EFFECTS OF CHANNEL STABILIZATION IN TUCSON STREAM REACHES ON INFILTRATION AND GROUND-WATER RECHARGE

VOLUME II
NATURAL STREAMFLOW STUDY

PREPARED BY:

C.B. CLUFF
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L.T. KATZ
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FINAL REPORT TO

PIMA COUNTY DEPARTMENT OF TRANSPORTATION AND FLOOD CONTROL DISTRICT

SEPTEMBER 1987

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VOLUME II
EXECUTIVE SUMMARY

Volume I of a companion study has shown, by means of a computer model, that the use of channel stabilization with soil cement to control flood damage can reduce infiltration from natural streamflow unless the channel is widened during emplacement of the bank protection.

This part of the study, Volume II, attempts to quantify the basinwide effect of channel stabilization on infiltration under the various cases studied in Volume I. It was prepared in response to Task 2 of the scope of services.

Natural Streamflow

Historic records of average daily streamflow on the Santa Cruz and Rillito Rivers were used to estimate infiltration from streamflow in the Tucson basin. The available continuous records at Congress St. bridge on the Santa Cruz River from 1918 to 1981 and records from at or near Oracle Rd. bridge on the Rillito River from 1918 to 1975 were used. These records showed an average annual measured runoff of 9,250 ac-ft in a total of 1,999 events on the Rillito River and an average of 15,263 ac-ft in a total of 3,283 events on the Santa Cruz River.

1984/1985 Natural Recharge Event

The scope of work called for a study of data recorded in the 1984/1985 sustained low flow recharge event on both the Rillito and Santa Cruz Rivers. Infiltration rates, volumes of recharge per day, and volumes of recharge per day normalized to stream length were computed. For the Santa Cruz, these figures were roughly 1.37 ft/day, 551 ac-ft/day, and 18 ac-ft/day/mi, respectively. For the Rillito River, the same figures were roughly 1.67 ft/day, 479 ac-ft/day, and 41 ac-ft/day/mi, respectively. In this way, a comparison of steady state infiltration conditions along the two reaches could be made. It was found that although the total volume infiltrating on a daily basis was larger on the Santa Cruz River, a greater recharge potential was demonstrated on the Rillito River, since it had a higher infiltration rate and volume of recharge relative to stream length. With an almost four month period of persistant flow, it was shown that steady state infiltration conditions were achieved on both streams prior to the measurement of infiltration rates. Upstream and downstream points of known discharge were first necessary in order to make loss calculations. Upstream values were from gaging done on the streams, and downstream values of zero were used, as all flow was observed to have infiltrated by the downstream end of each reach. To obtain the wetted stream areas between the known control points, an innovative procedure which entailed taking an aerial video of the stream reaches during flow was used.

Another major finding of the 1984/1985 natural recharge event study was the determination of the rate of inflow at which the entire flow volume was infiltrated by the downstream end of each reach. This rate was

found to be aproximately 240 cfs on the Rillito River as measured at Craycroft Rd. and 250 cfs on the upper Santa Cruz River as estimated measurements Continental Rd. This finding from the 1984/1985 recharge event was very helpful in the determination of infiltration from historic data as discussed below.

Natural Streamflow Infiltration

The streamflow data and the amount of low flow which entirely infiltrates along the length of the streambed on both the Rillito and Santa Cruz Rivers was used to calculate the natural infiltration from daily streamflow events in the historic records from the two streams. Burkham's (1970) equations of the form

$$I = C\,Q^{0.8}$$

were used to determine infiltration (I) for all flows (Q) greater than 240 cfs on the Rillito River and 250 cfs on the Santa Cruz River. Any flows of less than the 240 cfs and 250 cfs were assumed to infiltrate. The total annual infiltration for the 12 mile long Rillito River was found to be 8,318 ac-ft and for the 46.5 mile long Santa Cruz River this value was found to be 20,851 ac-ft. This is 693 ac-ft/mile/yr and 448 ac-ft/mile/yr for the two streams respectively. It was found that 41.1% of the Rillito River's infiltration and 22.0% of the Santa Cruz River's infiltration occurred when the flow was less than the low flow values at which all flow infiltrates on the two streams. The weighted average for all streams was 28.4%. Preliminary results from the computer model presented in Volume I showed that there was no effect from the soil cement embankments on low flow infiltration. Thus, 28.4% of the infiltration on the average would not be adversely affected by bank protection.

The natural infiltration on the other major streams was found by using ratios applied against Burkham's relationships determined from a shorter record, 1936 - 1963. These average annual infiltration values were found to be 7,426 ac-ft for Canada Del Oro, 9,722 ac-ft for Tanque Verde Wash, and 6,451 ac-ft for Pantano Wash. The total average annual infiltration for the basin was found to be 54,654 ac-ft.

Average annual synthesized streamflow and infiltration values for the main streams in the Tucson basin appear in Table E1.

This total infiltration was multiplied by first the percentage of infiltration affected by soil cement embankments of 71.6%. The total natural infiltration that could be affected by soil cement embankments was found to be 39,132 ac-ft/yr. This figure was then multiplied by the percentages of differential average annual infiltration shown in Table E2 to give the differential in acre-feet, also shown in Table E2.

TABLE E1

AVERAGE ANNUAL SYNTHESIZED STREAMFLOW AND INFILTRATION VOLUMES
FOR THE MAIN CHANNELS IN THE TUCSON BASIN 1918 - 1981

Inflow Point	Average Annual Inflow [ac-ft]	Average Annual Infiltration [ac-ft]	
		Low Flow	Total
Santa Cruz River at Contintental Rd.	27,730	4,579	20,851
Santa Cruz River from Rillito River	6,792	492	1,886
	34,522	5,069	22,737
Tanque Verde Wash	16,589	3,996	9,722
Pantano Wash	8,477	1,419	6,451
Rillito River	15,112	3,415	8,318
Canada Del Oro	11,785	1,633	7,426
Total	***	15,532	54,654

*** Total was not taken, since some inflows provided water to a subsequent reach and therefore would be counted twice.

TABLE E2

DIFFERENCES IN BASINWIDE RECHARGE (CUMULATIVE INFILTRATION VOLUMES) FOR SIX CASES

Case Number	Description of Channel before and after bank protection	Differential	
		%	Av. Ann. Infiltration [ac-ft]
1	Wide channel before and after bank protection	-14.7	-5,752
2	Narrow channel before and after bank protection	-24.8	-9,705
3	Narrow channel before, wide channel after bank protection	+24.9	+9,743
4	Wide channel before, narrow channel after bank protection	-48.6	-19,108
5	Channel widening without bank protection	+46.3	+18,118
6	Channel narrowing without bank protection	-31.7	-12,405

Mitigation of Possible Adverse Effects of Soil Cement Embankments

Approximately 26.2 miles of soil cement have already been installed on the major streams in the Tucson basin.

Several mitigation techniques are possible to reduce the effects of bank protection, including (1) increasing channel width whenever possible on remaining streambeds, (2) water spreading in streambeds through releveling after major flows, reduction of slope to 0.002 through drop structures and the use of "T" or "F" berms, (3) offstream detention basins in the upper reaches of streams, (4) careful use of onstream detention basins through the use of removable gates, and (5) large offstream detention basins near Rillito Narrows to capture most of the remaining surface streamflow before it leaves the Tucson basin and pump it back upstream in the basin to an appropriate location for recharge.

In all cases, except the final mitigation measure listed above, the immediate increase in infiltration must be reduced by the amount of decreased infiltration downstream. By contrast, any reduction in infiltration due to soil cement embankments in an upstream reach would cause some compensating increase in downstream infiltration.

Conclusions

The reduction in natural infiltration caused by soil cement embankments can be compensated for by increased natural infiltration through a combination of mitigation procedures.

EFFECTS OF CHANNEL STABILIZATION IN TUCSON STREAM REACHES ON INFILTRATION AND GROUNDWATER RECHARGE

VOLUME II

NATURAL STREAMFLOW STUDY

I. Introduction

This is the second volume of a comprehensive study carried out at the University of Arizona to characterize the effects of channel stabilization on in-stream recharge processes. Volume I reports on the use of a computer model to simulate the influence of bank protection and grade control structures on infiltration and recharge during a representative runoff event on the Rillito River in Tucson (Wilson et al., 1987). Five topics are covered in this, the second, volume concerning natural streamflow in the Tucson basin: (1) the historic streamflow on the Santa Cruz River and its tributaries, (2) the Winter/Spring 1985 natural recharge event on the Santa Cruz and the Rillito Rivers, (3) the historic infiltration from streamflow on the Santa Cruz River and its tributaries, (4) the effects of soil cement embankments on basinwide recharge, and (5) the mitigation of possible adverse effects of soil cement embankments. The general purpose of this volume is to evaluate the existing relationships among runoff, infiltration and groundwater recharge in order to better relate the model results to a basinwide view of recharge. The results of modification of present conditions can then be predicted, and mitigation techniques suggested.

Characterization of the distribution of streambed recharge is accomplished using available continuous historic streamflow records for 58 years on the Rillito (1918 - 1975) and 64 years on the Santa Cruz (1918 - 1981). These records were analyzed in order to determine the volume of flow represented by the various flow ranges. Only daily averages were used, since the hourly flow record was available for a relatively small number of years. The stage for the mid-point of each of the flow ranges corresponding to the 6 cases considered in the Volume I study was determined and the amount of time in days that each stage of flow occurred over the historic record was noted.

Video imagery of low flow recharge from snowmelt during the Winter/Spring 1985 streamflow event in the Tucson basin provided the data base for the second portion of this study. By analyzing this natural recharge event, various stream parameters were determined in order to better characterize present in-stream recharge potentials in the Tucson basin. These parameters include the total area available for infiltration, the wetted area and percent wetting from a sustained flow event of known discharge, the infiltration rate and volume from such an event, and the losses due to evaporation from the wetted surface. The goal in evaluating these parameters was to arrive at a more quantitative understanding of recharge processes in the Tucson basin.

With the historic streamflow information and the values for the above mentioned stream parameters, Burkham's (1970) infiltration formulas were used to determine the historic infiltration on both the Santa Cruz

and Rillito Rivers. These values are extrapolated to the other main channels of the Tucson basin. Infiltration data using Burkham's equations are compared with those from the computer analysis. The effect of embankment protection on recharge from a basinwide viewpoint is discussed. Policies and practices that could mitigate the adverse effects of bank protection on recharge are also discussed.

II. Streamflow on the Upper Santa Cruz and its Tributaries

This portion of the report is being written in response to Subtask 2a, part 1 which calls for an analysis of existing data to determine the opportunity for recharge in the basin from hydrographs of available stage records.

A. Study Area

The streams of interest, together with their watersheds, are shown in Figure 1. Numbers assigned to reaches in this figure are designations used in the following section of the report. The discussion of the impact of soil cement embankment protection on recharge will be limited to the portion of the Santa Cruz River between Continental and Avra Valley Rd. at the Rillito Narrows, Canada Del Oro, Tanque Verde Wash, Pantano Wash , as well as the entire stream channel of the Rillito River. Long term streamflow records are available only on the Rillito and the Santa Cruz Rivers. The records from these streams will be used to characterize streamflow distribution and to estimate natural recharge using the technique outlined by Burkham (1970) and discussed later in this section of the report. The infiltration relationships defined by Burkham were used in routing the streamflow upstream from the gaging station at Oracle Rd. bridge to the beginning of the Rillito River at the Craycroft Rd. bridge and from the Congress St. bridge gaging station to Continental Rd. gaging station on the Santa Cruz River. The distribution of these flows was determined using a computer program.

B. Streamflow Data

The annual streamflow on the Rillito River, determined from 58 years of streamflow record between 1918 and 1975, is shown in Table 1. This record was taken from daily average streamflow as measured at or in the near vicinity of the Oracle Rd bridge by the U.S. Geological Survey (USGS). An explanation of infiltration data given in Tables 1 and 2 will be given in section IV. The complete record is tabulated in Appendix A.

The annual streamflow on the Santa Cruz River is given in Table 2. The record of Santa Cruz River streamflow was measured at the Congress St. bridge for 64 years from 1918 to 1981. The complete record is given in Appendix A.

Outflow from the Rillito River which constitues tributary flow into the Santa Cruz River must also be considered. The annual record of this second source of inflow to the Santa Cruz River is given as Table 3. Again, the complete record is given in Appendix A.

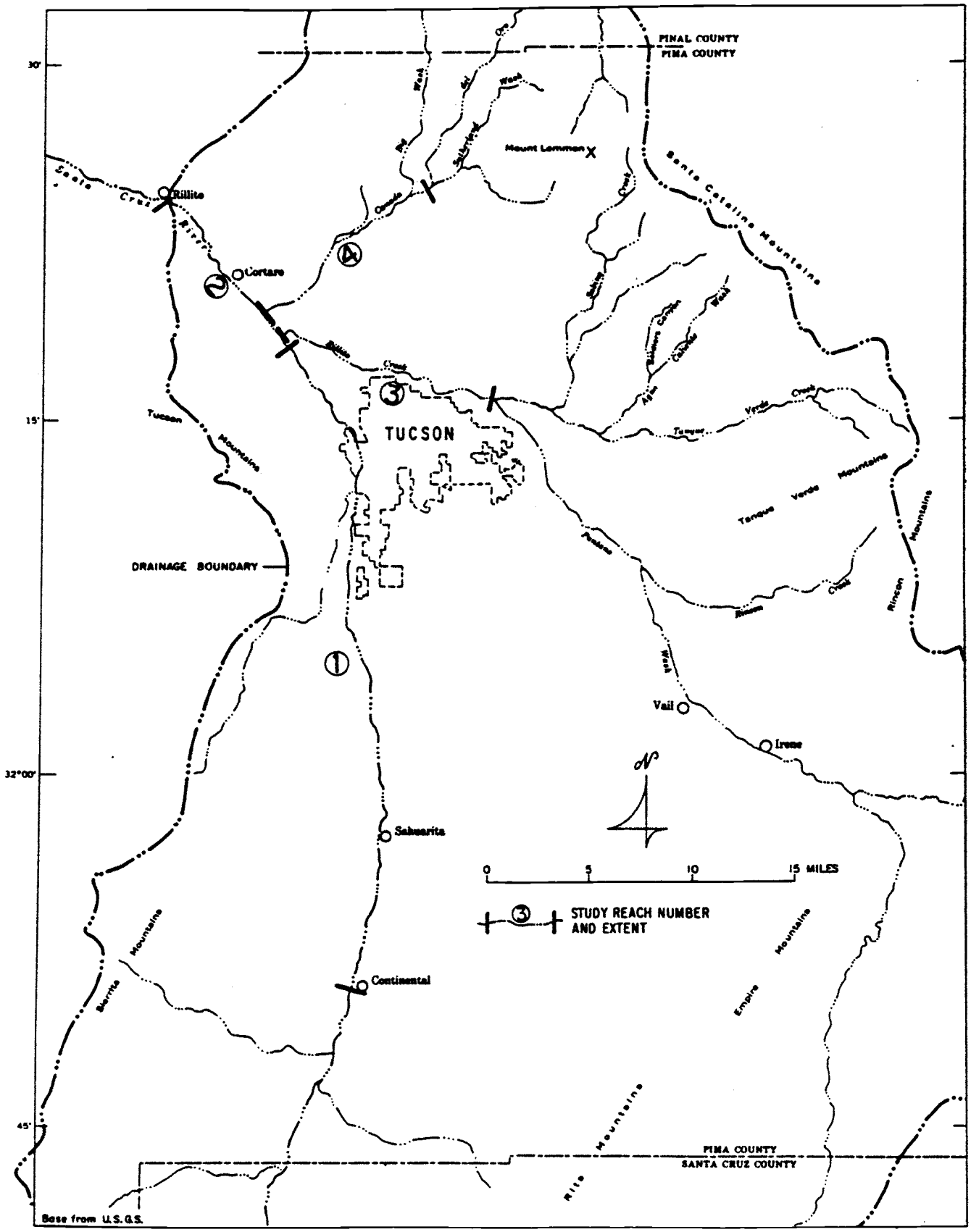


Figure 1. Study Area Map Showing Stream Reaches, Tucson Basin, Southeastern Arizona

TABLE 1

SYNTHESIZED AVERAGE ANNUAL INFILTRATION FROM AVERAGE DAILY HISTORIC STREAMFLOW ON THE RILLITO RIVER

[cfs-day]

YEAR	Measured Streamflow (Oracle Road)	Inflow (Craycroft Road)	Outflow (Santa Cruz River)	Infiltration When Inflow <240 CFS *	Total Infiltration
1918	6372	9503	5529	370	3975
1919	18765	28686	15308	3750	13380
1920	13117	22491	8384	7097	14111
1921	21424	30464	18606	1598	11861
1922	1526	2886	948	1006	1938
1923	3363	6055	1881	2499	4175
1924	2902	5129	1831	1836	3317
1925	2379	4247	1649	1000	2599
1926	980	1955	388	1277	1607
1927	2309	4791	842	3113	3949
1928	647	1312	308	657	1004
1929	13625	20011	11504	1607	8509
1930	5338	8893	4034	1476	4861
1931	6073	10008	4496	2102	5514
1932	7520	13147	4472	5257	8677
1933	831	1864	473	928	1392
1934	1058	2122	478	1176	1644
1935	9210	14368	7265	2224	7104
1936	1816	3383	1016	1402	2368
1937	2242	4092	1193	1916	2900
1938	1258	2244	829	755	1415
1939	3466	5452	2646	1090	2807
1940	4211	6356	3446	772	2911
1941	14999	23985	11480	4134	12508
1942	1086	2348	328	1659	2020
1943	1312	2569	569	1405	2000
1944	1608	2875	1089	852	1787
1945	1951	3637	1090	1855	2548
1946	1532	2942	748	1422	2158
1947	2075	3432	1550	696	1882
1948	484	1142	0	1142	1142
1949	1472	2849	744	1324	2106
1950	3660	5901	2790	1031	3111
1951	2086	3613	1441	963	2173
1952	3104	5754	1896	2013	3859
1953	878	1624	505	641	1119
1954	6570	10641	5146	1545	5497
1955	6200	10233	5013	977	5222
1956	159	375	0	375	375
1957	2125	3660	1286	1498	2374

* Actual value used in computer analysis was 242 cfs.

TABLE 1 CONT'D

[cfs-day]

YEAR	Measured Streamflow (Oracle Road)	Inflow (Craycroft Road)	Outflow (Santa Cruz River)	Infiltration When Inflow <240 cfs	Total Infiltration
1958	5680	10232	3181	4307	7052
1959	2647	4680	1561	1899	3120
1960	6803	11048	5043	2406	6006
1961	1369	2451	1007	486	1445
1962	2196	4022	1491	1260	2531
1963	2888	4829	2099	1191	2730
1964	4788	7578	3509	1821	4070
1965	518	1406	0	1406	1406
1966	26855	41413	21730	4489	19688
1967	955	1666	625	496	1041
1968	8206	12857	6494	1858	6365
1969	356	768	0	768	768
1970	3718	6075	2633	1707	3442
1971	5620	8949	4345	1306	4605
1972	1219	2570	538	1455	2032
1973	14207	22789	10905	3693	11887
1974	426	857	145	547	712
1975	280	616	121	348	495
TOTAL	270472	441888	198651	99882	243295
AVE	4663	7619	3425	1722	4195
AV AC-FT	9250	15112	6793	3415	8318

TABLE 2

SYNTHESIZED AVERAGE ANNUAL INFILTRATION FROM AVERAGE DAILY HISTORIC STREAMFLOW ON THE SANTA CRUZ RIVER -- CONTINENTAL ROAD INFLOW

[cfs-day]

YEAR	Measured Streamflow (Congress St.)	Inflow (Continental Road)	Outflow (Avra Valley Road)	Infiltration When Inflow <250 cfs	Total Infiltration
1918	487	4369	1195	706	3175
1919	13859	24324	6329	1832	18008
1920	3994	9973	5514	5514	9141
1921	16182	28917	7201	2071	21732
1922	5470	11526	1904	2389	9632
1923	7917	15271	3043	2243	12238
1924	1867	5083	495	3032	4590
1925	3498	7288	1094	1635	6202
1926	10174	16442	5772	2533	10652
1927	585	4597	242	3229	4357
1928	1472	3118	458	1299	2661
1929	12254	20684	6110	1642	14583
1930	4071	8768	1178	2822	7596
1931	18796	32895	8793	3406	24118
1932	7430	13624	3169	1437	10463
1933	3681	7096	1415	1361	5685
1934	3815	7952	1330	2444	6626
1935	10307	17951	5073	2678	12886
1936	4421	9285	1712	2384	7578
1937	4165	8649	1385	2506	7270
1938	3840	7307	1630	1888	5680
1939	12319	21488	5832	2360	15665
1940	6799	11957	3340	2279	8623
1941	2514	5937	551	2549	5391
1942	1540	4057	324	2459	3735
1943	5354	11367	1616	3280	9761
1944	4918	8568	2417	1034	6154
1945	10450	18154	5060	1776	13073
1946	7495	15117	2666	3787	12461
1947	3284	6924	1041	2271	5887
1948	4363	8849	1550	1526	7308
1949	5296	10402	2047	2011	8361
1950	14562	24374	7365	2006	17018
1951	3643	7039	1489	1703	5553
1952	3050	6789	865	2076	5931
1953	4896	9178	1984	1773	7199
1954	18133	31820	8453	2374	23383
1955	25303	41438	13075	1633	28375
1956	649	1558	185	539	1374
1957	1122	3005	182	2019	2824
1958	8942	17065	3585	2633	13490
1959	3463	7629	990	2299	6646

TABLE 2 CONT'D

[cfs-day]

YEAR	Measured Streamflow (Congress St.)	Inflow (Continental Road)	Outflow (Avra Valley Road)	Infiltration When Inflow <250 cfs	Total Infiltration
1960	6572	12377	2777	1700	9609
1961	8212	13769	4320	1705	9450
1962	4157	7500	1098	792	5604
1963	8168	15445	3301	2614	12153
1964	19227	31809	9951	1964	21872
1965	471	1570	30	1298	1541
1966	21752	37992	10241	2933	27701
1967	2967	5740	1238	1739	4504
1968	19266	30302	11086	2672	19224
1969	2622	5407	866	1707	4545
1970	4376	8826	1676	1856	7155
1971	5926	11995	1920	3858	10081
1972	2634	5722	846	1734	4880
1973	6665	12345	2869	1810	9482
1974	3927	8170	1431	2393	6744
1975	2922	6610	696	2610	5921
1976	5211	10444	1847	2808	8603
1977	2685	6266	566	2705	5706
1978	28629	45357	16117	4367	29255
1979	39189	62225	21744	4900	40497
1980	2877	6920	687	2929	6238
1981	4777	10462	1364	3215	9108
TOTALS	492615	894965	222453	147752	672962
AVE	7697	13984	3475	2309	10515
AV AC-FT	15263	27730	6891	4579	20851

TABLE 3

SYNTHESIZED AVERAGE ANNUAL INFILTRATION FROM AVERAGE DAILY HISTORIC STREAMFLOW ON THE SANTA CRUZ RIVER -- RILLITO RIVER INFLOW

[cfs-day]

YEAR	Measured Streamflow (Oracle Road)	Inflow (Rillito River)	Outflow (Avra Valley Road)	Infiltration When Inflow <130 cfs*	Total Infiltration
1918	6372	5529	4164	0	
1919	18765	15308	11627	0	3681
1920	13117	8384	5357	925	3026
1921	21424	18606	14571	0	4035
1922	1526	948	634	0	314
1923	3363	1881	1221	124	659
1924	2902	1813	1214	120	599
1925	2379	1649	1035	121	615
1926	980	388	272	0	117
1927	2309	842	493	114	349
1928	647	308	197	0	111
1929	13625	11504	8864	0	2640
1930	5338	4034	2839	0	1195
1931	6073	4496	3256	0	1241
1932	7520	4472	3158	126	1314
1933	831	473	316	0	156
1934	1058	478	320	0	158
1935	9210	7265	5432	0	1833
1936	1816	1016	688	0	329
1937	2242	1193	843	0	350
1938	1258	829	593	0	237
1939	3466	2646	1993	0	653
1940	4211	3446	2554	118	891
1941	14999	11480	8134	483	3346
1942	1086	328	211	0	117
1943	1312	5698	301	117	268
1944	1608	1089	759	0	329
1945	1961	1090	823	0	266
1946	1532	784	533	0	251
1947	2075	1550	1119	0	431
1948	484	0	0	0	0
1949	1472	744	486	0	257
1950	3660	2790	1973	112	817
1951	2086	1441	942	116	499
1952	3104	1896	1195	126	701
1953	878	505	343	0	163
1954	6570	5146	3656	113	1490
1955	6200	5013	3363	248	1650
1956	159	0	0	0	0
1957	2125	1286	882	124	404
1958	5680	3181	2080	232	1101

* Actual value used in computer analysis was 128 cfs

TABLE 3 CONT'D

[cfs-day]

YEAR	Measured Streamflow (Oracle Road)	Inflow (Rillito River)	Outflow (Avra Valley Road)	Infiltration When Inflow <130 cfs	Total Infiltration
1959	2647	1561	1057	109	504
1960	6803	5043	3649	113	1395
1961	1369	1007	681	0	326
1962	2196	1491	1043	0	448
1963	2888	2099	1535	0	564
1964	4788	3509	2594	108	915
1965	518	0	0	0	0
1966	26855	21730	16040	124	5690
1967	955	625	358	124	267
1968	9206	6494	4753	126	1741
1969	356	0	0	0	0
1970	3718	2633	1983	0	651
1971	5620	4345	3148	0	1197
1972	1219	538	350	0	189
1973	14207	10905	7783	239	3123
1974	426	145	92	0	53
1975	280	121	0	121	121
TOTAL	270472	198651	143508	4381	55143
AVE	4663	3425	2474	248	951
AVE AC-FT	9247	6792	4906	492	1886

Streamflow on the upper Santa Cruz River and its tributaries is of two basic types. One type is a direct response to overland runoff from both short duration convective storms and longer duration frontal storms. The second type occurs in response to snow melt. This latter type is generally characterized by a lower flow and longer duration than the direct response type of streamflow. In recent years, there has been flowing sewage effluent in the Santa Cruz River beginning at the Roger Road Treatment Plant. These effluent inflows and resultant infiltration were not included in our analysis.

C. Sreamflow Distribution

The distribution of daily streamflow averages determined for the Rillito River using 58 years of data (1918 - 1975), and for the Santa Cruz River using 64 years of data at Congress St. and 58 years of data on inflow from the Rillito River is given in Tables 4, 5 and 6. This data shows a skew towards a larger number of smaller events. The percent of the total number of events and the total flow in each flow category is also given in terms of the total number of events and total flow over the historical record. The infiltration data included in these tables will be discussed in section IV.

The low flow values at or below which all surface flow would infiltrate by the downstream end of the Santa Cruz and the Rillito Rivers were determined during the 1984/1985 natural recharge event which will be discussed in the following section. For the Rillito River, this value was seen to be approximately 240 cfs. For the Santa Cruz River, it was estimated to be 250 cfs for flow originating from Continental Rd. The value of appoximately 130 cfs used for the Rillito River inflow into the Santa Cruz River was estimated from the percent of the 240 cfs low flow estimate for the 4.3 miles of the Rillito River which has identical infiltration capacity according to Burkham (1970). These low flow values were of interest because equations used to compute infiltration were only valid for situations where inflow rate exceeded infiltration rate.

Table 4 on the Rillito River shows that 22.6% of the total flow going into the Rillito River at the Craycroft Rd. bridge was from events with discharges below 240 cfs. Flows below 240 cfs comprised 80.3% of the recorded events between 1918 and 1975. This type of event occurred on the average 27.7 times per year.

The flow at Craycroft Rd. bridge was projected upstream from Burkham's (1970) relationships using the recorded flow taken at or near Oracle Rd. bridge. These relationships will be discussed in section IV. Only the larger flows would reach the Oracle Rd. bridge gaging station such that many additional smaller flow events at Craycroft Rd. would not be included in the record. In addition, the measurement of low flow events at a typical United States Geological Survey (USGS) gaging station is very difficult. Many times low flow events go unrecorded because the flow does not go down the area of streambed where the intake pipe to the water level recorder is located.

TABLE 4

SYNTHESIZED INFILTRATION FROM HISTORIC AVERAGE DAILY STREAMFLOW CATEGORIES ON THE RILLITO RIVER - CRAYCROFT ROAD INFLOW

Stream Flow Size Category [cfs]	# of Events	Stream flow [cfs]	Infil-tration [cfs]	% # of Events	% of Flow	% Flow Infil-trated	% Total Infiltration Within Category
LESS THAN 240*	1606	99882	99882	80.3	22.6	100	41.1
240 - 500	183	64198	33463	9.2	14.5	52	13.8
500 - 1000	118	83492	38366	5.9	18.9	46	15.8
1000 - 2000	60	82121	33424	3.0	18.6	41	13.7
2000 - 3000	12	29994	10939	.6	6.8	36	4.5
3000 - 4000	11	36567	12652	.6	8.3	35	5.2
4000 - 5000	6	27726	9020	.3	6.3	33	3.7
5000 - 6000	1	5315	1684	.1	1.2	32	.7
6000 - 7000	2	12594	3865	.1	2.9	31	1.6
TOTAL	1999	441888	243295				

* Actual amount used in the computer analysis was 242 cfs

Table 5 contains the streamflow from the Santa Cruz River record at Congress St. projected back upstream to the Continental Rd. gaging station. This record shows that 16.5% of the flow was below 250 cfs. This flow condition occurred in 76.3% of the events. The Santa Cruz River averaged 39 low flow events per year. The actual number of low flow events at Continental Rd. would be higher than those recorded at Congress St. for the same reasons outlined above.

To complete the picture of streamflow on the Santa Cruz River, Table 6 contains the data on the distribution of inflow from the Rillito River tributary flow. This record shows that 2.2% of the inflow was below 130 cfs and that 9.4% of the total number of inflow events were in the low flow regime.

The computer model described in Volume I of this report was designed to depict cumulative infiltration on the Rillito River from a synthetic hydrograph. It was run for six cases involving two potential channel widths. Table 7 gives the stage for the median of each flow category for these channel widths as determined using the form of Manning's equation given in Volume I for the Rillito River. A roughness coefficient of 0.04 was assumed in all cases. This stage determination was accomplished as one of the requirements of Task 2a. It shows that low flows are not very deep if the flow is spread across the channel. Table 7 was constructed for the median value of the average daily flow categories. The instantaneous flows for any given day would be comprised of higher and lower flows with corresponding higher and lower stages.

The synthetic hydrograph used for the computer model on the Rillito River is given as Figure 8 in Volume I. This hydrograph covers a period of 90 hours. The hydrograph was integrated with respect to the total volume for each successive 24 hour period and expressed in terms of average flow for the 24 hour period in cfs-days. This method of expression allows for a direct comparison with the natural streamflow as reported by the USGS. The synthetic hydrograph described in this manner is given in Table 8.

The total flow from the synthetic hydrograph used for the modelling study was 7,241 cfs-days or 14,363 ac-ft. The total flow was exceeded in only 10 of the 58 years of record on the Rillito River (see Table 1). However, when the hydrograph was broken down into a daily component, as would have been reported by the USGS, the streamflow in the interval in which Day 1 and Day 3 flows are contained would have occurred 47 times in the 58 year record. The streamflow in the interval corresponding to the largest flow (Day 2) occurred 7 times during the 58 year record. Table 8 also contains the median stage for the case of a 326 foot wide stream channel. The peak stage, corresponding to the peak flow on Day 2 of 10,000 cfs from the hydrograph (Figure 10, Volume I) would have produced a stage of 4.8 feet, as indicated by Figure 11, Volume I.

TABLE 5

SYNTHESIZED INFILTRATION FROM HISTORIC AVERAGE DAILY STREAMFLOW CATEGORIES ON THE SANTA CRUZ RIVER -- CONTINENTAL ROAD INFLOW

Stream Flow Size Category [cfs]	# of Events	Stream flow [cfs]	Infil-tration [cfs]	% # of Events	% of Flow	% Flow Infil-trated	% Total filtration Within Category
LESS THAN 250	2506	147752	147752	76.3	16.5	100	22.0
250-500	333	119695	102637	10.1	13.4	86	15.3
500-1000	244	170349	133189	7.4	19.0	78	19.8
1000-2000	131	184359	129816	4.0	20.6	70	19.3
2000-3000	33	76701	50010	1.0	8.6	65	7.4
3000-4000	14	48125	29468	.4	5.4	61	4.4
4000-5000	8	35086	20642	.2	3.9	59	3.1
5000-6000	3	15835	9035	.1	1.8	57	1.3
6000-8000	5	32105	17726	.2	3.6	55	2.6
8000-10000	3	26206	13732	.1	2.9	52	2.0
10000-15000	3	38752	18955	.1	4.3	49	2.8
TOTALS	3283	894965	672962				

TABLE 6

SYNTHESIZED INFILTRATION FROM HISTORIC AVERAGE DAILY STREAMFLOW CATEGORIES ON THE SANTA CRUZ RIVER -- RILLITO RIVER INFLOW

Streamflow Size Category [cfs]	# of Events	Stream-flow [cfs]	Infil-tration [cfs]	% # of Events	% of Flow	% Flow Infil-trated	% Total Infiltration Within Category
LESS THAN 130*	37	4381	4381	9.4	2.2	100.0	7.9
130 - 500	248	63078	20376	63.1	31.8	32.3	37.0
500 - 1000	63	42869	11478	16.0	21.6	26.8	20.8
1000 - 2000	27	37267	8654	6.9	18.8	23.2	15.7
2000 - 3000	10	22888	4819	2.5	11.5	21.0	8.7
3000 - 4000	6	19438	3820	1.5	9.8	19.6	6.9
4000 - 5000	2	8729	1617	0.1	4.4	18.5	2.9
TOTAL	393	198651	55143				

* Actual amount used in computer analysis was 128 cfs

TABLE 7

MANNING'S EQUATION CALCULATION OF STAGE ON RILLITO FOR MEDIAN OF FLOW CATEGORIES AT TWO MODEL WIDTHS

Flow Category [cfs]	Median [cfs]	Depth [ft] for Bottom Width = 202ft	Depth [ft] for Bottom Width = 326ft
240*- 500	371	0.90	0.67
500 - 1000	750	1.37	1.03
1000 - 2000	1500	2.07	1.56
2000 - 3000	2500	2.82	2.12
3000 - 4000	3500	3.44	2.59
4000 - 5000	4500	4.00	3.01
5000 - 6000	5500	4.51	3.39
6000 - 7000	6500	4.99	3.75

* Actual amount used in manning calculation to determine median was 242 cfs

TABLE 8

COMPARISON OF 90 HR SYNTHETIC HYDROGRAPH WITH HISTORIC RECORD ON RILLITO RIVER

Event	90 Hr Hydrograph [cfs-day]	Flow Category [cfs-day]	Median Stage 326 ft width	# of Events in 58 Yrs	% of Total # of Events
Day 1	1482	1000 - 2000	2.07	47	2.4
Day 2	3837	3000 - 4000	3.44	7	0.4
Day 3	1806	1000 - 2000	2.07	47	2.4
Day 4	116	< 240*	--	1654	82.7
Total	7241				

* Actual amount used in the comparison analysis was 242 cfs.

III. 1984/1985 Natural Recharge Event

The following section consists of the analysis called for in Subtask 2, part 2, pertaining to recently collected video data and streamflow measurements on the Winter/Spring 1985 recharge event on the main stream channels in the Tucson basin.

A. Study Area

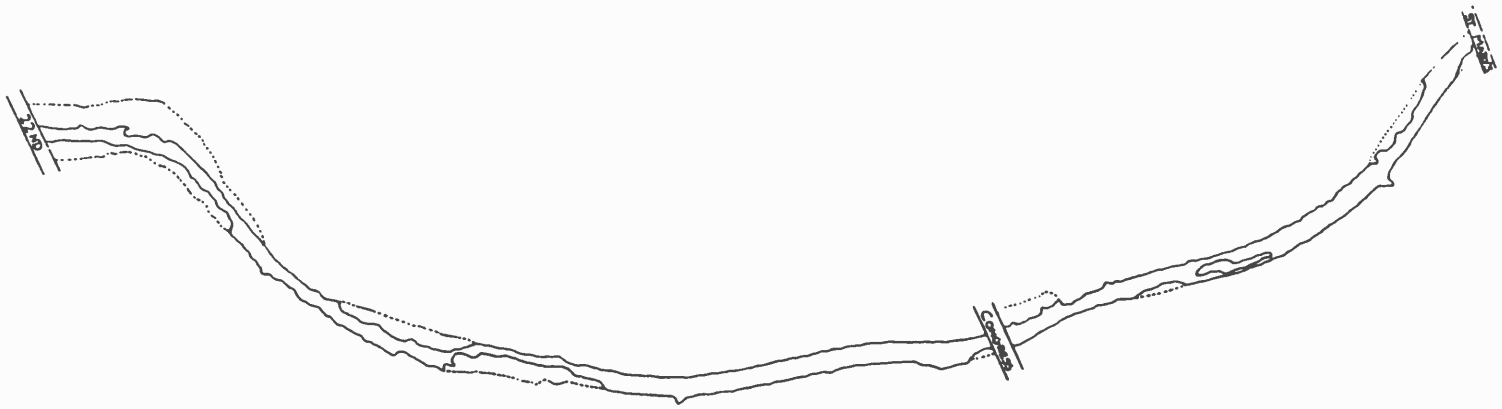
The Rillito River, Canada Del Oro, and the main stem of the Santa Cruz River, all found in the Tucson basin, comprise the stream system analyzed in this study of the 1984/1985 natural recharge event. Pantano and Tanque Verde Washes, also part of this system, were not analyzed. The Santa Cruz River, which flows north from the international border, is the major surface drainage in the basin, with the Rillito River and Canada Del Oro constituting tributaries to the Santa Cruz River. For the purpose of analysis, four reaches have been defined. These reaches are shown on the map of the study area -- Figure 1.

Reach 1 is made up of that portion of the Santa Cruz River between Continental Rd. in Green Valley, and Camino Del Cerro Rd. in Tucson. During the flow event under study, surface flow appears to have completely infiltrated by the time it reached the Camino Del Cerro Rd. crossing of the Santa Cruz River. Reach 2 begins at Camino Del Cerro and extends north to Avra Valley Rd. Flow in this region is largely due to treated effluent releases at the Roger Rd. and Ina Rd. treatment facilities. The northern limit of the Santa Cruz River study area, and the end of Reach 2, is at Avra Valley Rd. in an area known as Rillito Narrows. Here, the Tucson Mountains to the southwest and the Tortolita Mountains to the northeast converge and create a narrow zone which serves to restrict groundwater flow out of the basin.

Reach 3 comprises the entire Rillito River, from Craycroft Rd. to just west of I-10 where it joins the Santa Cruz River. Canada Del Oro, from I-89 to the tributary's confluence with the Santa Cruz River, is Reach 4. In order to allow for a more detailed analysis of smaller stream intervals, a number of sub-reaches have also been defined within each of the four reaches. The length of these intervals has no particular hydrologic significance, but corresponds to the length of the digitizing surface used to determine channel areas. Reductions of the channel area maps for Reaches 1 through 3 appear as Figures 2 - 4. Only that portion of the Santa Cruz River in Reach 1 north of 22nd Street, the portion that flows through the city of Tucson, is included as a figure in this report. Likewise, the map of Reach 4, Canada Del Oro, is considered to be of limited interest to the study and is not included here. On Canada Del Oro only two of the six sub-reaches had any surface flow during the period of study, and that flow which was present occupied only 8 and 10% of the available channel area respectively (refer to Table 12).

B. Theory

The basic theory behind this method of infiltration rate computation is most easily described using the analogy of a seepage pond. When an



Wetted Channel Area

Total Channel Area

Dry Region within Wetted Area

1,500 feet

Fig. 2a. Feb 11th, 1985 Streambed Conditions. Santa Cruz River. Reach 1, Sub-reach 4.

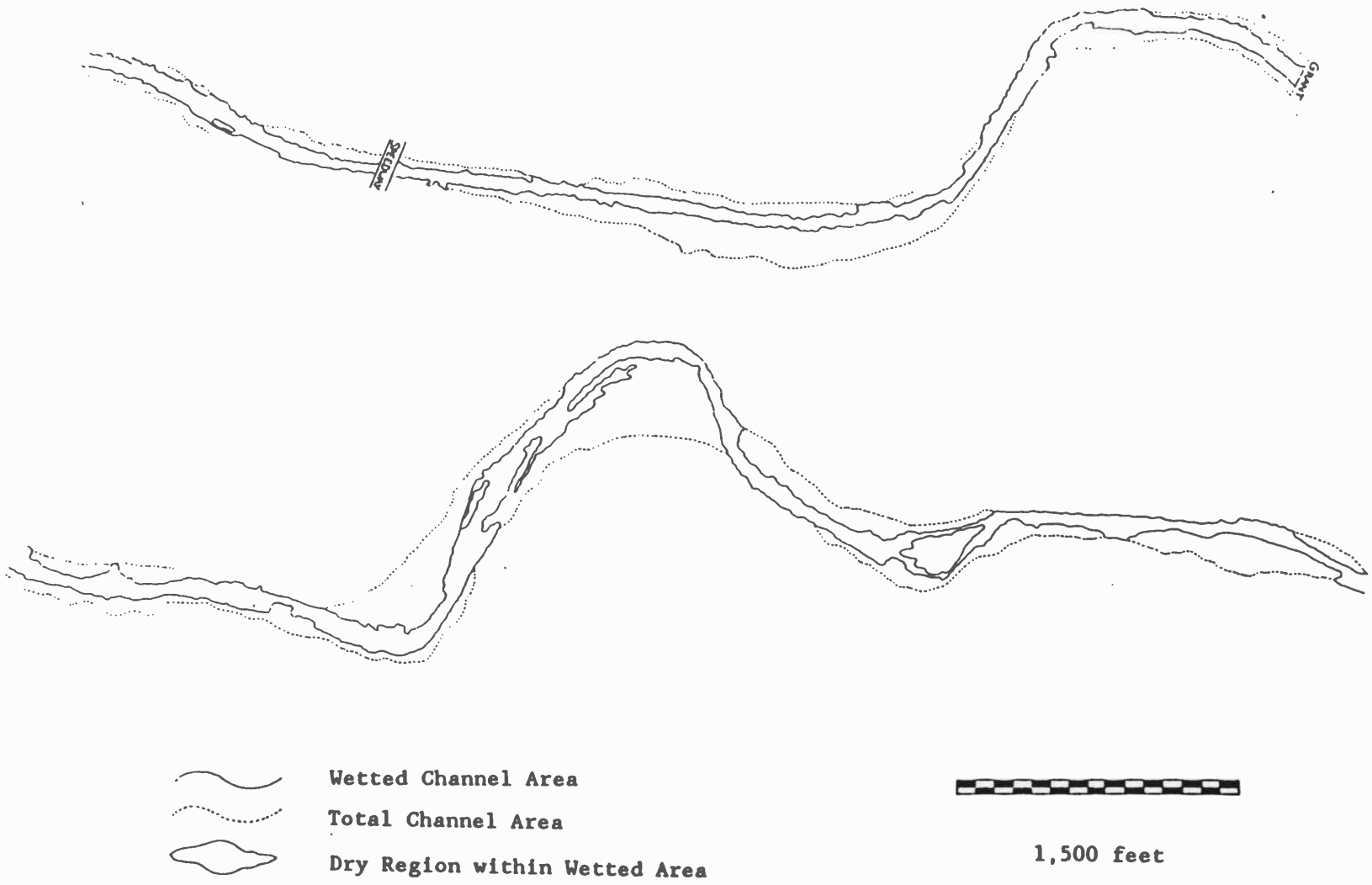
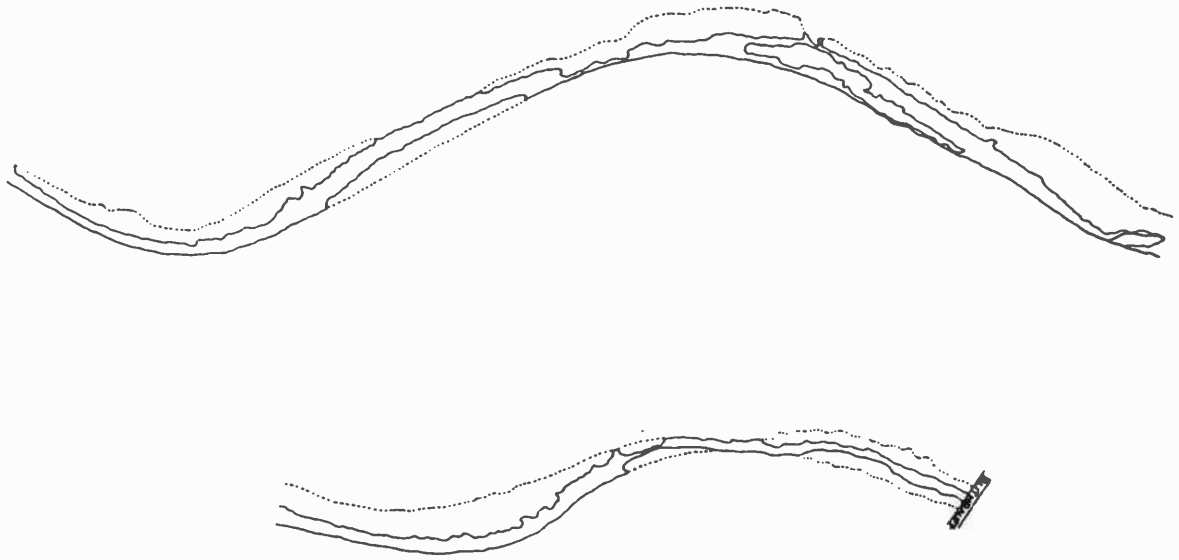


Fig. 2b. Feb 11th, 1985 Streambed Conditions. Santa Cruz River. Reach 1, Sub-reach 5.



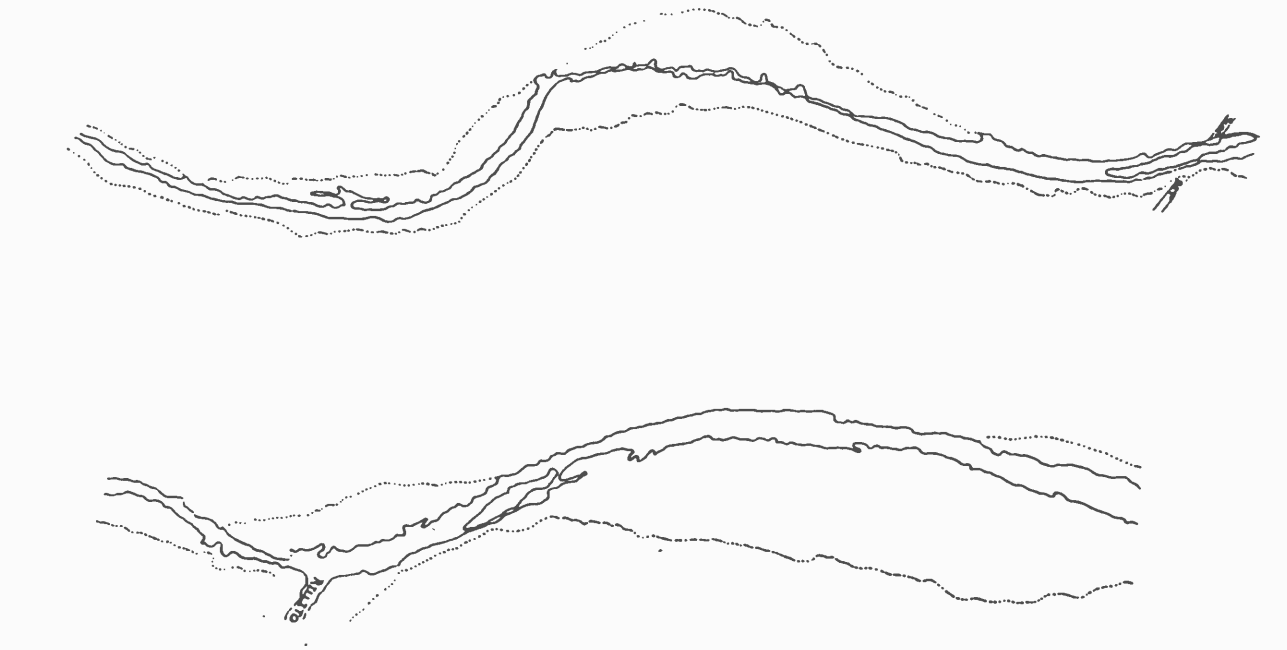
Wetted Channel Area

Total Channel Area

Dry Region within Wetted Area

1,500 feet

Fig. 2c. Feb 11th, 1985 Streambed Conditions. Santa Cruz River. Reach 1, Sub-reach 5.



Wetted Channel Area

Total Channel Area

Dry Region within Wetted Area

1,500 feet

Fig. 3a. Feb 11th, 1985 Streambed Conditions. Santa Cruz River. Reach 2, Sub-reaches 1 & 2.

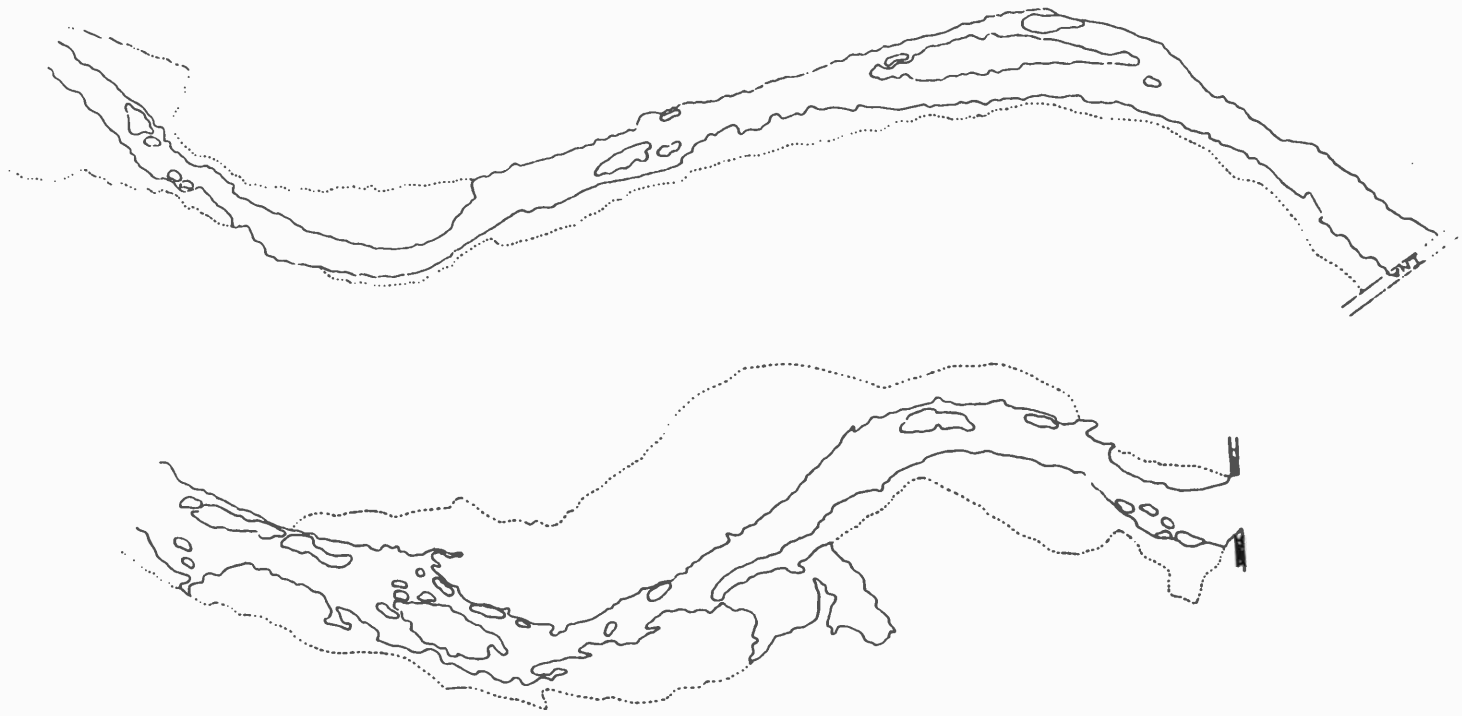


Fig. 3b. Feb 11th, 1985 Streambed Conditions. Santa Cruz River. Reach 2, Sub-reaches 3 & 4.

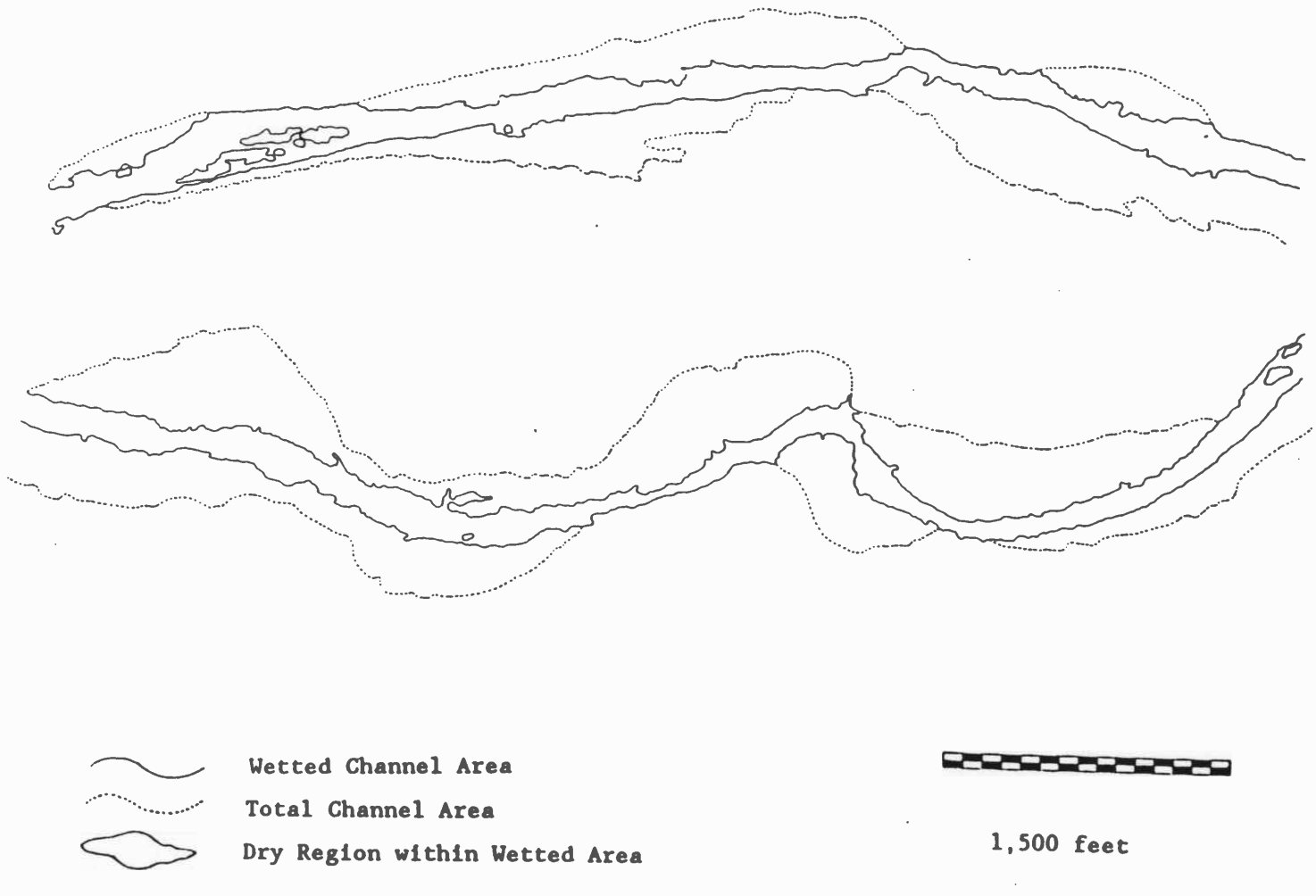
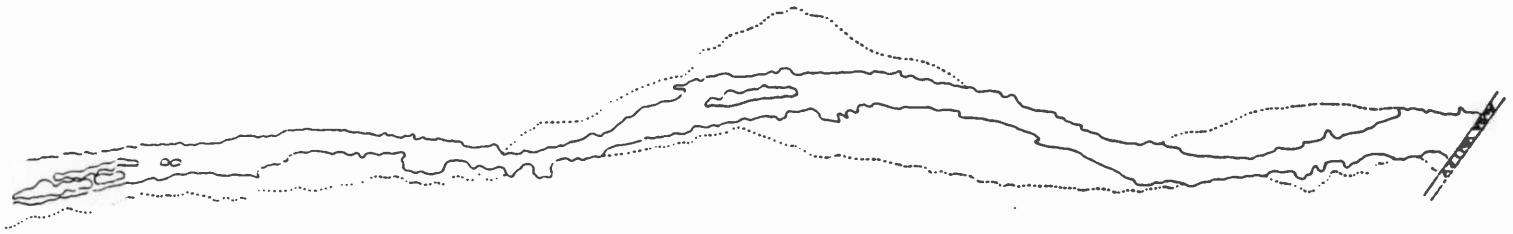


Fig. 3c. Feb 11th, 1985 Streambed Conditions. Santa Cruz River. Reach 2, Sub-reaches 5 & 6.



Wetted Channel Area

Total Channel Area

Dry Region within Wetted Area

1,500 feet

Fig. 3d. Feb 11th, 1985 Streambed Conditions. Santa Cruz River. Reach 2, Sub-reach 7.

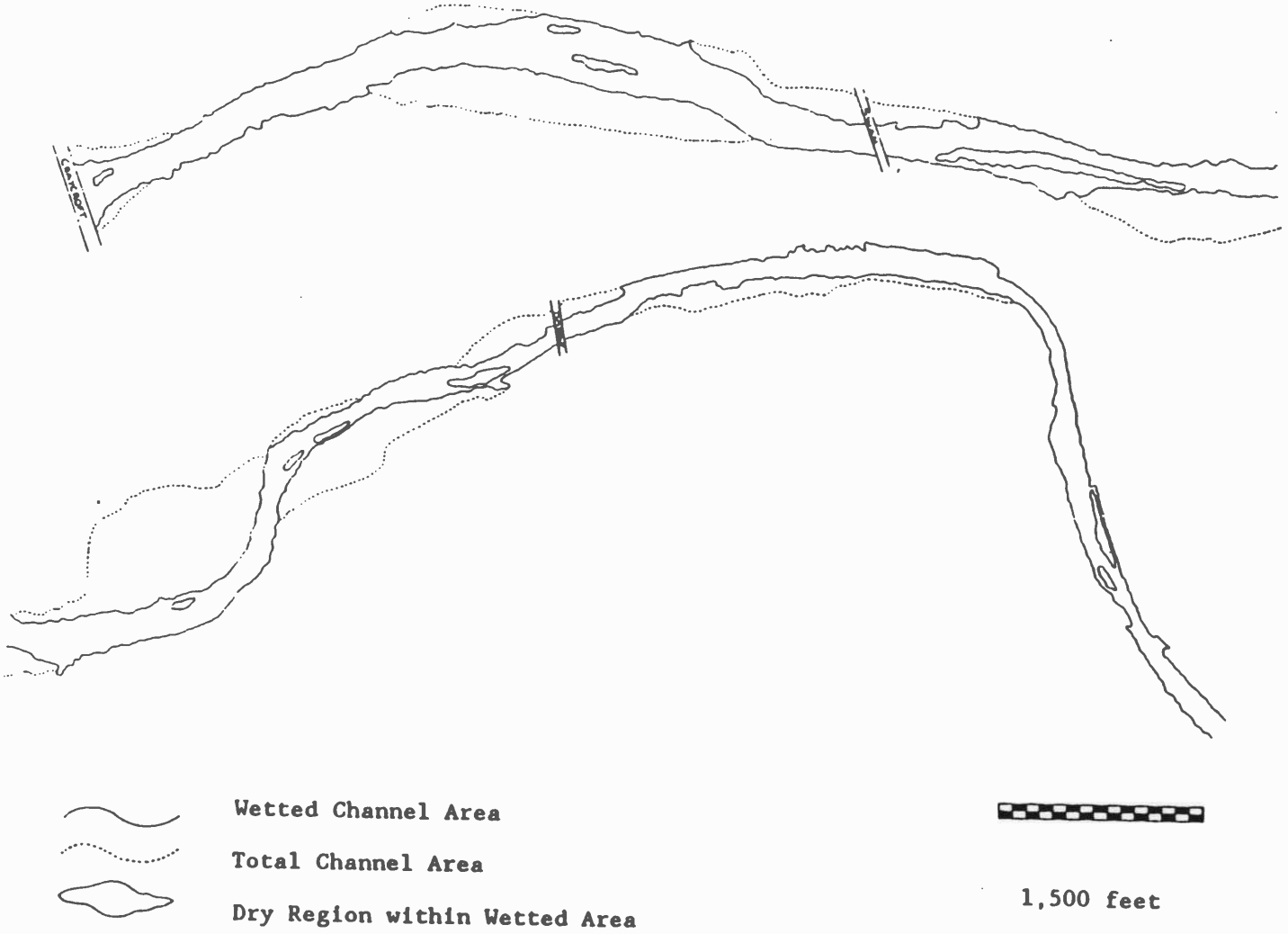
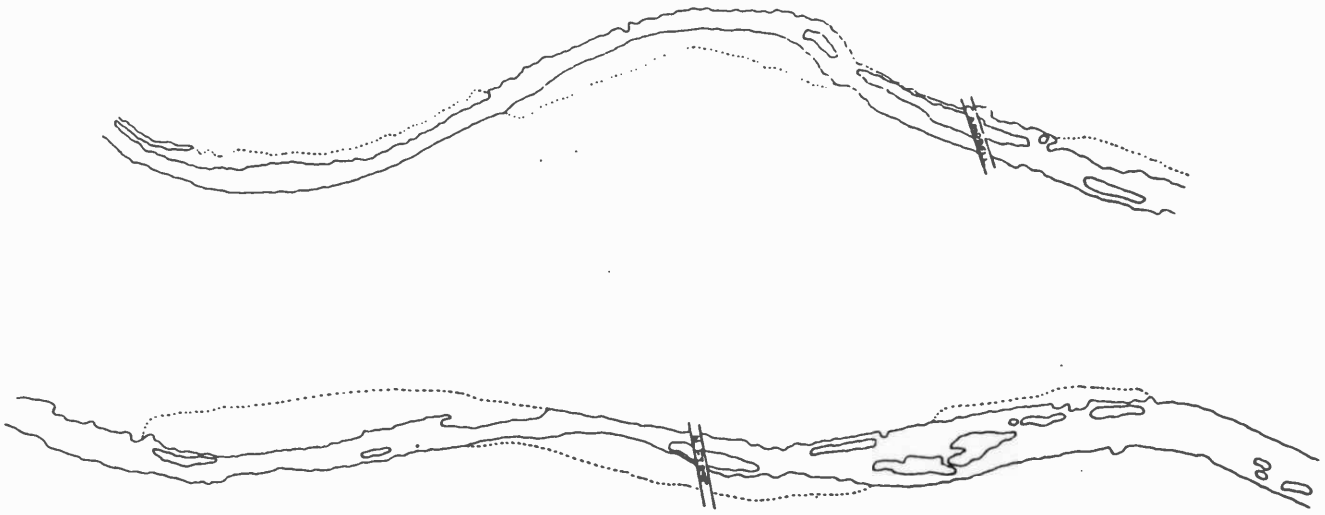


Fig. 4a. Feb 11th, 1985 Streambed Conditions. Rillito River. Reach 3, Sub-reaches 1 & 2.



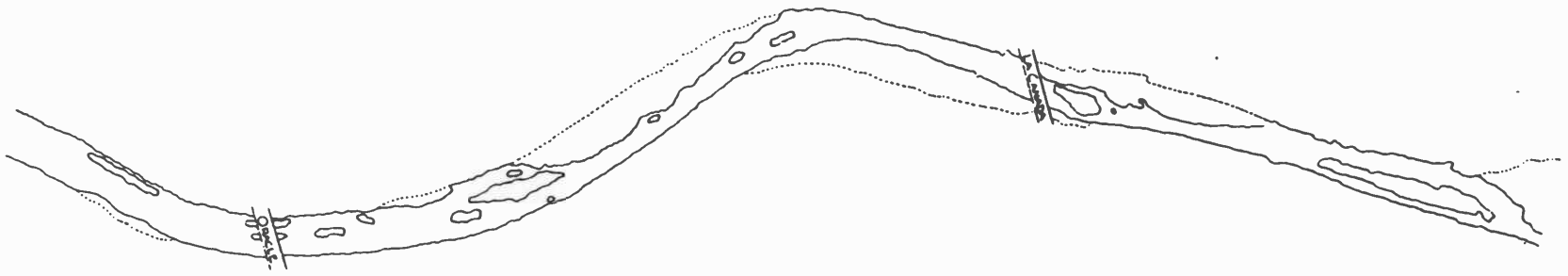
Wetted Channel Area

Total Channel Area

Dry Region within Wetted Area

1,500 feet

Fig. 4b. Feb 11th, 1985 Streambed Conditions. Rillito River. Reach 3, Sub-reaches 3 & 4.



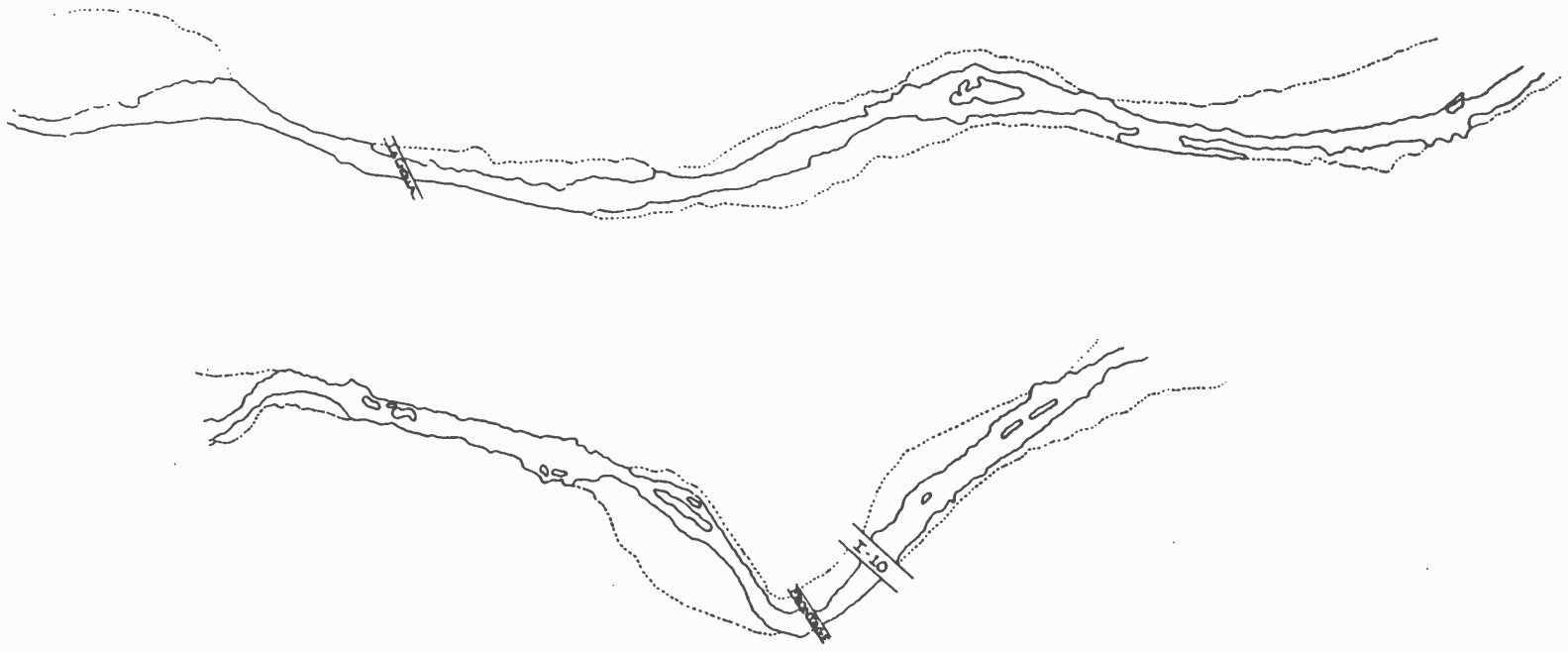
Wetted Channel Area

Total Channel Area

Dry Region within Wetted Area

1,500 feet

Fig. 4c. Feb 11th, 1985 Streambed Conditions. Rillito River. Reach 3, Sub-reach 5.



Wetted Channel Area

Total Channel Area

Dry Region within Wetted Area

1,500 feet

Fig. 4d. Feb 11th, 1985 Streambed Conditions. Rillito River. Reach 3, Sub-reaches 6 & 7.

area of the land surface is ponded with water, downward percolation of water into the unwetted soil occurs due to two driving forces: the suction gradient (dS/dz) arising from moisture (M) variation downward in the profile, and the gravitational gradient (dZ/dz) arising from the change in elevation from a reference datum as water seeps downward. In terms of Darcy's law,

$$\begin{aligned} q &= -K(M)\ dH/dz \\ &= -K(M)\ (dS/dz + dZ/dz) \\ &= -K(M)\ (dS/dz + 1) \end{aligned} \qquad (1)$$

where q is the specific flux or Darcian velocity and K(M) is the unsaturated hydraulic conductivity of the soil, which is a function of soil moisture content (M). With time the soil moisture content eventually becomes constant with depth in a uniform soil profile and steady state infiltration conditions are approached. Under these conditions, the soil suction gradient (dS/dz) goes to zero, and the only remaining driving force is the unit gravitational gradient. The governing flow equation becomes,

$$q = -K(M) \qquad (2)$$

In the case of streamflow, this flux is the infiltration rate (i), or rate at which flow losses occur. Since Darcy's law defines the specific flux as the discharge divided by the cross-sectional area, the discharge used in the case of streamflow losses is the difference between that measured upstream and downstream, and the area becomes the wetted surface of the stream between these two points. The resulting flow equation, from which infiltration rates in this study were obtained, is

$$q = i = (Q_{upstream} - Q_{downstream}) / A_{surface} \qquad (3)$$

In this way, knowledge of two discharge values and the wetted surface area between them allows one to calculate the infiltration rate and volume over any stream interval of interest. For both the Santa Cruz and the Rillito, an upstream gaged discharge was available, and a downstream value of zero was assumed, as almost the entire flow was observed to have infiltrated by the downstream end of both reaches.

C. Runoff Event

The analyzed streamflow event began in the middle of December 1984 and persisted until the beginning of April 1985 on both the Santa Cruz and Rillito Rivers. Winter frontal rainfall (Table 9) maintained continuously measureable flows at the Continental Rd. gaging station beginning December 18, 1984 (Table 10). On February 14, 1985, USGS attempted to gage the Santa Cruz River at Congress St. It was discovered that no flow remained by this date at this point on the stream. Measureable flow actually persisted downstream of Continental Rd. until April 1, 1985 -- a total of 105 days or almost 4 months.

TABLE 9

RAINFALL DURING PERIOD OF STREAM FLOW RECHARGE
DEC 1984 TO MAR 1985

[inches]

Date	WRRC Field Lab	Kitt Peak	Oracle	Santa Rita
DEC 1984				
12-3	0.00	0.00	0.00	1.11
12-4	0.86	1.02	0.42	0.12
12-5	0.04	0.00	0.02	0.00
12-8	0.07	0.20	0.06	0.00
12-10	0.00	0.00	0.03	0.69
12-11	0.31	1.15	0.83	0.51
12-12	0.17	0.15	0.49	0.46
12-13	0.38	0.70	1.44	0.21
12-14	0.30	0.20	0.03	0.00
12-15	0.01	0.10	0.01	0.21
12-19	0.02	0.05	0.06	0.00
12-20	0.09	0.43	0.05	0.21
12-26	0.00	0.00	0.00	0.46
12-27	0.04	0.32	1.24	2.38
12-28	0.77	1.65	0.53	0.59
12-29	0.25	0.20	0.57	0.06
JAN 1985				
1-7	0.00	0.00	0.00	0.10
1-8	0.22	0.61	1.17	0.48
1-9	0.15	0.25	0.30	0.00
1-13	0.06	0.05	0.26	0.15
1-14	0.00	0.07	0.03	0.11
1-15	0.00	0.00	0.00	0.60
1-16	0.05	0.05	0.08	0.00
1-23	0.00	0.36	1.06	0.00
1-24	0.79	0.73	0.43	0.34
1-25	0.00	0.00	0.03	0.05
1-26	0.11	0.40	0.89	0.77
1-27	0.38	0.00	0.07	0.01
1-28	0.00	0.00	0.02	0.00
1-29	0.00	0.08	0.02	0.12
1-30	0.04	0.05	0.47	0.05
1-31	0.00	0.00	0.30	0.00
FEB 1985				
2-2	0.00	0.00	0.00	0.03
2-3	0.26	0.53	0.42	0.09
2-4	0.37	0.63	1.01	0.77
2-5	0.25	0.60	0.16	0.00
2-10	0.00	0.00	0.01	0.00
2-20	0.00	0.00	0.00	0.05
2-21	0.00	0.65	0.21	0.60
2-22	0.25	0.00	0.12	0.04

TABLE 9 CONT'D

Date	WRRC Field Lab	Kitt Peak	Oracle	Santa Rita
2-23	0.00	0.00	0.07	0.00
2-27	0.00	0.00	0.42	0.17
2-28	0.68	0.00	0.08	0.00
3-2	0.00	0.00	0.00	0.03
3-3	0.00	0.02	0.07	0.00
3-12	0.01	0.00	0.08	0.00
3-14	0.00	0.00	0.00	0.05
3-15	0.11	0.00	0.21	0.00
3-18	0.00	0.00	0.00	0.02
3-19	0.00	0.00	0.05	0.00
3-28	0.00	0.00	0.00	0.31
3-29	0.15	0.30	0.52	0.00

TABLE 10

USGS GAGING OF THE SANTA CRUZ AT CONTINENTAL RD.
DEC 1984 TO MAR 1985

[Discharge, cfs]

Day	Dec 84	Jan 85	Feb 85	Mar 85
1	.00	382	270	60
2	.00	317	211	50
3	.00	272	188	45
4	158	210	198	45
5	4.0	191	632	24
6	1.0	171	806	12
7	.00	102	603	10
8	.00	73	428	10
9	.00	62	284	10
10	.00	54	284	9
11	.00	45	278	9
12	.00	43	100	9
13	190	48	93	8
14	280	33	96	8
15	6.8	34	90	8
16	.14	31	85	8
17	.00	18	80	7
18	22*	24	80	7
19	30	32	75	7
20	507	22	75	7.1
21	837	23	118	5.7
22	386	19	119	4.3
23	293	24	107	2.1
24	212	132	109	2.9
25	160	624	100	3.0
26	83	583	90	1.5
27	171	3040	80	2.1
28	5220	896	70	1.8
29	2000	702		.01
30	831	504		4.5
31	501	355		2.6*
Total	11892.94	9066.00	5747.00	383.61
Mean	384.00	292.00	205.25	12.40

* Continuous flow on the Santa Cruz from Dec.18, 1984 to April 1, 1985

The last time a comparable period of continuous flow was observed in the basin was in 1915, when measurable flow was recorded for 108 days between December 20th and April 6th at the Congress St. gaging station. In the 70 years of streamflow record between 1915 and 1985, no event has equalled or exceeded the duration of the Winter/Spring 1985 flow event on the Santa Cruz River (Appendix B). The observed frequency of an event of this duration is therefore 1 in 70, or 1.43%.

With no permanent gaging station on the Rillito River, the beginning of flow on this stream had to be estimated from the arrival time of discharge pulses recorded at a flood warning gage on Sabino Creek, an upstream tributary. From this record, flow was estimated to have begun around December 12, 1984 and did not recede above Craycroft Rd. until around April 10, 1985 -- a total of approximately 121 days.

Based on an examination of historic streamflow data on the Rillito River, similar to that done for the Santa Cruz River, the frequency of the duration of the Winter/Spring 1985 flow event on the Rillito River was also estimated. An analysis of continuous historic streamflow records from January 1918 to September 1975 (when the station on Rillito River was removed), plus partial records going back to 1911 (Appendix B), reveals that the longest duration of flow on the Rillito River was 50 days in 1916. No flows of the duration observed in 1984/1985 were ever recorded (Appendix B). This 65 year historic record was extended to the present based on visual observation that no runoff events with durations exceeding that of the 1985 flow occurred between September 1975 and Winter 1985. Using historic data to 1975 and visual observation information between 1975 and 1985, a frequency of no greater than 1 in 75, or 1.33%, was estimated for the 121 day Rillito River streamflow.

On February 11, 1985 a videotape of the streamflow along all reaches in the study area was taken from an aircraft flying over the streams. This video record of the flow constitutes the data base used to compute the stream parameters of interest. In order to compute infiltration rates and volumes of recharge from this data, it was necessary to have points of known discharge upstream and downstream on each of the reaches. An explanation of how these control points were defined follows.

The mean daily discharge at Continental Rd., the beginning of Reach 1, was 278 cfs on February 11, 1985 (Table 10). Field observations indicate that the flow measured at Continental Rd. had almost completely infiltrated by the time it reached the sewage treatment facility located just upstream from Camino Del Cerro Rd. Though maps of the February 11th flow (Figure 2) still show some wetted area at this downstream point, it was not possible from the video to discern the extent of the flow. In spite of this limitation, a decrease in the wetted surface area is definitely seen proceeding downstream to the end of Reach 1. For the purposes of this study, discharge at the downstream limit of Reach 1 is assumed to be zero. This assumption makes possible the determination of an approximate infiltration rate and volume of recharge per day for the reach in the absence of downstream gaging. The flow losses over the measured wetted area were computed using the upstream recorded discharge of 278 cfs and assuming a discharge of zero at the downstream endpoint of Reach 1.

A further implication of assuming discharge to be zero at Camino Del Cerro is that flow in Reach 2 on February 11, 1985 was largely due to the discharge of treated sewage effluent from the two wastewater facilities in the area: Roger Rd. Wastewater Treatment Plant and Ina Rd. Water Pollution Control Facility. Tributary flow on the Rillito River was assumed to have entirely infiltrated prior to its confluence with the Santa Cruz River on the study date, and it was not contributing substantial surface inflow into Reach 2. Average discharge from the two plants on February 11th was 40.29 cfs from Roger Rd. and 29.92 cfs from the Ina Rd. facility. As this effluent flow persisted beyond the downstream limit of Reach 2 at Avra Valley Rd., no point at which surface flow went to zero is available for this reach. Due to this lack of downstream control, no infiltration rate or volume of recharge could be determined for Reach 2.

The USGS does not routinely gage the Rillito River within Reach 3, and automatic recording devices are no longer maintained. In order to obtain a quantitative estimate of flow along Reach 3 during the study period, a Water Resources Research Center field group gaged the Rillito River at two locations. On February 11, 1985 the stream was gaged at Camino Del Terra (east of I-10) and a discharge of 55.7 cfs was obtained. Further downstream, at the Rillito River's confluence with the Santa Cruz River and the end of Reach 3, flow had almost entirely infiltrated and discharge was effectively zero on this day. In fact, the February 11th videotaping flight had been delayed for over a week while waiting for Rillito River streamflow to gradually recede to the point where almost the entire volume was being recharged prior to reaching the Santa Cruz. Under these circumstances, streamflow loss rates may be computed by assuming a downstream discharge of zero and simply dividing the upstream discharge by the wetted surface area (see eq. 3).

On February 12th, the day after the videotaping flight, the Rillito River was gaged at Craycroft Rd. by the Water Resources Research Center field group to determine an upstream discharge value. This gaging yielded a discharge of 241.6 cfs. On special request, the USGS gaged the Rillito River at Craycroft Rd. on February 14th in order to verify the accuracy of Water Resources Research Center measurements. A discharge of 207 cfs was obtained by the USGS, which is consistent with the expected slow decline in flow over a two day period. Two lines of evidence suggest that flows on the Rillito River were receding at this point in the recharge season: 1) visual observation and 2) upstream gaging at Sabino Canyon Rd. bridge. Flow volumes were observed to decrease between February 12th and the 14th. Further, during the study period, from late February to early April, the approximate location of the advancing or retreating flow front was tracked by accessing the channel from various bridges and intersecting streets. A record of these observations appears as Table 11. Though monitoring did not commence until later in February 1985, the general decline of streamflow from this point on is indicated.

TABLE 11

RECORD OF TERMINAL POSITION OF FLOW ON THE RILLITO RIVER
WINTER/SPRING 1985

Date	Location of Flow Termination
Retreat	
2-28	400 yds east of Oracle Rd.
3-1	450 yds east of Oracle Rd.
3-4	Country Club Rd.
3-5	50 yds east of Country Club Rd.
Brief Advance	
3-8	Country Club Rd.
3-12	Tucson Blvd.
3-13	300 yds east of 1st Ave.
Retreat	
3-14	400 yds west of Campbell Ave.
3-15	25 yds east of Tucson Blvd.
3-18	200 yds west of Dodge Blvd.
3-20	1000 yds east of Alvernon Way
3-22	450 yds west of Columbus Blvd.
3-24	300 yds east of Columbus Blvd.
3-26	800 yds east of Columbus Blvd.
3-27	300 yds west of Swan Rd.
3-28	100 yds west of Swan Rd.
3-30	50 yds east of Swan Rd.
4-1	300 yds east of Swan Rd.
4-3	700 yds east of Swan Rd.
4-5	1000 yds east of Swan Rd.
4-8	800 yds west of Craycroft Rd.

As further evidence of declining flow in the period following the videotaping flight, gaging conducted by a Water Resources Research Center technician upstream on the Rillito River at Sabino Canyon bridge demonstrated a substantial decrease in discharge between February 15th and February 19th. Discharge decreased from 182.1 cfs to 119.1 cfs over the four day period. Though none of this evidence is in itself completely conclusive, in combination the information supports the assumption that post-February 12th flows showed a gradual decline. In this way, infiltration rate and volume of water infiltrated were computed for Reach 3 by using the February 12th discharge as a good approximation of upstream discharge on February 11th, and assuming the flow to be zero at the confluence with the Santa Cruz River.

Reach 4, Canada Del Oro, has no gaging record for the period of interest. Visual observation suggests that flows were less substantial than those measured for the Rillito or the Santa Cruz Rivers. The entire flow volume had recharged by the time it reached La Canada Rd., and no flow past this point was occurring on February 11, 1985. Without an upstream discharge value, an infiltration rate and volume cannot even be estimated for this reach. The total available flow area is still of interest as a means of assessing recharge potential for comparison between stream reaches in the basin.

In order to utilize the simplified relationship between discharge and infiltration outlined in the preceeding section (see equation 3) we must demonstrate that steady state infiltration conditions were established for both the Santa Cruz and the Rillito Rivers on February 11, 1985, the day when the videotape was taken. The term steady state, as used in this report, refers to infiltration conditions that develop with time in a soil profile through which surface water is percolating. In a homogeneous soil, moisture content ultimately becomes uniform with depth above the wetting front and downward flow occurs only under the influence of gravitational forces. Thus, the suction gradient approaches zero and the governing flow equations are greatly simplified (see equations 1 and 2).

In the absence of supporting evidence from a streamside monitor well fitted with continuous recording equipment, steady state infiltration conditions on the Santa Cruz River may only be conjectured from streamflow records. As discharge data indicates (Table 10), flow on the Santa Cruz River began to recede immediately following February 11th. Since measureable and often higher discharge flows persisted for 55 days prior to the study date, it is likely that steady state infiltration conditions were established on the Santa Cruz River at this point in the recharge season. The assumption made here is that such conditions were indeed established. For the Rillito River, the assumption is based on groundwater level hydrographs.

Figure 5 is the continuous water level record from Tucson Water recording well C91, located on the north bank of the Rillito River near Columbus Blvd. From this record it is clear that steady state infiltration conditions were indeed achieved on the Rillito River during the Winter/Spring 1985 flow event. A plateau of almost constant high groundwater levels, more than 20 feet above the early December 1984 measurements, continues for close to three months. This indicates that the hydraulic conditions governing flow through the deep profile were no

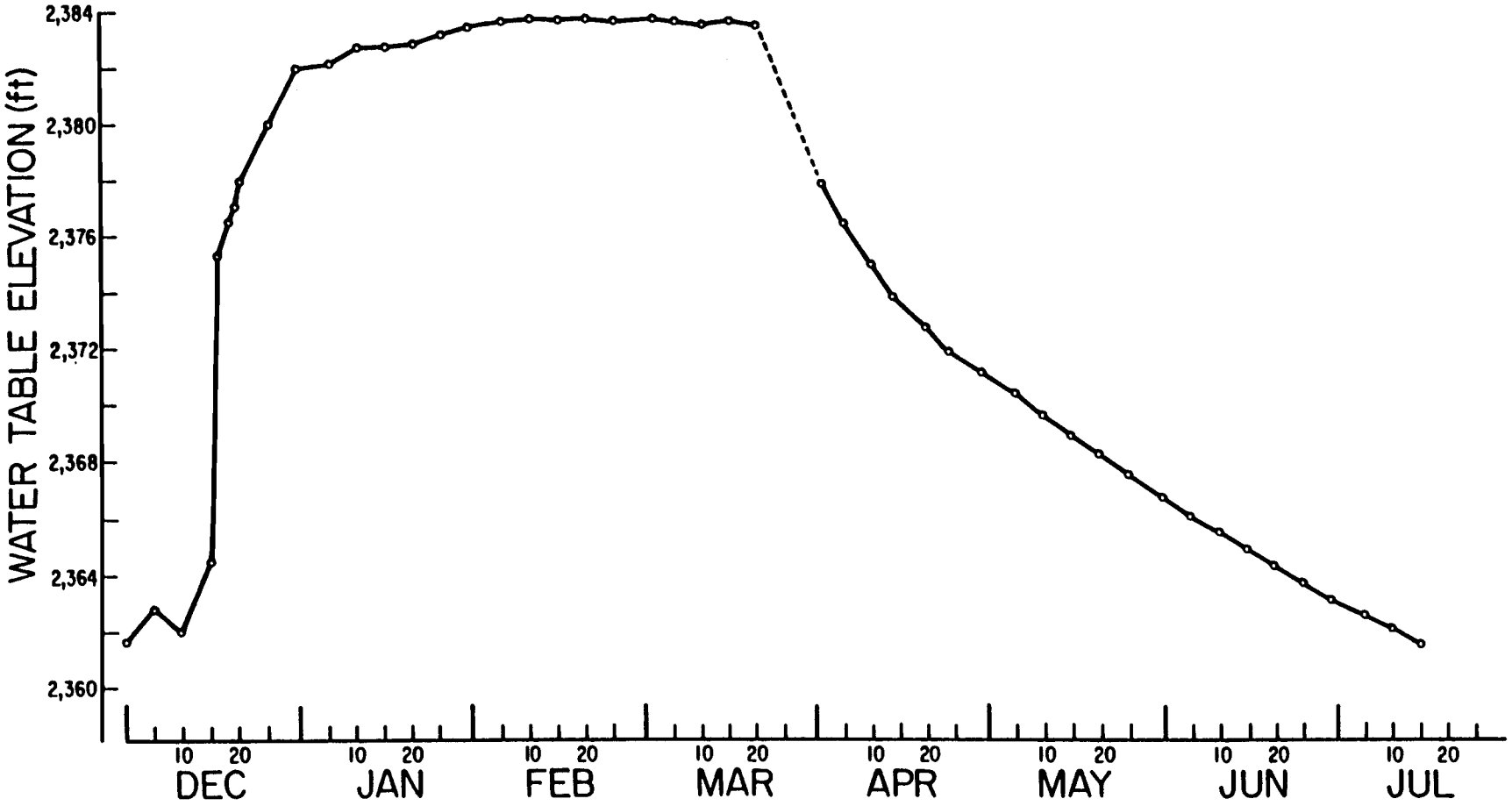


Figure 5. 1984–85 Groundwater Level Hydrograph. Recording Well C-91.

longer changing appreciably with time, and that the necessary conditions favoring steady state infiltration existed on the Rillito River.

D. Procedure

Aerial video imagery, obtained by flying over the stream reaches and photographing the February 11th, 1985 flow event, comprises the data base used in this study. A consideration in deciding to employ this innovative technique was that it proved to be lower in cost than the other available techniques. During the video filming, an effort was made to maintain a constant vertical distance between camera and stream, in order to preserve image scale. Still photographs were then taken of the video at overlapping intervals from a camera mounted a fixed distance in front of the video screen. Slides made from these stills were subsequently projected on a mapping surface, and a map was prepared delineating the maximum stream width, the currently active flow region, and any in-stream sand bars where wetting had not occurred. Reductions of these maps appear as Figures 2 - 4. A field survey was later made in order to verify any questionable boundaries.

In order to obtain a map scale, river crossing bridges and large streamside features were measured in the field. An average of the various scaling factors thus obtained was used for each case, resulting in a separate scale for each reach. The scales obtained for Reaches 1 and 2, the lower and upper Santa Cruz River, were very close. This indicates that the aircraft was able to keep its altitude fairly constant while following the Santa Cruz River north through the valley. Scales computed for the two tributary reaches, the Rillito River and Canada Del Oro, were also very similar to each other, but differed from those obtained for the Santa Cruz River. These scale changes indicate an increase in the flying elevation along Reaches 3 and 4, presumeably in response to the higher land elevation as the aircraft neared the basin's edge.

Digitizing of the wetted area and total available stream area for each of the defined sub-reaches was the next step. A Numonics digitizer, with built in area measurement capabilities, was used to insure accurate results. The wetted area was measured as the flow region occupied by the February 11, 1985 event, minus any unwetted islands within the channel boundaries. The total area was simply measured as the entire floodable region between the outermost stream banks as they existed on February 11, 1985 (Figs. 2 - 4). Using these two area measurements, calculation of various stream parameters was possible, both for the four reaches and for the sub-reaches defined within them.

Infiltration rates and volumes were computed using upstream and downstream points of known discharge. Under the circumstances defined by this study, where downstream discharges were assumed to be zero, the volume of water infiltrated per day was equal to the upstream discharge. In this case, the entire volume measured upstream was infiltrated by the downstream end of both the Rillito and Santa Cruz Rivers. When evaporation is subtracted, this volume represents the volume of water being recharged per day. Evaporation from the wetted surface area was determined using the pan evaporation data for February 11, 1985 measured at the Water Resources Research Facility. The value for this day was 0.19

inches of evaporation. Since the flow in most reaches was less than the 10 inch depth of the evaporation pan, the pan data was used directly without a coefficient.

E. Calculations

1. Wetted Area

$$A_w = A_{\text{flow channel}} - A_{\text{sand bars}} \quad (4)$$

2. Total Area

$$A_t = A_{\text{max possible bank to bank flow}} \quad (5)$$

3. Percent Wetting

$$W = (A_w / A_t) \times 100 \quad (6)$$

4. Infiltration Rate

$$i = Q(\text{upstream}) - Q(\text{downstream}) / Aw \quad (7)$$

for $Q(\text{downstream}) > 0$

$$i = Q(\text{upstream}) / A_w \quad (8)$$

for $Q(\text{downstream}) = 0$

5. Infiltration Volume per Day

$$I = A_w \times i \quad (9)$$

6. Evaporation Volume per Day

$$E = A_w \times \text{depth of pan evaporation / day} \quad (10)$$

7. Recharge Volume per Day

$$R = I - E \quad (11)$$

8. Recharge Volume per Day per Mile of Stream Length

$$R_L = R / \text{stream length} \quad (12)$$

F. Uncertainties and Assumptions

1. Flying Elevation

Nonuniform flying elevation results in scale variation from image to image, causing map scales to fluctuate. By measuring a large number of features in the field, it is hoped that any large variations of this kind are detected and minimized by averaging.

2. Scaling

Field measurement of stream-crossing and stream-side features was probably fairly accurate, but the measurement of the corresponding length on the projected slide was more difficult. Some error, due to inaccurate measurement of small and sometimes indistinct features on the video slide could have entered into the scaling calculations. To minimize the effects of any single faulty measurement, either on the high or the low side, a single composite scale was used. This composite represents an average of the values obtained from measuring several features on a given stream reach. It is hoped that this process will yield a better approximation of the true scale for each reach.

3. Determination of Boundaries

The wetted area was quite easily determined, as the wetted region was dark and prominent in the colored aerial photography. A clear bank most often delineated the maximum channel width, but there were several regions in which, even after a field survey, some personal judgement had to be exercised in defining the total channel area. Where no distinct bank limit existed, boundaries were defined as the expected lateral extent of the high flow channel. It is hoped that such judgements were for the most part correct, and that any errors would not be substantial in comparison with the large areas in question.

Any post-February 11, 1985 changes in the channel morphology due to bank erosion or emplacement of bank protection, do not appear on these maps, nor are they accounted for in any calculations. Erosional changes would be minimal, since there have been no major floods since 1985.

4. Two-Dimensional Channel

The determination of the wetted channel area and the entire channel area from aerial photography has one inherent limitation that could be important under certain circumstances. An aerial view results in a flat image of a flow event and therefore does not account for the area contributed by stream banks. This area, though not as extensive as the

channel bottom, is also a surface available for infiltration and recharge. To account for the stream banks, an average bank wetted area could be projected over the length of the stream and added to the channel bottom area determined from aerial imagery.

In the case of the Winter/Spring 1985 event, flow was very shallow and confined to an inner channel. Therefore, any bank area wetted by the flow was assumed to be insignificant in comparison with channel width and length.

5. Determination of Discharge

The discharge value used for the upstream control point on the Santa Cruz was that measured by the USGS. A measurement taken on February 12th by the Water Resources Research Center staff had to be used for the Rillito where a February 11th value was not available. As the record of the location of the wetting front (Table 11) and the hydrograph of groundwater levels in the near-stream monitoring well (Fig. 5) indicate, flow volume on the Rillito River was not changing at a very dramatic rate at this point in the recharge season. In addition, there was a complete absence of rainfall between the 5th and 22nd of February (Table 9). Because of these conditions, it is assumed that discharge on these two days would not have differed substantially.

Field observations confirm that flow had almost entirely infiltrated by the time it reached the downstream control points on both the Santa Cruz and the Rillito. These observations allow us to assume a downstream discharge values of zero for both streams without introducing any significant error.

G. Results

1. Discussion

The wetted area, total channel area, and percent wetting have been determined for each of the four reaches. In order to facilitate a better understanding of recharge variations along these reaches, the values were also computed for a number of sub-reaches at smaller increments of distance. Maps of Reaches 1 - 3 delineating channel areas appear as Figures 2 - 4, and the calculated area values are tabulated in Table 12. As the length of reaches and sub-reaches varies, comparison of wetted area and total channel area values between reaches is not very instructive. In general, longer reaches have larger wetted and total stream areas. The exception to this trend is Reach 4 (Canada Del Oro) which, though it is shorter than Reach 3, Rillito River, has a larger total channel area. In other words, Canada Del Oro is a wider stream on the average and therefore has more surface area available for flow and the possibility of subsequent recharge. Canada Del Oro should have a higher recharge potential than the Rillito River, given this increased channel area. In fact it is probable that the Rillito River, with its greater natural long-term snowmelt-induced streamflow is actually recharging larger volumes of water during the flow season. Discharge measurements, if available, would have made quantification of this comparison possible.

TABLE 12

CHANNEL AREA DATA

Sub-reach	Wetted Area [acres]	Total Area [acres]	% Wetting
Reach 1 -- Upper Santa Cruz (Streamflow)			
1) Continental to Mile 9.34 (.43 mi S. of Pima Mine Rd.)	116.947	312.853	37.38
2) Mile 9.34 to Mile 16.98 (I-10 bridge)	123.171	228.877	53.81
3) Mile 16.98 to Mile 20.87 (Irvington)	74.108	182.521	40.60
4) Mile 20.87 to Mile 24.95 (St. Mary's Rd.)	40.886	106.990	38.21
5) Mile 24.95 to Mile 29.95 (Camino Del Cerro)	47.417	117.351	40.41
Entire Reach 1	402.530	948.592	42.43
Reach 2 -- Lower Santa Cruz River (Sewage Effluent Releases)			
1) Camino del Cerro to Mile 1.08 (just N. of Sunset Rd.)	6.623	31.403	21
2) Mile 1.08 to Mile 2.03	11.700	49.748	23
3) Mile 2.03 to Mile 3.33 (Ina Rd. Bridge)	27.578	53.174	52
4) Mile 3.33 to Mile 4.37 (Cortaro Rd.)	26.754	82.258	33
5) Mile 4.37 to Mile 5.62 (N. of Pima Farm Rd.)	23.487	65.530	36
6) Mile 5.62 to Mile 6.99	21.039	85.395	25
7) Mile 6.99 to Mile 8.28 (Avra Valley Rd. Bridge)	20.264	44.225	46
Entire Reach 2	137.446	411.734	33

TABLE 12

Sub-reach	Wetted Area [acres]	Total Area [acres]	% Wetting
Reach 3 -- Rillito River (Streamflow)			
1) Craycroft to Mile 1.6 between Swan and Dodge)	57.945	110.379	52.60
2) Mile 1.6 to Mile 3.8 (between Dodge and Campbell)	46.367	99.753	46.48
3) Mile 3.8 to Mile 4.2 (just west of Campbell)	26.264	52.487	50.04
4) Mile 4.2 to Mile 5.8 (between N. First and Oracle)	41.179	75.422	54.60
5) Mile 5.8 to Mile 8.5 (between La Canada and La Cholla)	53.858	90.795	59.32
6) Mile 8.5 to Mile 10.4 (just W. of Camino Del Terra)	36.087	100.036	36.07
7) Mile 10.4 to Mile 11.6 (just W. of I-10)	25.331	55.045	46.02
Entire Reach 3	287.031	583.918	49.20
Reach 4 -- Canada Del Oro (Streamflow)			
1) I-89 to Mile 1.62 (1st Ave)	8.256	101.143	8.2
2) Mile 1.62 to Mile 4.5 (La Canada)	19.919	191.815	10.4
3) Mile 4.5 to Mile 6.04 (La Cholla)	0	127.583	0
4) Mile 6.04 to Mile 7.79 (Magee Rd.)	0	67.673	0
5) Mile 7.79 to Mile 9.39 (Thornydale Rd.)	0	82.918	0
6) Mile 9.39 to Mile 10.58 (Santa Cruz River)	0	48.460	0
Entire Reach 4	28.175	619.593	0.45

Percent wetting is a better parameter for comparison between reaches or sub-reaches of varying length. Given that flow is decreasing downstream in all reaches due to infiltration, a channel of uniform width should show a monotonic decrease in percent wetting in the downstream direction. Channels are, of course, not of uniform width. However, an analysis of the variation in percent wetting values along a stream can indicate areas of stream width variation or intervals where streambed morphology allows for spreading or containment of flow. A variety of channel characteristics might effect percent wetting on a given reach. If a certain area has proportionately finer-grained sediments than the the remainder of the stream, low infiltration rates causing increased spreading of flow (and higher percent wetting) would result. Channel morphology could also be a contributing factor. A zone of channel narrowing would result in higher percent wetting, as the same flow volume would have a smaller region in which to flow. A wide zone would have the opposite effect. Similarly, the structure of the channel bottom could be an important factor controlling spreading. Percent wetting values would vary accordingly. In general, variation in percent wetting along a stream reach is of interest as a means of assessing relative recharge potential.

For Reach 1, percent wetting was 42.43 and varied from between 37.38% and 53.81% for the five sub-reaches. The high overall percent wetting value was mainly the result of an anomolous one mile interval, centered on Pima Mine Rd. in sub-reach 2, which was effectively 100% wetted by the February 11, 1985 flow. When studied in more detail in the field, geologic and hydrologic explanations for this anomoly became evident. The region displays a deeply incised, narrow, meandering channel, which is bounded laterally by fine-grained, strongly cohesive sediments. This material is both resistant to erosion and of a low infiltration capacity. Entrenchment and limited recharge in channel regions bounded by this sediment have resulted. Referring to Table 12, it can be seen that the measured percent wetting value is very close for four out of the five sub-reaches within Reach 1. The fifth sub-reach (#2) contains this geologically and hydrologically anomolous region, and was therefore wetted to a significantly greater degree by the same flow. Incorporation of this one high value had the effect of increasing the overall percent wetting figure for Reach 1.

The lower Santa Cruz, Reach 2, was 33% wetted by the sewage effluent discharges that made up the flow in this region. Percent wetting varied from between 21 and 52 on the seven sub-reaches. This variation is much greater than that observed in Reach 1. With flow in this region being the result of effluent releases, high values would be expected to occur at Camino Del Cerro and Ina Rd., the two points of effluent discharge. Decreases in percent wetting should be seen downstream from these points. As this trend is almost reversed, channel morphology or streambed characteristics such as those discussed above must be affecting flow spreading. In addition, previous infiltration studies demonstrated the development of a shallow flow-impeding layer during prolonged sewage effluent flows (Herbert, 1976).

Percent wetting on Reach 3, the Rillito River, was determined to be 49.20, whereas the seven sub-reaches varied from between 36.07% and 59.32%. Again, variations probably reflect differences in channel morphology or streambed properties along this reach. Installation of

embankment protection, which involves a certain amount of channel widening or narrowing, had already occurred in some areas, and could be causing the calculated percent wetting to vary along the stream.

For Reach 4, which is comprised of that part of Canada Del Oro between the I-89 bridge and the confluence with the Santa Cruz River, percent wetting has little meaning. Wetted areas were only present in two of the six sub-reaches, due to the fact that runoff from snowmelt was not as substantial on this stream. Surface flow had completely infiltrated on Reach 4 several miles upstream of its confluence with the Santa Cruz River.

Infiltration rates, calculated for the Santa Cruz and the Rillito Rivers from known discharge control points, are of special interest in assessing relative recharge capabilities. As mentioned earlier in the report, indications that steady state infiltration conditions had been reached on both streams may be found in the sustained flow record for the Santa Cruz (Table 10), and the high water level plateau in the continuous recording well record for the Rillito (Figure 5). Reach 1 was used to compute an infiltration rate for the Santa Cruz River, with a measured discharge of 278 cfs which had effectively infiltrated by the downstream end of the reach at Camino Del Cerro Rd (equation 8).

For the Rillito River, Reach 3, a February 12, 1985 discharge of 241.6 cfs was used to compute the infiltration rate where a February 11th measurement was not available. Here too, the flow was assumed to have infiltrated downstream, necessitating only a single measured discharge (equation 8). The values obtained in this way are 1.37 ft/day for the Santa Cruz and 1.67 ft/day for the Rillito River. The infiltration volumes, calculated on a daily basis from these rates, are 551.27 ac-ft/day and 479.09 ac-ft/day for the Santa Cruz and the Rillito respectively.

In order to compute the volume of water actually being recharged from the two streams, surface flow lost to evaporation had to be determined and subtracted from the calculated infiltration volumes. For Reach 1 on the Santa Cruz River, evaporation expected to occur over the wetted area was determined to be 6.44 ac-ft/day, resulting in a final recharge volume of 544.83 ac-ft/day. With an estimated 4.58 ac-ft/day lost to evaporation on the Rillito River, Reach 3, a final recharge volume of 474.51 ac-ft/day was calculated. Looked at in this manner, the Santa Cruz River was clearly recharging a greater volume of water than the Rillito River during the 1985 flow event. But, when these volumes are normalized by stream length, the Rillito River has the better relative recharge potential: 40.91 ac-ft/day/mi, compared with 18.19 ac-ft/day/mi for the Santa Cruz River. These figures are perhaps the most valuable in terms of evaluating recharge on a basin-wide scale. A summary of the computed channel parameters for each stream reach appear as Table 13.

2. Comparison with Past Findings

As a means of evaluating these study results, it is worthwhile to review some of the infiltration values for the Santa Cruz and the Rillito

TABLE 13

COMPUTED CHANNEL PARAMETERS

	Reach 1	Reach 2	Reach 3	Reach 4
Reach Length, [miles]	29.95	8.28	11.60	10.58
Wetted Area [acres]	402.5297	137.4458	287.0317	28.1750
Total Area [acres]	948.5919	411.7344	583.9182	619.5931
% Wetting [percent]	42.43	33	49.20	0.45
Infiltration Rate [ft/day]	1.37	--	1.67	--
Infiltration Volume per Day [acre-ft/day]	551.27	--	479.09	--
Evaporation Volume per Day [acre-ft/day]	6.44	--	4.58	--
Recharge Volume per Day [acre-ft/day]	544.83	--	474.51	--
Recharge Volume per Day per Mile of Stream [acre-ft/day/mile]	18.19	--	40.91	--

Rivers that appear in the literature. In general, the reported values are higher than those obtained in this study. This may reflect greater instantaneous infiltration rates during high discharge flows. Matlock (1965) has shown that maximum absolute streamflow losses occur at high discharges, though infiltration relative to flow volume is higher under conditions of low discharge. Furthermore, water table mounding, which would be expected to occur in a sustained flow event, can slow infiltration and downward percolation of surface water (Turner et. al., 1943). As the infiltration rates and volumes quoted from other sources were computed on an average annual basis, they would take into account both the sustained, low-flow winter events and the flashy, high discharge summer flows. In this study, only a single, continuous winter event is being closely analyzed. Though rates and daily volumes are smaller, the total volume of recharge would be substantial over the almost 4 month period of flow observed in this winter 1985 event.

For the Santa Cruz River, an early calculation by Todd (1959) resulted in an infiltration rate of 3.8 ft/day. Matlock (1965) used streamflow data from October 1953 to September 1963 and looked at flow losses over gaged reaches to obtain infiltration rates ranging from 3 - 6.7 ft/day for the stream reach between Continental Rd. and Tucson (corresponding to Reach 1 in this study). This same reach was analyzed by Burkham (1970), who used streamflow data to establish an empirical relationship between inflow rate and infiltration rate. Using the measured inflow rate for February 11, 1985 at Continental Rd., Burkham's equation yields an infiltration rate of 0.71 ft/day for the upper Santa Cruz River. This value is closer to the 1.37 ft/day calculated in this study, perhaps due the fact that the actual measured discharge could be incorporated into calculations.

The Rillito River has been studied by several investigators, and a range of infiltration values are available. A group led by Turner (1943) obtained infiltration rates between 1.1 and 3.7 ft/day from snowmelt runoff. The lowest values were observed in high water table areas, which explains why the value of 1.67 ft/day arrived at in this study fits in on the low end of the range. Matlock (1965) used two methods to compute infiltration rates for Rillito River flows. Both apply to snowmelt runoff, but a range from 2.4 to 6.5 ft/day was calculated from seepage runs, and a study of groundwater level changes yielded a rate of 2.8 ft/day. As was done for the upper Santa Cruz River, the Burkam (1970) equation for the Rillito River may be used to calculate the infiltration rate associated with a measured flow of 241.6 cfs. A rate of 0.95 ft/day is obtained from his empirical relationship. This value is, as was seen for the Santa Cruz River, somewhat closer to the infiltration rate of 1.67 ft/day obtained in this study.

Other transmission loss studies on the Rillito River have been conducted by Moench and Kisiel (1970) and a group led by Flug (1980). In both of these studies, flow losses have been computed on an the basis of average annual volume of infiltration rather than volume infiltrated per day for a particular event. Because of this, a comparison with the findings of these researchers is beyond the scope of this report.

It is interesting to note that the values of earlier researchers were obtained by measuring streamflow in local streams when the groundwater

table was at a much higher level than it is now. Prior to the 1950's, for instance, groundwater elevation contours were uniform across the central well field. There was relatively little pumpage at the time, and no large gradient towards the central well field as there is now. Based on this scenario, the more recent values of infiltration should be higher, not lower, than those previously measured. Thus it appears that the dominant factor, and the main reason for lower values measured for February 1985, is the length of sustained flow prior to the time measurement is made. In 1985, both mounding effects and perhaps surface plugging had reduced the infiltration rate below that found by previous investigators. As was shown earlier, it appears that mounding of the water table had stabilized and reached a steady state condition before the infiltration rate was measured (Figure 5).

IV. Natural Infiltration on the Upper Santa Cruz River and Its Tributaries

The above monitoring of a specific long term, low flow event was useful in the determination of the natural infiltration rates and volumes of recharge associated with such events on the upper Santa Cruz River and its tributaries in the Tucson basin. The use of this data will be further discussed in section V. This section is concerned with the determination of basinwide infiltration computed from the historic record of streamflow on the major streams, which is Subtask 2b, part 1.

A. Procedure

Burkham's (1970) relationships for streamflow losses along the main channels in the Tucson basin were used to compute the volume of infiltration associated with historic flows on the Santa Cruz and Rillito Rivers. By determining the total infiltration volume contributed by the various ranges of flow magnitude, the effect of embankment protection on this infiltration could be projected to a basinwide scale using the results of the computer simulation study.

The approach taken by Burkham was to derive the relationship between cumulative inflow and infiltration rates for each of the major stream reaches in the basin by using historically measured inflow and outflow data. In his analysis, all stream losses are assumed to be due to infiltration. Thus, the difference between inflow and outflow volume per time is equal to the volume per time of infiltration through the streambed. A log-log plot of cumulative inflow rate (upstream measured discharge) vs. cumulative infiltration rate (the difference between inflow and outflow rates) yielded the coefficient in the empirical equation

$$I = C\,(Q)^{0.8} \qquad (13)$$

in which

I = cumulative infiltration rate [cfs]
difference between inflow and outflow volumes per time during corresponding time intervals
C = a variable coefficient
Q = cumulative surface water inflow rate [cfs]

This equation was also given on the basis of infiltration per mile in the following manner.

$$I/mile = C1\ (Q)^{0.8} \qquad (14)$$

in which

C1 = a variable coefficient to account for stream length

Using this equation, along with the appropriate coefficient for the stream reach of interest, the volume per mile of infiltration associated with each historic streamflow event could be determined. The total volume of in-stream infiltration that has occurred in the basin over time was then computed by incorporating data on the amount of time each flow magnitude was seen to have occurred in the historic record.

It is important to consider the assumptions incorporated into Burkham's empirical relationships:

1) The cumulative inflow rate is greater than the cumulative infiltration rate. When this is not the case, Burkham's inflow-infiltration relationship breaks down. In this study, the inflow rate below which the entire flow volume may be recharged along the length of each stream was estimated from observation of the Winter/Spring 1985 flow event. When the inflow volume per time was less than this critical value of 240 cfs for the Rillito River and 250 cfs for the Santa Cruz River, Burkham's equations were not used and all inflow was assumed to infiltrate. A low flow value of 130 cfs for the Rillito River inflow into the Santa Cruz River was estimated from the percent of the 240 cfs low flow estimate for the last 4.3 miles of the Rillito River which has identical infiltration capacity according to Burkham (1970).

2) The net difference between losses due to evaporation from the stream surface and gains due to precipitation on the stream surface is zero. All streamflow losses are assumed to be due to infiltration.

3) The coefficient C is a constant for all locations along a given reach of stream for all time.

With the streamflow information presented in the previous two sections of the report and Burkham's relationships for determining the infiltration, streamflow losses were determined for each of the daily recorded average flows in the historic record. These infiltration values are given in Tables 1, 2 and 3.

The infiltration values for the 4.3 miles below Oracle Rd. bridge on the Rillito River were determined from equation (13) by applying the coefficients given in Burkham's work.

$$I = 4.3\ (0.11)\ (Q)^{0.8} \qquad (15)$$

where

Q = discharge measured at Oracle Rd. bridge [cfs]

The cumulative infiltration rate for the 7.7 miles between Craycroft Rd. and Oracle Rd. bridges was determined in a similar manner from

$$I = 7.7\ (0.18)\ (QU)^{0.8} \qquad (16)$$

where

QU = discharge measured upstream at Craycroft Rd., computed from equation (17) [cfs]

$$QU1 = Q + (7.7)\ (0.18)\ (Q)^{0.8} \qquad (17a)$$

$$QU2 = Q + (7.7)\ (0.18)\ (QU1)^{0.8} \qquad (17b)$$

.
.
.

$$QU5 = Q + (7.7)\ (0.18)\ (QU4)^{0.8} \qquad (17e)$$

Equation (17a) when used alone actually underestimates the input streamflow at Craycroft Rd. bridge, since it is using the terminal streamflow, Q, of the reach to estimate the infiltration over the reach. In order to reduce this underestimation, the equation was iterated five times. In this way, the error was reduced to a negligible amount. After five iterations, the difference between the new estimation of Q and that from the previous estimation was generally less than 1 or 2%. The procedure was to take the estimated upper streamflow (QU1) from the first equation (17a) and to use this value for QU1 in equation 17b. The calculation was repeated five times, each time using the value of QU obtained from the preceeding calculation, as illustrated above.

Once the upper flow at Craycroft Rd. was estimated in the manner outlined above, the total infiltration for the Rillito River was estimated by summing equations (15) and (16) for all flows with discharges of over 240 cfs measured at Craycroft Rd. All streamflow below 240 cfs was assumed to infiltrate along the length of the stream, as observed during the Winter/Spring 1985 recharge event reported on in the preceeding section.

The discharge flow from the Rillito River flowing into the Santa Cruz River was determined from the relationship,

$$QL = Q - 4.3\ (0.11)\ (Q)^{0.8} \qquad (18)$$

where

QL = cumulative outflow rate [cfs]

The infiltration values for the 17.8 mile reach on the Santa Cruz River between the Congress Rd. and Avra Valley Rd. bridges was determined from Burkham's equation,

$$I = 17.8\ (0.11)\ (Q)^{0.8} \qquad (19)$$

For the 28.5 mile reach extending upstream from the Congress St. bridge to the Continental Rd. bridge, the infiltration values were computed from,

$$I = 28.5\ (.06)\ (QU)^{0.8} \qquad (20)$$

The total infiltration on the Santa Cruz River originating from Continental Rd. was determined as the sum of equations (19) and (20), except that for all stream inflow less than 250 cfs the entire volume was assumed to infiltrate. Hence, the infiltration was set equal to the inflow in this case.

The infiltration on the Santa Cruz River due to to inflow from the Rillito River along the 9 mile reach between the Rillito River confluence and Avra Valley Rd. bridge was computed from,

$$I = 9.0\ (0.11)\ (QL)^{0.8} \qquad (21)$$

where

QL was determined from equation (7)

Once the infiltration was determined for both the Rillito and the Santa Cruz Rivers, relationships were extended to Canada Del Oro, Tanque Verde Wash and Pantano Wash by using Burkham's 1936 - 1963 ratios of streamflow and infiltration as given in the following equations,

$$\text{Streamflow Pantano Wash} = \qquad (22)$$

$$\text{Average Inflow Rillito + Santa Cruz (1918-1981)} \times \frac{\text{Average Inflow Pantano (1936-1963)}}{\text{Average Inflow Rillito + Santa Cruz (1936-1963)}}$$

$$\text{Infiltration Pantano Wash} = \qquad (23)$$

$$\text{Infiltration Rillito + Santa Cruz (1918-1981)} \times \frac{\text{Infiltration Pantano (1936-1963)}}{\text{Infiltration Rillito + Santa Cruz (1936-1963)}}$$

Equations were developed for Canada Del Oro and Tanque Wash in a similar manner.

B. Results and Discussion

1. General

The annual infiltration for each year as calculated using daily inflow values is given in Table 1 for the Rillito River and Tables 2 and 3 for the Santa Cruz River. These tables show that 41.1% of the infiltration on the Rillito River during the period of record occurred when inflow was less than 240 cfs. As mentioned above, this is the critical value below which all streamflow is seen to infiltrate along the reach. On the Santa Cruz River, 22.0% of the inflow at Continental Rd. and 51.1% of the inflow from the Rillito River infiltrated when the flows were less than 250 cfs, the low flow value for the Santa Cruz River.

These tables also indicate the large amount of variation in annual flow, ranging on the Rillito River at Oracle Rd. from a maximum of 26,855 cfs-days measured in 1966 to only 156 cfs-days in 1956. On the Santa Cruz River, the flow measured at Congress St. bridge ranged from 39,189 cfs-days in 1979 to 471 cfs-days in 1965.

In Tables 4, 5 and 6 the amount of inflow and the resulting infiltration in the different inflow categories are presented. These tables show that the low flow infiltration is more important on the Rillito than it is on the Santa Cruz River.

Comparing the two streams in terms of the total volume of water infiltrated, the Rillito River infiltrated 55.1% of its inflow and the Santa Cruz River infiltrated 75.2% of the flow from Continental Rd. and 37.3% of the Rillito River inflow. An average of 8,318 ac-ft per year was recharged on the 12 mile long Rillito River. 20,851 ac-ft per year was recharged on the 46.6 mile long stretch of the Santa Cruz River between Continental Rd. and Avra Valley Rd., and 1,886 ac-ft per year on the 9 miles between the Rillito River's confluence with the Santa Cruz and Avra Valley Rd. This constitutes 693 ac-ft/mile/yr on the Rillito River and 447 ac-ft/mile/yr on the Santa Cruz River from Continental inflow and 210 ac-ft/mile/yr below the Rillito River confluence due to tributary inflow.

The years when the peak volume of water infiltrated was in 1966 on the Rillito River with a total infiltration of 39,051 ac-ft and 1979 on the Santa Cruz River, with a synthesized infiltration of 80,305 ac-ft from Continental Rd. inflow.

The inflow and infiltration values obtained above were extended to the lower 9.9 miles of Canada Del Oro, the lower 10.5 miles of the Tanque Verde Wash and the lower 21.5 miles below Vail gaging station on the Pantano Wash. The method outlined in the procedure was used to make the extension. A summary including data produced through this extension is given in Table 14. The total average natural infiltration per year in these channels is 54,654 ac-ft.

The hydrograph used in the model study was described as average flow for 24 hour increments, as shown in Table 8. When this synthetic flow was treated as inflow on the Rillito River at Craycroft Rd. bridge and Burkham's infiltration equations were applied (eqns. 15 & 16) the infiltration shown in Table 15 was obtained.

The total amount of infiltration for the synthetic hydrograph was 36.7% of the total volume of runoff in the 12 mile reach of the Rillito River. This compares with a percent of infiltration based on the computer model as given in Volume I of 38.7. This estimate is based on multiplying the 464 acre foot per mile infiltration value obtained in the computer run for the case of a wide channel before bank stabilization (Table 3, Volume I) by the 12 mile length of stream channel on the Rillito River for a total loss of 5,568 ac-ft. This is 38.7% of the total volume of streamflow (14,363 ac-ft) in the 90 hour synthetic hydrograph. This close comparison shows that the two techniques (Burkham and the computer simulation) produced similar results for the typical section of stream studied. The percent infiltration, as determined by the computer model, is reduced in the other five cases considered.

TABLE 14

AVERAGE ANNUAL SYNTHESIZED STREAMFLOW AND INFILTRATION VOLUMES
FOR THE MAIN CHANNELS IN THE TUCSON BASIN 1918 - 1981

Inflow Point	Average Annual Inflow [ac-ft]	Average Annual Infiltration [ac-ft]	
		Low Flow	Total
Santa Cruz River at Contintental Rd.	27,730	4,579	20,851
Santa Cruz River from Rillito River	6,792	492	1,886
	34,522	5,069	22,737
Tanque Verde Wash	16,589	3,996	9,722
Pantano Wash	8,477	1,419	6,451
Rillito River	15,112	3,415	8,318
Canada Del Oro	11,785	1,633	7,426
Total	***	15,532	54,654

*** Total was not taken, since some inflows provided water to a subsequent reach and therefore would be counted twice.

TABLE 15

RILLITO RIVER INFILTRATION VALUES OBTAINED USING EQNS. 15 & 16
FOR SYNTHETIC HYDROGRAPH

Event	Streamflow [cfs-day]	Infiltration [cfs-day]
Day 1	1412	596
Day 2	3837	1292
Day 3	1806	700
Day 4	116	73
Totals	7241	2661

V. Effects of Soil Cement Embankment on Natural Basinwide Recharge

The following two sections are presented in response to Subtask 2b, which requires the effects of embankment protection estimated through the modelling study reported on in Volume I to be projected on a basinwide scale. Mitigation practices are also to be suggested.

There have been approximately 26.2 miles of soil cement embankment placed by Pima County Flood Control District in the Tucson basin. The location of this bank protection is given in Table 16.

The computer model described in Volume I was used to make a run using a flow of approximately 240 cfs. This unpublished preliminary run indicated that bank stabilization with soil cement will not affect the infiltration from low flows less than 240 cfs on the Rillito River. Similar effects would be expected for the other streams. The long term snow melt discharges will generally be below the 240 cfs rate and thus not be affected by bank protection.

In addition to not affecting low flows, it is expected that the soil cement embankments would reduce sediment loading in the streambeds beginning with the first flood with sufficient velocity to erode unprotected banks. This reduced sediment loading due to elimination of bank erosion, would allow the stream to pick up more sediment from the streambed. This would tend to keep the channel more sediment free and thus increase the infiltration rate. In addition to keeping the streambed more free of finer sediment, there would tend to be less sediment in the water. Matlock (1965), has shown that sediment-laden water infiltrates at a slower rate. No attempt to quantify the change in infiltration rate due to reduced sediment load was made in this study. Increased infiltration due to reduced sediment load was not considered in using the computer model in Volume I. The velocity of the winter snow melt discharges, particularly on Tanque Verde Wash and the Rillito River, are low enough that sediment control would not be necessarily be reduced due to bank protection.

Another factor to consider is that although soil cement embankments will reduce the infiltration of moderate and high flows, some of the excess water will infiltrate downstream of the bank protected region before leaving the basin. A higher percentage of moderate flows will infiltrate downstream from bank protected areas than with the high flows.

Since soil cement embankments do not have an effect on infiltration in low flow regimes, 41.1% of the recharge on the Rillito River (Table 4) and approximately 22.0% on the Santa Cruz River from Contintental Rd. (Table 5) and 7.9% from Rillito River inflow (Table 6) would not be affected by soil cement embankment installation. These percentages were determined using 58 years of daily streamflow on the Rillito River and 64 years of daily streamflow on the Santa Cruz River. Any streamflow less than approximately 240 cfs on the Rillito River and less than 250 cfs on the upper Santa Cruz River was tabulated and the percent of low flow discharge was determined for each of the two streams.

Burkham (1970) determined that the infiltration characteristics of Tanque Verde Wash were similar to those of the Rillito River, and that the infiltration characteristics of Pantano Wash and Canada Del Oro were similar to those of the Santa Cruz River. He used the same coefficients to estimate infiltration on these similar reaches. According to Burkham, his relationships are not valid for low flow discharges. However, in this study, the similarity in infiltration characteristics was assumed for the low flow discharges, even though Burkham's relationships were not actually used to compute low flow infiltration. The percentage of low flow determined for the upper Santa Cruz River was used to determine the amount of low flow in Canada Del Oro and Pantano Wash. Similarly, the low flow percentage for the Rillito River was used to determine the low flow in Tanque Verde Wash. The total low flow was added up for the various reaches. This total low flow was expressed as a percentage of the total flow in all of the reaches. This percentage was found to be 28.4. Thus, 28.4 percent of the total infiltration from the basin wide flow would not be affected by soil cement embankments.

According to the unpublished Volume I modelling results, infiltration from moderate and high streamflow events will be adversely impacted by soil cement embankments unless the stream channel is widened. Those data were not included in Volume I. The infiltration from moderate and high flows affected by soil cement embankments would be 71.6% (100 - 28.4 = 71.6%).

The results of the computer study in Volume I, showing the percent change in infiltration rate due to the different cases of streambed management, are shown in Table 17. Also shown in Table 17 is the percent change in infiltration rate multiplied by the average annual basinwide infiltration that is affected by embankment modification. The infiltration impacted by embankments is 71.6 % of the total average annual basinwide infiltration of 54,654 ac-ft. This amounts to 39,132 ac-ft. This value was multiplied by the percent change in infiltration rate to obtain the figures in the last column of Table 17. For example, if all of the major stream channels were treated according to case 1, the average annual basinwide infiltration would be reduced by 5,752 ac-ft.

TABLE 16

SOIL CEMENT BANK PROTECTION INSTALLED IN THE TUCSON BASIN AS OF 1987

Stream Reach	Approx. Miles Protected
Santa Cruz River	6.1
Rillito River	5.5
Tanque Verde Wash	1.4
Pantano Wash	2.7
Canada Del Oro	10.5
Total	26.2

TABLE 17

DIFFERENCES IN BASINWIDE RECHARGE (CUMULATIVE INFILTRATION VOLUMES) FOR SIX CASES

Case Number	Description of Channel and Modification	Differential	
		%	Av. Ann. Infiltration [ac-ft]
1	Wide channel before and after bank protection	-14.7	-5,752
2	Narrow channel before and after bank protection	-24.8	-9,705
3	Narrow channel before, wide channel after bank protection	+24.9	+9,743
4	Wide channel before, narrow channel after bank protection	-48.6	-19,108
5	Channel widening without bank protection	+46.3	+18,118
6	Channel narrowing without bank protection	-31.7	-12,405

VI. Mitigation of Possible Adverse Effects of Soil Cement Embankments

There are several types of mitigation techniques that Pima County Flood Control District could employ to offset the reduction of infiltration due to bank protection. Many mitigation measures have been outlined in a report prepared by the Water Resources Research Center for the United States Army Corps of Engineers (Resnick et.al., 1981). Some of the leading mitigation measures are listed below.

1) One of the best mitigation procedures is to increase the channel width wherever possible. The data presented in Table 17 can serve as a general guide as to how much the channel will need to be widened to offset the effect of either no channel widening or a required narrowing in some designated channel areas. For example, if 33% of the stream channels were narrowed and bank protected (case 4), and the other 67% were widened and then bank protected (case 3), the basinwide infiltration would not be significantly changed. There would be a reduction of 6,306 ac-ft, but an off-setting increase due to widening of 6,489 ac-ft.

2) The streambed could be relevelled after major streamflow events to enhance water spreading. Even with relevelling, the low flows would not completely cover the channel due to braiding. The reduction of braiding, so that water would completely cover the streambed, could be accomplished with the use of drop structures and "T" or "L" berms, as used in Orange County, California. In order to optimize water spreading using this system, Orange County Flood Control District reduced the original slope of the Santa Ana River from 0.004 to as low as 0.0021 using drop structures (Orange County, 1971).

According to the study of the Winter/Spring 1985 recharge event, spreading of low flows over the entire streambed on both the Santa Cruz and Rillito Rivers should increase the amount of recharge. The approximate increase can be determined for the Rillito and the Santa Cruz Rivers. As the analysis of the Winter/Spring 1985 runoff showed, less than 50% of the channel was used to infiltrate the entire streamflow of 240 cfs. Thus, if 100% of the stream channel were used, the Rillito River should be able to infiltrate twice as much water, or approximately 500 cfs. This is based on the assumption that the surface area of wetted streambed controls the infiltration rate and that bank protection would not affect the infiltration rate of flows up to 500 cfs. The modelling of Volume I, in general, showed that there was an increase in infiltration rate per mile when the streambed was widened. More Volume I computer runs would have to be made to show: (1) that the relationship between the infiltration rate/mile and streambed width over a flow range between 240 to 500 cfs is linear and, (2) that there is little or no bank protection affect on infiltration if the flows are 500 cfs or less and spread over the entire channel. Using Burkham's infiltration relationships, under historic conditions, the computer analysis showed that 52% of the streamflow in the 240 to 500 cfs-day range is infiltrated. This information is given in Table 4. With full utilization of the channel streambed that was available in 1984/1985, and assuming a linear relationship between the infiltration rate/mile and stream width for the 240 to 500 cfs-day flow range, the remainder of the 240 to 500 cfs-day flows could be infiltrated for an annual average increase of 1,051 ac-ft/year. Furthermore, if the assumption that there is no infiltration

reduction due to bank protection from streamflows in the 240-500 cfs range is correct, then the 1,051 ac-ft/year savings would be expected in the future even with full bank protection.

On the Santa Cruz River, due primarily to its longer length, grading of the channel would not conserve much additional water. 86% of the 250 to 500 cfs flow is already being infiltrated. Grading would only increase infiltration by 14%, or 529 ac-ft/yr.

On both the Rillito and the Santa Cruz Rivers, wherever water spreading was implemented, there would be a tendancy for a larger percentage of the total flow to be infiltrated in the upper end of the reach. It is a desireable basinwide management goal to try to infiltrate water upgradient from as many production wells as possible.

3) A third mitigation procedure would be to use offstream detention basins that could be filled until the level of flow in the stream dropped sufficiently such that release back into the stream channel could be made to promote infiltration. The problem of sediment deposition in the stream channels, which reduces natural infiltration (Matlock, 1965), would be avoided by using an offstream rather than an onstream detention basin.

As an example of the effect of a system of this type, a 1000 ac-ft capacity detention basin on the Rillito River was modelled (25 surface acres, 40 feet deep). Any time the flow was above 240 cfs, water would be stored in the detention basin and then released when the flow dropped below 240 cfs. Releases would be made such that the total flow in the river would be kept below 240 cfs. This detention system was modelled for the 58 years of daily historic record used in the above analysis. The computer model analyzes each daily event of streamflow. It stores any available streamflow greater than 240 cfs as long as there is room in the storage reservoir. It releases water any time the flow in the channel drops below 240 cfs, thus providing room to store the next input of flow above 240 cfs. It was found that this system could store and release 2,250 ac-ft/year of streamflow at a maximum rate of 240 cfs. However, the analysis showed that 38.1% of the 2,250 ac-ft savings would have infiltrated before reaching the Santa Cruz River without the detention basin. Thus, the net savings would be reduced to 1,393 ac-ft/year with the 1,000 ac-ft detention basin. Other detention basins could be built on the Rillito River and other streams to increase savings. Existing gravel pits, principally along the upper Pantano Wash and lower Santa Cruz River, could be used. Landfills that have been placed in old gravel pits could be removed and the land used for offstream detention basins. It should be noted that the use of 30 to 40 ft. deep detention basins might require the use of a low-head pump to return water to the stream. This might be done with low cost, high efficieny, low-head propeller pumps. Also, the sediment would have to be removed periodically. This might be done at little or no cost by selling the sediment, when the reservoir was dry, for top soil.

4) A fourth type of mitigation procedure would be the use of detention gates on the stream channels to detain flow and release it at a slower rate. This method does pose an additional risk of reduction of infiltration by sedimentation in the detention area. Studies have shown that whenever streamflow is stopped, a sediment layer quickly forms over

the streambed and the infiltration rate is drastically reduced (Matlock, 1965; Laursen, 1987). Water level data collected by the Water Resources Research Center showed that the 1983 flood on the Santa Cruz River almost completely sealed active sand and gravel pits that it flooded. It is doubtful that the streambeds would be completely sealed by on-stream detention, since subsequent floods could clean them out. However, the effects of sealing should be carefully considered. Flows high enough to remove sediment may not come for several years, and in the mean time low flow events might not be able to infiltrate in the streambeds where on-stream detention has been used.

5) A fifth type of mitigation that could be used would be a detention reservoir just west of Rattlesnake Pass, as proposed by Cluff (1983). This consists of a gravity fed offstream detention basin that would remove floodwaters from the Santa Cruz River near Cortaro Rd. bridge above Rillito Narrows. This would collect all floodwaters that would not have infiltrated in the basin and pump the water upstream to a suitable location for streambed recharge. A 60,000 ac-ft compartmented detention reservoir system was modelled and found to conserve 23,120 ac-ft/year of floodwater, using the runoff record from 1951 to 1981 at Cortaro Rd. bridge. The compartmented detention reservoir was proposed to reduce evaporation losses while the water was in storage.

VII. Conclusions

Although there are some adverse effects on infiltration stemming from the use of bank stabilization with soil cement, there is ample opportunity for mitigation measures to be carried out.

The simplest mitigation measure is to make the channel wider where ever possible to offset reductions from those areas where widening is not possible. The use of offstream detention basins should be preferred over the use of onstream detention, as the latter involves a reduction in infiltration due to sedimentation. The apparent savings from detention basins must be reduced by the amount of water that would have infiltrated anyway had the basin not been used.

The adverse effect on the infiltration rate caused by a particular section of soil cement embankment near the headwaters of the Rillito River, for example, must be reduced because of the increase in flow which would accompany this decrease in infiltration. The increased flow would result in an increased infiltration downstream. However, as shown in the column giving percent flow infiltrated in Table 4, 52% or less of the increase in flow above the 240 cfs low flow value would infiltrate in the Rillito River before reaching the Santa Cruz River. Thus, there would be a net loss to the Rillito stream system. Some of this loss would be infiltrated in the lower Santa Cruz River, but the value to the water budget of the Tucson basin would be lessened due to the downstream location of the infiltrated water.

Although more investigation is necessary, the recommendations made in Volumes I and II of this study contain sufficient information so that a combination of mitigation procedures could be selected to eliminate any overall adverse effects of embankment protection of the water supply of the Tucson basin.

APPENDIX A

HISTORIC STREAMFLOW RECORDS

APPENDIX B

HISTORIC STREAMFLOW DURATION DATA

APPENDIX B

FLOW DURATION DURING WINTER SEASON (DEC. 21 -- MAR. 21) ON RILLITO RIVER AT ORACLE ROAD BRIDGE

Year	Maximum Flow Duration [days]	Dates of Flow
1912	7	Mar.4 - Mar.20
1913	Data Fragmented	---
1914	3	Feb.23 - Feb.25
1915	Data Fragmented	---
1916	50	Jan.17 - Mar.7
1917	3	Feb.27 - Mar.1
1918	7	Feb.28 - Mar.6
1919	25	Feb.2 - Feb.26
1920	25	Jan.5 - Jan.29
1921	0	---
1922	3	Jan.3 - Jan.5
1923	0	---
1924	16	Dec.20 - Jan.4
1925	0	---
1926	0	---
1927	14	Feb.15 - Feb.28
1928	0	---
1929	0	---
1930	12	Mar.16 - Mar.27
1931	9	Feb.26 - Mar.6
1932	35	Feb.9 - Mar.14
1933	13	Jan.31 - Feb.12
1934	0	---
1935	12	Feb.6 - Feb.17
1936	8	Feb.16 - Feb.23
1937	5	Feb.6 - Feb.10
1938	4	Mar.3 - Mar.6
1939	0	---
1940	2	Feb.23 - Feb.24
1941	16	Feb.23 - Mar.10
1942	8	Jan.8 - Jan.15
1943	2	Mar.5 - Mar.6
1944	0	---
1945	8	Mar.9 - Mar.16
1946	1	Jan.6
1947	0	---
1948	0	---
1949	4	Jan.13 - Jan.16
1950	0	---
1951	0	---
1952	7	Mar.17 - Mar.23
1953	3	Mar.9 - Mar.11
1954	4	Mar.22 - Mar.25
1955	0	---
1956	1	Jan.29

Year	Maximum Flow Duration [days]	Dates of Flow
1957	3	Jan.9 - Jan.11
1958	23	Mar.7 - Mar.29
1959	0	---
1960	21	Jan.11 - Jan.30
1961	0	---
1962	13	Jan.24 - Feb.5
1963	4	Feb.10 - Feb.13
1964	0	---
1965	8	Mar.11 - Mar.18
1966	26	Dec.9 - Jan.3
1967	0	---
1968	12	Mar.9 - Mar.20
1969	2	Jan.15 - Jan.16
1970	8	Mar.11 - Mar.18
1971	0	---
1972	4	Dec.26 - Dec.29
1973	34	Mar.12 - Apr.14
1974	0	---
1975	0	---

FLOW DURATION DURING WINTER SEASON (DEC.21 -- MAR.21) ON SANTA CRUZ RIVER AT CONGRESS STREET BRIDGE

Year	Maximum Flow Duration [days]	Dates of Flow
1906	76	Nov.17 - Jan.31
1907	Not available	---
1908	Fragmented Data	---
1909	Fragmented Data	---
1910	11	Dec.21 - Dec.31
1911	67	Oct.1 - Oct.31
1912	92	Oct.1 - Dec.31
1913	88	Jan.1 - Mar.29
1914	Not available	---
1915	108	Dec.20 - Apr.6
1916	14	Jan.20 - Feb.2
1917	0	---
1918	2	Feb.28 - Mar.1
1919	2	Dec.22 - Dec.23
1920	65	Nov.24 - Jan.26
1921	5	Dec.13 - Dec.17
1922	31	Jan.1 - Jan.31
1923	0	---
1924	49	Nov.25 - Jan.12
1925	0	---
1926	10	Jan.4 - Jan.13
1927	32	Dec.4 - Jan.4
1928	2	Feb.16 - Feb.17
1929	0	---
1930	5	Mar.16 - Mar.20
1931	7	Feb.12 - Feb.18
1932	7	Jan.14 - Jan.20
1933	2	Feb.8 - Feb.9
1934	2	Jan.28 - Jan.29
1935	15	Feb.5 - Feb.19
1936	18	Dec.20 - Jan.6
1937	1	Jan.7
1938	3	Jan.20 - Jan.22
1939	1	Feb.5
1940	5	Feb.13 - Feb.17
1941	7	Feb.7 - Feb.13
1942	21	Dec.31 - Jan.20
1943	1	Mar.5
1944	0	---
1945	1	Dec.25
1946	3	Jan.5 - Jan.7
1947	2	Mar.18 - Mar.19
1948	0	---
1949	4	Feb.16 - Feb.19
1950	0	---

Year	Maximum Flow Duration [days]	Dates of Flow
1951	0	---
1952	1	Dec.24
1953	1	Dec.21
1954	5	Mar.22 - Mar.27
1955	2	Jan.3 - Jan.4
1956	1	Jan.29
1957	2	Jan.27 - Jan.28
1958	2	Feb.4 - Feb.5
1959	0	---
1960	0	---
1961	2	Dec.29 - Dec.30
1962	5	Jan.23 - Jan.27
1963	3	Feb.10 - Feb.12
1964	1	Feb.24
1965	2	Dec.28 - Dec.29
1966	9	Feb.7 - Feb.15
1967	0	---
1968	18	Dec.13 - Dec.30
1969	2	Jan.14 - Jan.15
1970	7	Feb.27 - Mar.5
1971	0	---
1972	0	---
1973	10	Mar.12 - Mar.21
1974	0	---
1975	2	Jan.29 - Jan.30
1976	2	Dec.23 - Dec.24
1977	2	Dec.31 - Jan.1
1978	18	Feb.28 - Mar.17
1979	27	Jan.17 - Feb.12
1980	5	Feb.13 - Feb.17
1981	5	Mar.2 - Mar.6

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