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PROJECT COMPLETION REPORT

OWRT PROJECT NO. B-012-ARIZ

HYDROLOGICAL AND ENVIRONMENTAL CONTROLS ON WATER MANAGEMENT IN SEMIARID URBAN AREAS

Agreement No. 14-31-0001-3056

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ABSTRACT

Rainfall and runoff studies initiated in 1968 by the University of Arizona provide data for three small urban watersheds with different land use patterns in Tucson, Arizona. Annual precipitation of about 11 inches produces annual runoff, as measured at outflow flumes, ranging from 1.30 to 3.95 inches, produced by 15 to 23 runoff events per year. About 60 to 70 percent of the annual runoff events occur in the summer season, as does 65 to 75 percent of the annual volume of measured runoff.

Water samples collected on a lumped basis show generally high concentrations of suspended sediment, bacterial loading, and dissolved organics. Initial field treatment and exploratory laboratory studies of treatment methods indicate that three days is an optimal length of time for detention storage of runoff, reducing average pollutant concentrations to 62 mg/l of turbidity, total coliform of 70-3200 organisms per 100 mg/l, and 7 mg/l of chemical oxygen demand. Simple laboratory treatment with alum and polyelectrolyte yielded an 80 percent reduction in COD, 90 percent reduction in bacterial loading, and appreciable clarification of the runoff samples.

Continuing research should be conducted to utilize a longer data record for improving understanding of rainfall-runoff relations; to use distributed sampling within individual watershed areas to define specific pollutant source areas; and to incorporate economic and legal questions involved in the utilization of urban runoff in an arid area.

HYDROLOGICAL AND ENVIRONMENTAL CONTROLS ON WATER MANAGEMENT IN SEMIARID URBAN AREAS

INTRODUCTION

The inception of the research reported here arose from the realization that only meager knowledge was at hand regarding the effects of urbanization in a semiarid environment upon the quantitative characteristics of storm runoff events and upon the quality of runoff yielded during such events. It was recognized that some of the changes wrought by urbanization bore directly upon (1) the increase of real or potential hazards to public health or safety through flooding or through pollutional loading of the runoff, and (2) the cost or efficiency of controlling, treating, and beneficially utilizing the runoff.

Objectives and Scope of Study

Accordingly, the specific objectives of this research were formulated in the project proposal as follows:

1. To initiate and continue rainfall and runoff studies for selected semiarid urban and suburban watersheds relative to differing development intensities and types (residential, commercial and industrial) and to analyze the quantitative effects of various catchment surface properties on runoff under various intensities and duration of rainfall.

2. On a preliminary basis, to establish appropriate sampling criteria, and to sample and analyze the urban runoff for dissolved and suspended organic and inorganic material in order to provide a basis for the evaluation of potential pollutional effects on ground waters of the basin; and to initiate exploratory studies for treatment methods in the control and management of urban runoff waters.

3. To evaluate the environmental influences on water yield and quality as a basis for investigation of feasible design criteria for storm sewers, water control structures, or drainage and treatment facilities, in order to effect salvage and use of urban runoff and possibly to alleviate existing or potential hazards to public health or safety.

Location of Study Area

The physical setting for the research is three urban and suburban experimental watersheds in the Tucson metropolitan area, complemented by one rural (Atterbury) watershed, whose components are referred to for comparison or as "control" areas. A 24-year record of rainfall and runoff is available for Atterbury Experimental Watershed, where instrumentation for measurements was started in 1956. Data collection on the three urban (High School, Arcadia, and Railroad) watersheds was begun in 1968, and the network of rainfall and runoff measuring devices and structures was completed during 1969 and 1970 under this project. Maps of the urban watersheds are shown in Figures 1 through 4.

The watersheds were selected for instrumentation and study after field reconnaissance was made to determine the general land-use patterns in each area. The purpose was to obtain hydrologic and water-quality data for a variety of land uses, and so to compare the effects of different types and degrees of urbanization on the quantity and quality of runoff. The land-use and related characteristics of the three urban and suburban watersheds are described in a later section under "Rainfall and Runoff Studies."

Previous Work and Continuing Studies

Exploratory sampling (and qualitative analysis) of runoff from High School and Arcadia Watersheds was initiated in 1968 under OWRR (later OWRT) Project A-011-ARIZ, in which an inventory and characterization of salvageable water resources of all kinds was conducted for the Tucson basin, in order to evaluate possibilities for reuse of the salvaged waters, including storm runoff, sewage effluent, and industrial processing and cooling effluents. It was that initial study which gave impetus to further research under OWRR Project A-020-ARIZ and to the current and continuing research on urban runoff in particular.

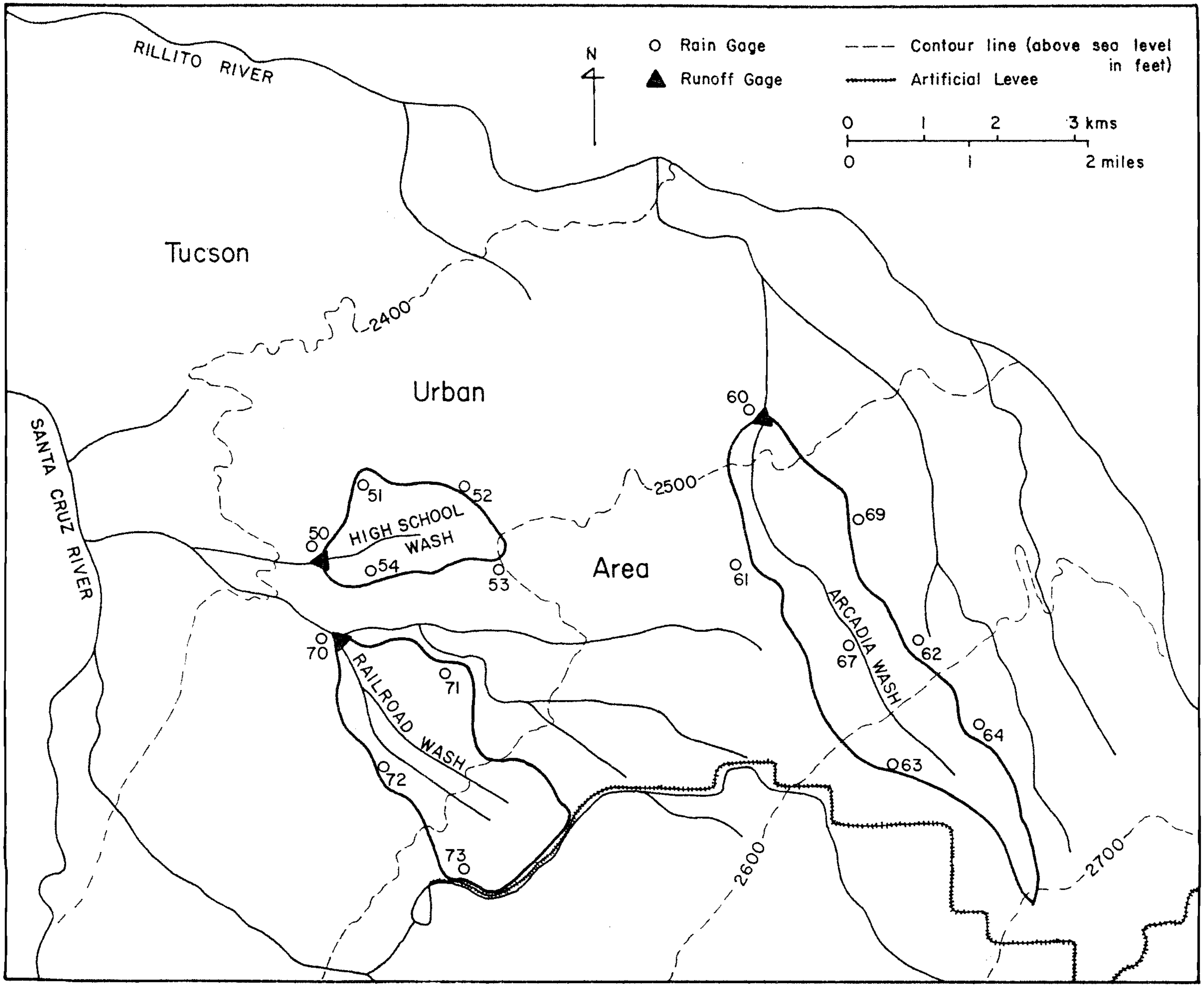
Under Project A-020, modeling methods were formulated which included an examination of potential uses or reuses of regional salvageable water resources, of which urban storm runoff was only one input source. The methods and results of that study are given in the series of partial technical completion reports pertaining to that project, and related work is present in a dissertation by DeCook (1970).

In Project B-012-ARIZ, which is the subject of this report, urban storm runoff is the water source specifically considered as input to the system, and its quality and flow characteristics as modified by the urban environment are examined as a basis for improved design criteria for water control structures or water utilization facilities within the urban environment. Moreover, the continuing research emanating from Phase II of the Project (B-023-ARIZ) proceeds to pilot studies to determine feasibility of operational techniques for treatment, storage, and use of the urban runoff and to examine the economic and legal aspects of conducting these operations.

RAINFALL AND RUNOFF STUDIES

Rainfall and runoff studies for urbanizing semiarid regions are, of course, necessary for determining the effect of urbanization of these areas on storm runoff quantity and quality.

In this section, the experimental watersheds are described; the precipitation characteristics discussed; and an analysis of rainfall-runoff relationships presented.



Water Resources Research Center, University of Arizona.

FIGURE 1 - EXPERIMENTAL URBAN WATERSHEDS IN THE CITY OF TUCSON, ARIZONA, 1971.

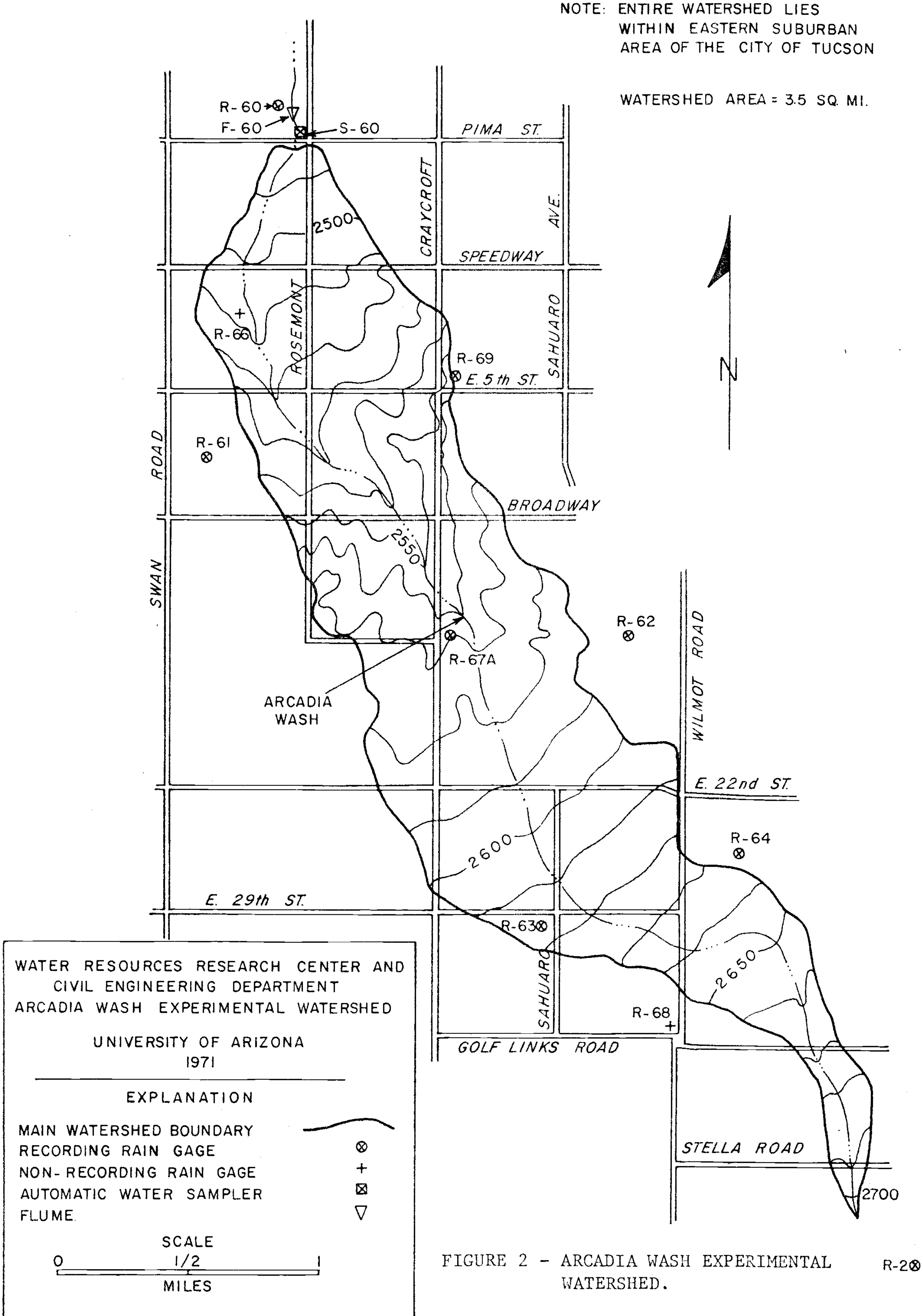


FIGURE 2 - ARCADIA WASH EXPERIMENTAL WATERSHED.

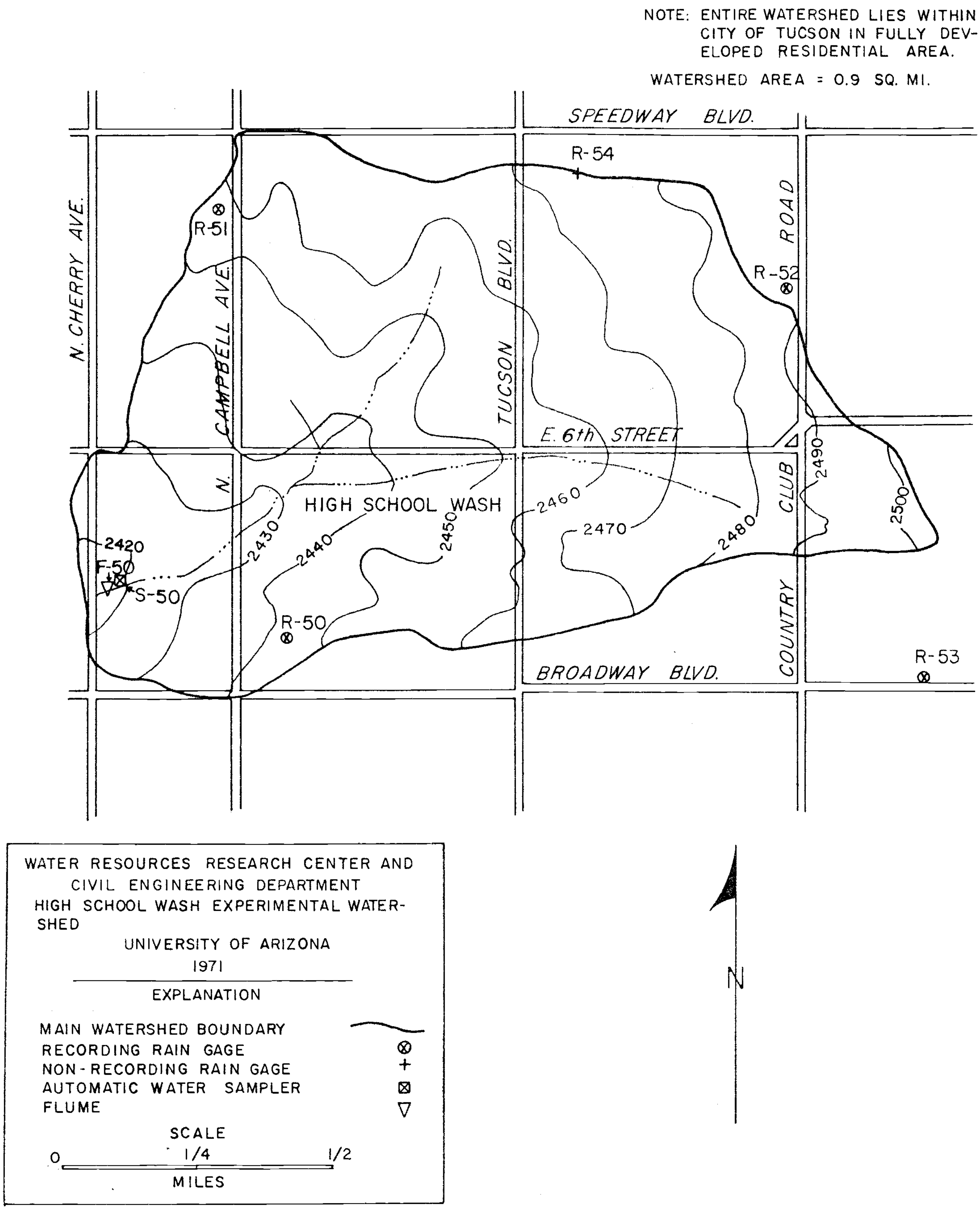


FIGURE 3 - HIGH SCHOOL WASH EXPERIMENTAL WATERSHED.

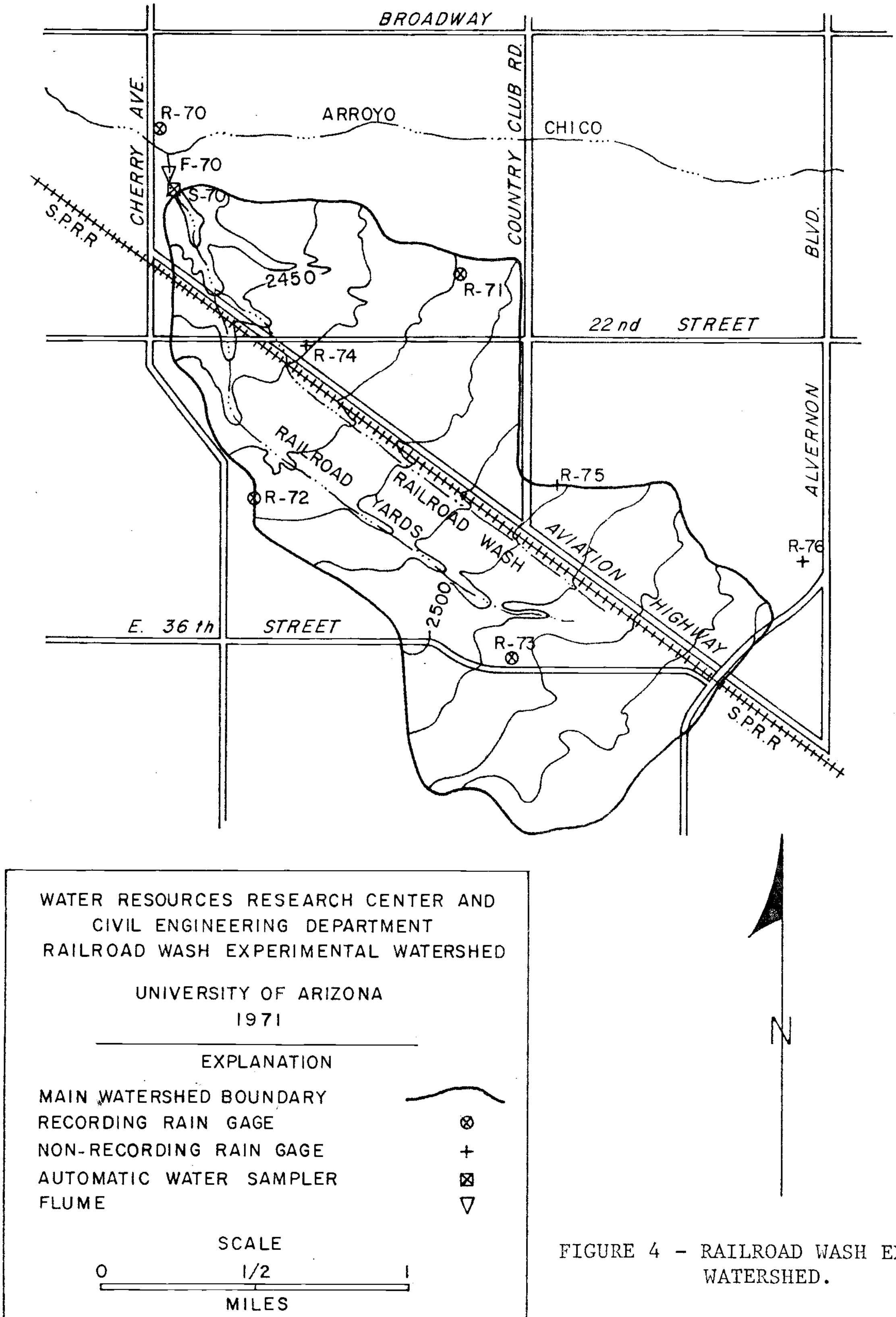


FIGURE 4 - RAILROAD WASH EXPERIMENTAL WATERSHED.

Description of Experimental Watersheds

The three watersheds selected for the project, containing High School Wash, Arcadia Wash, and Railroad Wash, are all within the boundaries of the City of Tucson, Arizona. The Watersheds are typical for the prevailing conditions in the City and they represent varying degrees of urbanization, land use, and imperviousness. The locations of the Watersheds relative to the major drainage pattern of the area are shown in Figure 1. Both High School Wash and Railroad Wash discharge into Arroyo Chico which flows into the Santa Cruz River. Arcadia Wash flows into Rillito Creek, which joins the Santa Cruz River a few miles downstream. The three Watersheds are not adjacent to one another but the distances between their centers are between two and four miles. The climatic conditions in the three Watersheds may be assumed to be identical. The surface soils of the three Watersheds are typical of the entire region. The upper few inches of most of the pervious areas consist of fairly fine sands which are permeable and result in relatively high rates of infiltration. The main stream channels are unlined and also consist of permeable sands.

The largest of the three Watersheds is the Arcadia Wash Watershed, which covers an area of 3.5 square miles. The area is highly developed but about 16 percent of the area, mostly near the upper end of the Watershed, is classified as undeveloped. The map of the Watershed given in Figure 2 shows only the main streets spaced at 1/2-mile intervals on a square grid system. The spaces between the main streets are subdivided into residential streets in a rectangular pattern. Most of the main street intersections in the area are developed into commercial zones including large parking facilities. There is also fairly intensive commerical development along some of the main streets shown in Figure 2. The residential streets contain mostly single family houses but there are also some multiple apartment units and trailer courts in the area. Except for some automobile repair shops there is practically no industrial development in the area.

The Watershed is drained by an ephemeral stream, Arcadia Wash, which flows into Rillito Creek about two miles downstream from the gaging station. The Wash is regulated throughout most of its length but it is not lined. It has a natural sandy bottom into which some of the water infiltrates during storms. The average slope of the terrain is about 0.9 percent. The area of the Watershed is practically without any storm drains. During and following rainstorms, water flows along the streets that are graded toward the Wash. The water enters the channel through inlets at the sides of streets crossing the wash and its small tributaries. The Watershed has an elongated, nearly rectangular shape. Its length is about 4.5 miles and its average width is about 0.8 miles. The length of the well-defined main channel is about four miles and its mean slope is 0.75 percent. The total length of the Arcadia Watershed main channel (to the Watershed boundary) is 5.3 miles. The mean slope for the entire stream is 0.84 percent. The slopes of the streets in which flow takes place vary in the range of 0.2-1.6 percent, with a mean value of about 0.8 percent.

The High School Wash Watershed covers an area of 0.95 square miles and has a nearly trapezoidal shape. The mean length of the Watershed is about 1.2 miles and its mean width about 0.8 miles. It is a highly developed, well-established part of the City, mostly residential but with some commercial development similar to that of the Arcadia Watershed. The undeveloped portion of the Watershed is estimated at about 5 percent. The nature of the residential area is similar to that described above for the Arcadia Watershed except that there is a somewaht larger proportion of single family housing. The map of the Watershed, Figure 3, again shows only the main roads, omitting the residential streets.

The area of the Watershed is drained by two channels which join at about 0.5 miles above the gaging station. The channels are partly regulated but not lined, so that some water infiltrates as it flows in the channels. The length of the main channel (to the Watershed boundary) is about 1.6 miles. The mean slope of the main channel is 1.10 percent. The slope of the second channel is about the same, while the general slope of the terrain is about 1.0 percent.

Most of the main and secondary streets in both watersheds serve as the drainage channels for storm runoff. These streets are asphalt or concrete strips laid on existing grades without gutters or roadside ditches. During rainstorms the water flows along the main streets and enters the main channel and its tributaries through inlets at the sides of the streets which cross the channel. There are practically no storm drains (pipes) in either of the watersheds.

The Railroad Wash Watershed, which covers an area of 1.9 square miles, is different from the other two Watersheds by a number of its features. The most prominent is the different land use. Whereas the Arcadia and High School Watersheds have no industrial development, the Railroad Watershed has about 26 percent of its area occupied by industries. Of these the largest single industry is the Southern Pacific Railroad yards occupying a strip of land between the two main channels of the Watershed (Figure 4). The two channels are artificial unlined drainage channels, which join the natural channel about 0.4 miles upstream from the gaging station. Another prominent feature in the Watershed is the highway and railway line which pass approximately along the axis of the Watershed. One more feature worth mentioning is that a large portion of the Watershed boundaries are not natural. The southeast border is defined by a flood protection levee and a portion of the eastern and northeastern border is formed by a diversion channel.

The Watershed has an elongated roughly rectangular shape about 2.1 miles long, with an average width of 0.9 miles. The length of the main channel is about 2.3 miles and its mean slope is 0.87 percent. Outside the central strip occupied by the railroad yards and other industries there are two strips of residential areas. These have the same general characteristics of the other two Watersheds except that the density of housing is higher to some extent. The size of the undeveloped portion of the Watershed is about 20 percent and it is concentrated in the upper part of the Watershed.

A summary of the hydrologically significant properties of the three Watersheds is presented in Table 1. The proportional area (in percent) occupied by various land use categories for each of the watersheds is given in Table 2. This compilation was prepared on the basis of aerial photographs,

TABLE 1 - SUMMARY OF WATERSHED CHARACTERISTICS

CHARACTERISTIC	ARCADIA WATERSHED	HIGH SCHOOL WATERSHED	RAILROAD WATERSHED
Area of Watershed (sq mi)	3.5	0.95	1.9
Length of Main Stream (mi)	5.3	1.6	2.6
Length of Defined Channel (mi)	3.5	1.3	2.3
Slope of Main Stream (%)	0.84	1.10	0.87
Mean Watershed Slope (%)	0.9	1.0	0.8
Average Elevation above MSL (ft)	2600	2460	2480
Imperviousness ratio	0.24	0.30	0.35

TABLE 2 - PERCENTAGES OF LAND USE CATEGORIES AND POPULATION DENSITIES

LAND USE	ARCADIA WATERSHED	HIGH SCHOOL WATERSHED	RAILROAD WATERSHED
Residential (net)	60.4	65.5	38.7
Commercial and Institutions	6.9	5.5	1.5
Industrial	0.0	0.0	26.3
Paved Streets and Parking Lots	13.3	19.9	11.5
Unpaved Roads	1.7	3.4	1.0
Parks, Grassed Areas	2.1	0.6	1.3
Open, Undeveloped	15.6	5.1	19.7
Gross Population Density (persons/acre)	7.0	7.1	5.2
Population Density for Residential Area (persons/acre)	8.5	7.5	9.7

printed at a scale of about 1:5000, augmented by a field reconnaissance. The population density figures were computed from an available map of census tracts. Using the land use categories in Table 2, values of the imperviousness ratio were estimated for each Watershed. The values given in Table 1 were based on the sum of the area of paved streets and parking lots, plus 70 percent of the area of the commerical and industrial parts, plus 10 percent of the net residential areas.

A description of the definitions used for the land classification categories in Table 2 is as follows. Residential areas include all land use for single-family dwellings, town houses, rowhouses, garden apartments, and higher density apartment development. Commercial land use includes retail stores, service establishments, professional activity, motels and restaurants. The term institutions refers to the parts of the watershed area on which only the buildings of schools, hospitals, churches and medical centers are located. The industrial classification refers to all classes of industrial land use involving manufacturing, processing, storing, and distribution. This category also includes railroad facilities and rights-of-way associated with industrial areas. Heavy industry is minor in Tucson and is essentially clustered about the railroad yards. It should be noted that neither High School nor Arcadia Watersheds contain any industrial activities. Paved areas include streets and large parking lots at shopping centers, churches, and schools. Park areas consist of any grassed and landscaped area at parks or schools. Undeveloped areas include open land which has not as yet been developed for any use and is still covered by the natural desert shrubbery of the region. Due to the large number of alleys and unpaved roads which exist in the City, the inclusion of an unpaved road characteristic was also made.

Instrumentation

Each of the three Watersheds is equipped with a critical depth flume (Venturi flume) and an automatic water sampler at its outlet. Each Watershed has also a number of recording raingages distributed over its area, as well as some non-recording raingages. The locations of the various instruments are marked on Figure 1 for the entire area and on Figures 2, 3, and 4 for the individual watersheds. The critical depth flumes were built at the various sites in the period November 1969 through July 1970. They were put into operation as each flume was completed, in the period March 1970 to August 1970. The automatic water samplers were installed in the period September 1970 through December 1970 at the three sites. The recording raingages were installed over the period March 1968 through December 1970.

Flow measurements for the Arcadia and High School Watersheds were started prior to the installation of the critical depth flumes at temporary sites. Actual measurements of flow at the two temporary sites were started in July 1968 and March 1968 respectively. Flow measurements at the Railroad Watershed flume were started in April 1970. Samples of runoff water were collected manually during a number of storms before the installation of the automatic samplers. These were collected at five-minute intervals until peak flow was reached and at 20-minute intervals through the recession of flow.

The critical depth flumes are all long-throated Venturi flumes designed by John Replogle of the U.S. Water Conservation Laboratory (USDA) in Phoenix, Arizona. Theoretical rating curves were also prepared for the three flumes by John Replogle. The rating curves were later corrected using actual measurements of flow and gage height carried out by the staff of the U.S. Geological Survey in Tucson, Arizona. Each flume is equipped with an automatic water stage recorder (type SR Flood Hydrograph Recorder) operating in a stilling well connected by a pipe to the gaging cross-section of the flume.

The automatic water samplers were fabricated at the Water Resources Research Center laboratory of the University of Arizona. The basic design of the sampler was obtained from the Watershed Research Center of the Agricultural Research Service (USDA) in Tucson, Arizona. The samplers were housed in closed sheds near each of the critical depth flumes.

The recording raingages are of the Belfort weighing-recording type. The time interval between division lines on their chart is 10 to 15 minutes. The accumulated quantity scale of the charts enable the readings to be made to 0.01 inch. A total of 14 recording raingages were installed in the three Watersheds. Six gages were installed in Arcadia Watershed and four gages were installed in each of the other two Watersheds. Two non-recording raingages also were installed in each of the three Watersheds to augment the rainfall records collected.

Rainfall Regime

The rainfall regime in the Tucson Basin is influenced by the semi-arid climate of the region and by its general geographical and topographical features. Southern Arizona in general and the Tucson Basin in particular are characterized by two distinct rainfall seasons...a summer season which occurs usually during the months of July, August, and September and a winter season starting in October and lasting through March. The months of May and June have only minimal rainfall.

The moisture source of the summer rains is generally air from the Gulf of Mexico, which invades the southwestern United States in late June or early July. Updrafts caused by orographic lifting or thermal convection form thunderstorm cells. The resulting rain is typically of high intensity and short duration, and usually covers an area of less than 25 to 35 square miles. An isohyetal map of thunderstorm rainfall shows a definite maximum, or storm center. The isohyets are nearly elliptical with the steepest rainfall gradients along the major axis. The regular isohyetal patterns of rainfall from individual thunderstorms are a result of the mechanics of convective thunderstorm formation. Thunderstorm cells are formed by orographic or thermal uplifting and are characterized by a strong updraft in the center of the cell and low velocity downdrafts around the periphery. The thunderstorm has been described as having three stages of development:

1. Cumulus stage--characterized by updrafts throughout the cell.
2. Mature stage--characterized by the presence of both updrafts and downdrafts at least in the lower half of the cell.
3. Dissipating stage--characterized by weak downdrafts prevailing throughout the cell.

The storm cells are usually not stationary. By plotting isohyetal patterns for short intervals of time during a thunderstorm it is possible to trace the movement of the center of the storm cell. An example of such a moving rainfall cell is shown in Figure 5 for the storm event of 8-8-1971 over the Tucson area. The isohyets shown are for rainfall amounts (in mm) for various five-minute periods during the storm.

The winter precipitation in southern Arizona is the result of frontal activity or orographic uplift of polar Pacific air masses. These moisture-bearing air masses are brought into the area by migratory extra-tropical cyclones as they move in a west to east direction. The resulting rainfalls are normally of low intensity and may be of fairly long duration. The isohyetal patterns of precipitation from winter or frontal storms are generally irregular because of the nature of the storms. They are not as predictable as the patterns produced by summer rainfall.

The two seasons of rainfall are also reflected in the pattern of average monthly rainfall for the Tucson area. Meteorological data collected at the University of Arizona over a period of 30 years are summarized in Table 3. A graphical presentation of the mean monthly precipitation (Figure 6) clearly shows the two rainfall seasons. The mean annual rainfall for Tucson is about 10.7 inches. Approximately half of this quantity is obtained in the summer months of July, August and September and most of the rest is distributed over the seven-month period of October through April.

Analysis of Rainfall Observations

Rainfall data were collected from a number of recording and non-recording raingages on each of the three Watersheds. Regular observations began for the High School Watershed in March 1968, for Arcadia in July 1968, and for the Railroad Watershed in January 1970. Yearly summaries of the rainfall data for the three Watersheds are given in Appendix A. The summaries list for each storm event, the mean rainfall for the watershed concerned, and the maximum rainfall recorded for that storm at any of the gages. The method of averaging is also indicated in the summary, using T for Thiessen's method and A for arithmetic averaging. It should be noted that the number of gages used to compute the mean rainfall is not the same for the various watersheds, and that even for a given watershed the number of gages was not the same for all storm events for various reasons, mostly malfunctioning of the recorders.

Grouping the data presented in Appendix A by months, a table of monthly values of rainfall and of the number of rainfall events has been prepared (Table 4). The monthly rainfall values are average rainfall values for the areas of the watersheds concerned. The values were derived from individual values for the month concerned in the period of record up to the end of 1971. The means were thus computed on the basis of between two and four individual values.

The number of rainfall events per month ranges from zero to about 11 events per month for the three watersheds studied. The monthly values are about the same for the three Watersheds independent of their size. The

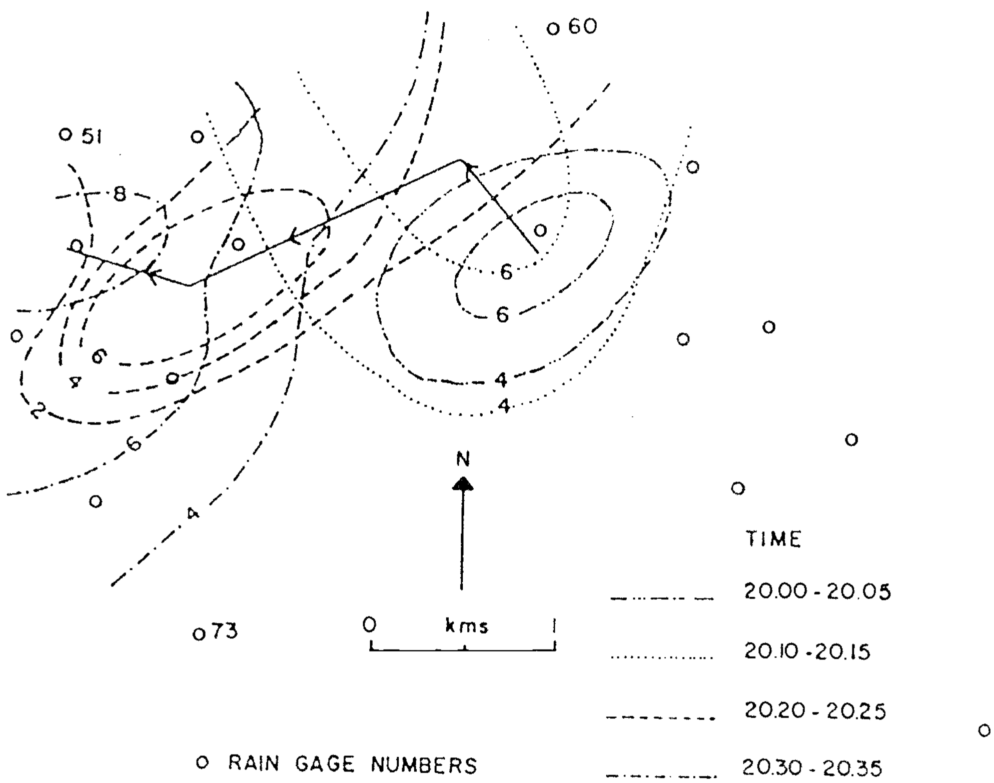


FIGURE 5 - MOVEMENT OF A RAINFALL CELL OVER TUCSON.

Isohyets show rainfall amounts (mm) for 5-minute periods.

TABLE 3

Meteorological Data for the Tucson Area

Month	Precipitation (in.)			Temperature (^{o}F)		
	High	Low	Average	High	Low	Average
January	2.53	0.00	0.83	56.4	43.8	51.4
February	2.79	Trace	0.75	61.2	48.7	54.2
March	2.39	0.00	0.74	63.6	53.5	58.5
April	1.94	0.00	0.45	71.0	60.6	66.3
May	0.76	0.00	0.14	79.7	69.4	74.2
June	1.45	0.00	0.20	86.9	77.8	82.7
July	4.60	0.50	2.09	89.8	83.8	87.3
August	4.62	0.22	2.06	89.7	82.1	85.2
September	3.78	0.00	1.15	84.4	78.0	81.2
October	2.49	0.00	0.61	76.5	63.3	70.6
November	2.53	0.00	0.60	63.8	52.6	59.0
December	7.27	0.00	1.09	57.6	47.8	52.4
Annual	15.80	5.72	10.72	70.5	66.5	68.5

Values presented are based on 30 years of records at The University of Arizona Station.

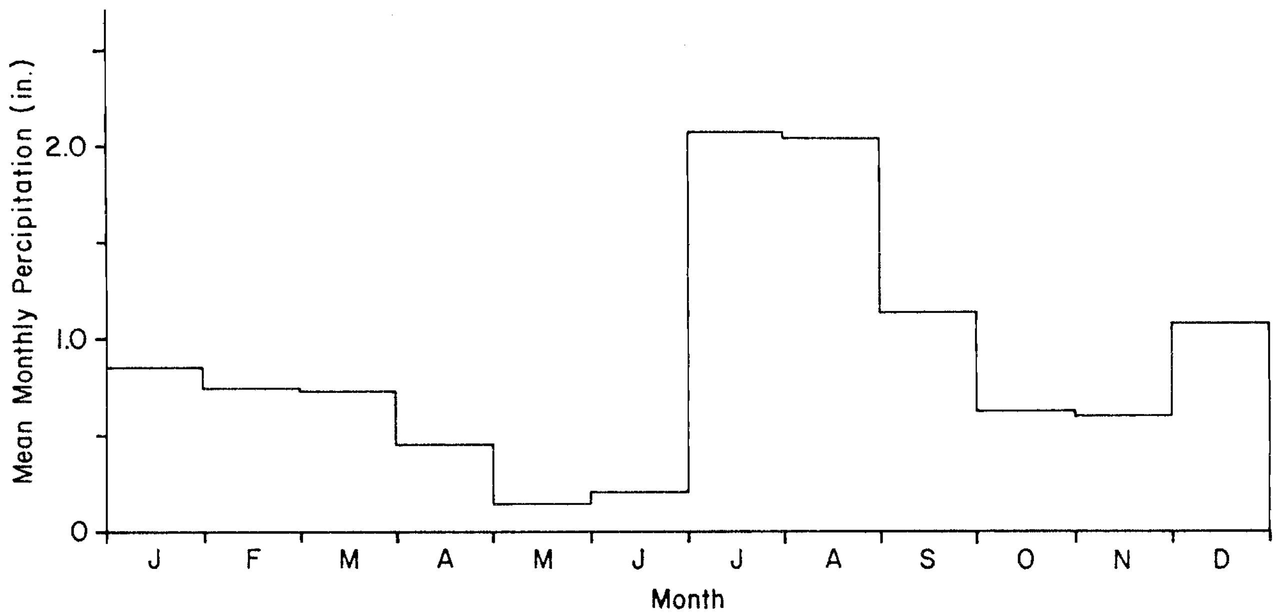


FIGURE 6 - MEAN MONTHLY PRECIPITATION IN THE TUCSON AREA.

Base: 30-year record at the University of Arizona.