

The Metabolism of Cities

In the U.S. today attention is focused on shortages of water and the pollution of water and air. There is plenty of water, but supplying it requires foresight. Pollution calls for public economic decisions

by Abel Wolman

The metabolic requirements of a city can be defined as all the materials and commodities needed to sustain the city's inhabitants at work and at play. Over a period of time these requirements include the construction materials needed to build and rebuild the city itself. The metabolic cycle is not completed until the wastes and residues of daily life have been removed and disposed of to a minimum of nuisance and hazard. Man has come to appreciate that the city is a closed ecological system, and methods that once appeared satisfactory for the disposal of wastes no longer seem acceptable. He has the evidence of his eyes and nose to show that his planet cannot assimilate without limit the untreated wastes of civilization.

One article could describe the complete metabolism of the modern city. Moreover, many of the metabolic processes—such as food, fuel, clothing, durables, construction materials and energy present no special problem. Their supply is handled routinely, either through local initiative and industry or through large organizations (public or private) that operate about as efficiently in one city as another. I

SHROUDED about 100 days a year, Los Angeles (opposite page) has made a resolute effort to reduce the volume of air-pollution emissions. California will require exhaust control systems on all new cars and trucks sold in the state, beginning with 1966 models. These systems should do much to remove the unburned hydrocarbons and carbon monoxide now released from automobile exhausts (see illustration on page 186). The topographic and meteorological factors that underlie smog development in Los Angeles are unique in the U.S.

shall be concerned therefore with three metabolic problems that have become more acute as cities have grown larger and whose solution rests almost entirely in the hands of the local administrator. Although he can call on many outside sources for advice, he must ultimately provide solutions fashioned to the unique needs of his own community. These three problems are the provision of an adequate water supply, the effective disposal of sewage and the control of air pollution.

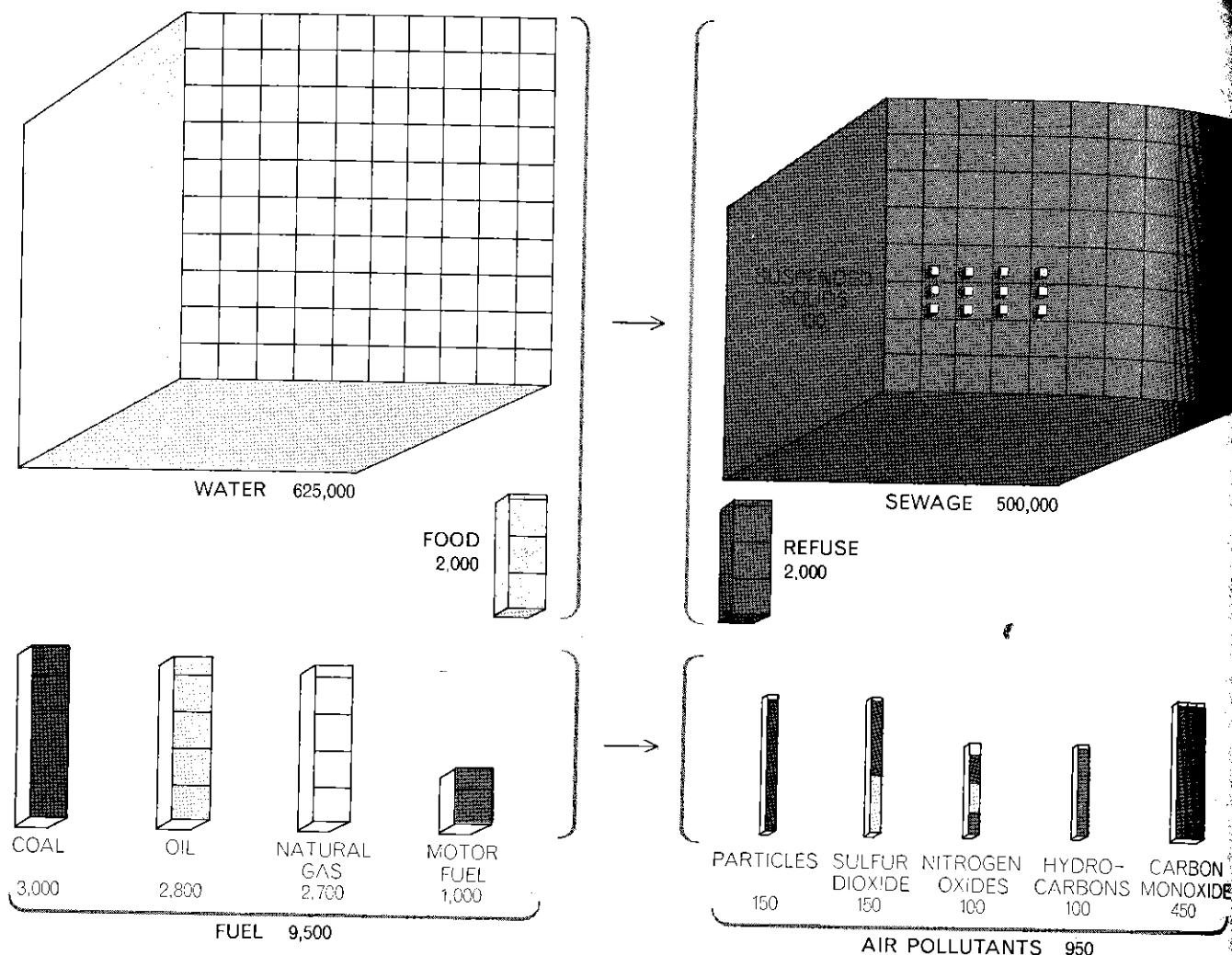
That these three problems vary widely from city to city and that they are being managed with widely varying degrees of success is obvious to anyone who reads a daily newspaper. It is ironic, for example, that New York City, which houses the nation's (if not the world's) greatest concentration of managerial talent, should be running short of water while billions of gallons of fresh water flow past it to the sea. It is not easy for people living in arid countries, or even for those living in the southwestern part of the U.S., to have much sympathy with New York's plight.

This summer, while New Yorkers were watching their emptying reservoirs and hoping for rain, Californians were busy building an aqueduct that would carry water some 440 miles from the Sacramento River, near Sacramento, to Los Angeles and other cities in the southern part of the state. And thanks to earlier examples of foresight, people in southern California were watering their lawns and filling their swimming pools without restriction, while in New York and New Jersey lawns were dying and pools stood empty. In the water-rich Middle Atlantic states water shortages are largely the result of delayed action and fail-

ures of management—sometimes exacerbated by political jockeying.

If American cities have had such unequal success in supplying their citizens with water, it is hardly surprising that some should have an even less satisfactory record in controlling water and air pollution, areas in which the incentives for providing remedies are much weaker than those that motivate the supplying of water. To make matters worse, pollutants of water and air often do not respect state boundaries. For example, the wastes of five states—Michigan, Indiana, Ohio, Pennsylvania and New York—have contributed to the accelerated pollution of Lake Erie. "The lake," according to the U.S. Public Health Service, "has deteriorated in quality at a rate many times greater than its normal aging process." The fourth-largest and shallowest of the five Great Lakes, Lake Erie is the main water supply for 10 million U.S. citizens as well as for the huge industrial complex that extends for 300 miles along the lake's southern shore from Detroit to Buffalo. The combination of treated and partially treated municipal sewage and industrial wastes that enters Lake Erie directly, and also reaches it indirectly through a network of rivers, has disrupted the normal cycle of aquatic life, has led to the closing of a number of beaches and has materially changed the commercial fishing industry. Last month the five states, in consultation with the Public Health Service, reached agreement on a major program of pollution abatement.

Although engineers concerned with water supply, sewage disposal and air pollution are accustomed to thinking in terms of large volumes, few laymen quite appreciate the quantities of water, sewage and air pollutants involved in



METABOLISM OF A CITY involves countless input-output transactions. This chart concentrates on three inputs common to all cities, namely water, food and fuel, and three outputs, sewage, solid refuse and air pollutants. Each item is shown in tons per day for a hypothetical U.S. city with a population of one million. Water, which enters the city silently and unseen, overshadows all other inputs in volume. More than .6 ton (150 gallons) must be supplied to each inhabitant every day. After about 20 percent of the water has been diverted to lawns and other unrecoverable uses, it returns, contaminated, to the city's sewers. The city's most pervasive nuisance, air pollution, is accounted for chiefly by the combustion of

fuels. (If refuse is burned in incinerators, it can also contribute heavily, but that contribution is not included here.) The various air pollutants are keyed by shading and color to the fuel responsible. Most of the particle emission (soot and fly ash) is produced by coal burned in electric power plants, and in well-designed plants more than 90 percent of the particles can be removed from the stack gases. For this hypothetical city one may assume that 135 of the 150 tons of particles produced by all fuel consumers are removed before they reach the atmosphere. All other emissions, however, pollute the atmosphere in the volumes shown. Sulfur dioxide is based on use of domestic fuels of average sulfur content.

the metabolism of a modern city. The illustration above expresses these quantities in the form of an input-output chart for a hypothetical American city of one million population. The input side of the chart shows the requirements in tons per day of water, food and fuels of various kinds. The output side shows the metabolic products of that input in terms of sewage, solid refuse and air pollutants. The quantities shown are a millionfold multiplication of the daily requirements of the average city dweller. Directly or indirectly he uses about 150 gallons (1,250 pounds) of water, four pounds of food and 19 pounds of fossil fuels. This is converted into roughly 120 gallons of sewage (which assumes 80 percent recovery of the

water input), four pounds of refuse (which includes food containers and miscellaneous rubbish) and 1.9 pounds of air pollutants, of which automobiles, buses and trucks account for more than half.

As of 1963 about 150 million out of 189 million Americans, or 80 percent, lived in some 22,000 communities served by 19,200 waterworks. These 150 million people used about 23 billion gallons per day (b.g.d.), a volume that can be placed in perspective in several ways. In 1960 the amount of water required for all purposes in the U.S. was about 320 b.g.d., or roughly 15 times the municipal demand. The biggest user of water is irrigation, which in 1960

took about 140 b.g.d. Steam electric utilities used about 98 b.g.d. and industry about 60 b.g.d. Since 1960 the total U.S. water demand has risen from about 320 b.g.d. to an estimated 370 b.g.d., of which municipalities take about 25 b.g.d. [see illustration on opposite page].

Thus municipalities rank as the smallest of the four principal users of water. Although it is true that water provided for human consumption must sometimes meet standards of quality that need not be met by water used in agriculture or industry, nevertheless throughout most of the U.S. farms, factories and cities frequently draw water from a common supply.

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able water is enormous: about 1,200 b.g.d. This is the surface runoff that remains from an average daily precipitation of some 4,200 b.g.d. About 40 percent of the total precipitation is utilized where it falls, providing water to the vegetation of economic value: farm crops and pasturelands. About 30 percent evaporates directly from the soil or returns to the atmosphere after passing through vegetation that has no particular economic value except insofar as it may prevent erosion of the land.

It is obvious that one cannot expect to capture and put to use every drop of the 1,200 b.g.d. flowing to the sea. The amount that can be captured depends on what people are willing to pay for water. One recent estimate places the economically available supply at about half the total, or 600 b.g.d. In my opinion this estimate is conservative; I would suggest a supply of at least 700 b.g.d.

In this volume would be inadequate by the year 2000—if all the water drawn for use were actually consumed. This, however, is not the case and will not be then; only a small fraction of the water withdrawn is consumed. In 1960 "consumptive use," as defined, amounted to about 90 b.g.d. of the 320 b.g.d. withdrawn. Most of the remaining 230 b.g.d. was returned to the source from which it was taken, or to some other body of water (in some instances the ocean). A small fraction of the used water was infiltrated into the ground to help maintain water tables.

Estimates by a Senate Select Committee a few years ago projected a consumptive use of about 120 b.g.d. in 1960 and of nearly 160 b.g.d. in the year 2000, when total demand may reach 900 b.g.d. It will be apparent in the illustration on the next page, where the projections are plotted, that agriculture accounts for the biggest consumptive use of water. It is conservatively estimated that 60 percent of the water employed for irrigation is lost to the atmosphere as the result of evaporation directly from the soil or indirectly through plants. (The amount of water incorporated into plant tissue is insignificant; roughly 1,000 gallons of water are needed to produce about 10 cents' worth of crop.) In contrast, from 80 to 90 percent of the water withdrawn by municipalities, industry and electric utilities is available for reuse. It is for this reason that the projected withdrawal

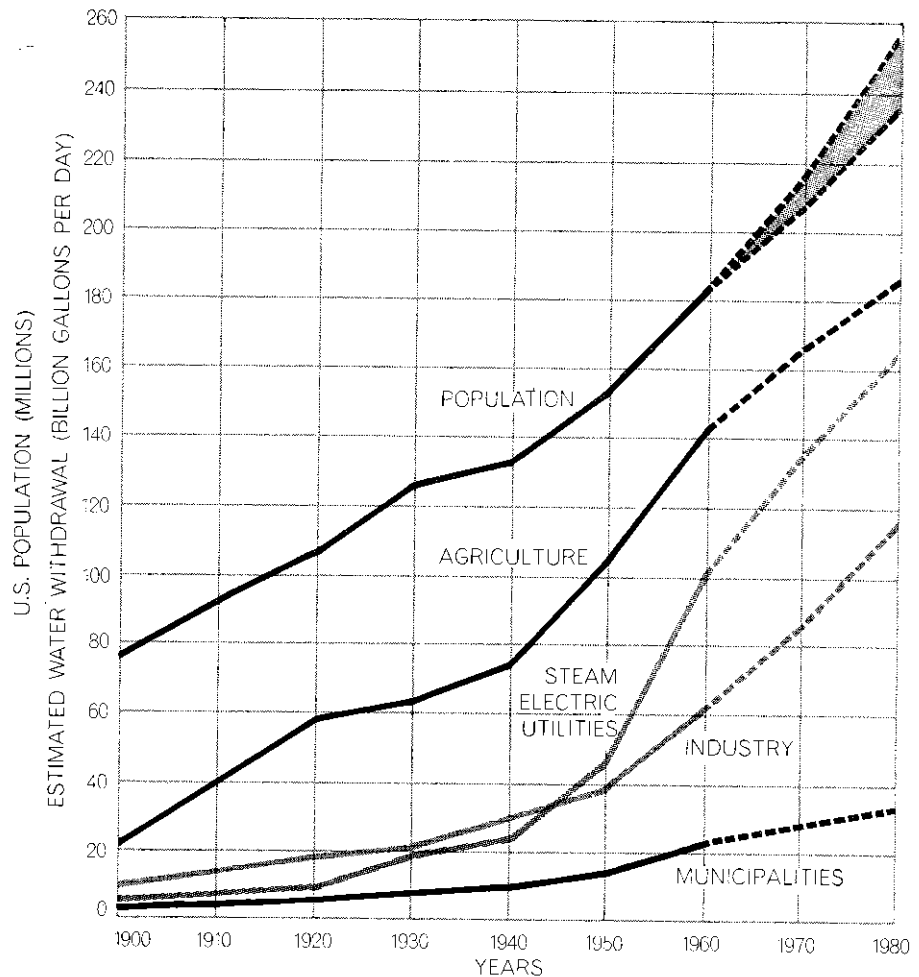
rate of 900 b.g.d. in the year 2000 should not prove difficult to meet, whether the economically available supply is 560 b.g.d. or 700 b.g.d. Of the 900 b.g.d. that may be required in A.D. 2000 to meet human, industrial and agricultural needs, approximately 740 b.g.d. should be available for reuse.

These estimates, moreover, are pessimistic in that they make only minor allowances for reductions in industrial or agricultural demands as a result of technological changes and in that they provide for no significant increase in the cost of water to hasten such changes. Thus we must reasonably conclude that for many years beyond A.D. 2000 total water shortages for the U.S. as a whole are highly improbable.

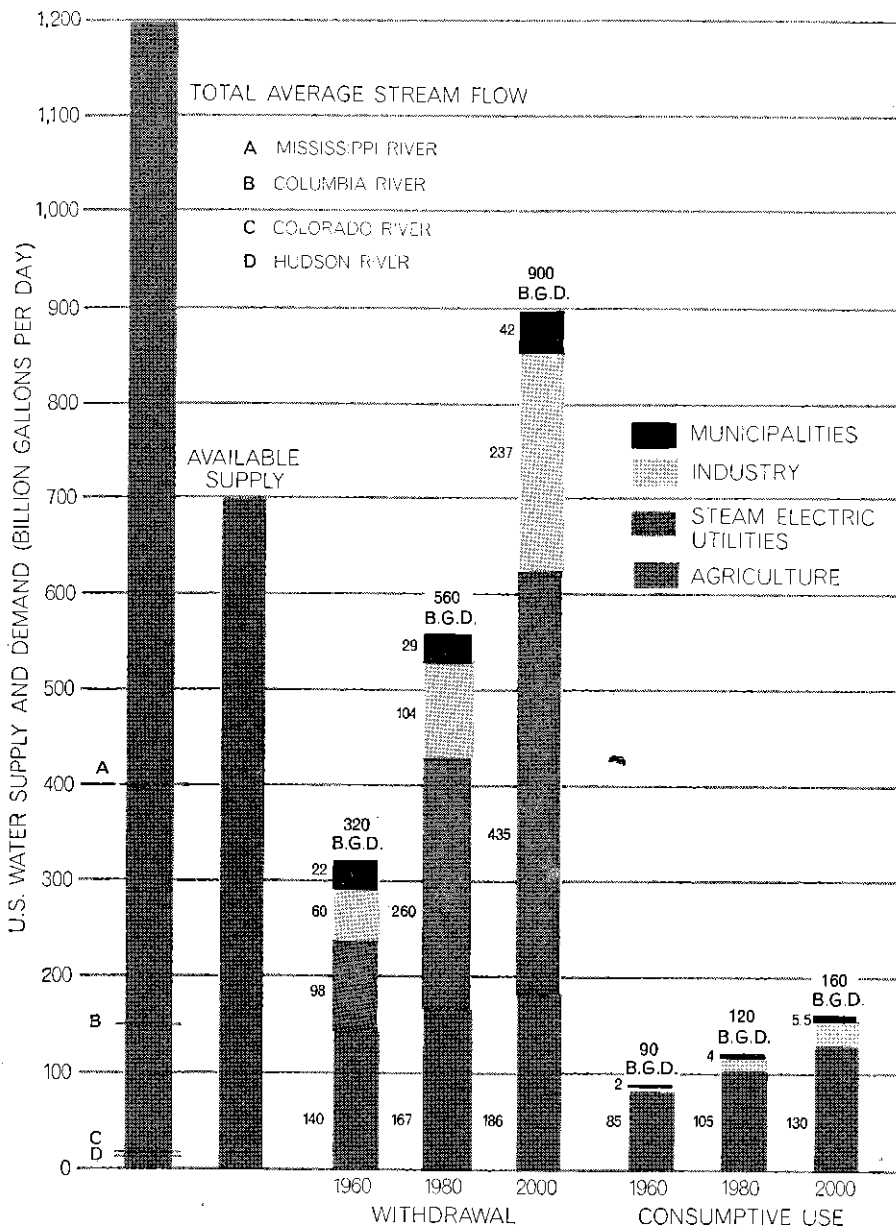
If water is going to remain so plentiful into the 21st century, why should New York and other cities find them-

selves running short in 1965? The immediate answer, of course, is that there has been a five-year drought in the northeastern U.S. With the completion in 1955 of two new reservoirs in the upper reaches of the Delaware River, and with the extension of the Delaware aqueduct to a total distance of more than 120 miles, New York City believed it could satisfy its water needs until the year 2000. This confident forecast reckoned without the unprecedented drought.

There is no point in criticizing New York's decision to depend so heavily on the Delaware watershed for its future needs. The question is what New York should do now. As long ago as 1950, in an earlier water shortage, New York was advised to build a pumping station on the Hudson River 65 miles north of the city to provide an emergency supply of 100 million gallons per day, or more



U.S. WATER REQUIREMENTS will be 53 percent greater in 1980 than in 1960, according to the most recent estimates of the Department of Commerce. Virtually all water used by agriculture is for irrigation; nearly 60 percent of all irrigated land in the U.S. is in five Western states (California, Texas, Colorado, Idaho and Arizona) where water tends to be scarcest. Steam power plants need water in huge amounts simply to condense steam. In 1960 municipalities used about 22 billion gallons per day (b.g.d.), which represented only about 7 percent of the total water withdrawal of about 320 b.g.d. The important distinction between water "withdrawal" and "consumptive use" is shown in the illustration on next page.



U.S. WATER SUPPLY consists of the approximately 1,200 b.g.d. that flows to the sea through the nation's waterways. This is the streamflow that results from an average precipitation volume of some 4,200 b.g.d. About 70 percent of all precipitation returns to the atmosphere without ever reaching the sea. The average flow of four important rivers is marked on the streamflow column. The author estimates that about 700 b.g.d. of the total streamflow can be made available for use at a cost acceptable to consumers. The estimates of water withdrawal and consumptive use for 1980 and 2000 are (with slight rounding) those published a few years ago by a Senate Select Committee. The 1980 estimate is 13 percent higher than that of the Department of Commerce shown in the illustration on the preceding page. "Consumptive use" represents the amount of water withdrawn that subsequently becomes unavailable for reuse. Except for irrigation, consumptive use of water is and will remain negligible. Thus a 700-b.g.d. supply should easily meet a 900-b.g.d. demand.

as needed. (New York City's normal water demand is about 1.2 b.g.d. The average flow of the Hudson is around 11 b.g.d.) The State of New York gave the city permission to build the pumping station but stipulated that the station be dismantled when the emergency was over. By the time the station was built (at a point somewhat farther south than the one recommended) the

drought had ended; the station was torn down without ever having been used. This July the city asked the state for permission to rebuild the station, a job that will take several months, but as of mid-August permission had not been granted.

Meanwhile there has been much talk of building atomic-energy desalination plants as the long-term solution to New

York's water needs. The economic justification for such proposals has never been explained. New York now obtains its water, delivered by gravity flow to the city, for only about 15 cents per 1,000 gallons (and many consumers are charged only 12 cents). The lowest predicted cost for desalination, assuming a plant with a capacity of 250 million or more gallons per day, is a highly optimistic 30 to 50 cents per 1,000 gallons. Since a desalination plant would be at sea level, its entire output would have to be pumped; storage and conveyance together would add about 20 cents per 1,000 gallons to the basic production cost. Recent studies in our department at Johns Hopkins University have shown that if desalinated water could be produced and delivered for as little as 50 cents per 1,000 gallons, it would still be cheaper to obtain fresh water from a supply 600 miles away. (The calculations assume a water demand of 100 million gallons per day.) In other words, it would be much cheaper for New York City to pipe water 270 miles from the St. Lawrence River, assuming that Canada gave its consent, than to build a desalination plant at the edge of town. New York City does not have to go even as far as the St. Lawrence. It has large untapped reserves in the Hudson River and in the upper watershed of the Susquehanna, no more than 150 miles away, that could meet the city's needs well beyond the year 2000.

Few cities in the U.S. have the range of alternatives open to New York. The great majority of inland cities draw their water supplies from the nearest lake or river. Of the more than 150 million Americans now served by public water supplies, nearly 100 million, or 60 percent, are reusing water from sources that have already been used at least once for domestic sewage and industrial waste disposal. This "used" water has of course been purified, either naturally or artificially, before it reaches the consumer. Only about 25 percent of the 25 b.g.d. now used by municipalities is obtained from aquifers, or underground sources. Such aquifers supply about 65 b.g.d. of the nation's estimated 1965 requirement of 370 b.g.d. Most of the 65 b.g.d. is merely a subterranean portion of the 1,200 b.g.d. of the precipitation flowing steadily to the sea. It is estimated, however, that from five to 10 b.g.d. is water "mined" from aquifers that have been filled over the centuries. Most of this mining is

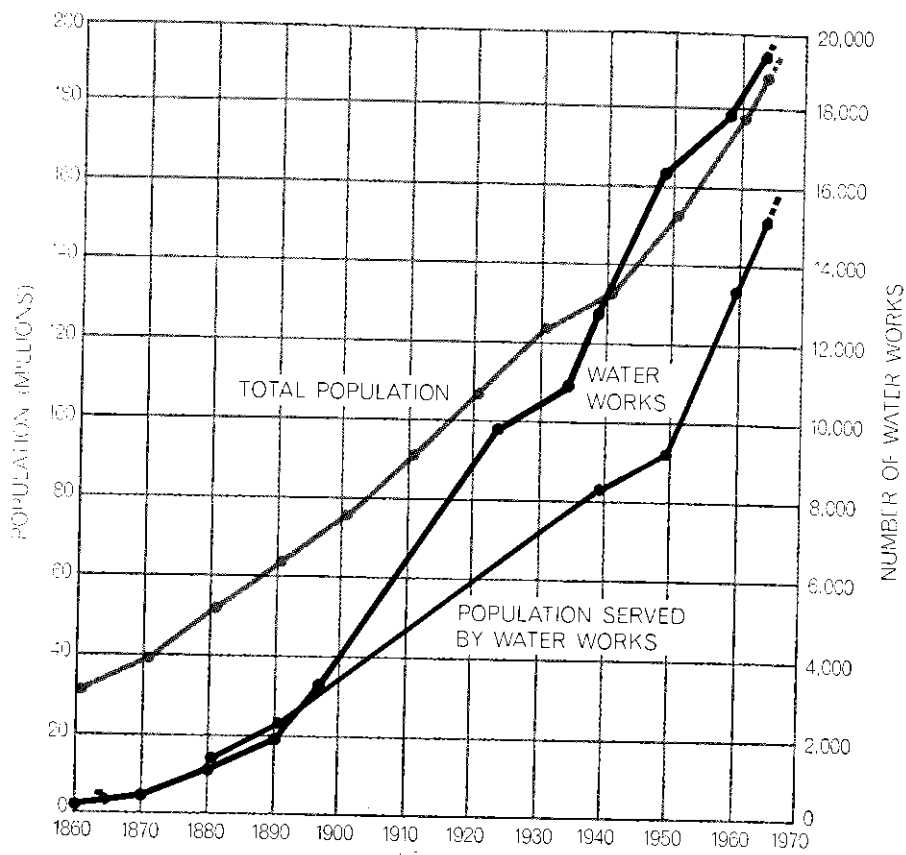
s. The economic proposals have been made in New York now and by gravity about 15 cents per many consumers (cents). The desalination, capacity of 2 per day, is a 50 cents per lineation plant entire output; storage and could add billions to the cent studies Hopkins University desalinated and delivered cheaper to supply 600 million gallons it would be City to pipe the St. Lawrence Canada gave a desalination town. New go even as a large untapped River and the Susquehanna miles away, eds well be have the n to New Y land cities d om the nea more than served by p ly 100 mill y water fr v been used ewage and This "use purified, eit fore it reach it 25 perc ed by mun aquifers, uch aquife f the nation ent of 3% l. is merely : 1,200 b.g. g steadily ower, the ater "mined n filled ov 's mining

West Texas, New Mexico, Arizona and California.

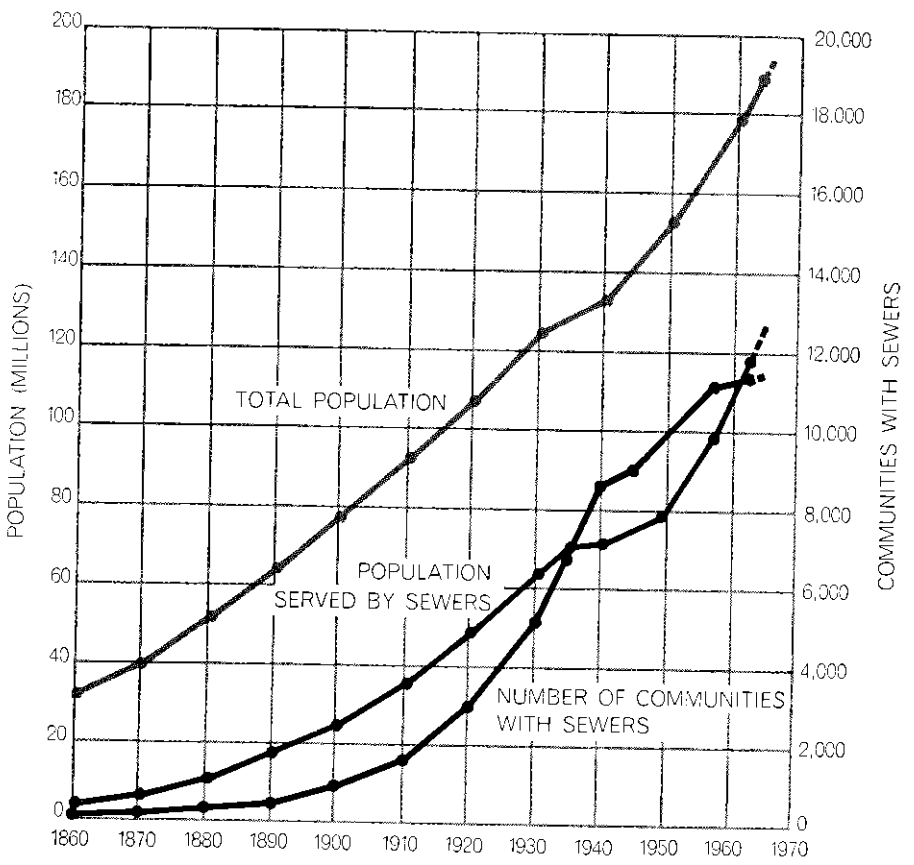
fact that more than 150 million Americans can be provided with safe drinking water by municipal waterworks regardless of their source of supply tests the effectiveness of modern treatment methods. Basically the treatment consists of filtration and chlorination. The use of chlorine to kill bacteria in municipal water supplies was introduced in 1908. It is fortunate that such a cheap and readily available substance is so effective. A typical reagent is about one part of chlorine to a million parts of water (one p.p.m.). The amount of chlorine needed to kill bacteria and also to "kill" the taste of decayed organic substances—many of which come in contact with decayed vegetation—is adjusted by monitoring the amount of free chlorine present in the water five to 10 minutes after treatment. This residual chlorine is usually held to about .2 p.p.m. In cases where unusually large amounts of organic compounds are present in the water causing the public to complain of a bad taste, experience has shown that the palatability of the water can be improved simply by adding more chlorine. Contrary to a widely held impression, free chlorine itself has no taste; the "bad" taste usually attributed to chlorine is due chiefly to organic compounds that have been too heavily chlorinated. When they are more heavily chlorinated, the bad taste usually appears.

Throughout history impure water has been a leading cause of fatal disease in such waterborne diseases as typhoid fever and dysentery were still common in the U.S. less than a century ago. In 1900 the U.S. death rate from typhoid fever was 35.8 per 100,000 population. If such a rate persisted today, deaths from typhoid would far exceed those from automobile accidents. In 1936 the rate had been reduced to 1.25 per 100,000, and today the disease is almost unknown in the U.S.

In underdeveloped nations, where many cities are still without adequate water supplies, waterborne diseases are among the leading causes of death and disability. In Central and South America more than a third of 75 million people living in towns or cities with a population of more than 2,000 are without adequate water service. Similarly, in India about a third of the urban population of 80 million are without an adequate water



GROWTH OF MUNICIPAL WATER SUPPLIES accelerated after 1880, when less than a fourth of the U.S. population was served by waterworks. By 1939 the number served by waterworks exceeded 60 percent and by 1963 the figure had reached nearly 80 percent.



GROWTH OF SEWERAGE FACILITIES has lagged behind the growth of community water supplies, chiefly because people are reluctant to pay taxes for what long seemed a nonessential service. Nevertheless, 63 percent of the population was served by sewers in 1962.

