Urban Growth and the Water Regimen

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1591-A

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By JOHN SAVINI *and* J. C. KAMMERER

HYDROLOGIC EFFECTS OF URBAN GROWTH

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ABSTRACT

The continuing growth and concentration of population and industry in urban and suburban areas in recent decades has caused a complex merging of social, economic, and physical problems, The interrelationships of man and his use and development of the land and water resources is a particularly significant aspect of urbanization, but there has been relatively little study to date of the effect of urban man upon natural hydrologic conditions.

As urban man changes an area from one of field and forest to one of buildings and streets, he covers land where water once entered the soil, and thus creates or aggravates problems of drainage, including storm-water runoff. As he requires increasing amounts of water for home and factory, he drills deeper wells, and builds longer aqueducts and larger dams and reservoirs. As he disposes of unwanted waste materials, he either treats them by using water or pollutes the receiving body of water. As he dredges and deepens coastal streams carrying salt water, and as he pumps greater quantities of water from wells in coastal areas, he increases the likelihood of salt-water contamination. These and many other urban effects upon hydrology deserve increasing study if we are to provide for the best use of the water and land resources available to the Nation's urban centers.

THE HYDROLOGIC IMPACT OF URBANIZATION

The growth of urban areas in the United States is one of the major sociologic trends of our times. The growth of population in city and suburb during the past half century (fig. 1) has been tremendous and the trend is continuing. At the same time, the social, political, and economic problems resulting from this growth have become increasingly complex. Basic to many of these problems is man's need for land and water, and his effect upon these resources as he occupies and builds, with ever-increasing density, upon land once occupied only by field or forest. This report is a preliminary appraisal of some of the effects of urban man's activities upon his water resources as they occur both on and beneath the surface of the ground.

Urbanization may be defined as the process of change in land occupancy and use resulting from conversion of rural lands to suburban, industrial, and urban communities. The obvious effects are to

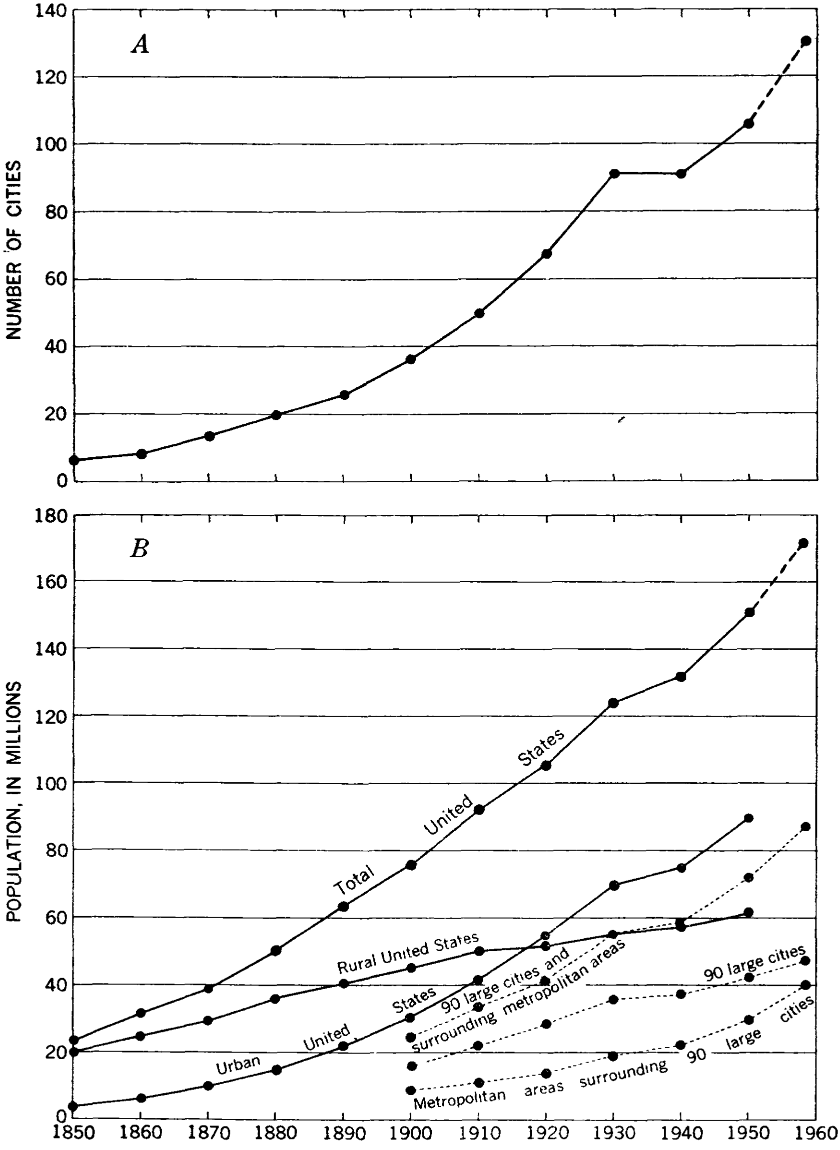

FIGURE 1.—Population trends in the United States, 1850-1958: *A*, Number of cities with a population of more than 100,000; *B*, Number of people in continental United States. From U.S. Bureau of the Census, 1952; Bogue, D. J., 1953; Sales Management, Inc., 1958.

increase population density and the concentration of residential, industrial, and commercial buildings and facilities with the resultant increase of impervious areas. The hydrologic impact then includes the effects of these changes on the natural drainage, runoff, ground water, sediment, water quality, water demands, and measures for disposal of wastes and surplus waters.

The problems associated with urbanization are common to many parts of the United States, wherever the landscape has been changed from a predominantly rural setting to a close grouping of buildings intersected by a network of paved streets. The problems increase in magnitude as the cities grow. Therefore, the principal centers of urbanization in continental United States may be considered to be the 168 metropolitan areas, including all cities of more than 50,000 population, which in 1950 contained 56 percent of the Nation's population but only 7 percent of the land area (pl. 1).

Population densities in urban areas usually range from 2,500 to 10,000 persons per square mile, but in densely populated parts they may exceed 25,000 persons per square mile (U.S. Bureau of Census, 1952, chap. 1, p. 5).

The rapid increase of population in urban and suburban areas causes a heavy draft upon the resources of the surrounding countryside and upon industry. For example, the farmer is required to produce more foodstuffs, from the dwindling lands available, through improved methods of production, one of which is the use of irrigation, a method that adds to the competitive demand for water. Industry also must produce more goods and services, thereby requiring large additional quantities of water. As our standard of living improves, so do the number of modern water-using conveniences in the home, such as garbage-disposal units, automatic washers, and even swimming pools. Many urban and suburban dwellers maintain beautiful lawns, shrubs, and flower gardens, which require large quantities of water during dry seasons. Water-using airconditioners are also used in increasing numbers in office buildings and factories to create better conditions for workers.

Urbanization raises a double problem, namely, an increased demand for water for municipal, industrial, and recreational purposes, and a decrease in locally generated ground-water supply because of the "roofing over" with housing, pavements, and industrial buildings areas that formerly consisted of moisture-holding soil and small streams. The disposal of domestic sewage and industrial wastes without contamination of natural water courses or aquifers is an additional problem. The concentration of large numbers of water users within a relatively small area not only affects the quantity and quality of the local water supply, but also may require the importation of water from other areas. The hydrologic impact of an urban area thus may extend far beyond its own borders.

Each city and metropolitan area has its problems of water supply, floods, drainage, and waste disposal, and the history of such problems dates back many centuries. Even in the United States, cities have had water problems for more than 150 years. For example, the following portion of the will of Benjamin Franklin, reveals his concern and observations on this subject as it applied to Philadelphia at the time of his death in 1790 (Smyth, 1907, p. 506):

> And, having considered that the covering of a groundplot of the city with buildings and pavements, which carry off most of the rain and prevent its soaking into the Earth and renewing and purifying the Springs, whence the water of wells must gradually grow worse, and in time be unfit for use, as I find has happened in all old cities, I recommend that at the end of the first hundred years, if not done before, the corporation of the city * * * [bring] by pipes, the water of Wissahickon Creek into the town, so as to supply the inhabitants * * *.

Until recently each city could solve its water problems in a methodical, although increasingly expensive manner. It simply added to its systems of pumping, storage, distribution, or treatment—often by tapping a source of water farther from the existing source. In doing so, relatively little thought was given as to the effects on neighboring cities or on agricultural or private industrial supplies (except in arid areas). The concentration of population and industry, and the increased rate of water use and sewage disposal in urban and suburban areas, now is becoming so great that water problems often overlap from one area to another. Lewis Mumford, in his paper "The Natural History of Urbanization," highlights this increasingly critical matter of water supply and demand (Mumford, 1956, p. 395):

> Already, New York and Philadelphia * * * find themselves competing for the same water supply, as Los Angeles competes with the whole state of Arizona. Thus, though modern technology has escaped from the limitations of a purely local supply of water, the massing of population makes demands that, even apart from excessive costs (which rise steadily as distance increases), put a definite limit to the possibilities of further urbanization. Water shortages may indeed limit the present distribution long before food shortages bring population growth to an end.

Streams in densely populated regions often are so heavily loaded with municipal and industrial wastes at successive points downstream that natural purification is prevented, and downstream users must eliminate the pollution by treatment or seek other sources of water supply.

Another important type of pollution problem occurs in many coastal cities that draw at least part of their water from underground sources, when large-scale pumping lowers water levels in wells to such a degree that salt water from the sea or brackish water from tidal streams and bays moves inland into the aquifers. The movement is usually slow, but once saline water encroaches upon well supplies, its replacement by fresh water is extremely difficult.

These examples illustrate that the hydrologic effects of changes in man's use of water and land will become more intensified, and overlapping, as population, industry, and per capita water use continue to increase, and more open land is covered by urban streets and structures. Thus, there is a growing need for a more thorough study and evaluation of these changes and of their impact on the urban environment.

THE STAGES OF URBANIZATION

The several stages during the period of conversion in land use from rural to urban may be classified as the rural, early-urban, middle-urban, and late-urban stages. The characteristics of these stages are described in the succeeding paragraphs. The summary given in the table below lists some of the hydrologic effects during the sequence of changes in land and water use associated with urbanization.

RURAL STAGE

In the rural stage the land may be in its virgin state or in cultivation or pasture. Frequently there are forested areas and there may be occasional farm buildings and dwellings. The water supply is drawn from wells, springs, creeks, or farm ponds. Farm ponds are often used to store water for dry periods. Sewage is usually disposed of through septic tanks or pit privies. Garbage may be fed to farm animals. There may be some contamination of surface water by excreta from domestic animals. The quantity of water used in an electrified, rural home may be about the same amount as in an urban home.

EARLY-URBAN STAGE

The early-urban stage ("exurbia") is characterized by a semirural area in which city-type homes are built on large plots and are interspersed here and there with schools, churches, or shopping centers. Water supply is usually obtained by pumping from individual wells, the rubbish is burned, the garbage buried, and sewage is disposed of in septic tanks or cesspools. Home owners may have fish ponds or farm ponds for recreational use. Their use of water will be rather large, but, even so, the effects of such developments on the hydrology of the area are relatively small.

Hydrologic effects during a selected sequence of changes in land and water use associated with urbanization

Change in land or water use	Possible hydrologic effect
Transition from preurban to early-urban stage:	
Removal of trees or vegetation	Decrease in transpiration and increase in storm flow. Increased sedimentation of streams.
Construction of scattered city-type houses and limited water and sewage facilities.	
Drilling of wells	Some lowering of water table.
Construction of septic tanks and sanitary drains.	Some increase in soil moisture and perhaps a rise in water table. Perhaps some waterlogging of land and contamination of nearby wells or streams from overloaded sanitary drain system.
Transition from early-urban to middle-urban stage:	
Bulldozing of land for mass housing, some topsoil removed, farm ponds filled in.	Accelerated land erosion and stream sedimentation and aggradation. Increased flood flows. Elimination of smallest streams.
Mass construction of houses, paving of streets, building of culverts.	Decreased infiltration, resulting in increased flood flows and lowered ground-water levels. Occasional flooding at channel constrictions (culverts) on remaining small streams. Occasional over-topping or undermining of banks of artificial channels on small streams.
Discontinued use and abandonment of some shallow wells.	Rise in water table.
Diversion of nearby streams for public water supply.	Decrease in runoff between points of diversion and disposal.
Untreated or inadequately treated sewage discharged into streams or disposal wells.	Pollution of stream or wells. Death of fish and other aquatic life. Inferior quality of water available for supply and recreation at downstream populated areas.
Transition from middle-urban to late-urban stage:	
Urbanization of area completed by addition of more houses and streets, and of public, commercial, and industrial buildings.	Reduced infiltration and lowered water table. Streets and gutters act as storm drains creating higher flood peaks and lower base flow of local streams.
Larger quantities of untreated waste discharged into local streams.	Increased pollution of streams and concurrent increased loss of aquatic life. Additional degradation of water available to downstream users.
Abandonment of remaining shallow wells because of pollution.	Rise in water table.
Increase in population requires establishment of new water-supply and distribution systems, construction of distant reservoirs diverting water from upstream sources within or outside basin.	Increase in local streamflow if supply is from outside basin.
Channels of streams restricted at least in part to artificial channels and tunnels.	Increased flood damage (higher stage for a given flow). Changes in channel geometry and sediment load. Aggradation.

Hydrologic effects during a selected sequence of changes in land and water use associated with urbanization—Continued

Change in land or water use	Possible hydrologic effect
Transition from middle-urban to late-urban stage—Continued	
Construction of sanitary drainage system and treatment plant for sewage.	Removal of additional water from the area, further reducing infiltration and recharge of aquifer.
Improvement of storm drainage system.	
Drilling of deeper, large-capacity industrial wells.	Lowered water-pressure surface of artesian aquifer; perhaps some local overdrafts (withdrawal from storage) and land subsidence. Overdraft of aquifer may result in salt-water encroachment in coastal areas and in pollution or contamination by inferior or brackish waters.
Increased use of water for air conditioning.	Overloading of sewers and other drainage facilities. Possibly some recharge to water table, owing to leakage of disposal lines.
Drilling of recharge wells	Raising of water-pressure surface.
Waste-water reclamation and utilization.	Recharge to ground-water aquifers. More efficient use of water resources.

MIDDLE-URBAN STAGE

The middle-urban stage is characterized by large-scale housing developments, more schools and shopping centers, some industrial buildings and enlarged networks of streets and sidewalks. Municipal systems to supply water of acceptable purity, and sewers to dispose of sewage may be built. However, some domestic sewage may still be discharged to septic tanks and subsurface disposal systems. Domestic food wastes may be collected by truck or discharged through kitchen-disposal units to septic tanks or sewer systems.

In this stage of development the effects on hydrology become greater and, in many ways, approach those of the city itself. The water supply may be imported or may be derived from well fields within the area and distributed, usually by local water companies. Inadequate or inoperative septic tanks or the extensive use of stable detergents, may cause pollution of aquifers near the surface. Direct runoff from rainfall is likely to increase thus creating a need for adequate drainage facilities to dispose of storm waters. The amount of sediment delivered to streams may increase many fold during and between the several stages of urbanization, chiefly as a result of construction and development activities.

LATE-URBAN STAGE

The late or advanced, urban stage is characterized by a large number of structures; such as homes, apartments, commercial and industrial buildings and streets and parking lots, which occupy all or most of the former rural land area. A large part of the area is roofed or paved. Sanitary sewers and large, but frequently inadequate, storm sewers remove human and industrial wastes and provide drainage. The smallest streams are eliminated entirely and the slightly larger streams are confined to artificial channels and canals and may be obstructed by bridge piers. Riparian owners commonly construct buildings and other structures that encroach upon the natural stream floodway and even into the channel. The hydrologic and hydraulic effects of these changes are quite severe. Storm flows may increase considerably and low lying areas may be flooded more frequently. Stream pollution is greatly increased. Water supplies must be imported from greater distances. Most urban areas are almost entirely dependent upon water that falls in nonurban territory. At the same time storm and waste waters from these areas are collected in sewer systems and transported to disposal points in large bodies of water. Thus we have the phenomenon of a technological culture whose demand for water is steadily rising at the same time that its processes accelerate the return of locally stored and precipitated water to the sea.

CLASSIFICATION OF HYDROLOGIC EFFECTS

The hydrologic effects of urbanization may be classified according to (1) the sequence of usual occurrence, (2) changes separately associated with man's use of water and man's use of the land, (3) type of hydrologic process affected, or (4) changes affecting quantity of water on the one hand and quality of water on the other. Most of the effects discussed in the remainder of this report are classified according to either the quantity or to the quality of the water supply. Separate sections are presented to describe the effects on floods and drainage; erosion, sedimentation, and channel geometry; and land subsidence.

EFFECTS ON QUANTITY OF WATER SUPPLY

Water shortages are usually symptoms of a rapidly growing demand for water. The rapid growth of cities, industries, agricultural water uses and a continually growing population have created and intensified the competition for our Nation's water resources. Drought periods aggravate the problem of adequate water supply. The problem is not so much one of how to increase the total water supply but one of how to distribute the supply from periods and places of abundant water to periods and places of shortage of water; not so much one of how to prevent droughts, as it is one of how to prepare for them so that they have little effect on available water supply. Thus, there is a need for sound water-management planning.

In some of the highly populated areas of the Nation the answer is not simply the building of new reservoirs, drilling of new wells, or construction of water conduits. Adequate reservoir sites are limited and there is competition for the use of these facilities as the demand for water increases. Flood control requires an empty reservoir; hydroelectric power and municipal water supply require a full reservoir whose water level can be lowered as water is needed; recreation and wildlife management require a reservoir with a relatively constant level; and pollution abatement needs a reservoir that will stabilize streamflow throughout the year. Achievement of the maximum benefits in the public interest in use of reservoirs therefore requires careful evaluation and reconciliation of these needs.

An underlying factor in a large number of water-supply problems is the usual coincidence of the seasonal period of maximum water demand with the period of minimum available supply. Thus, in the warmest part of the year there is a maximum demand for water for home and community swimming pools, lawn watering, commercial and domestic air-conditioning, and other cooling and washing purposes, as well as for irrigation. Concurrent with these demands is the usually lower-than-average streamflow resulting from diversions for irrigation (primarily a consumptive water use), the reduced rainfall common in the West, and seasonally high evaporation and transpiration rates.

TRENDS IN WATER USE

There are two principal trends in urban use of water. First, there is a gradual increase in the amount of water used in each home as well as by the total community served by a municipal water system, including hotels, restaurants, office buildings, and some local industries. As the per capita use of water from municipal supplies has been rising slowly but steadily, population has also been increasing, but at a faster rate, so that in the past 50 or 60 years there has been a substantial growth in amount of water used by municipal water systems. A part of this growth is shown graphically in figure 2, based on data for 59 large cities.

The second trend, occurring simultaneously, is the tremendous increase in water use by industries having their own sources of water supply. Commonly these industries are located within or on the fringes of major urban areas. The increase of water use by industry has been especially large since 1930, for the Nation as a whole, as shown on figure 3. The magnitude of this water use in relation to to other water uses in 1955 is shown in figure 4. The data for 1955

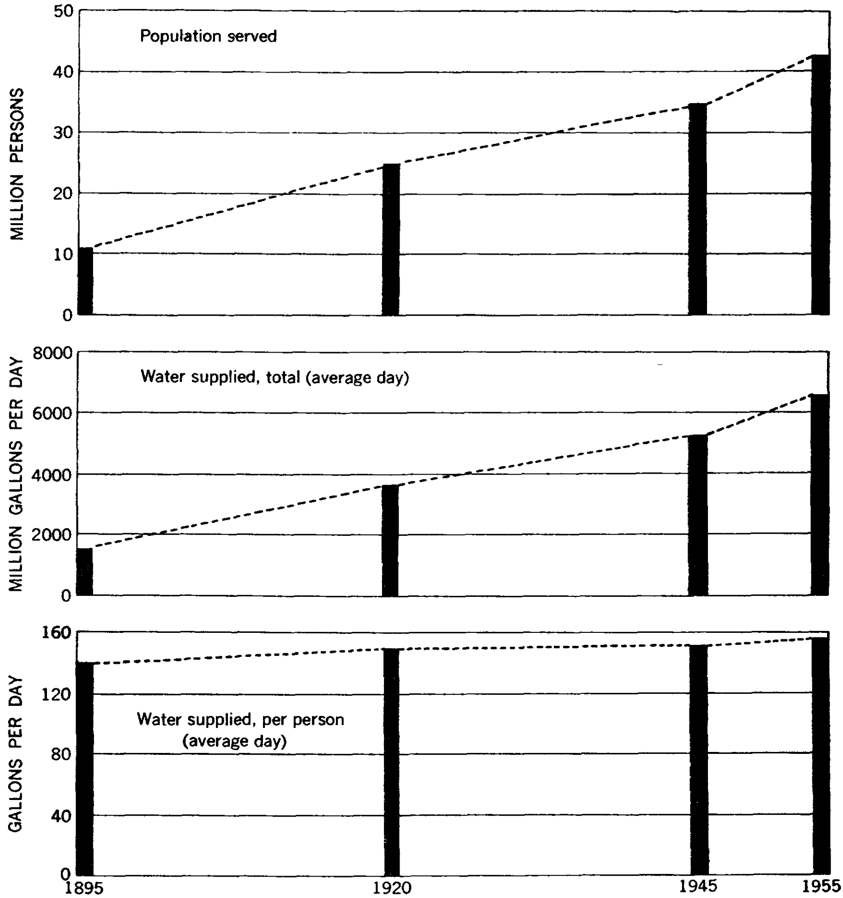

FIGURE 2.—Trends in municipal water use in 59 United States cities, 1895–1955. (Sources of Data: American City, 1920, 1921; Baker, 1897; Flinn and others, 1927; U.S. Public Health Service, 1948, 1956.)

shown in figures 3 and 4 were determined by separate surveys; there are some differences in subtotals for types of industrial use.

These upward trends in water use by municipal water systems and self-supplied industrial water systems are likely to continue for many years. Only as areas approach the limit of the local and imported water supply available, and as the cost of water to the customer becomes a major consideration in the household or industrial budget, is the marked upward trend in water use likely to level off.

PER CAPITA USE OF WATER

Analysis and prediction of water use in an urban area are based upon data on per capita use of water and on population. The meaning of the term "per capita use" is sometimes misunderstood, especially

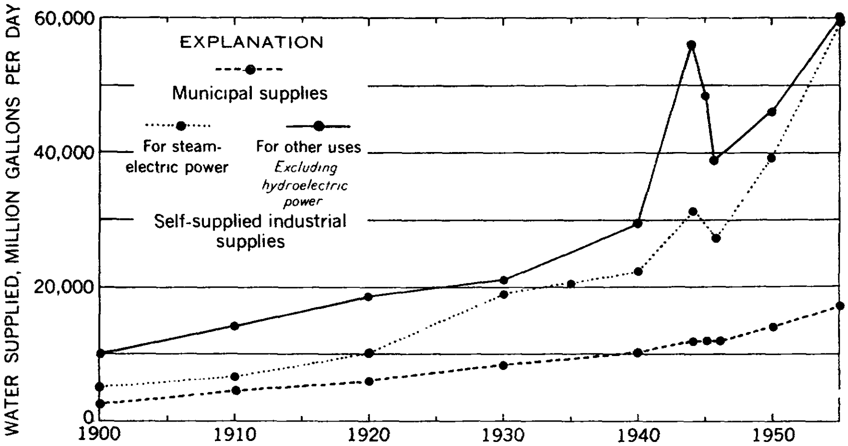

FIGURE 3.—Trends in municipal and industrial water use, United States, 1900–55. From Picton (1956, p. 4).

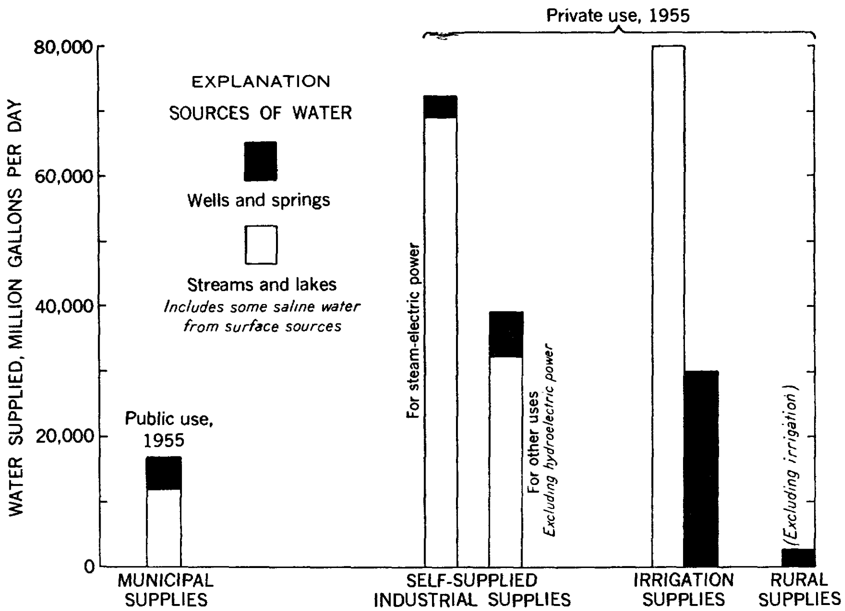

FIGURE 4.—Types and sources of water supplies, United States, 1955. From MacKichan (1957, p. 11, 13).

when comparing sets of data from two or more sources, because the term has been used in various ways.

At present the average urban home or electrified rural home uses 40 to 60 gallons of water a day per person (Seidel and Baumann, 1957, p. 1538, 1544; Porges, 1957, p. 1576; Frank, 1955, p. 4). The ratio of per capita use of water for household purposes depends to a greater extent on whether or not the home is electrified than on whether it is in an urban or rural area. The difference in magnitude of the total water used for domestic purposes between urban and electrified rural areas is therefore due to the difference in concentration of population.

A more general use of the term "per capita use," however, is based on the public-supply or municipal-supply use. In this sense the per capita use is the total water used by a municipal water system divided by the number of persons served. It thus includes all domestic, commercial, industrial, and public uses. A summary of municipal use of water per capita in 1955 is given in table 1. This table indicates that per capita use tends to be higher in very large cities (10 systems, each serving more than 1,000,000 people), than in cities of smaller size.

TABLE 1.—*Total and per capita use of water in the United States, 1955*

Type of water supply	Number of cities or water systems	Total water used (million gallons per day)	Population served (millions of people)	Per capita use of water (gallons per day)	Source of data
Domestic; part of municipal supply.	206	----------	----------	59	Porges, 1957.
	111	----------	----------	44	Seidel and Baumann, 1957.
Municipal supply (including municipal water for commerce and industry).	(1)	17,000	115	148	MacKichan, 1957.
	580	12,100	83.7	145	Porges, 1957.
	477	About 9,600	About 70	137	Seidel and Baumann, 1957.
	[2] 10	4.340	25.7	169	Do.
	59	6.560	42.2	156	(3)
Self-supplied industrial	(1)	110,000	164	670	MacKichan, 1957.
Combined municipal and self-supplied industrial.[4]	(1)	127,000	164	770	Do.
Combined municipal, self-supplied industrial, rural, and irrigation.[4]	(1)	240,000	164	1,500	Do.
Hydroelectric power	(1)	1,500,000	164	9,100	Do.

[1] Nationwide.
[2] Each serves more than 1 million people.
[3] Compiled from various sources for this report; see figure 2.
[4] Excluding water for hydroelectric power.

AVERAGE USE, MAXIMUM USE, RE-USE, AND CONSUMPTIVE USE

Most water-use data in this report have been expressed as averages, such as average daily use, average home use, or average annual use for the Nation. The actual use shows considerable daily, seasonal, and local variations from the averages. For example, the 1955 study of municipal supplies by the U.S. Public Health Service revealed that the daily rate of use during the maximum-use month of the year was 140 percent of the rate for use on an average day, and on the maximum day was 162 percent of the rate for the average day (Porges, 1957, p. 1576). An example of local variation is the range from 108 to 235 gpcd (gallons per capita per day) for 10 of the largest municipal water systems which had a combined average of 169 gpcd (table 1).

One of the most outstanding effects of urbanization upon water use is the concentration of peak water demand within certain hours of the day during periods of hot, dry weather. During such times there is a large daytime use of water for commercial air-conditioning units and for lawn-watering; and then there is a second peak in use of water for lawn-watering during the early evening hours, unless restrictions are imposed. This pattern as documented by Hatcher (1956, p. 374–375), is shown in figure 5. The figures show trends in water use by type of use in Kansas City, Mo., hourly on July 12, 1954, the day of maximum use during that year. Maximum daily rate of use was almost 170 percent of the average daily rate of use.

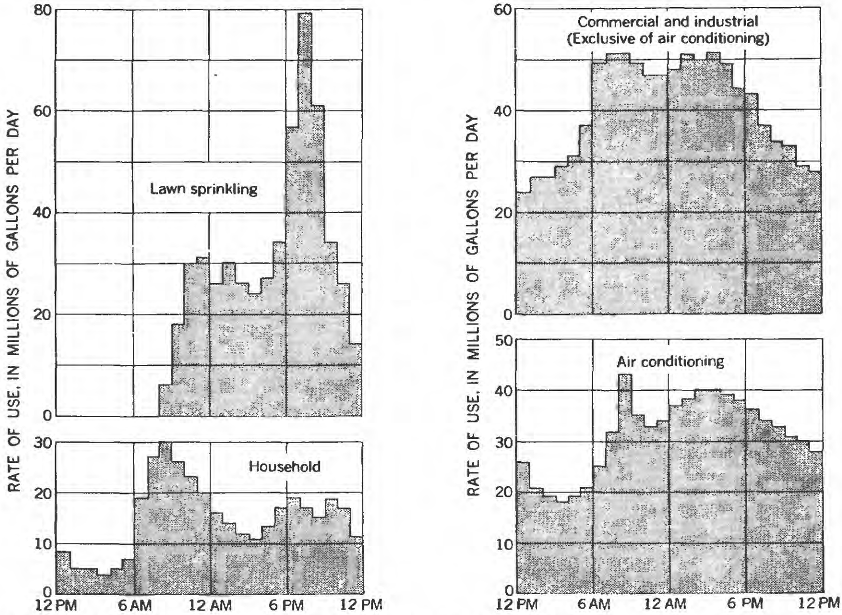

FIGURE 5.—Hourly trends in water use on maximum day (July 12) of use in 1954 of public water supply of Kansas City, Mo. Based on data prepared by M. P. Hatcher for 1955 conference of the American Water Works Association.

The examples of average and maximum water use given earlier in this report have not indicated whether the quantities represent water that is used once and is not available for re-use, or water that is re-used many times over. The total amounts, therefore, may include water that has been re-used and counted more than once. The latter situation often exists, and many published water-use totals are believed to contain large, but usually unknown, quantities of water that have been used at least twice, and therefore counted two or more times in computing the total amount. The re-use of water is especially common in heavily populated or highly industrialized regions where most of the municipal and self-supplied water supplies are obtained from sources within the region.

The principal factors limiting re-use of water are consumptive use and contamination or pollution. The major consumptive use of water is in irrigation, in which 50 to 95 percent of the water used returns to the atmosphere by evaporation and transpiration. Water for other consumptive uses is probably less than 5 percent of that total. However, water used once and then discharged as waste by some cities and industries may be so poor in quality that cost of treatment for re-use is prohibitive. Highly polluted waste water not only is of little value for re-use, but is likely to restrict the use of the water into which it is discharged.

THE FUTURE

For many years the total amount of water used in the United States has been following an upward trend that is likely to continue for some time to come. Picton (1956, p. 4) estimated that water used for all purposes (excluding hydroelectric power) will increase 76 percent in the 20 years from 1955 to 1975. The actual increase probably will vary considerably from place to place, but a large part of the increase may be concentrated within and on the fringes of the major urban areas, thus adding to supply and demand problems that already have become acute.

In some areas the upward trend in water use may be temporarily halted or even reversed by a thorough appraisal of existing uses and application of conservation measures. This occurred in New York City as a result of water shortages in 1949 and 1950; average consumption reached annual peaks of 1,204 and 1,203 mgd in 1948 and 1949, dropped to 982 mgd in 1950, and still averaged no more than 1,155 mgd in 1955, 4½ years after water-use restrictions had been removed (New York City Board of Water Supply, 1956, p. 27; New York City Engineering Panel on Water Supply, 1951, p. 20).

National and international events can also affect trends in water use, such as occurred during the industrial expansion in the early 1940's as a result of World War II. At that time the use of water by self-supplied industries greatly exceeded that of the preceding years, and then decreased for 2 or 3 years before resuming an upward trend (see fig. 3). The war occurred during a cycle of wet years, during which water was generally plentiful. Had the war occurred during a time of drought, the water problems would have been much more critical than they were.

URBAN DEMAND VERSUS URBAN SUPPLY

A characteristic of urban areas is that the concentration of large numbers of people results in water demand exceeding locally generated or accessible supply of potable water. Thus, urbanization almost inevitably necessitates importation of water by natural or artificial means. As Howson (1957, p. 1359) points out, 1 out of every 8 persons having access to public water supply on the North American continent takes water from a system which transports it from a source 75 miles or more away. This has come about through the necessity to seek more remote sources as local water supplies are fully developed, ruined by pollution or contamination, or become exhausted. Tulsa, Oklahoma, for example, abandoned the Arkansas River as a source of supply after it had been contaminated by brine from oil wells, and developed the Spavinaw impounded supply. New York City during the past 50 years has met increasing water demands by importing water through a system of tunnels and aqueducts from reservoirs constructed as far away as the headwaters of the Delaware River.

Increase in water requirements, elevation and type of source of supply, and quality of the water were all important considerations in the development of distant water-supply sources for the Seattle, Portland, East Bay, and San Francisco areas. In Colorado, the cities of Denver and Colorado Springs have found that their water supplies on the eastern slope of the Rocky Mountains are inadequate and are using tunnels to bring water from sources on the western slope. Denver has developed and is enlarging its supply on the western slope and bringing the water to the city through the Moffat Tunnel. A second tunnel, 23 miles long, is being driven under the Continental Divide to bring water from the Blue River to Denver. Water for Colorado Springs is brought from the western slope through the Hoosier Tunnel for 8,000 feet to a point on the eastern slope of the Continental Divide, where it flows about 100 miles and drops more than 4,000 feet to the city (American City, 1956, p. 188).

The impact of urbanization upon water supply is illustrated by the urban-water requirements in California. The population of California increased from 7 million to 10.5 million between 1940 and 1950 and was estimated to be 14 million in 1957. Forecasts indicate that the population will reach about 20 million by 1970 and later may reach 42 million. Examination of patterns of present urban development shows that the large population centers are along the coast, and the smaller urban areas are inland. However, only one percent of the State's total area is urban. Approximately two-thirds of the State's population is concentrated in the three metropolitan areas of San Francisco, Los Angeles, and San Diego. All three are areas of limited water supplies and must depend on imported water to meet their needs. The California Water Resources Board placed 1950 urban water requirements at 1.7 million acre-feet per year, and estimated that ultimate development of 7.8 million acre-feet per year or 4½ times the present rate would be required (Bookman, 1957, p. 1053–1054).

EFFECTS OF CHANGE FROM AGRICULTURAL TO URBAN USE

The effects of urbanization upon water use during the growing season in an area partly occupied by irrigated lands were evaluated in a study in Los Angeles County (California State Water Resources Board, 1956). Data for 1950 and 1955, shown in the following table, reveal that the seasonal use of water per acre in both years was slightly greater in the urban and suburban areas than on the irrigated lands, and therefore the partial replacement between 1950 and 1955 of irrigated lands by urbanized areas resulted in an increased use of water per acre, even during the growing season.

Land use and mean seasonal use of water, coastal Los Angeles County, 1950 and 1955

[Source of data: California State Water Resources Board, 1956]

	1950	1955
Population (thousands of people)	4, 122	5, 034
Area (thousands of acres):		
Urban and suburban land	375	457
Irrigated land	133	87
Total	508	544
Seasonal use of water (thousands of acre-feet):		
Urban and suburban land	726	900
Irrigated land	222	156
Total	948	1, 056
Water used per unit area (acre-feet per acre):		
Urban and suburban land	1. 9	2. 0
Irrigated land	1. 7	1. 8
Average	1. 8	1. 9

EVAPORATION, TRANSPIRATION, AND INFILTRATION

The hydrologic processes of evaporation, transpiration, and infiltration are affected by man's use of both water and land. The most pronounced (and yet rarely measured) effects of urbanization on these processes are caused by changes in land use associated with the growth of a city and its suburbs. Land which was formerly forest, farm, or open field is leveled to some extent by displacement of topsoil, earth, and fill from one place to another, and then covered by structures and pavement. In an advanced stage of urbanization, only lawns, gardens, cemeteries, and public parks exhibit any of the conditions of soil and vegetation that may be comparable, at least in part, to those in a pre-urban environment.

How have these major changes in land use affected the three hydrologic processes? Obviously, in the extreme conditions of change to completely paved and roofed areas, there is no longer any removal of water through transpiration, infiltration of water is negligible, and evaporation is probably small except on heated surfaces at beginning of rainfall or in places where water is trapped in undrained depressions in pavements or roofs. During the intermediate stages, in suburban areas where each home has a yard and lawn, the changes in removal of water by evaporation and transpiration and infiltration sometimes may be too small to be measured by methods and instruments now in use.

Because water is imported for domestic purposes, and for lawn watering, and for disposal of sewage through septic tanks, infiltration, evaporation and transpiration may actually increase, as in the Whitney Terrace area of Boise, Idaho (p. A–20). In parts of the country where large amounts of water are used in sprinkling lawns (see fig. 5), water is applied during the periods of warm weather when there has been little or no rain, and therefore all or most of the water returns to the atmosphere by evaporation and transpiration.

Measurements and estimates of consumptive use of water through evaporation and transpiration in areas under various types of land use were made during the hydrologic study of the Raymond Basin, Pasadena, Calif., 1937–45 (Gleason, 1952, p. 1008–1009). The annual consumptive use in areas where surfaces were impervious, such as streets and sidewalks, was about 5 inches of water, in estate and other residential areas it was about 24 inches, and for lawns and tree areas it was 36 inches or more. Gleason concluded from the results of this investigation that replacement of a rural or agricultural environment by an urban one in the area studied has decreased consumptive use and increased deep percolation to the ground water, increased runoff, and increased production of sewage. He further concluded that in areas of much greater precipitation, a greater reduction of consumptive use would result from urban development, and in areas of much less precipitation, urban development might increase rather than decrease consumptive use.

Comparative data for other urban areas are not available because there have been few, if any, other studies of consumption of water by evaporation and transpiration in urban areas conducted in as detailed a manner as that in the Raymond Basin. However, many studies have been made of the consumptive use of water by vegetation in rural and forested areas. For a given local area, such data may be used to estimate consumptive use of water during the pre-urban environment. Data on consumptive use as determined from a number of tank and soil-moisture studies in valley areas, have been compiled by Blaney (1952, p. 958–959, based on the work of Blaney, Taylor, Lee, Elder, Morin, Gatewood, and Robinson). These data show annual consumptive use by grass and brush ranging from 10 to 48 inches in 12 localities in California and New Mexico, with use by trees ranging from 32 to 91 inches, during 5 studies made in California, Arizona, and New Mexico.

Precipitation that neither evaporates immediately nor runs off to a nearby stream enters the ground by infiltration or is temporarily retained in depressions on the surface of the ground. Infiltration rates vary widely with different soils. Data on a study of infiltration in some soils during an hypothetical 2-inch rain lasting 3 hours are presented in table 2. This study indicated that the amount of infiltration in many natural soils would be large.

TABLE 2.—*Cumulative precipitation, infiltration, and runoff during hypothetical 3-hour storm*

[Rainfall totals 2 inches, at constant rate of 0.67 in. per hour, on nearly level, well-drained surface already wetted by precipitation on previous day]

Duration of storm (minutes)	Cumulative precipitation (inches)	Average for 68 soils [1]		Cecil sandy loam [1]		Impermeable surface (paved)	
		Infiltration (inches)	Runoff (inches)	Infiltration (inches)	Runoff (inches)	Infiltration (inches)	Runoff (inches)
15	0.17	0.17	0.00	0.17	0.00	0.0	0.17
30	.33	.33	.00	.33	.00	.0	.33
60	.67	.67	.00	0.58– .63	0.04–.09	.0	.67
120	1.3	1.3	.00	.88–1.1	.27–.45	.0	1.3
180	2.0	[2] 2.0	.00	[1] 1.1 –1.5	.54–.86	.0	2.0

[1] Computed from data by Free and others (1940, p. 8–9, 14, 44): infiltration rates determined by flooding-infiltrometer method (steel tubes, 9 inches in diameter, 10 or 14 gage, 18 or 24 inches long, with 2 or 3 inches of tube protruding above the surface); reduced infiltration rates after 60 minutes represent reduction caused by turbid water used to simulate natural conditions.
[2] Unless entirely transpired and (or) evaporated, a part of this amount would later appear as runoff after moving some distance laterally; the time of travel might vary within wide limits, such as between 1 day and several months.

GROUND-WATER LEVELS AND PRESSURES

Declines in ground-water levels and pressures are caused by changes in water use during urbanization as increased rates of pumping from wells, and such changes in land use as substitution of paved or roofed surfaces for cultivated or natural soils and vegetation. Less commonly, there are changes in urban water or land use that cause water levels to rise. Changes in water use in many parts of the country have been well documented and correlated with declining water levels. However, the effects of changes in land use are almost always masked and difficult to determine because of the substantially larger and concurrent fluctuations caused by changes in rate of natural or artificial recharge, and in rate of ground-water discharge from wells.

The term "water level," as used in the following discussion, means either the elevation (or depth below land surface) of the water table in unconfined aquifers or the water-pressure surface of confined (artesian) aquifers. Natural recharge is the replenishment of ground water by precipitation upon a pervious surface or by seepage underground from a stream or lake. Artificial recharge is replenishment by diversion of water into the ground through wells, excavations, or spreading areas.

As pumpage from a well or a well field is increased, the water level declines at that place until a new level of equilibrium is reached. The rate of water flowing toward each well from its source of recharge is then equal to the rate of water being discharged at the well. If pumping exceeds the rate of recharge, the water level in the well continues to decline until the supply is exhausted or until the rate of discharge is reduced. For most urban areas the present rates of withdrawal are not exceeding the rates of recharge, but it is probable that the recharge rates are being exceeded in a few areas.

The exact location and degree of ground-water overdevelopment, suggested to some extent by declining water levels, are difficult to determine because of the frequently changing patterns of pumping and the difficulty of measuring accurately the rates of recharge and discharge. However, many of the substantial water-level declines in urban areas presumably represent a combination of the above-named effects, that is, an hydraulic adjustment to the increased rate of pumping and a degree of overdevelopment in one or more parts of the general area. Examples of major declines of water level during various periods of time, together with pumpage data for 1949, are given in the following table.

McGuinness (1951), Thomas (1951), and many others have called attention to declining ground-water levels in urban areas where substantial quantities of ground water are used. However, there is no nationwide depletion of ground water, and large undeveloped supplies remain in many areas (Fishel, 1956).

Examples of major declines of water level in urban areas

[Source of data: Thomas, 1951, p. 110–112, 115, 117, 120, 132, 145]

Location	Pumpage in 1949 (mgd)	Decline of water level or water-pressure surface (feet)
Arkansas, El Dorado	10	170 since 1921.
Georgia, Savannah	About 50	As much as 100 since 1880.
Illinois-Wisconsin, Chicago-Milwaukee.	110	100 or more since 1880, in a 2,500-square-mile area.
	30 or more	8–20 since 1915.
Indiana, South Bend	45	230 since 1914.
Louisiana, Baton Rouge	More than 50	As much as the 60 in Minneapolis and 100 in South St. Paul industrial district.
Minnesota, Minneapolis-St. Paul.		
Ohio, Norwood	17	80 since 1910.
Tennessee, Memphis	10 from "1400-foot sand"	50 since 1925.
Texas, Dallas-Fort Worth	34, including adjacent areas to north and south.	As much as 500 in Fort Worth business district and nearly 300 at Dallas, since pumping started.

While this subject of water-level changes caused by changes in water use has been documented extensively in hydrologic literature, the effect of changes in land use upon ground-water levels has received relatively little attention in hydrologic investigations because of the difficulty of separating the latter effect from the more pronounced effect of changes in water use.

Thomas (1951, p. 191–192), in his summary of effects of urban use of land upon ground water, points out that some of the most significant changes in water level have resulted from construction of buildings, pavements, and other impermeable surfaces upon the land. The structures and surfaces prevent infiltration and divert precipitation by drains and sewer systems or by snow-removal equipment. Thomas states that in densely settled areas, such as Manhattan Island, N.Y., storm sewers act as substitutes for the natural drainageways. In many cities storm sewers are cut deeply enough below the water table that they carry off ground water as well as storm runoff, so that the original water table continues to decline and the ground-water reservoir can be recharged neither by precipitation nor by leakage from storm sewers. On the other hand, in the residential parts of many urban areas, the water collected from roofs is discharged into the ground, and therefore, the infiltration and ground-water recharge in the suburbs may be equivalent to that occurring prior to residential development.

Thomas cites Brooklyn, N.Y., south Philadelphia, Pa., and Baltimore, Md., as among the best examples of recharge areas of important ground-water reservoirs being almost completely covered by buildings, streets, and sidewalks. It has been estimated that replenishment of the ground-water reservoir has been reduced 30 to 40 mgd as a result of about half of the 70 square miles of Brooklyn being covered by these types of impermeable surfaces. In contrast, Thomas refers to the Raymond Basin (Pasadena, Calif.) as an area in which urbanization has increased the amount of precipitation which reaches the water table by infiltration because, as a result of watering lawns and gardens with water imported from other areas, there is never any great deficiency of soil moisture throughout the growing season.

Occasionally the urban use of water and land causes water levels to rise to such an extent that drainage and waste-disposal problems are created or intensified. The Whitney Terrace area in Boise, Idaho, covers about 3,200 acres and is located on an old river terrace southwest of the Boise River. In 1955 the area was about 35 percent urban. The population in 1957 was estimated to be between 20,000 to 25,000. Urban expansion, largely in the form of residential-type buildings has continued to the north at a rapid rate and is encroaching upon irrigated farm lands. The natural drainage is blocked at many places by streets and by urban dwellings. Where the water table had been at least several tens of feet beneath the surface prior to urbanization and irrigation, it has now risen to a point near the surface, creating serious problems of drainage. Although the acreage of irrigated land has decreased, the amount of ground-water recharge has increased yearly. This is due partly to heavy watering of lawns, infiltration from some of the irrigation ditches, and the outflow from septic tanks. Almost all the domestic water now used is imported from outside the area or is pumped from deep aquifers that are unrelated to the shallow aquifers in which rise of the water table is creating the drainage problem. The recharge in 1955 from all sources was estimated to be 2.4 acre-ft per acre per year and, under the existing system of sewage disposal, complete urbanization may increase recharge to about 3.3 acre-ft per acre. The annual volume of sewage effluent is equivalent to about 0.44 acre-foot per acre per year in the 3,200-acre area. Full urban development would increase the amount to about 1.26 acre-ft per year, an increase of about 0.82 acre-foot per acre per year (West, 1955).

ARTIFICIAL GROUND-WATER RECHARGE

Artificial recharge of aquifers is practiced both in agricultural and in urban areas as a means of maintaining aquifers or obtaining greater yields from them or for disposing of excess flood or waste waters. This type of recharge, frequently accomplished by "water spreading," may also be done through use of infiltration pits, shafts, and wells. Artificial recharge of aquifers is a method that may be used to maintain the level in an aquifer and compensate for the effects of urban buildings and streets in reducing infiltration and natural recharge. Such measures are of importance in concentrated urban areas dependent on local ground-water supplies.

As early as 1889, Denver, Colo., began a small recharge project to maintain its domestic supply. Large recharge projects have been carried out on Long Island since the early 1930's to prevent the encroachment of salt water and to increase the amounts of water available for industrial and municipal use. A survey by questionnaire in 1955, sponsored by the American Water Works Association, showed that there were then in operation 120 public-supply recharge projects in 15 States, but predominantly in two States: 87 in California and 13 in Massachusetts (American Water Works Assoc., 1956, p. 493, 496).

Muckel and Schiff (1955, p. 302), point out the importance of artificial recharge as a part of the planned use of ground-water reservoirs:

> Many ground-water reservoirs can hold far more than the largest artificial surface reservoir, yet few are fully utilized to store flood waters. Holdover

storage in ground-water reservoirs can be provided with little loss of water by evaporation. Few undeveloped economical surface reservoir sites remain in the West, and the utilization of underground storage is a planned development.

A principal measure of the success of a recharge project is how great and how long a rate of infiltration is maintained, and this in turn is dependent upon the condition of the water and of the ground, the position of the water table, and the method of recharge. The recharging water should be relatively free of silt and other fine particles, and the ground should be coarse-textured and stable enough to permit a continuous inflow of water. The subject is complex because of the extremely wide variety of water, soil, and subsurface conditions that exist in nature as well as those modified by man. Bliss and Johnson (1956) have described and analyzed some of these factors by field and laboratory studies carried out in California.

A knowledge of the rate of water movement on, into, and beneath the ground is essential in the analysis of the feasibility of an artificial recharge project. The velocity of water in rivers is measured in feet per second, whereas the velocity of ground water is measured in feet per day, month, or year. Under natural conditions, infiltration rates are of the order of an inch or some fraction of inch of rainfall per hour, and this rate is comparable to some rates of artificial recharge by water spreading. Muckel and Schiff (1955, p. 306) suggest the following:

> Average infiltration rates of 1.5 feet a day on large spreading areas for a spreading period that may last up to 9 months would be satisfactory. Higher rates are desirable.
>
> Treatments to increase infiltration and percolation rates are designed to enlarge soil pores, improve aggregation, stabilize aggregates, and establish continuity of pores through the surface soil or through lower, less permeable layers or both. Involved are dispersion, slaking, and swelling of soil particles; leaching and deposition of material; biological and chemical activity; and compaction, which tends to clog pore space.

At Peoria, Ill., artificial recharge through pits has been in progress for several years, and experiments to improve the method continue. Suter (1956, p. 357, 360) reported that in 1954–55 a pit with an area of 2,500 square feet had a high recharge rate of 20–25 mgd per acre, equivalent to about 28–35 inches per hour. The pit was planned to be used only during the 6–7 months when the Illinois River water has a temperature of less than 60° F.

One of the most rapidly urbanized parts of the nation is the 276-square-mile area of Nassau County, Long Island, N.Y. The county had a population of 303,000 in 1930, but in 1957 was estimated to have 1,300,000 or more. The growth of Nassau County was described in Engineering News-Record (1957, p. 31) as follows:

> Within that area are a total of well over 14,000 miles of paved road * * *. Within 11 years, a total of 184,496 one-family and 12,677 multi-family units have been built. In addition, 5,500 stores and one-story business structures have been erected, as have 1,187 industrial buildings * * *.
>
> The question of drainage is closely related to the geological character of Long Island—a 120-mile strip of sand and gravel running almost due east from Manhattan Island. At its widest, the island is about 16 miles wide. Outside of a few springs, there are practically no natural watercourses, and for drinking and industrial water it depends on a huge lens of underground supply that is replenished by rainfall. * * *
>
> * * * the vast urbanization of the area brought with it a double problem: An immensely increased demand for drinking and industrial water plus the "roofing over" of enormous square footages of land, with paved roads, driveways, sidewalks, houses, garages, industrial buildings.
>
> The result was a greatly increased runoff with no place for the water to go. This situation was aggravated by the increased drawdown on the underground water supply * * *.

To meet the problems just cited, Nassau County in 1928 began the construction of storm-water recharge basins, which have not only disposed of storm water more rapidly, but have increased recharge to the ground water basins, thus raising water levels and lessening the threat of salt-water encroachment. There are now more than 400 of these basins, ranging in area from a 150-foot square (about ½ acre) to 22 acres. Land developers are required by county building specifications to include paved streets and sidewalks with curbing at a specified slope, storm and sanitary sewers, and storm-water recharge basins in their projects.

An interesting example of a water-control system that includes artificial recharge as a secondary but important function, was completed in October 1957 in one of the metropolitan areas of southern California (Engineering News-Record, 1958a, p. 47):

> A pressing need to nurse underground water supplies as well as to control floods from fire-devastated watersheds has led to the development of a dual purpose flood control project protecting San Bernardino, Calif. By its use of sandy bottomed or completely unlined channels and extra detention basins to promote percolation into the ground, the project incorporates water conservation features while performing its primary role of controlling flood runoff.
>
> The dual-purpose system * * * consists of a network of ten major detention-debris-spreading basins, three dams, ten miles of channel, and three miles of underground conduit. The completed project will serve to reduce a 100-year storm runoff to that of a 10-year storm before emptying into the Twin Creek Channel, a tributary of the Santa Ana River.

In parts of California, the practices of capturing flood waters by the use of storage reservoirs, improved conveyance channels, and water spreading grounds have resulted in retaining about 85 percent of flood waters that, in years past, would have reached the ocean directly (Rawn and Bowerman, 1957). Thomas (1951, p. 274–275) mentions the probable potential usefulness of ground-water reservoirs in flood-control programs, but cautions that not all ground-water problems will be solved by recharge.

Over most of the Nation's area such [artificial-recharge] practices would have no direct effect upon the more productive ground-water reservoirs. Artificial recharge can be deemed successful only if it augments the storage in a ground-water reservoir where it can be used, and therefore a knowledge of the hydrologic characteristics of that reservoir is prerequisite.

Two examples of artificial recharge for the purpose of prevention of salt-water contamination are cited in the section on "Contamination of aquifers".

CONSERVATION BY USE OF WASTE WATER

The concentration of industries in urban areas often results in re-use of the available water supply one or more times. Thus, one of the important secondary effects of urbanization is the planning and construction of reclamation facilities for the conservation of process waters and the utilization of waste waters from other sources. Irrigation with sewage effluent from urban areas has proven beneficial to some agricultural and recreational lands.

Uses of waste water have been the subject of research sponsored by the California State Water Pollution Control Board since its activation in 1950. In 1954, the board contracted with the University of Southern California for a project to include studies of existing waste-water reclamation and utilization projects. These investigations include: (1) the economic factors of waste-water reclamation and utilization; (2) participation with local and other agencies in planning, conducting, and integrating control tests on reclamation of waste-water and projects for its utilization which are being operated by local agencies; and (3) potential uses of reclaimed waste water by industry, agriculture, and other water users with particular emphasis on one or two typical water-shortage areas (California State Water Pollution Control Board, 1955, p. 3). Much of the impetus for research on reclamation of industrial wastes has come from the necessity of industry to control pollution and conserve potable water, and the desire to maintain good public relations.

Sewage effluent has been shown to be an adequate medium for leaching of alkali soils, or improvement of barren soil when chemical concentrations permit and health regulations are complied with. In some areas, reclamation of sewage provides the only source of economical water for recreational and industrial use. The use of sewage effluent for planned recharge of the ground water is feasible, but so far has been limited to a very few locations. Metropolitan areas have large quantities of effluent available, which with proper planning can provide supplies for industry, parks, golf courses, or ground-water recharge.

EFFECTS ON QUALITY OF WATER SUPPLY

DISPOSAL OF WASTES

The twin problems of providing a safe water supply and a sanitary method of sewage disposal are as old as civilization. Under primitive conditions, a camp was set up near a spring or stream, and the wastes were scattered over the adjacent countryside. When sanitary conditions became undesirable, the camp was moved. The establishment of permanent towns and cities, however, required more adequate disposal facilities. Increased urbanization has, of course, increased the complexity of these problems.

The convenience of water-distribution systems has stimulated interest in their development, and at the same time has contributed to the complexity of the waste-disposal problem. Greater volumes of sewage and contaminating waste waters are being produced. The development of highly congested areas has required the construction of central sewer systems to replace privies and cesspools with their threat to health. While the present-day need for supplying water in abundant quantities and of satisfactory quality has been satisfied temporarily in most cases, waste removal is still far from satisfactory in many urban areas (Jensen and Vogel, 1949, p.1).

Many of our streams are utilized as sources for domestic and industrial water supply and concurrently as convenient sewers for both untreated and inadequately treated domestic and industrial wastes. The amount of resulting polluting material is sometimes beyond the capacity of the stream to purify or dilute to an unobjectionable concentration. A study by the U.S. Public Health Service revealed that in 1951 there were 11,800 sources of municipal waste and 10,400 sources of industrial waste discharging into our streams and lakes; 6,700 of the municipalities had sewage-treatment plants, but only 3,531 of these plants were of adequate capacity. Only 2,595 of the industrial plants were treating waste waters (U.S. Public Health Service, 1951, p. 15).

In their discussion of water quality problems in California, Banks and Lawrence (1953, p. 60–61), presented general definitions and explanations of various conditions of pollution and degradation, and summarized these conditions in tabular form below.

Causes of damage to the quality of water resources[1]

Pollution		Degradation	
Polluting material	Source	Cause	Agent
Domestic sewage.		Return of irrigation water.	Surface drainage.
Industrial wastes:			Percolation.
Organic wastes	Food-processing plants: Fruit and vegetable canneries. Fish canneries and fish-reduction plants. Slaughtering plants. Wineries. Breweries.	Interchange of water between aquifers.	Improperly constructed, defective, or abandoned wells. Differences in pressures resulting from excessive withdrawal from an aquifer.
Sulfite waste liquor.	Lumber mills, mill ponds. Pulp mills.	Overdrafts on aquifers.	Sea-water intrusion. Salt-water balance. Upward or lateral diffusion of connate brines.
Mineral wastes	Metal processing plants: Plating works. Steel mills. Mines and ore-processing plants: Mine drainage. Water used in processing ores. Dredging. Petroleum and natural gas wells and refineries: Drilling wastes. Production wastes, brines, and oils. Refinery wastes. Terminal loading wastes. Abandoned oil and gas wells. Chemical plants.	Natural processes	Inflow or percolation of highly mineralized water from springs and streams. Accelerated erosion.
Water used for cooling purposes.			
Solid and semisolid refuse.			

[1] This is not intended to be a complete listing of industrial wastes that may cause trouble.

The discharge of sewage-treatment-plant effluents into lake waters tends to stimulate the growth of aquatic plant life. Treated sewage contains nutrients that are more readily available than in raw sewage because the organic substances have been broken down to release nitrogen and phosphorous. Sewage is further enriched by the increased use of detergents containing phosphates. Ultimately, if the supply of nutrients is great enough, odorous masses of dead and decaying algae may appear along the shore line and aquatic weed growth will flourish and cover the shallow areas of a lake, perhaps rendering it virtually useless for recreation, home sites, or water supply. (Washington State Pollution Control Comm., 1955.)

Lake Washington, in the State of Washington, covers an area of about 50 square miles and receives the drainage from approximately 180 square miles, including the Seattle-Everett metropolitan area. Much of this area is developing rapidly. More than 15,000 people presently use the lake as a source of domestic water supply. The value of Lake Washington for recreation and of its shores for home sites is well known. However, much of the populated area was not served by sewers in 1957. City and county health department surveys indicated that much of the land was unsatisfactory for individual septic tanks and drain fields because of unfavorable soil conditions. Thus, the amount of septic-tank effluent that can be disposed of within the soil is limited. When the amount exceeds this limit, the effluent appears on the surface or seeps into water courses and eventually reaches the lake. As a result, Lake Washington is in the first stages of an enrichment that may bring ultimate degradation of its water, unless corrective measures are applied.

The increase in temperature of stream waters caused by man may also be considered a type of stream degradation. Water passed through a steam-electric power plant may be raised 15 to 20 degrees Fahrenheit before being returned to the stream. The Mahoning River in the Youngstown, Ohio, area is an example of a stream adversely affected by high-temperature return waters. W. P. Cross (Cross and others, 1952, p. 32) states that about 95 percent of the river water withdrawn is used for cooling purposes and is returned to the river unchanged in quality except for higher temperature. He states also that, as the mean river temperatures on streams unaffected by industrial use approximate the mean monthly air temperatures, the difference between mean air temperatures and mean river temperatures is a measure of the effect of industrial use on river temperatures.

During the year ending September 30, 1950, the average monthly temperature of river water at Lowellville and Niles (within 10 miles upstream and downstream respectively from Youngstown) was 7° to 51° F higher than the average monthly air temperature at Youngstown, the water temperatures at Lowellville reaching maximums of more than 90° F in 8 of the 12 months. An inventory of industrial use of raw river water was made in 1949 by the Mahoning Valley Industrial Council. The total use of 1,220 mgd on October 17, 1949, was more than 10 times the flow of the Mahoning River at Youngstown on the date of the inventory, thus showing how intensively the water is used and re-used in this highly industrialized area. Since 1944, increased low flows from the operation of upstream reservoirs have reduced river temperatures (Cross and others, 1952, p. 33, 51).

EFFECTS OF WASTES ON AQUATIC LIFE

Water of adverse quality and its effects on aquatic life have been and are being studied extensively by fish and wildlife conservationists. The pollution of streams and estuaries by domestic and industrial wastes have a marked harmful effect on the propagation of birds, game, fish, and shellfish. For example, water of adverse quality may affect anadromous fish by discouraging the adults in their upstream migration, killing them by toxicity or disease before they reach the spawning grounds, destroying their eggs by providing an environment unfavorable for hatching, or causing newly hatched fish to die through the destruction of the young fish or their food supply (Sylvester, 1958, p. 11).

In order to evaluate the effects of various discharges of industrial wastes and domestic sewage into a body of water, the primary water uses must first be determined. In Puget Sound and the estuarial waters of the State of Washington, these uses include the passage of anadromous fish, culture of oysters and other shellfish, rafting and sorting of logs, pleasure boating, and activities associated with industrial and municipal development. In 1950, an investigation by the Survey Division of the Washington State Pollution Control Commission demonstrated that the Grays Harbor area was one of the most contaminated bodies of water in the State (Washington State Pollution Control Comm., 1957a). The discharge of raw sewage was found to have two effects: first, bacterial contamination, which is a health hazard, and, second, depletion of dissolved oxygen because domestic sewage, in conjunction with industrial waste, creates a high oxygen demand upon the waters of the area. Harvesting from some of the available potential oyster-growing areas in Grays Harbor has been restricted, by order of health authorities, because the areas are near outlets for domestic sewage. The pollution is believed also to have caused the marked decline in the number of salmonoid-fish in the area, which are highly prized by sports fishermen and are an important source of income for commercial fishermen.

The effects of pollution by sewage of urban origin on the culture of shellfish are known from surveys made by the Washington Pollution Control Commission (1957b) in the Bellingham area in the summer of 1957. Extensive portions of the project study area are used for the culture of shellfish. The normal yield ratio of 5-year old Pacific oysters is said to be 1 gallon of meat per bushel of oysters. Based on records furnished by the oyster industry, the yield has declined steadily in this area since 1949 and 1 gallon per 10 bushels is the present yield for the beds in Samish Bay. Oyster growers in the survey area report abnormally high oyster mortalities. During the investigation, sulfite-wastes from the pulp mills in this area were detected over the commercial oyster growing area in Samish Bay. Although evaluation of toxicity tests on shellfish are not generally agreed to be conclusive at this time, it was presumed that the sulfite-waste contamination may be associated with the deterioration of the oyster harvest.

CONTAMINATION OF AQUIFERS

The causes and effects of man's use of water, and occasionally the land, which result in contamination of aquifers, are well documented in hydrologic literature. Contamination occurs in three principal ways: by downward movement of a polluted water or other pollutant from the land surface or from the bottom of a stream or lake; by lateral or vertical encroachment of a naturally occurring inferior underground water, such as an ancient unflushed brine; and by underground encroachment of a brackish or salt water having its origin in an existing salt-water body, such as a bay, sea, or a tidal stream ending in salt water (Parker, 1955, p. 615–635).

Man's actions in his urban environment cause many of these effects. The most direct method of contamination of an aquifer is the intentional use of a well for disposal of waste. Although this practice is still carried on in some rural areas, regulations and inspections probably have eliminated this form of waste-disposal in most urban areas except where the well used may have been drilled into a water-bearing formation already known to contain unusable water. Contamination can occur also when waste materials are dumped upon the land surface and the solvent action of rain water causes some parts of the material to seep into the ground. The movement of water through the soil and within most types of water-bearing formations is slow, except when discharged into wells or into rock deposits of very high porosity, and therefore the pollutant may take months or years to reach an aquifer from which water is being withdrawn. Once contaminated, an aquifer may have to be abandoned as a source of water until the pollutant is flushed out. The processes of filtration, dilution, and discharge under natural conditions may take years to become effective, and artificial methods are sometimes very expensive.

One of the most common types of ground-water contamination in urban areas is a result of the increasing withdrawal of water from an aquifer, for municipal or industrial use. This causes the water level or pressure to decline, which in turn may result in the lateral movement of inferior water into the part of the aquifer being used, for example, saline water from an adjacent bay or coastal area. Contamination by inferior waters has been investigated and described in various parts of this country and abroad for many years, and has been well summarized and illustrated by Parker (1955, p. 615–635).

As part of its periodic reports of findings, a Task Group on Underground Waste Disposal and Control, American Water Works Association described in 1957 a group of case histories. The following examples serve to illustrate the widespread distribution and varied character of the problems (Am. Water Works Assoc., 1957, p. 1334–1335).

In certain areas in the eastern United States, particularly in Maryland and New York, serious ground-water problems developed as a result of the disposal of chemical wastes. At a chemical manufacturing plant in Maryland during World War II, large quantities of acidic wastes were dumped into a nearby estuarine swamp and the screens on wells drilled into the underlying Patuxent formation in the immediate vicinity became highly corroded in only a few months. Chemical analysis showed the ground water in this area to be highly acidic, having a pH of 3.0. Because there were relatively few wells in the area, the extent of the contamination has not been determined, but is probably confined to the aquifer underlying the immediate area. The dumping of wastes into the swamp was subsequently discontinued.

In Nassau and Suffolk counties, Long Island, New York, wastes from local aircraft plants were emptied into nearby leaching pits, and water samples, subsequently collected from the aquifer underlying the area, showed traces of cadmium and hexavalent chromium. When informed of the potential danger of further contaminating the ground water, the aircraft industries installed plants to treat the wastes before they were dumped into leaching pits.

An Ohio industry discharges large volumes of calcium chloride waste to the headwaters of a major stream. The volume and concentration of the waste are such that the water supplies of downstream municipalities, which are obtained from wells in the gravel deposits along the river, are adversely affected. One city had to abandon its water supply for this reason, and the water supplies of several other municipalities are seriously affected; one of these cities is more than 100 miles downstream.

Salt-water contamination is a present or potential threat to ground water developments in many coastal areas. This problem is being met (Power, p. 94, 1952) in Brooklyn, N.Y., and in Los Angeles, Calif., as follows:

On Long Island, salt-water intrusion threatened serious trouble some years ago. The answer there combined engineering and law. As a whole, the Island has ample water. The eastern end uses relatively little but the western end, part of New York City, pumps heavily. Pavement and buildings cover much of the area, so natural recharge rate is low.

As long ago as 1933, underground water level got as much as 30 feet below sea level. The usual fresh-water barrier was no longer there and salt water began to seep into the aquifer.

The state government stepped in, passing a law requiring all users of 100,000 gallons per day in affected areas to secure permits. Permit holders had to return unpolluted water to recharge wells after use. In addition, wells were drilled close to the shore and fresh water pumped down. The purpose was not to recharge the aquifer but to effect a fresh-water barrier between salt and lower ground water.

The following table is abridged from the same report, and summarizes the distances and time of subsurface travel of various types of pollutants.

Examples of distance and time of travel of various types of pollutants
[Source of data: Am. Water Works Assoc., 1957, p. 1339]

Nature of pollution	Pollutant	Observed distance of travel (feet)	Time of travel
Sewage polluted trenches intersecting ground water.	Coliform bacteria	65	27 weeks.
River water in abandoned wells	Intestinal pathogens	800	17 hours.
	Tracer salts	800	17 hours.
Coliform organisms introduced into soil	Coliform bacteria	164	37 days.
Introduced bacteria	*Serratia marcescens*	69	9 days.
Chlorinated sewage	Dye	300	24 hours.
Industrial wastes	Picric acid	15,840	4–6 years.
Do	Chromate	1,000	3 years.
Salt	Chlorides	200	24 hours.
Weed-killer wastes	Chemical	105,600	6 months.

The return of unpolluted water through industrial recharge wells has caused water levels to rise gradually in some parts of the Brooklyn area, and slowed the rate at which salt-water contamination was increasing. However, recharging of the artesian aquifer with water containing less salt from the shallow formations proved to have only temporary and more or less local effect in reducing salinity. More pronounced changes have occurred since 1947, when the New York Water Service Corporation discontinued its pumpage of about 27 mgd (Lusczynski, 1952, p. 4–6).

Sea-water encroachment has been studied during the past 30 years in California. According to Laverty and van der Goot, (1955, p. 887), the State reported in December 1950 that the west coast basin in Los Angeles was the most seriously affected of 20 ground-water basins suffering serious salt-water encroachment or in immediate danger from it. The west coast basin extends 6–8 miles inland to the Inglewood Fault and about 11 miles along the coast from the Palos Verdes Hills to Ballona Creek. An experimental fresh-water barrier was created in November 1953 by injection of about 5 cfs of Colorado River water at 8 wells, spaced 500 feet apart and 2,000 feet inland from the ocean, which caused levels to rise from a level 6 to 12 feet below sea level to a level 4 to 8 feet above sea level. Laverty and van der Goot (1955, p. 907) listed the following conclusions for areas with comparable geologic and hydrologic conditions to the west coast basin:

1. Prevention and control can be successfully realized in a confined coastal aquifer by recharge through wells.

2. Recharge can pressurize a confined aquifer continually through a given reach, thereby reversing a pre-existing landward gradient and preventing further sea water intrusion.

3. Recharge will provide significant replenishment to the inland ground water basin with only a relatively small oceanward loss of fresh water.

4. Recharge can be performed in an aquifer previously degraded by sea water intrusion and—within the physical limitations as established at the test site—will not have any consequential deleterious effect on inland pumped supplies. In

fact, all evidence collected to date indicates that the degraded portion of the aquifer can be reclaimed by recharge through wells.

EFFECTS ON FLOODS AND DRAINAGE

It is difficult to evaluate the extent to which flood magnitudes may have been increased by man's activity, for certain types of rainfall will produce catastrophic floods under any conditions. Man takes a calculated risk when he builds his towns, cities, and other installations on the flood plain of a river. He, thus, is responsible for flood damages, if not for the floods that cause them. Urban encroachment upon natural flood plains leads to an increased potential damage by a flood of given magnitude.

Urbanization is undoubtedly an important factor in causing local floods. Continued rapid development of suburban areas results in rapid increase of areas of virtually water-proofed surface. Storm runoff from the impervious areas is not only greatly increased in volume, but the time of concentration of critical storm flows is shorter. The result is the virtual "dumping" of storm waters on lower lying areas at rates greater than the capacities of existing drainage facilities, whose improvement and enlargement do not keep pace with the development and expansion of the city. In many urban areas the annual losses resulting from inadequate storm drainage facilities range from those caused by temporary inconveniences to extensive damage to highly valuable property by actual inundation.

Some idea of the difference in magnitude of storm water in rural and in urban areas is shown in table 2. The counterpart of the hypothetical example of a 2-inch storm in 3 hours might actually occur once in every 5 or 10 years in many parts of the United States. In some rural areas, there would be very little runoff, while in downtown paved areas almost all the water would appear soon as runoff.

The storm-drainage problem is regarded and undertaken as a municipal function in every modern community throughout the world. The extent of the attention given to it is related to and dependent upon many factors, such as: intensity and duration of heavy rains; topography, including land slopes and available natural water courses; soil conditions, particularly perviousness; extent of paved surfaces and roofs; value of property to be protected against flooding; and the ability and willingness of the taxpayers to meet the attendant costs.

Storm drainage facilities prevent flood damage and allow the convenient use of streets during periods of intense rainfall. They are relatively expensive because their capacity must be many times that of domestic waste systems. Los Angeles County, after spending 179 million dollars on storm drains to relieve local flooding, finds that it needs additional storm drains costing about a billion dollars to provide adequate relief from local floods and to protect as yet undeveloped areas. (Engineering News-Record, 1958b, p. 28). In Tacoma, Wash., important urban development in the western part of the city has been halted because of lack of storm drains.[1]

The floods of April-June, 1952, in Salt Lake City, Utah, illustrate the contributing effects of man's activity in changing the natural drainage (U.S. Geol. Survey, 1957). The major trans-city tributaries to the Jordan River have been piped underground. The smallest streams have been eliminated entirely and the flows of the next larger streams have been placed in small culverts which were not large enough to carry the flood waters. During the 1952 floods all 13th Street was sand bagged to create an artificial channel. Even this measure did not prevent some flooding. Because of debris plugged drains and small culverts and the inadequate carrying capacity of larger culverts draining the area, water accumulated behind the railroad embankments parallel to the Jordan River. Water was released to other low lying areas, although causing some flooding of homes, in order to prevent a sudden outburst and damage to more heavily populated areas. Presumably there would have been some flooding in the Salt Lake City area even though urbanization had not taken place, but the modification of the natural channels undoubtedly influenced the magnitude and nature of the flood.

STUDIES OF STORM RUNOFF IN URBAN AREAS

Several studies have been made of the relation between rainfall and runoff from small urban areas. In St. Louis, Mo., Horner and Flynt (1936) studied the runoff from parts of several city blocks tributary to storm-sewer inlets and the runoff from both roofs and ground surfaces of one city block. The information included in their report is from measurements of rainfall and storm flow from nearly all heavy rains that occurred from 1914 to 1933. The relation of runoff to rainfall, defined in several ways, was shown to vary widely. Also, the runoff from a given drainage area was related to the season of the year and general climatic conditions and affected by antecedent precipitation, soil moisture, infiltration capacity, type of soil, depression storage, surface retention, rainfall intensities, gutter storage, and geology. Obviously a definition of the hydrologic performance of watersheds under different degrees of urbanization presents a challenge to the hydrologist.

W. I. Hicks (1944) described the results of certain hydraulic investigations and rainfall-runoff gagings for improved urban drainage

[1] Brown and Caldwell, 1957, Metropolitan Tacoma sewage and drainage survey, p. 23, (Report for the city of Tacoma).

areas of different sizes and types of development. R. K. Linsley presented a method of calculating probable flows for drainage design in Redwood City, Calif.[2] Data were not available on Redwood City streams for comparison with results obtained by the methods proposed.

Ven Te Chow investigated Boneyard Creek in Champaign-Urbana, Ill., in connection with studies of the hydrology of an urban watershed (Chow, 1952). Other studies are in progress. Preliminary analysis of peak flows on Eubanks, Town, and Lynch Creeks in Jackson, Miss., indicates that these streams which drain urbanized areas have peak discharges higher than those of adjoining streams draining areas that are not urbanized (U.S. Geol. Survey, 1955). In all five studies cited above, preurban calibration data to demonstrate exactly the changes effected by urbanization are lacking.

Basic research in the hydrology of storm drainage systems in urban areas is being carried out in Baltimore, Md., by the Johns Hopkins University (Middleton, 1957, p. 50). A study of rainfall and runoff relations as affected by various drainage-area parameters is included in this research. At present, flows from 7 urban areas ranging in size from 10 to 400 acres are gaged, 4 by a newly developed flow meter, and 3 by stage measurements only. Two recording systems which simultaneously record rainfall on and runoff from, 14 inlet areas provide good opportunity for detailed study. About 5 years of rainfall records now exist for a network of 10 recording gages covering an area of 50 square miles.

Although storm drainage in urban areas is a problem of very great economic importance, there is a scarcity of basic information on the rainfall-runoff relationships in urban areas. A program of collection of basic data covering urban-areas of different types, and of different geologic and climatic environments, is highly desirable. There is need also for research to establish the nature and degree of the effects of urbanization on the basic hydrologic processes. A better understanding of these detailed effects would facilitate and improve the adequacy of planning to alleviate or prevent undesirable effects.

EFFECTS ON EROSION, SEDIMENTATION, AND CHANGES IN CHANNEL GEOMETRY

As a city or residential community builds, much of the cover of natural vegetation is removed, numerous excavations are made, natural drainage is restricted and eliminated entirely in many places, roads and streets are cut across the natural drainage patterns, and the biological balance within the soil is disrupted, causing the natural erosion processes to be accelerated, especially during periods of construction. Observation of streams below areas where new housing

[2] Adamson, P. L., 1953, Report on flood control and drainage facilities for city of Redwood City, Calif.

or building projects are in progress shows that a heavy load of sediment is transported during and after rainfalls. This load may cause aggradation in channels downstream and reduce their water-carrying capacity.

Chartiers Creek in southwestern Pennsylvania flows through heavily industrialized Allegheny and Washington Counties. At the time of preparation of this report the population of Allegheny County was 90 percent urban. There are 1,897 farms in the county but the number is rapidly diminishing. Two-thirds of Washington County's land area is still devoted to agriculture. In 1950, 255,000 people were living in 35 municipalities within a watershed area of 278 square miles. The greatest concentration of population and a large percentage of the major industries are located along Chartiers Creek and in the lower part of the watershed.

Appraised in terms of general damage, 4 of the most severe floods in the Chartiers Creek valley have occurred within the past 15 years. The severity of these floods may be attributed, in part, to heavy residential development in sections of the watershed. Since the end of World War II, many new suburban residential developments near Pittsburgh have been located in this area. The valley also has received its share of new commercial and industrial developments.

The most destructive flood in the history of the Chartiers Creek valley occurred at Canonsburg, Bridgeville, Heidelberg, and Carnegie on August 5 and 6, 1956. Damage was greatest along the creek from above Canonsburg to below Carnegie. The gage reading at Washington, the city furthest upstream, was the fifth highest recorded there, but at Carnegie, where considerable aggradation has occurred, the reading exceeded all previous records. Compared with that of previous floods, the damage in Washington was relatively light because a flood-control project was completed prior to the August deluge. A mile and a quarter of the stream had been dredged and widened, thereby increasing the efficiency of the channel and making it possible for the flood waters to be carried off quickly. It is at least possible that the intense flooding at Carnegie resulted from the more concentrated runoff caused by increased capacities of upstream channels brought about by the channel-improvement work.

EFFECTS ON LAND SUBSIDENCE

Subsidence of the land surface has been reported in many areas of heavy ground-water draft, and is a problem of considerable importance when it occurs in urban areas. Measured subsidence attributed to ground-water withdrawal has been as great as 1.5 feet at Las Vegas, Nev., 3 feet near Texas City, Tex., and 6 feet at San Jose, Calif. In Mexico City, Mexico, the annual rate of subsidence increased from

1.6 inches in 1937 to 5.5 inches in 1948 and 11.5 inches in 1954. The land surface at the Palace of Fine Arts has subsided 16 feet since 1937 (Thomas, 1956, p. 549). In California, areas where land subsidence is creating problems are the La Verne area east of Los Angeles, and the Santa Clara, and the San Joaquin Valleys. The subsidence has affected existing engineering structures and influences the planning, construction, and maintenance of proposed structures. It has affected irrigation, drainage and sewerage systems, flood-control channels, levees, roads, bridges, power installations, and pipelines (American City, 1957, p. 27).

A less obvious but very important effect may be the permanent loss of ground-water reservoirs.

RELATIVE SIGNIFICANCE OF VARIOUS EFFECTS

This report has stressed the increasing impact of urbanization upon hydrology; the wide variety of hydrologic effects that result from this impact and the marked differences, both in the relative significance and in the present quantitative knowledge of these effects.

The hydrologic effects of urbanization result from one or both of two main types of action on the part of urban man; these are urban man's use of the water and his use of the land. There is considerable evidence in hydrologic literature that man's use of both water and land can modify the quantity and quality of surface and ground waters and their modes of occurrence. If water is consumed during its use and returned to the atmosphere as vapor, those resources are correspondingly reduced. If water is utilized nonconsumptively, it remains in liquid state and is eventually returned to the surface or ground-water body, but with possible alteration of the chemical or physical properties. The return of this water to a stream or aquifer may cause the pollution or degradation of far larger quantities of water.

Those effects which have resulted from man's use of water are generally the better documented in hydrologic literature, and include:

(1) Increase in both total use and per capita use.

(2) Increasing development of new water-supply sources that may require transportation over great distances.

(3) Increasingly frequent conflicts wherein two or more types of water users seek the same supply.

(4) Diminished streamflow as a result of diversions of water.

(5) Declining water levels and pressure in ground-water reservoirs.

(6) Increasing number of artificial recharge projects, for purposes of water supply and for flood control.

(7) Increase in amount of wastes disposed to streams and possible increase in pollution when wastes are inadequately treated.

(8) Increased re-use of waste water in agriculture and industry.

(9) Land subsidence.

Many of the above effects are so interrelated as a consequence of diminishing quality of supply and increasing demands for quantity, that assignment of relative importance to them is not practical. The primary significance probably is that they are interrelated. In any river basin, be it large or small, any substantial change in water use and waste disposal must be carefully planned within the existing hydrologic framework of that basin. Perhaps the single most critical effect of man's use of water is the gradual deterioration in quality of water, and the increasing need to be alert to prevent or abate further contamination, whether it results from waste disposal or from salt-water encroachment. Waste water now constitutes an ever increasing portion of the Nation's water supply. The use of this resource is dependent upon economics, greater need accompanied by proper planning, and the research required to eliminate technical problems and to reduce costs.

Changes in the surface- and ground-water resources resulting from man's occupancy and modification of the land are generally less well documented than those resulting from his use of water. Most of these changes have been inadvertent, and many may have been in progress for years, or even centuries, before anyone recognized the possibility of a relationship between the water resources and the modifications in land created by man's activities. As any evidences of the natural hydrologic conditions prior to man's occupancy of a region are rarely found, the evaluation of man's activities upon the surface- and ground-water resources of the nation is not an easy task. Accordingly, the total effects due to man's activity in most places can only be generalized, extrapolated, or assumed (Thomas, 1956, p. 543–544).

The quantities of water in streams, lakes, and ground-water reservoirs are continually fluctuating owing to natural causes. These causes and the resulting changes must be identified and evaluated before the effects of man can be evaluated with assurance. As Thomas (1956, p. 542) and others have pointed out, our methods of measurement throughout the period of record also must be carefully examined in order to be assured that apparent changes in water resources are not traceable to changes in technique and equipment.

There is considerable interrelationship among the various effects and problems; probably the most significant effect, because of its widespread occurrence and substantial impact, is the increase in rates and peak stages of storm runoff. This subject is the most spectacular and, apart from flood-damage reports, has received the most attention in urban environments. Storm runoff from urban areas has been investigated only to a limited degree as compared to studies and resulting information available on man's use of water. Except for consulting engineers' reports to their clients, there appear to have been no more than 5 to 10 studies of storm runoff specifically related to urban areas and documented in hydrologic literature generally available to the public. These studies, to which reference already has been made, have been made principally in St. Louis, Mo., Los Angeles, Calif., Champaign, Ill., and, most recently, in Baltimore, Md.

There is a need for a program directed toward investigation of the effects of urbanization on hydrology with emphasis on adding to the knowledge of hydrologic effects of land use on water resources. A more factual basis is needed for the study of the many hydrologic problems that are important in urban areas, such as drainage, erosion, sedimentation, flood control, adequate storm sewers, water supply, waste disposal, and their solution through urban planning. An important conclusion resulting from one of the studies described in this report is that the most widespread and hence the most significant hydrologic problem resulting from urban development is control and removal of storm runoff from urban areas. As a land-area becomes urban the changes in storm runoff are important for many reasons, but the most urgent single need is basic data on which to document the storm-runoff characteristics of existing urban watersheds. Such data are a prerequisite to intelligent design of storm-runoff facilities in early stages of urbanization.

There are relatively few data obtained specifically to determine one or more effects of urbanization. Existing hydrologic data of various kinds, collected for other purposes might provide the basis for analysis of one or more effects of urbanization, perhaps mainly of changes in storm runoff. This opportunity may be limited, however, because hydrologic data generally are available only for larger areas. Such records show the composite effects of all factors, natural and artificial, which influence the hydrology of the area. Usually the urbanized portion of a large watershed is relatively small.

The hydrology of urban areas is quite complex, thus minimizing the possibility of obtaining much specific information from general studies of large areas. The hydrologic changes caused by urbanization undoubtedly vary with geography, climate, season of the year, geology, and other local factors. Some effects, therefore, must be obtained from specific studies designed to measure a very limited number and kinds of effects.

There is also a need for studies to analyze the integrated effects of urbanization on the hydrology of areas in different climatic zones, such as was carried out in the Raymond Basin area of Los Angeles.

These studies involve consideration of changes in both water and land use, and should lead to a better understanding of the changes in water use that occur when land uses change, such as from agriculture to suburban housing developments. With the possible exception of the Raymond Basin, there have been no comprehensive and detailed studies of multiple hydrologic changes created by urbanization of an area and, without exception, no such studies have been made which document the pre-urban hydrologic conditions of the same area. Such studies should form a valuable contribution to hydrology both in terms of research and practical applications.

In summary, the effects of urbanization of most pressing importance are those related to water supply, pollution, drainage, and storm runoff. Of all the effects discussed in this report, these are the only ones almost universally characteristic of urban areas. Research on the causes, movement, and treatment of pollution has been done for a number of years by governmental and private organizations, and is continuing. Problems related to water supply for urban areas are acute in many areas and must be solved by sound engineering and planning, based on adequate basic data on water resources. These problems are not new and have been receiving greater emphasis in basic data programs. Some research on storm runoff problems in urban areas has been done but storm runoff and associated problems still are most deserving of emphasis at this time.

SELECTED REFERENCES

American City, 1920–21, Water-supply statistics of metered cities: The Am. City, v. 23, no. 6, p. 613–620; v. 24, no. 1, p. 41–49.

——— 1956, Fifty-three miles in 68 days: The Am. City, v. 71, no. 6, p. 188–189, 191.

——— 1957, Don't pump till the ground caves in: The Am. City, v. 72, no. 12, p. 27.

American Water Works Association, 1956, Artificial ground water recharge: Am. Water Works Assoc. Jour., v. 48, no. 5, p. 493–498.

——— 1957, Underground waste disposal and control: Am. Water Works Assoc. Jour., v. 49, no. 10, p. 1334–1342.

Baker, M. N., 1897, The manual of American waterworks, 4th issue: 611 p., New York, N.Y., Engi. News Pub. Co.

Banks, H. O., and Lawrence, J. H., 1953, Water quality problems in California: Am. Geophys. Union Trans., v. 34, no. 1, p. 58–66.

Blaney, H. F., 1952, Consumptive use of water—definitions, methods, and research data: Am. Soc. of Civil Engineers Trans., v. 117, p. 949–973.

——— 1955, Climate as an index of irrigation needs, *in* U.S. Dept. of Agriculture Yearbook, Water, p. 341–345.

Bliss, E. S., and Johnson, C. E., 1952, Some factors involved in ground-water replenishment: Am. Geophys. Union Trans., v. 33, no. 4, p. 547–558.

Bogue, D. J., 1953, Population growth in standard metropolitan areas, 1900–50: U.S. Housing and Home Finance Agency, 76 p.

Bookman, 1957, Urban water requirements in California: Am. Water Works Assoc. Jour., v. 49, no. 8, p. 1053–1059.

Breasted, Charles, 1933, Exploring the secrets of Persepolis: Natl. Geog. Mag., v. 64, no. 4 (October), p. 381–420.

California State Water Pollution Control Board, 1955, Survey of direct utilization of waste waters: California State Water Pollution Control Board Pub. no. 12, 80 p.

California State Water Resources Board, 1956, Water utilization and requirements of California: California State Water Resources Board Bull. 2, v. 1, 227 p.

——— 1956, Los Angeles land and water use survey, 1955: California State Water Resources Board Bull. 24, 67 p.

Chow, Ven Te, 1952, Hydrologic studies of urban watersheds, rainfall and runoff of Boneyard Creek, Champaign-Urbana, Ill.: Illinois University, Civil Engineering Studies, Hydraulic Engineering Ser., no. 2, 66 p.

Cross, W. P., Schroeder, M. E., and Norris, S. E., 1952, Water Survey Circ. 177, 57 p.

Engineering News-Record, 1957, The county that became a city (Nassau County, N.Y.): Engi. News-Record, v. 159, no. 14, p. 30–31, 33–34, 37.

——— 1958a, Flood control system nurses runoff [San Bernardino, Calif.]: Engi. News-Record, v. 160, no. 10, p. 47–48.

——— 1958b, A billion dollars worth of storm drains: Engi. News-Record, v. 160, no. 11, p. 28.

Fishel, V. C., 1956, Long-term trends of ground-water levels in the United States: Am. Geophys. Union Trans., v. 37, no. 4, p. 429–435.

Flinn, A. D., Weston, R. S., and Bogert, C. L., 1927, Waterworks handbook, 3d ed.: 871 p., New York, McGraw-Hill Book Co.

Frank, Bernard, 1955, The story of water as the story of man *in* U.S. Dept. of Agriculture Yearbook, Water, p. 1–8.

Free, G. R., Browning, G. M., and Musgrave, G. W., 1940, Relative infiltration and related physical characteristics of certain soils: U.S. Dept. of Agriculture Tech. Bull. 729, 52 p.

Gleason, G. B., 1952, Consumptive use of water, municipal and industrial areas: Am. Soc. of Civil Engineers Trans., v. 117, p. 1004–1009.

Golden, J. F., 1957, Six hundred gallons per capita daily domestic demand: The American City, v. 72, no. 7, p. 127–130.

Hatcher, M. P., 1956, The lawn-sprinkling load, Kansas City, Mo.: Am. Water Works Assoc. Jour., v. 48, no. 4, p. 373–376.

Heath, J. R., 1958, Seattle's need for additional water: Am. Water Works Assoc. Jour., v. 50, no. 1, p. 115–118.

Hicks, W. I., 1944, A method of computing urban runoff: Am. Soc. of Civil Engineers Trans., v. 109, p. 1217–1268.

Horner, W. W., and Flynt, F. L., 1936, Relation between rainfall and runoff from small urban areas: Am. Soc. of Civil Engineers Trans., v. 101, p. 140–206.

Howson, L. W., 1957, Factors affecting long-distance transmission of water: Am. Water Works Assoc. Jour., v. 49, no. 10, p. 1359–1368.

Jensen, E. C., and Vogel, J. H., 1949, Sewage collection and treatment works in the State of Washington: Bur. of Governmental Research and Services in cooperation with Assoc. of Washington Cities and Washington State Dept. of Health, Report No. 86, 106 p.

Krieger, J. H., 1955, Progress in ground water replenishment in California: Am. Water Works Assoc. Jour., v. 47, no. 9, p. 909–913.

Laverty, F. B., and van der Goot, H. A., 1955, Development of a fresh-water barrier in southern California for the prevention of sea-water intrusion: Am. Water Works Assoc. Jour., v. 47, no. 9, p. 886–908.

Lusczynski, N. J., 1952, The recovery of ground-water levels in Brooklyn, New York, from 1947 to 1950: U.S. Geol. Survey Circ. 167, 29 p.

MacKichan, K. A., 1957, Estimated use of water in the United States, 1955: U.S. Geol. Survey Circ. 398, 18 p.

MacKichan, K. A., and Graham, J. B., 1954, Public water-supply shortages: U.S. Geol. Survey Water Resources Review, supp. no. 3, 8 p.

McGuinness, C. L., 1951, The water situation in the United States with special reference to ground water: U.S. Geol. Survey Circ. 114, 138 p.

Middleton, H. K., 1957, Hydraulic research in the United States, 1957: U.S. Bur. of Standards Misc. Pub. no. 221, 220 p.

Muckel, D. C., and Schiff, Leonard, 1955, Replenishing ground water by spreading, *in* U.S. Dept. of Agriculture Yearbook, Water, p. 302–310.

Mumford, Lewis, 1956, The natural history of urbanization, *in* Thomas, W. L. (ed.), Man's role in changing the face of the Earth, p. 382–398: Chicago, Ill., Univ. of Chicago Press.

New York City Board of Water Supply, 1956, Fifteenth annual report, 1955: 108 p.

New York City Engineering Panel on Water Supply, 1951, Future water sources of the City of New York: 81 p.

Parker, G. G., 1955, The encroachment of salt water into fresh, *in* U.S. Dept. of Agriculture Yearbook, Water, p. 615–635.

Picton, W. L., 1956, Summary of information on water use in the United States, 1900–1975: U.S. Dept. of Commerce, Business Service Bull. BSB–136 (January), 8 p.

Porges, Ralph, 1957, Summary of 1955 USPHS survey of treatment facilities in communities of 25,000 and over: Am. Water Works Assoc. Jour. v. 49, no. 12, p. 1567–1580.

Power (mag.), 1952, Water: Power, v. 96, no. 9, p. 71–118.

Rawn, A. M., and Bowerman, F. W., 1957, Planned water reclamation: Sewage and Industrial Wastes, v. 29, no. 10, p. 1134, October 1957.

Sales Management, Inc., 1958, Survey of buying power: 820 p.

Seidel, H. F., and Baumann, E. R., 1957, A statistical analysis of water works data for 1955: Am. Water Works Assoc. Jour., v. 49, no. 12, p. 1531–1566.

Smyth, A. H. (ed.), 1907, The writings of Benjamin Franklin: 10 v., New York, Macmillan Co.

Suter, Max, 1956, High-rate recharge of ground water by infiltration: Am. Water Works Assoc. Jour., v. 48, no. 4, p. 355–360.

Sylvester, R. O., 1958, Water quality studies in the Columbia River basin: U.S. Fish and Wildlife Service Special Scientific Report—Fisheries no. 239, 134 p.

Thomas, H. E., 1951, The conservation of ground water: 327 p., New York, McGraw-Hill Book Co.

——— 1956, Changes in quantities and qualities of ground and surface waters *in* Thomas, W. L. (ed.), Man's role in changing the face of the Earth, p. 542–563: Chicago, Ill., Univ. of Chicago Press.

U.S. Bureau of the Census, 1952, U.S. census of population, 1950, v. 1, number of inhabitants: 54 chaps.

U.S. Geological Survey, 1955, Floods of April 12, 1955, Eubanks, Town, and Lynch Creeks, Jackson, Miss.: U.S. Geol. Survey open file rept., 12 p.

——— 1957, Floods of April–June 1952 in Utah and Nevada: U.S. Geol. Survey Water-Supply Paper 1260–E, p. 577–686.

U.S. Public Health Service, 1948, Inventory of water and sewage facilities in the United States, 1945: paging by States.

——— 1951, Water pollution in the United States: U.S. Public Health Service Pub. 64 (Water Pollution Series no. 1), 44 p.

——— 1956, Municipal water facilities for communities of 25,000 population and over, Dec. 31, 1955: 1953 p.

Washington State Pollution Control Commission, 1955, An investigation of pollutional effects in Lake Washington: Washington State Pollution Control Comm. Tech. Bull. no. 18, 18 p.

——— 1956, Facts about the Seattle sewage problem: Washington State Pollution Control Comm., Inf. series no. 10, 4 p.

——— 1957a, A reinvestigation of pollution in Grays Harbor, 1956–57: Washington State Pollution Control Comm. Tech. Bull. no. 21, 51 p.

——— 1957b, Pollution investigation in northern Puget Sound: Washington State Pollution Control Comm., Tech. Bull. No. 22, 27 p.

West, S.W., 1955, Ground-water and drainage problems in the Whitney terrace area, Boise, Idaho: U.S. Geol. Survey open file rept., 21 p.

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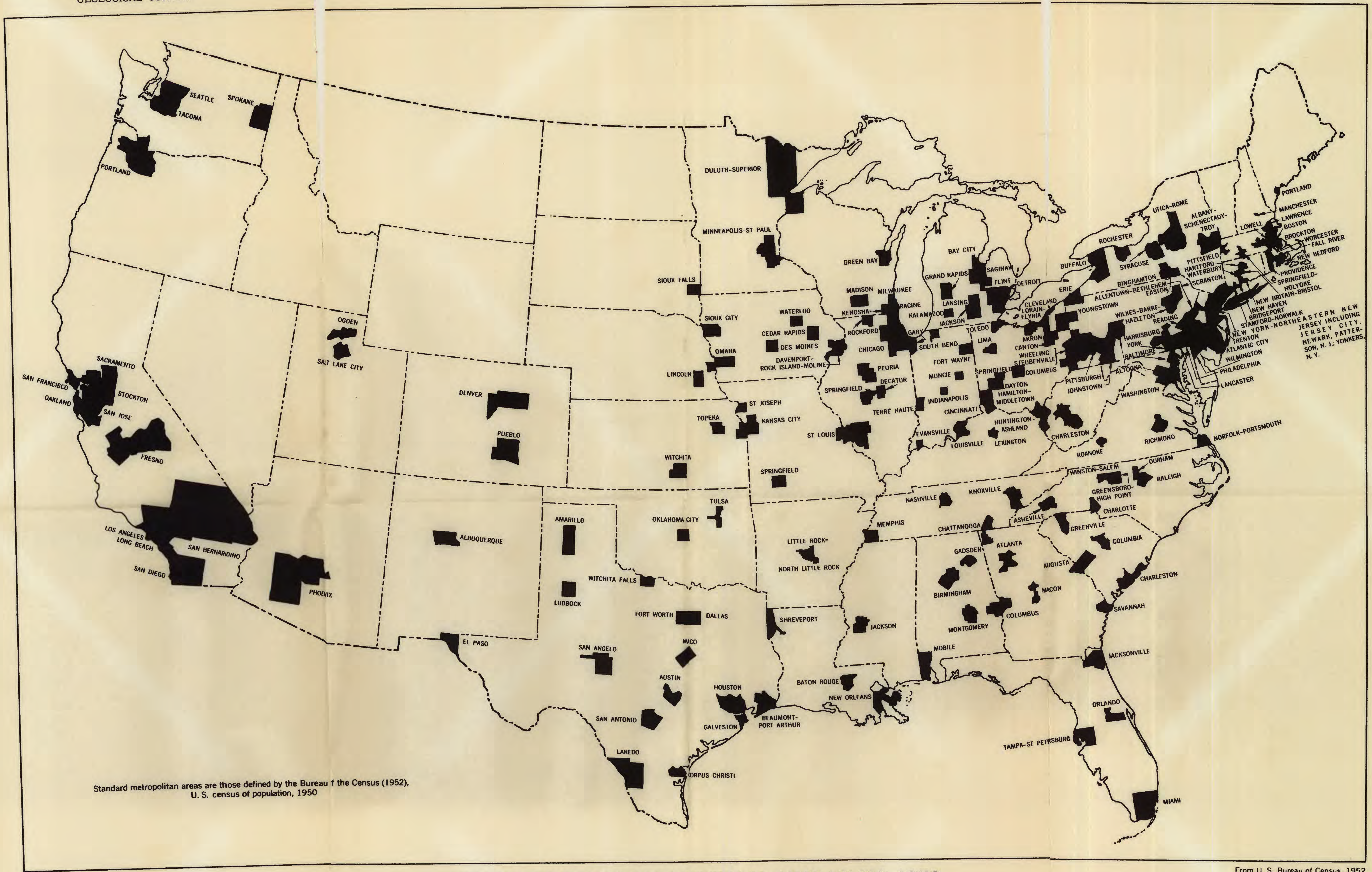
* U.S. GOVERNMENT PRINTING OFFICE : 1962 O—658643



Standard metropolitan areas are those defined by the Bureau f the Census (1952), U. S. census of population, 1950

From U. S. Bureau of Census, 1952

STANDARD METROPOLITAN AREAS IN 1950