IMPACTS OF URBAN-MODIFIED PRECIPITATION ON MAN'S ACTIVITIES[1]

Stanley A. Changnon, Jr.
Illinois State Water Survey

URBAN AREAS AFFECT THE WEATHER: AN INTRODUCTION

For at least 700 years persons who have dwelt in large cities have been at least vaguely aware that their climate was different from that their rural cousins experienced. Awareness of the higher intercity temperatures, lower winds, and smokier conditions occurred because of great differences. These weather differences began to be quantified at several European cities at least 100 years ago such that the "urban heat island" has been widely known for many years.

The wide adoption and use of the better atmospheric measurement devices beginning late in the 19th Century in the United States resulted in the initiation of records that by the 1950's had sufficient lengths so that a few interested climatologists were able to quantify urban-rural climactic differences with certainty. These pioneer researchers found all features of the climate including the humidity, radiation, clouds, rainfall and storms apparently were different inside large cities. Differences found in many cities have been averaged to provide the urban-rural differences shown in Table 1.

An interesting feature of the relatively few urban climatic studies done in the 1950's and 1960's was the suggestion that the urban effect on climate was extending well beyond the city in conditions aloft-clouds and rainfall. All other urban effects on climatic conditions were contained within the city were the "forcing functions" (heating, buildings, and pollutant sources) were located.

This possible areal extension of an urban effect on weather well beyond the city raised the sprectre of 1) a group accidentally doing something potentially harmful to someone else, and 2) man beginning to demonstrate that his land use changes had the capability to modify his climate over large areas. This was conceived as a particularly threatening situation where cities are sufficiently close to form a megalopolis.

These and a host of other intriguing scientific and environmental questions posed by these suggested urban-produced cloud and rain anomalies led to climatic studies of 9 cities. Warm season increases in rain,

[1] For presentation at the AAAS Meeting in Denver, February 1977.

Table 1. Weather Changes Resulting from Urbanization

Weather conditions	Average Changes, as a Percentage of Rural Conditions		
	Annual	Cold season	Warm season
Solar radiation (langleys)	-22	-34	-20
Temperature (^{o}F)	+2	+4	+1
Humidity (relative)	-6	-2	-8
Visibility (frequency)	-26	-34	-17
Fog (frequency)	+60	+100	+30
Wind speed (mph)	-25	-20	-30
Cloudiness (frequency)	+8	+5	+10
Rainfall (amount)	+14	+13	+15
Snowfall (amount)	±10	±10	--
Thunderstorms (frequency)	+16	5	+29

thunder and hail were suggested at the 7 largest cities including Houston, New Orleans, Washington, Detroit, St. Louis, Chicago and Cleveland. All the cities with populations over 1 million. The two smaller cities studied, Tulsa and Indianapolis, did not have apparent urban rain anomalies in or beyond them, and they were under 1 million population.

The growing concerns and interests in this subject area also caused a group of atmospheric scientists in 1970 to plan a major meteorological research program called METROMEX (Metropolitian Meteorological Experiment) which was to focus its attention on the St. Louis urban area. This program was designed to have major field and analytical efforts so as to define the reality of the rain anomalies and to unravel the mysteries of how any anomalies were being produced. Due to the complexity of the surface-to-air-to-cloud-to-rain linkage, there remained scientific uncertainty over the reality and causes of the apparent anomalies identified from the climatic studies. Its worthy of note that historical records for the St. Louis area, although insufficient in areal detail, suggested a shift in rainfall and related stormy conditions in the early 1950's.

The four objectives of METROMEX were 1) to define and describe the anomalies in precipitation and related phenomena, 2) to attempt to explain the causes of any of the precipitation aberrations found, 3) to develop means for translation of the atmospheric findings to other areas, and 4) to identify the impacts of the urban-altered precipitation on man's activities.

This paper deals with the fourth objective, selected atmospheric and environmental impacts identified as relating to the St. Louis altered precipitation. The impact research is not complete and is far from being as extensive as might be desired. Amazingly little has been done to measure the effect of other urban weather changes on man and his activity. Indeed all too little research has been done on the entire subject of weather effects on man and his environment. Primary topics of impact research to date in METROMEX have concerned the potential effects of the urban-altered precipitation anomalies on agricultural and water resources. Much research still remains, particularly that dealing with societal and legal implications of accidentally altered weather and climate.

The effects or impacts of the St. Louis urban industrial complex of the atmosphere are those impacts most clearly defined. These alterations in both the frequencies and magnitude of various weather conditions produce a locally different climate that exists in and directly above the city and also extends in a plume like fashion beyond the city. Urban effects on clouds have been noted out to 100 kilometers and effects on air quality well beyond 200 kilometers.

It is well to realize that the urban-rural difference in climate varies constantly, fluctuating with time and space such that the downtown St. Louis temperature may be 10°C warmer than the rural area at night and only 1°C different at noon. Or on a given day it may be 5°C different in the midday. The urban-related rain increased found from 1 to 40 kilometers east of St. Louis will occur in the rainfall pattern on some days but will not exist in the rains on other days. Thus, the urban climate varies considerable with the actual weather conditions. In a discussion of impacts of inadvertent weather modification it is appropriate to first discuss those direct effects noted in atmospheric phenomenon.

IMPACTS ON ATMOSPHERIC PROCESSES, WEATHER AND CLIMATE

The temperature, moisture, winds, and visibility (due to aerosols) are all altered by 5 to 15% at the surface in and adjacent to the St. Louis urban area. These perturbations are often found to extend vertically from 500 to 2,000 meters on summer afternoons.

The city, in general, through alterations of the local temperature, moisture, and wind fields plus the additional nuclei from aerosols, acts as a trigger of cloud and rain activity. This often occurs in urban-produced convergence zones (developed in the low-level wind flow), and the place of cloud activity and ensuing rainfall depend on the surface conditions, direction of the flow on any given day, and the degree of atmospheric instability.

Convective clouds are found to be increased by 5 to 10% in and around St. Louis and over an oil refinery complex, and the incoming solar radiation is reduced by a similar amount. Precipitation forming inside the urban clouds typically starts at lower levels than in rural clouds, indicating large urban-generated aerosols may assist in the coalescence process. However, clouds over the city have their bases generally 300 to 600 meters higher than rural clouds, reflecting the thermodynamic influence of the city, lifting the condensation level.

Major convective storm clouds have been found to merge more often just east of St. Louis than anywhere else in the St. Louis region, and this is a result of the more frequent urban-generated clouds and storm cells. The morphology of the urban-induced rainfall then typically involves urban initiation (due to thermodynamic effects coupled with microphysical effects) of clouds and precipitation during and often before other storms develop naturally. These locally triggered storms then occasionally initiate other local storms, and these more frequent storms within the urban area in turn merge to produce heavier rain, stronger winds and hail as they move to the east of the city. Internal characteristics of convective clouds, both those over and downwind of St. Louis, differ from those elsewhere. The rainfall is also urban enhanced in existing precipitation systems moving thru the area.

As a result of these conditions, summer rainfall is found to be 5 to 30% greater east of St. Louis in a fan-shaped area extending out 40 kilometers than elsewhere in the area. The placement and magnitude of this increased rainfall on any given day or on any given summer varies according to the weather conditions and their frequencies. There is no appreciable decrease in rainfall beyond this area of increase. Local rain increases occur in all types of summer seasons including wet, dry, and normal conditions.

The effects of the city on convective clouds and precipitation are also realized in severe local weather. The frequency of short-duration heavy rainfall rates 50 to 100% higher in the fan-shaped (4000 square kilometer) area east of St. Louis. The frequencies of thunderstorms in this area is also increased, being 25% greater with the duration and intensity of lightning being 30% more than that elsewhere. Surface wind gusts in the downwind area are also found to be 50 to 100% greater. Hail is dramatically altered east of St. Louis with 80% more hail days, 200% more hailstorms, and 300% greater hail intensity (number and sizes of hailstones). However, there is no evidence collected in METROMEX that the urban effects affect tornado activity.

As shown in Figure 1, the urban effects on weather are classed as "direct impacts". This includes the effects on the atmosphere and the ensuing changes in rain, hail and other conditions at the surface.

IMPACTS ON THOSE USING WEATHER INFORMATION

The aforementioned direct effects of an urban-industrial area on the atmospheric processes and surface weather conditions has a clear and obvious value in furthering a better understanding of how man can produce a signal in climate. This has relevance for growing concerns and speculation about man-made climatic changes on a regional, hemispheric or global scale. The St. Louis results furnish clear evidence

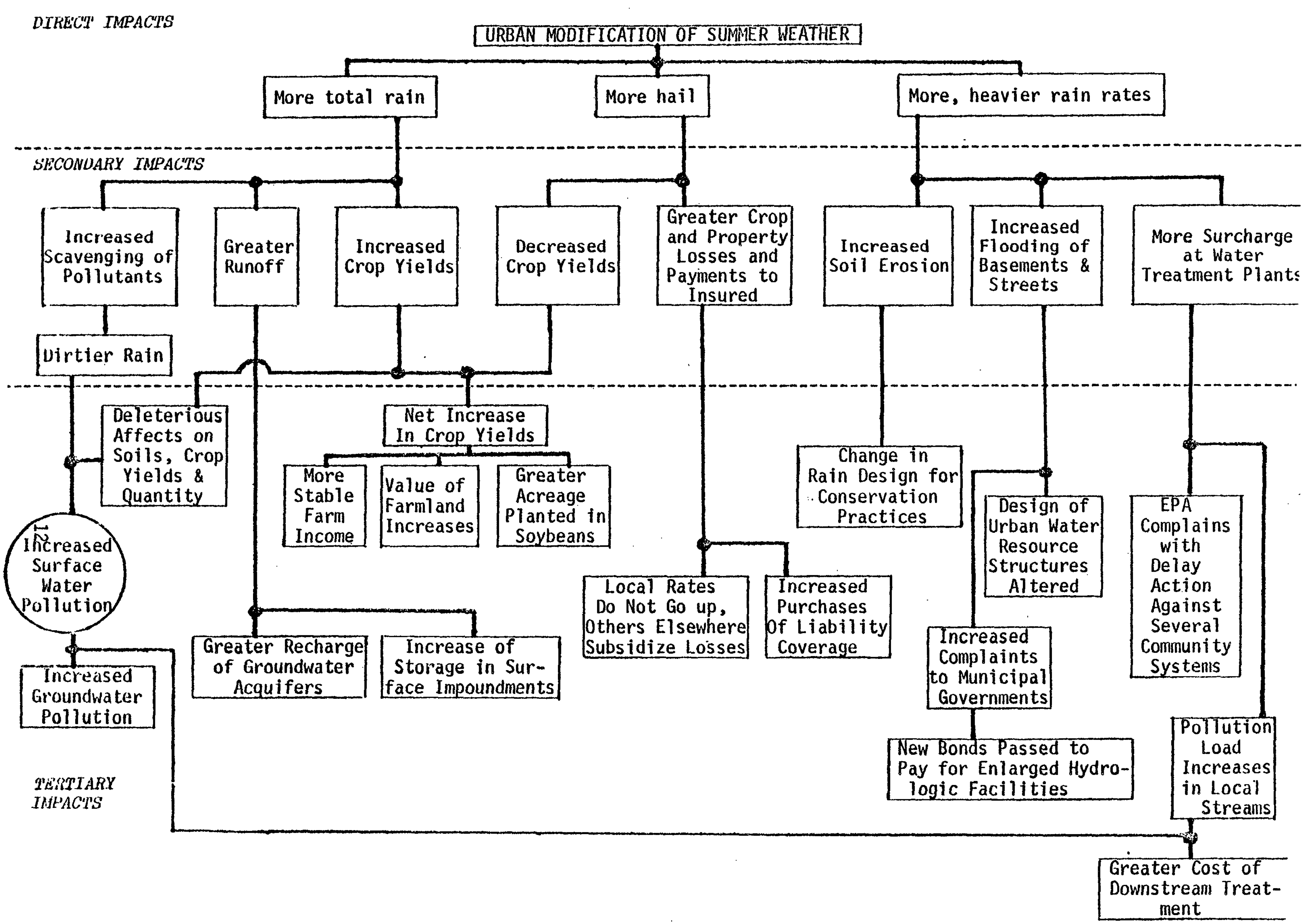

Figure 1. Impacts from urban modified precipitation at St. Louis

that man can produce a significant climatic change, identifying when and where it occurs.

Of a more direct and applied nature to the weather practitioner are the improvements in urban-area weather forecasts. An improvement in rainfall forecasting in areas where 70% of the nation's population lives has material advantages in the human and industrial activities of that area. Expected impacts of the METROMEX results include development of better predictions of precipitation through knowledge of the weather conditions when the city will initiate rainfall. Furthermore, a capability to recognize and forecast those conditions when urban effects will induce relatively heavy ($\leq$3 cm) rainfalls in and east of the city will be of benefit particularly to transportation and hydrologic system operations.

Another series of impacts generated by the operational aspects involving radars and aircraft of METROMEX have helped show the dimensions of the operational effort will be needed to conduct midwestern weather modification efforts including the fact that such operations will be needed on a full-time basis. The METROMEX results also suggest that large rban-generated condensation nuclei help initiate coalescence process and thus make more clouds produce rain. This suggests a modification process that should be considered for the Midwest. Urban effects also led to local showers and convective storms during regional dry periods. These kept the immediate urban and rural area from being as droughty as other areas. This suggests there is some hope to partially alleviate some drought conditions and it illustrates those weather conditions when rain presumably could be purposely induced during dry summer periods. Results showing rain increases coupled with hail and wind increases are disturbing, suggesting that they are sufficiently well-linked processes so that purposeful weather modification to make more summer rainfall could also lead to more hail and surface wind damage. However, an encouraging note, as shown in the next section, is that the effect on agricultural production from the added rain, hail, and winds east of St. Louis is a net increase in crop production.

AGRICULTURAL IMPACTS IN THE RAIN INCREASE AREA

The study of agricultural impacts has focused largely on possible shifts in the yields of the primary crops, corn and soybeans, in the effect area. Measures of the local alterations of crop yields was achieved using a "target-control" analysis wherein the yields in the target or effect counties were compared with those of surrounding counties in both the pre-effect period and post-effect period.

The urban-increase temperatures and cloudiness appear to have no notable effect on agricultural practices or local yields. The length of the growing season in the rural areas has not been altered, and the primary urban-produced weather change relating to agriculture is that to precipitation, both rain and hail. The chain of direct to secondary impacts is illustrated in Figure 1.

The increased hail frequency and intensity in the 4,000 km^2 area east of St. Louis result in greater crop losses with an area average annual loss due to hail of 0.6 bushel/acre to corn and 0.2 bushel/acre to soybeans more than in surrounding areas. This loss amounts to about 178,000 bushels of corn annually, or about one-half million dollars, and a loss of 48,000 bushels of soybeans or about $300,000. Thus, the annual total hail loss in the effect regions is $0.8 million.

Conversley, the summer rainfall increases have led to increases in the corn and soybean yields in the same area east of St.Louis. The net yield increases in the area, after discounting for the known losses due to hail and wind, and the unknown losses due to pollutants, are 1.2 bushels/acre to corn and 0.4 bushel/acre to soybeans, as annual averages. These increases amount to an additional 66 bushels of corn per farm on the average, representing about 400,000 bushels of corn for the effected area, for a value of $1.0 million. The added annual average yield of soybeans is 16 bushels per farm or a 100,000 for the area, representing $0.6 million income. The net agricultural benefit to the 4,000 km^2 area effected by the St. Louis altered precipitation (excluding any soil losses due to heavier rains) is a 2 to 5% increase in grain crop yields, amounting to an average annual gain of $1.6 million.

The increases in yields are most notable in summers with dry or near-normal rainfall with no increase evident in wetter summers. Hence, the urban-rain effect also has provided a more stable farm income, a tertiary impact (Figure 1). Values of agricultural lands in this area reflect this stability and added income, being 6% greater in the 1960's than predicted by values in surrounding areas. Furthermore, the amount of soybean acreage in the effected area has increased relatively more than that in the non-rain effect areas, now being 9% greater and another tertiary impact. This also reflects perceived financial gains by farmers in the effected area. However, corn acreage has not increased in a relative sense.

The Water Survey METROMEX program also included measurements of the rainfall chemistry, including the pH of the rainfall, in the agricultural area east of St. Louis. The average seasonal values varied considerably (4.0 to 6.5), some being quite acid, but the effect on yields has not yet been studied. There is some evidence in the crop yield analysis that suggests that the pollution effects exist. The actual crop yield increases noted above, after accounting for the effects of added rain and hail, were less by about 0.5 bushel/acre than other studies of crop-weather relations in Illinois would have predicted. This may be a reflection of pollutant damage to crop production.

The increased frequency of heavier rainfalls that clearly will cause more soil erosion will have an ultimate effect on agricultural production, although the amount of loss is unknown. However, knowledge of its potential effect has led the Soil Conservation Service to alter their design criteria for terracing and other soil conservation practices in the two effected couties.

ALTERATIONS IN INSURANCE-RELATED LOSSES

The urban-increased hail, heavy rains, winds, and thunderstorm activity have produced crop and property losses that have an impact on the regional economy and on the insurance industry. The greater crop losses due to hail are evident in the crop-hail insurance loss patterns east of St. Louis. Insurance rates, particularly for all-peril policies, for the area just east of St. Louis should be, but are not higher. This loss situation will eventually impact on the FCIC, private insurance firms, and the buyer of insurance. Essentially, the insurance buyers in other areas are subsidizing this greater loss at this time.

The amount of liability purchased in the area of altered weather is 12% more per unit area than in the surrounding areas (Figure 1). This indicates that some farmers have recognized this increased crop risk in the impacted effect area. Property damages such as flooded basements and lightning damages have not been investigated, but the 30 to 100% increases in these events suggest the existence of more property damage and inconveniences in the area. Information about the urban-related local high loss areas will ultimately cause insurance rate structures to be altered in the areas of storm activity beyond major cities.

WATER RESOURCE IMPACTS

In the impacted area east of St. Louis, the average streamflow is increased, and in small basins of 50 to 150 km^2 the warm season increase is 10 to 20%. The more frequent short-duration (5 to 180 minutes) heavy rainfall rates produced recommend a major alteration of the storm designs for values in the 2- to 10-year recurrence intervals. In general, these rainfall events have become twice as frequent. These alterations and the heavy rainfall rates impact directly in storm runoff conditions, producing a doubling of local suburban flooding occurrences, particularly in basements and streets, with the frequency of surcharges, or bypasses, of waste water treatment plants being doubled. This has resulted in increased streamwater pollution, and an inability of many communities to meet federal and state standards for stream pollution and management of water treatment plants.

The streamwater in basins east of St. Louis has been found to have 1 to 200% more pollutants, with great increases in zinc, nitrates and sulfates. These increases are partially due to the added rainfall which helps scavenge the St. Louis generated pollutants. Groundwater pollution has increased in a similar degree, and as a result new industrial wells have been drilled. The METROMEX rainfall and streamwater quality data also have been useful inputs in the testing and development of hydrologic models in water quality modeling. These are essential in meeting the federal EPA (under Section 208) requirements for the development of regional water quality plans. These are being developed in the St. Louis region under a 3.3 million dollar grant to local planning agencies.

IMPACTS ON URBAN AND REGIONAL PLANNING

A variety of the precipitation-related impacts identified during METROMEX have general planning-related applications for the city, the suburbs, and local industry. These are in addition to those relating to the agricultural and urban hydrologic systems that are already in practice (such as the SCS terracing redesign and the redesign of sewer systems).

At this time, results suggest that the urban rain alterations are due to an integration of the entire urban complex and are not due primarily to one isolatable and controllable factor such as a particular compound in the effluent from automobile exhaust or from a specific factory. Although the exact sources have yet to be identified, the local St. Louis sources of large condensation nuclei is of some importance. If the source can be found, a potential exists for partially altering the "urban effect" on summer rainfall. However, it will be difficult to present a specific set of do's and don'ts for altering the urban effects on precipitation processes, <u>should they be deemed harmful</u>. Our cloud and radar studies have shown that a large refinery complex produces demonstrable (100 to 200%) but very local increases in convective clouds and the initiation of rainfall. These effects could be potentially minimized in <u>future arrays</u> of large industrial complexes.

A major question that this impact analysis cannot answer is whether the urban-related cloud and rain alterations in and east of St. Louis are sufficiently beneficial or harmful to deserve consideration in urban planning efforts aimed at wise land use. Our qualitative assessment of the agricultural and water resource impacts suggest that the net effect is a disbenefit for the area east of St. Louis. Planners could minimize this urban rain effect east of the city by 1) altering possible forcing functions (sources of large nuclei in industrial water released to the atmosphere), or by 2) attempting to minimize human settlements within the area which will suffer most from wet (rain) and dry deposition of pollutants, from more frequent flooding, and increased water pollution. In the area of effect to the east of St. Louis or other cities existing knowledge would suggest the location of water supply sources (reservoirs) for the city and a grain-type agriculture. Both of these would achieve a net benefit from the added summer precipitation and would suffer least from the higher rainfall rates and more severe weather.

IMPACTS ON GOVERNMENT AGENCIES

One of the interesting by-products of the METROMEX results relates to the impacts of findings on activities admissions of various local, federal, and state agencies, seen as tertiary impacts (Figure 1). For example, several METROMEX results impact of agencies that must encourage energy development (ERDA) and set controls (EPA), based on knowledge of environmental impacts related to energy production and other human alterations of the land surface.

The St. Louis studies have shown that urban-produced alterations of clouds and rain are largely the result of the entire urban agglomeration, not just one easily controllable human or industrial activity.

METROMEX results have shown that the fossil-fuel power plants around St. Louis are among the major contributors to the local SO_2 concentrations in the air. Furthermore, METROMEX results have shown that the conversion of sulpher dioxide to sulphates is aided by the cloud processes; thus conversion to sulphate and the acid rain problem is partially produced by the increase in urban clouds. The additonal rainfall scavenges pollutants, helping to produce 20% more sulphate in the streamwater east of St. Louis than elsewhere in the region. Furthermore, the altered (often smaller) cloud droplet sizes often produced in clouds out 5 to 100 km downwind of St. Louis reveal that the pollution is altering clouds, potentially in an undesirable way by making them more stable and less able to make rain.

Although METROMEX has not been aimed at the control-optimization issue of air pollution, the project has and will define several pollution aspects that relate to fossil-fuel power plants. These include 1) how plants should be spatially distributed, and 2) how they should be allowed to release effluents so as to minimize effects on clouds and rainfall quality. More than half of the atmospheric pollutants deposited in and east of St. Louis are rainborne, resulting in a more polluted rainfall and streamwater and groundwater east of St. Louis and elsewhere in the region.

The increases in convective clouds and rain initiations related to a large refinery complex suggest that large industrial complexes and future power parks with concentrated sources of waste heat, moisture and aerosols released to the atmosphere will produce frequent convective clouds and increased rainfall. In general, the METROMEX information also relates to another basic thrust of certain governmental research control programs; that being the effect of altered land use on weather and climate.

SUMMARY

Many of the impacts so far identified from the urban modification of weather at St. Louis are presented in Figure 1. This diagram shows the causal breakdown deriving from the direct impacts (more total rainfall in summer, more hail, and more heavy rainfall rates), and how these direct impacts on climatic conditions lead to a series of secondary impacts, which in turn multiply into a series of teritary impacts. Obviously, many more impacts exist than are demonstrated in this figure.

The key climatic effects of the St. Louis studies are the increased cloudiness (up 10%), the increased summer rainfall (up 30%), and increased severe storm activity (up 10 to 100%). All are related to urban effects on the summer atmosphere. These increases occur over and just east of St. Louis in a 4,000 km^2 area.

The more intense and polluted urban rains affect water resources leading to more run-off (+15%), more local flooding (+50 to +100%), and more stream and groundwater pollution (+1 to +400%). The findings relating to altered weather conditions reveal how to better design and execute midwestern weather modification experiments; suggest use of seeding materials; the potential for useful rainfall increases in summer dry periods; and that man-induced summer rain increases may also result in more hail, stronger winds, and lightning.

Urban-altered precipitation results in a net, local area increase of 2 to 5% in grain crop yields. This increase is now reflected in the value of agricultural lands and in certain planting strategies used by local farmers. The urban-induced increases in severe storm activity lead to 100 to 400% increases in crop-hail losses, affecting farmers and the insurance industry. Delineation of those conditions when urban showers are triggered or when heavy rains result because of urban factors will lead to improvements in weather forecasting and water management for urban areas.

The city, as a whole, leads to the rain changes discerned, indicating there is no controllable way for urban planners to "design out" the problem. However, the wisest use of land from this viewpoint calls for agricultural land use, as opposed to suburban development, east of the city. The results on cloud and rainfall processing and subsequent deposition of urban-generated pollutants also relate to the missions of government agencies concerned with the environment and land use management. Certain findings focus on proper siting and controls of fossil-fuel power plants in industrial complexes so that large releases of heat and moisture are not concentrated in a small area.

The key question, as yet unanswerable with available impacts, is whether the various weather and precipitation-related changes produced by a major city represent a net benefit or loss when all factors are considered. As shown in Figure 1, derivation of true human and economic values will be very complex. Clearly, further research into the environmental impacts, social aspects including public attitudes, and the legal issues of inadvertent (urban) weather modification needs to be pursued to help derive an effective assessment of the impacts and priorities that should be assigned to them.