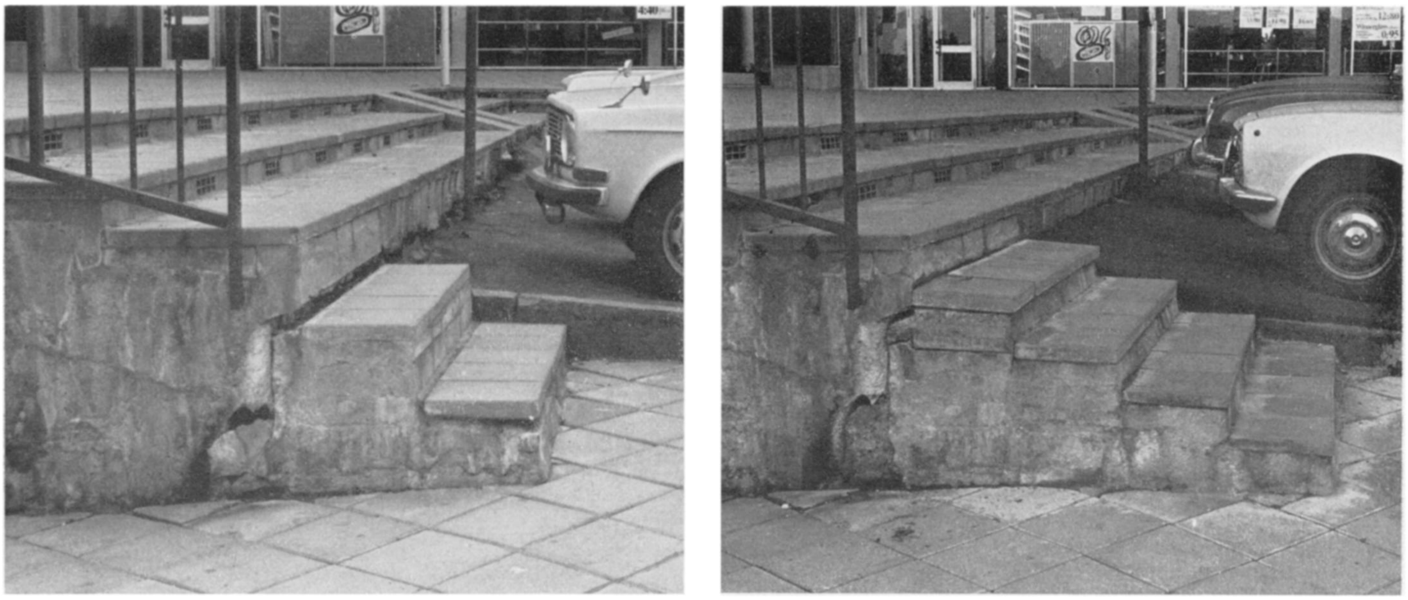
With a difference between the levels outside and underneath the houses thus established, the conditions were no longer stable and a slide began. When this process was discovered, most of the piles along the façades were found to be broken or so severely damaged that their load-bearing capacity was nil.

A catastrophe with a total collapse of the buildings was prevented only because the cellars of the most critically situated buildings were designed as air raid shelters, with heavily reinforced walls, etc. These walls transferred the loads from the peripheral zone to more centrally situated foundation pile groups.

The first stage repairs comprised complete excavation of the heavy overload and replacement of the façade piling. A complete remodelling of the shopping center is contemplated as a later and final stage.

Photo Arne Barthelsson, commissioned by STEGA.
Figures: STEGA.

The picture show the results of a rapid subsidence process at a parking lot located in a shopping center in Solna, a suburb of Stockholm. Originally the stairs consisted of three steps. In 1971 two steps had to be added, and in 1972 two more steps were added. Photo: Arne Barthelsson, commissioned by STEGA.



The Swedish studies show that snow that has been cleaned away and deposited in lakes or watercourses may contain a considerable amount of different kinds of pollutants. From the city of Stockholm it is reported that during one year about 850,000 m^3 of snow was deposited in receiving waters. It has been estimated that this volume contained about 30,000 kg of lead, 6,000 kg of oil and 130,000 kg of sodium chloride, etc.

It may be recalled that a certain relation exists between pollution, precipitation and urban storm runoff. Therefore the runoff from industrial areas can be expected to be more heavily polluted. Such areas must obviously be regarded as deleterious to the environment.

Many treatment plants do not have the capacity to take care of the large volumes of water resulting from urban runoff. The only way to handle this situation in most cases is to discharge a certain quantity of untreated water into receiving waters. Thus there is apparently a link between urban runoff and the deterioration of the environment.

The situation is complicated by the leakage of ground water *into* sewer systems. The leakage is generally considered to be caused by leaky joints, ruptures, etc in pipe systems. The American Public Works Association (17) was involved in a study that reported the infiltration into sewer systems may average as much as 15 percent of the total flows handled by sewer systems; peak infiltration may be 30 percent.

Another effect of urbanization is perhaps less well known. Urbanization and other human activities have increased land erosion. This occurs especially with suburban development. American studies have shown that sediment yields in suburban areas that are under development can be as much as five to 500 times greater than in rural areas. Such sediment degrades water quality and accelerates eutrophication.

The following statement given by the US Office of Water Resources Research (18) seems to be a very interesting contribution to the discussion of the role of pollution caused by sediment: "The importance of sediments as pollutants is increasing, particularly in view of the ability of soil to absorb pesticides and other organics, including oily substances, and to release these materials in the water resource. Indeed, this facility of sediments to receive chemicals from the solution phase, when properly understood, may be subject to manipulation and made to serve effectively to trap and immobilize harmful wastes moving in our environment."

POLLUTION FROM SOLID WASTES

There are many ways in which water quality can be affected by urbanization. One of the biggest pollution problems in urbanized areas is that of solid wastes. Not only in Sweden, but in many other countries solid wastes may contaminate surface waters and groundwater. Thus Swedish Professor Yngve Gustafsson (19) found that leaking water from a solid waste dumping site on land can be ten times as polluted as municipal waste water. One dumping site alone has been observed to contribute as much pollution as an urban area of several thousand inhabitants. The deterioration is in some cases substantial if the dumping site is supplied with process slurries, oil products, scrapped vehicles, deceased animals, etc.

The managing of solid wastes sites is not the only problem; the locating of suitable sites for the disposal of increasing amounts of solid wastes in urban areas raises many questions.

In Sweden treated solid wastes have, in some cases, been used for reclamation. A land fill project is being conducted in an area outside the southern city of Malmö, Sweden's third largest population center, in order to gain land from Öresund, the stretch of water between Sweden and Denmark. According to an early plan, the reclamation work will progress in three stages, resulting in the creation of recreational areas and an enlargement of the harbor (Fig 6). A dike will protect the deposited solid wastes from the sea. Of course many unsolved questions must be answered. Will there be any leaking through the protecting dikes? How great is the risk for groundwater contamination? This problem is similar to that of contamination by solid waste deposits on land.

Referring to the disposal of solid wastes, the US Council on Environmental Quality (20) claims: "Concentrations of mineral and agricultural wastes are spread widely over the land and are mostly isolated from population concentrations, although some deleterious effects on urban residents are nevertheless suspected, and have been documented in isolated instances. The bulk of the other wastes are disposed of in or near urban areas and represent an ever-present threat to public health. Space available for municipal solid waste land-disposal is fast disappearing. Integrated management of urban residuals in air and water and on the land is regarded as a necessity for adequate environmental protection in the future."

THE WATER SUPPLY PROBLEM

In this section the problem of water that is unevenly distributed spatially shall be considered in relation to urbanization. Water has always been one of the basic necessities of life. The earliest sites man chose for communal living were located close to a well, a spring or a water course. If the site was built around a well or spring it developed in a radial pattern, whereas if it was established on the banks of a stream or river it developed into a linear community.

Until the discovery of the wheel the outer boundary of the community was determined by the maximum carrying distance from the water supply. The historical development can be traced from wells, to large reservoirs near population centers, to the transfer of water from distant sources.

Densely populated areas, e g in the USA have already given rise to a series of water problems. As mentioned earlier, water is certainly not available in sufficient quantities near all population centers. Thus one of the biggest problems of today is to match supply with demand. This can be a rather complicated problem, as can be seen from the following example. Soon after the onset of the drought period that settled over the Northwestern US from 1963—1966, the reservoirs supplying the city of New York with water were practically empty. One might expect that a city through which a large river flows would be guaranteed a continuous water supply. However, the thirst of the citizens of New York could not be quenched by taking water from the Hudson River which flows through the city, because the river is so heavily polluted.

The same kind of problem occurs in many conurbations. Calcutta, to mention another example, stands astride a great river, yet it is a difficult matter to provide an adequate year-around water supply for the city's inhabitants.

Many urbanized areas rely on groundwater supply to a considerable extent. For instance, groundwater accounts for more than two thirds of all water used in Israel. In some European countries e g Denmark, the Federal Republic of Germany and the Netherlands, it provides three quarters or more of the water supply. London, Hamburg, Copenhagen and the areas around Basel and Vienna are all suffering from the chronic problem of falling groundwater level due to extensive withdrawal.

WATER TRANSFER

Rapidly increasing demand for water due to increasing population has forced many large cities to import water from other regions. Locally of course desalination may be an alternate way of obtaining large quantities of potable water.

One well-known Swedish example of water transfer is the Bolmen Project. Lake Bolmen is the tenth largest lake in Sweden, and is located in the southern part of Sweden (Fig 7). There are plans to withdraw 6 m^3/s or 190 million m^3/year from Lake Bolmen. The water will be transferred to some south Swedish cities. This quantity is supposed to be sufficient until the year 2000, assuming the prognoses for population development in the concerned cities are correct. The tunnel that will convey the water will be 80 km long with a cross section area of 9 m². It will in places be as deep as 50 m below the surface.

When the Bolmen project was being planned, the possibility of transferring water to West Germany, especially to the Hamburg area, was also considered. This part of the project has, however, been dropped.

Today Sweden is rather well supplied with potable water but the situation may change soon because part of this supply may be needed by the water-poor northern part of continental Europe. A transfer of water to continental Europe may thus become a reality.

In the USA the demand for water has made a series of transfer projects necessary. The largest of these is the North American Water and Power Alliance (NAWAPA) (21). The NAWAPA plan was proposed in 1964 to involve a series of projects ranging over a period of 20 years. According to the plan, Alaskan and Canadian rivers will provide water for seven provinces of Canada, 33 states in the United States and three northern states in Mexico. Initially, the system would provide 130 km³, but according to the plans it will later be expanded to provide 300 km³.

Such a project gives rise to many questions. There has begun, especially in prospective exporting regions such as the Pacific Northwest and Canada, a discussion of what price should be set on water. The exporters are trying to protect their interests by demanding careful study of the water needs, not only in their own regions but also in the prospective importing regions.

The introduction of water from one catchment area to another to which it does not belong can bring about a number of hydrological problems. These problems arise in many countries where reservoirs are built in order to store water for later delivery to other sites. Little is known about the effects of water transfer on the hydrologic cycle, regional water balance, or water quality.

THE PRICE OF WATER

When water is transferred between two or more countries, economic problems are encountered. The transfer problem may belong to one of two categories. In first category the water exported is withdrawn from a watercourse entirely situated within the borders of the exporting country. In the other category it flows through both countries and the exporting and importing countries share the costs and benefits.

In a discussion of water transfer, the questions of the cost and the value of water come into play. It is not an easy matter to assign costs to water resources; value judge-

Figure 6. A project to use solid wastes to gain land from Öresund, the stretch of water between Sweden and Denmark, is being conducted in Malmö, Sweden's third largest city. The first step is to use solid wastes to raise the level of the shore area and the second step is to gain land from the sea by using solid wastes as landfill. A third step is also planned. The project will result in an enlargement of Malmö's harbor and will provide land for recreational purposes.

ments are involved and intangibles have to be dealt with. The cost of water can be defined as the price in monetary units per quantity of water we must pay in order to make available at a given time and at a given place a certain amount of water. The value of water may be defined as the maximum amount we are willing and able to pay to obtain a given flow at a given time at a given place.

Stated in another way, the value of water corresponds to the minimum amount we would be willing to accept as compensation if there was a proposition to take away from us a given flow at a given place at a given time.

Let us consider a hypothetical water course that is not used for any form of human activity. A project to increase the flow in this water course would of course not interest us. However, if someone proposed a plan to withdraw a given amount of water, we would certainly hesitate. In that situation we should raise questions concerning the effects on the ecological system and we might claim that this proposition would detract from the water's recreational value. We would also speculate about the importance of the watercourse to the future development of power generation stations, water supply plants, etc. Thus we may conclude that even those watercourses presently unused by man may have some value. In fact the first problem to solve seems to be the one concerning the mutual economic and social benefits to the countries participating in a water transfer project. Experiences have shown that the best water conveying arrangements are made when the water transfer is based on mutual benefits.

There are about forty bilateral water transfer treaties in the world. A water transfer treaty should not only take into consideration the existing situation, but it must also take into account the foreseeable demand for water. Such a prediction is very difficult to make, but treaties should be flexible enough to allow for adjustable demands. This is important because generally the water is needed for economic development of the importing countries. Technological innovations may also change the demand for water.

A first step on the way to solving water transfer problems was taken when the "Helsinki Rules" were prepared by the International Law Association and established in 1966, even though these rules are in many respects vaguely formulated. For instance it is stated in the Rules that each country is entitled to a "reasonable and equitable share in the beneficial uses of waters of an international drainage basin." However, the difficulties involved in practical application of the Rules should not be underestimated.

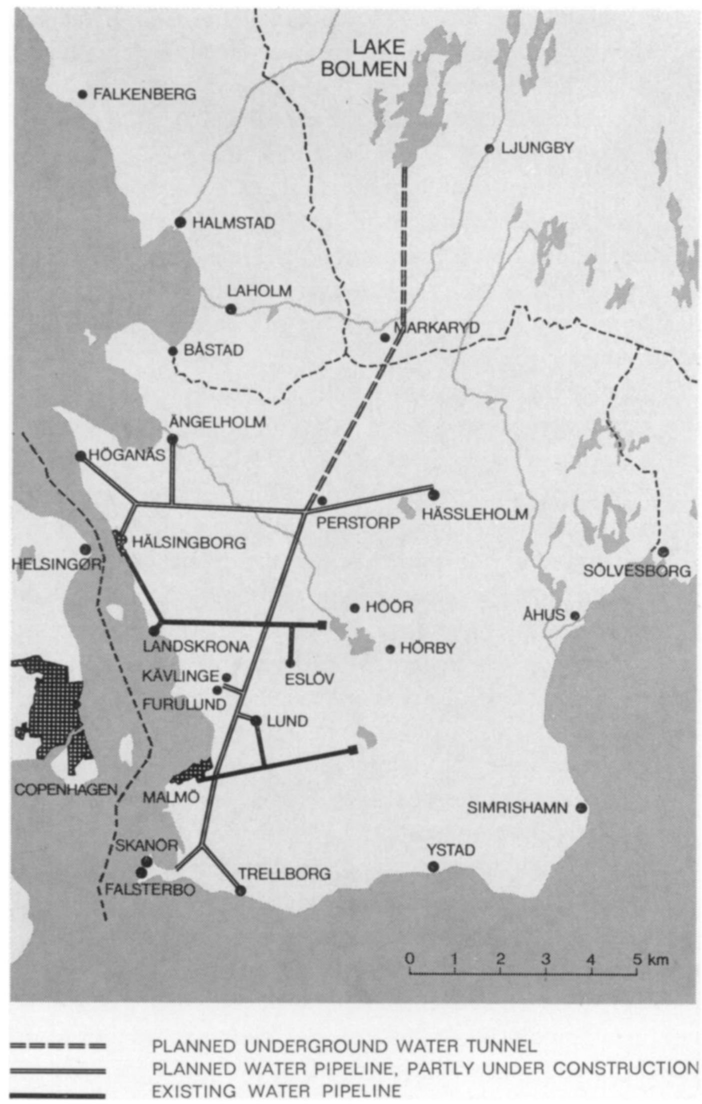


Figure 7. Map showing the existing and planned water supply system in Skåne in the southernmost part of Sweden. A tunnel from Lake Bolmen will supply the heavily urbanized area along the west coast of Skåne.

NEED FOR URBAN HYDROLOGY RESEARCH

There are many other hydrological problems that could be mentioned. But in my opinion the most severe problem of urban hydrology is not any one of those already mentioned in this article, but the fact that the field of urban hydrology does not seem to receive any research investments. It has been pointed out that empirical methods developed before the turn of the century are still in general use, according to Mc Pherson and Tucker (22). In spite of the great number of experimental and theoretical studies that have been conducted on urban runoff, very little is, in fact, known at present about the magnitude or time history of urban runoff. However, one must admit there has been very rapid development in other areas of hydrology during the last decades.

This rapid development has been greatly stimulated by the work carried out by more than one hundred countries participating in the International Hydrological Decade. This UNESCO program was created in order to coordinate international research and training programs in hydrology.

Unfortunately, during this important period the experimental work has been conducted mainly in agricultural, forest or wilderness areas. However, the situation seems to be changing which means that more experimental and theoretical work will be devoted to urban areas.

There is certainly a need for hydrologic data from urban areas, but in order to obtain these data we need suitable measuring devices for making observations in such areas. An exciting development in hydrology is the rapidly advancing use of stochastic processes and systems analysis.

Most of the rapid progress made recently in the field of hydrology can be ascribed to the extensive use of mathematical and statistical methods. Theoretical hydrology, especially, has made considerable progress in linear and nonlinear analysis of hydrologic systems, adaption of transient and statistical concepts in ground water hydrodynamics, application of heat- and masstransfer theories to evaporation analysis, etc.

SYSTEMS ANALYSIS

As water plays a progressively multipurpose role in urbanized areas, systems analysis takes on increasing importance in the study of the effects of urbanization on hydrology.

Systems analysis could consider, for example, a water system built to take care of the following:

a) supplying of water to municipalities and industries
b) carrying away of waste water
c) production of hydro-electric power
d) provision of recreational facilities
e) irrigation of agricultural lands
f) maintenance of sufficient water depth for navigation on water cources
g) desalination of water.

The ultimate goal of systems analysis may be to optimize the process due to certain constraints imposed on the system. Modern hydrology and water resource allocation are concerned with the scientific questions involved in such a systems analysis. This may be regarded as an effort to systemize a complicated situation that can no longer be handled by intuition alone.

THE NEED FOR ACTION

In many countries there is need for immediate action in the field of urban hydrology. This is because their populations are increasing enormously, measured in absolute numbers.

Japan serves as an example. The rapid increase there necessitates the construction of new residential cities with a proposed average population of 300,000 inhabitants. Such cities will be located in the Tama district. It is noteworthy that these new cities will be planned in rural areas, thus bringing about fundamental changes in land use. It is very interesting to see that the Government of Japan in cooperation with universities and research institutes has recently launched a special experimental study in the Tama district (23). Several kinds of experimental basins ranging from 10 km^2 to 1,000 km^2 will be studied. Comparisons will be made between hydrologic conditions in these areas and in similar areas in other cities.

TOMORROW'S PROBLEMS

There will be two big water supply problems in the future. The one problem will be to supply densely populated areas with water and the other will be to provide enough water for irrigation.

Teclaff (24) and others have predicted that severe shortages will arise and have already arisen as a consequence of local competition between people and crops for water, especially in arid and semi-arid areas. In California and Arizona the demand from city dwellers for water has led to a shrinking of the aquifers. The situation is serious and serves to illustrate the difficult problem of how to supply city dwellers with water, and at the same time supply water for irrigation in order to increase the food supply.

In order to avoid water supply problems in the future, it is necessary that the hydrologic situation in potential urban areas be investigated carefully, with special attention devoted to the water balance, runoff, infiltration, evaporation etc. It is important that planners take into consideration the fact that urbanization gives rise to great local water needs and causes great amounts of pollution.

A study of the global water situation shows that the foreseeable demand for irrigation water may be on the order of 70 percent of all fresh water available.

This requirement may be diminished in the future if foods can be developed that require less water to produce than present foods. Until then, however, a tremendous amount of water is required for irrigation, and it is hoped that considerably better irrigation methods will be developed.

In the USSR, large-scale projects involving the rerouting of rivers have been started. The aim is to reroute great quantities of water to potentially fertile areas in the central steppes. Large-scale projects of this sort, however, may perhaps have geoscientific effects such as changes in the earth's rotation, climatological changes, as well as biological-ecological effects. It is not yet possible to predict the magnitude of such effects.

Today most large-scale water problems are solved by the transfer of water. It seems likely that two different methods, recirculation and desalination, will be used in the future to deal with the urban water crisis.

References and Notes:

1. G P Kalinin and V D Bykow, *Impact of Science on Society,* Vol XIX, No. 2 (1969).
2. I Savini and J C Kammerer, *Urban Growth and the Water Regimen* (US Department of the Interior, Geological Survey, Water Supply paper 1591, A, GPO, Washington D C 1961).
3. H E Landsberg in *Man's Role in Changing the Face of the Earth* (University of Chicago Press, Chicago 1956).
4. R E Munn, *Descriptive Micrometeorology* (Academic Press, 1966).
5. U Högström in *Svensk naturvetenskap 1972,* Yearbook of the Swedish Natural Science Research Council (Allmänna förlaget Stockholm 1972, ISBN 91-38-004 71-1). English summary.
6. W Viessman, W R Keating and K N Srinivasa, *Water Resources Research,* Vol 6, No. 1, pp 275—279 (1970).
7. G Lindh and M Falkenmark, *Hydrologi — en inledning till vattenresursläran* (Studentlitteratur, 1972).
8. P M Felton and H W Lull, *Public Works,* Vol 941, pp 93—94 (1963).
9. H W Lull and W E Sopper, *Hydrologic Effects from Urbanization of Forested Watersheds in the Northeast* (USDA Forest Service Research Paper N E — 146, 1969).
10. R I Marsal, in *First Panamerican Conference on Soil Mechanics and Foundation Engineering,* Vol 3 (Mexico 1960).
11. B E Löfgren, in *Land Subsidence,* (AIMS-Unesco Publication No. 88, 1970).
12. R Zayc (in press).
13. C W Howe, *Journal of American Water Works Association,* Vol 63, No. 5 (1971).
14. Å Fleetwood, *Vatten,* 2 (1969).
15. A Nordström, in Proceedings of *Nordisk Hydrologisk Konferens,* Vol 3 (Stockholm 1970).
16. G Söderlund, in *Vad skall vi göra med dagvattnet?,* MVC-rapport 1 (Berlingska Boktryckeriet, Lund 1972).
17. *American Public Works Association, Control of Infiltration and Inflow into Sewer Systems,* Publication of the Environmental Protection Agency, No. 11022 (Washington D C 1970).
18. *Office of Water Resources Research, 1970 Annual Report* (US Department of the Interior, GPO, Washington DC 1971 p 20).
19. Y Gustafsson, *Vatten,* 3 (1969).
20. *Environmental Quality,* The First Annual Report of the Council on Environmental Quality (GPO, Washington DC 1970).
21. C W Howe and K W Easter, *Interbasin Transfers of Water* (The Johns Hopkins Press, 1971).
22. M B Mc Pherson and L S Tucker, *Basic Information Needs in Urban Hydrology* (A S C E, US Department of the Interior, 1969).
23. S Inokuti (in press).
24. L A Teclaff, *Abstraction and Use of Water: A Comparison of Legal Regimes* (United Nations Publication, New York 1972).

Gunnar Lindh, D Tech, is professor of applied hydraulics at the Institute of Technology, University of Lund. He is a member of the Swedish IHD committee and was the first chairman of the Nordic Association for Hydrology. He is also a member of the UNESCO Subgroup on the Hydrologic Effects of Urbanization.

The work of the Division of Hydraulics at the University of Lund deals to a great extent with the hydrologic effects of urbanization, the application of stochastic methods and systems analysis to water resource problems, etc.