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RAINFALL-RUNOFF RELATIONSHIPS FOR A MOUNTAIN WATERSHED IN SOUTHERN ARIZONA

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ABSTRACT

A network of rain gauges and two recorder-equipped flumes were installed near the head of Cottonwood Canyon on Mt. Hopkins in the Santa Rita Mountains pursuant to a water development study for the Smithsonian Institution's Mt. Hopkins Astrophysical Observatory. The watershed is generally characterized by steep slopes, a dense evergreen woodland cover predominated by several species of oaks, isolated bedrock exposures and talus chutes. The watershed for the lower flume site comprises about 145 acres (58.60 ha) with an elevation range from about 6775 to 8580 feet (2,065 to 2,615 m). Rainfall-runoff measurements were made during the summer and fall of 1977. A runoff efficiency of 0.56 percent was calculated for the lower-flume watershed. However, since physical evidence of surface flow was found only in side drainages receiving runoff from culverts located along the Mt. Hopkins access road, a second calculation was made, using only the total area of contributing road surface as the watershed area. This yielded a runoff efficiency of 27.0 percent. The latter value, adjusted for infiltration on the slopes below the culverts, agrees well with measured efficiencies for compacted-earth water harvesting catchments. Based on the above, recommendatons were made for developing a water supply system using the access road, modified to increase its effectiveness, as a water harvesting system and having two surface reservoirs for storage. A computer model was used to test the capability of the system to meet the projected water needs of the observatory.

INTRODUCTION

At the request of the director of the Smithsonian Institution's Mt. Hopkins Astrophysical Observatory, the authors undertook the study described herein. The request was based on the need for additional water to meet projected growth in demand. The existing water supply system consists of two springs in the upper part of Cottonwood Canyon and appurtenant pumps, lines and storage tanks. Due to the seasonal nature of the spring flows, it had already been necessary during several periods to haul water, at an estimated cost of $0.10/gallon, from the valley floor. Projected increases in the number of staff members over the next ten years required the identification and development of additional supplies. The study initially focused on Cottonwood Canyon due to its proximity to the observatory's facilities, historical record of significant surface flow and the presence of several practicable dam sites. A second alternative being considered at this time was the construction of a paved water harvesting catchment on a flat area near the summit of Mt. Hopkins.

PHYSICAL SETTING

The Santa Rita Mountains, of which Mt. Hopkins is the second highest peak (8,580 ft, 2,615 m) lie approximately 40 miles SSE of Tucson. The observatory facilities, reached by a dirt road from Amado, are located on a ridge extending SE from the main peak at an elevation of about 7,700 feet (2,347 m). The generally south-facing slope extending down from the summit and the generally west-facing slope extending down from the above-mentioned ridge, form the uppermost part of the watershed for the north branch of Cottonwood Canyon.

The portion of the watershed studied lies in the southern half of Sec. 14 and northern half of Sec. 15 of T. 20 S., R. 14 E. (Mt. Wrightson Quadrangle, 15 minute series). It varies in elevation from about 6,775 to 8,580 ft (2,065 to 2,615 m).

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The slopes are generally steep, ranging from 50 to 70 percent, and are covered with dense vegetation. Several species of evergreen oaks dominate the tree cover, but alligator junipers are common along the drainages and occur occasionally on the slopes. A variety of native grasses and shrubs occur as ground cover. Several large isolated outcrops of the bedrock, a fractured diorite, occur on the south-facing slope below the summit and talus chutes and rock slides constitute other non-vegetated areas. The narrow dirt access road climbs the west-facing slope of the watershed to the facilities on the ridge, making several switchbacks in the process. It then continues to the summit, cutting across the watershed again near the top of the south-facing slope. The average annual precipitation for the period 1970-77, as measured on the ridge, was 20.26 inches (7.98 cm). During 1977, about 70 percent of this annual total fell during the period 6/24 through 9/27.

INSTRUMENTATION AND DATA REDUCTION

A 3-foot (0.81 m) H-flume (Holtan, 1962) (henceforth called the lower flume) was installed in the stream channel at an elevation of about 6,775 ft. (2,065 m), thus defining the lower extent of the study area. A 1.5 foot (0.46 m) H-flume (the upper flume) was installed at an elevation of about 7,100 ft. (2,164 m). Stage recorders at each flume were operated from 6/28/77 through 9/27/77. See Figure 1 for flume locations.

A programmed Wang calculator was used to convert the time-stage data, read from the recorder charts, to runoff data. Hydrographs were also plotted for each storm. Total volume for extended periods of base flow was determined as accurately as possible from the charts. The total runoff at the upper flume for the period 6/20/77 through 9/27/77 was estimated to be 225,760 gallons (855 m^3). For the same period, at the lower flume, the estimate was 301,660 gallons (1,143 m^3).

A recording rain gauge located on the ridge at Knoll #1 was operated from 6/24/77 through 9/27/77. Six plastic rain gauges were also recorded from 6/27/77 through 9/29/77. These were located at each flume, in two places on the ridge, on the road near the summit and at the summit. See Figure 1 for locations.

Table 1 presents storm precipitation data for the seven gauges. Combinations of the totals for the individual plastic gauges were used in calculating average precipitation totals for the upper-flume watershed and the lower-flume watershed. These were then adjusted downward by a fixed percentage, based on the difference between the total for the plastic rain gauge at Knoll #1 and the total for the recording rain gauge at the same location. These adjusted values were then used in the runoff efficiency calculations discussed in the next section.

RUNOFF EFFICIENCY CALCULATIONS

For the initial calculations, the watershed boundaries for the upper and lower flumes were adjusted to take into account culvert locations. The areas were then determined by planimetry to be 74.6 acres (30.2 ha) for the upper flume and 144.7 acres (58.6 ha) for the lower flume. The runoff efficiencies for the upper and lower watersheds were then calculated to be 0.80 percent and 0.56 percent, respectively.

Visual inspection of the side drainages after runoff events indicated, however, that the side drainages on the south-facing slope of the watershed were contributing no surface flow to the main channel. Only those side drainages on the west-facing slope which received runoff from the road surface via one or more culverts appeared to be contributing surface flow to the main stream. Therefore, an additional calculation was made in which the total area of road surface on the west-facing slope within the lower-flume watershed was considered to constitute the effective watershed. The road surface areas for appropriate sections of the road were determined from extensive road-width measurements made with a distance wheel. This calculation yielded a runoff efficiency of 27.0 percent.

A well-maintained, compacted-earth catchment at the Atterbury Experimental Watershed near Tucson had a measured runoff efficiency of about 35 percent during its initial 18 months of operation. The Mt. Hopkins road surface, being continuously compacted by traffic, certainly has an actual runoff efficiency of at least this magnitude, but infiltration on the slopes between the culverts and the main stream channel would easily account for the lower calculated efficiency.

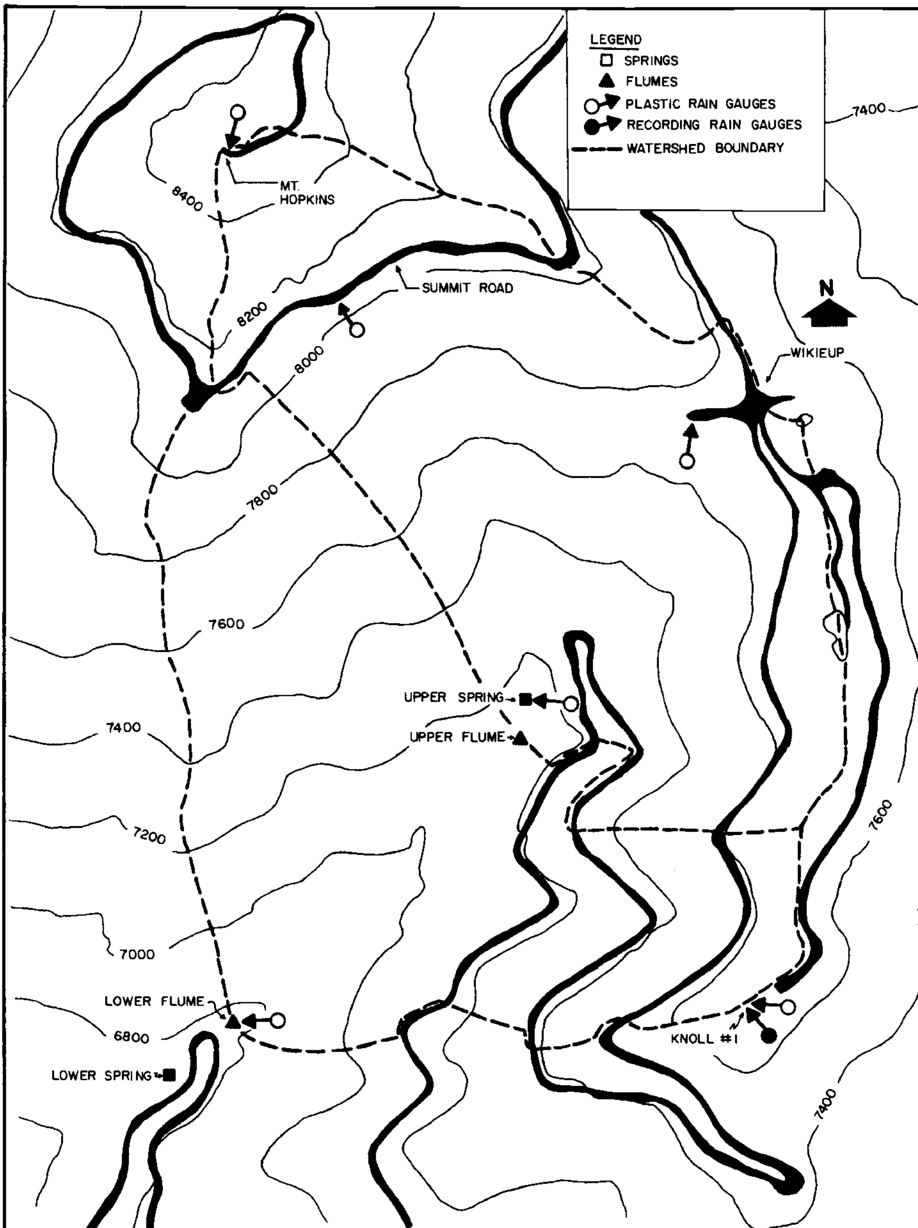

Figure 1. Map of the Cottonwood Canyon Watershed.
1" = 400' Contour Interval = 200'

TABLE I

STORM PRECIPITATION DATA IN INCHES FOR UPPER COTTONWOOD CANYON

Date of Storm Event	Mt. Hopkins (Summit)	Summit Road	Knoll* #1 (R.G.)	Knoll** #1 (P.G.)	Wikieup	Upper Flume	Lower Flume
7/3/77	.76	.82	.94	.92	.90	.95	.78
7/9-10/77	1.25	1.30	.53	.60	1.75	1.05	.77
7/11/77	1.25	.96	1.78	1.90	1.15	1.35	1.40
7/12/77	.28	.36	.36	.38	.32	.40	.40
7/14/77	1.10	1.55	.82	.90	1.30	1.30	1.25
7/18/77	.10	.10	.10	.15	.17	.10	.10
7/19/77	1.00	.96	1.51	1.80	1.60	1.20	1.60
7/20-21/77	.13	.15	.14	.21	.15	.15	.15
7/22-26/77	.54	.68	.52	.58	.60	.68	.92
7/28/77	.09	.07	.32	.33	.10	.15	.32
7/30/77	.03	.02	.01	.01	.01	.01	.02
8/1/77	2.00	.90	.55	.70	1.05	1.20	1.25
8/2/77	.46	.50	.20	.22	.32	.34	.40
8/8-9/77	.34	.34	.22	.25	.27	.27	.25
8/12/77	.90	1.20	.93	1.10	.96	.94	1.05
8/13/77	.37	.59	.72	.74	1.13	.74	.55
8/14/77	.03	.05	.06	.06	.09	.06	.04
8/15/77	.10	.16	.19	.20	.15	.20	.15
8/15/77	.08	.08	.08	.09	.11	.12	.09
8/16-19/77	.45	.44	.47	.51	.62	.68	.55
8/19-22/77	.25	.30	.28	.30	.32	.32	.30
8/22/77	.50	.50	.34	.34	.32	.36	.50
9/2/77	.08	.06	.06	.11	.08	.10	.10
9/3/77	.40	.50	.38	.40	.42	.52	.50
9/9/77	.28	.30	.20	.21	.25	.24	.24
9/11/77	.34	.38	.48	.50	.44	.48	.48
9/26/77	.38	.30	.61	.64	.40	.52	.50
Total Precipitation	13.49	13.57	12.80	14.15	14.98	14.43	14.66

*Recording gauge
**Plastic gauge

EFFECT OF CULVERT LOCATIONS ON WATERSHED BOUNDARIES

As the study progressed, the focus gradually shifted from Cottonwood Canyon to a smaller unnamed drainage immediately to the south. This was prompted by the presence in this drainage of a ready-made storage reservoir, created by the emplacement of fill during the road-building process. By plugging the existing culvert and sealing the upstream slope of the road fill, an effective dam could be created at low cost. Although this new site had a much smaller watershed than that calculated for the lower flume, simple modifications could create a contributing road surface area greater than that for the lower flume. Since, by this time, it had been determined that area of road surface was apparently the most important factor determining runoff, it was decided to take advantage of this low-cost storage site.

The culvert locations that affected the watershed boundaries for this potential storage reservoir were studied to determine how much additional road surface might be brought into the effective watershed by blocking selected culverts. For purposes of comparison, boundaries were determined for the watershed as it would have existed without the road and culverts, the watershed as presently affected by the culvert locations and the watershed as it would be if certain changes were made to incorporate additional road area. The three watersheds were then planimetered, with the following results: pre-road watershed, 35.5 acres (14.4 hectares); present watershed, 32.7 acres (13.23 hectares); possible future watershed, 51.3 acres (20.76 hectares). The results indicate not only that the blocking of selected culverts would significantly increase the size of the watershed for the proposed reservoir, but also that the present watershed is actually smaller than the pre-road watershed. It appears that when dealing with small mountain watersheds whose boundaries are crossed by roads, one cannot safely ignore the effect of culvert location.

It was also found that, by closing off certain culverts and making several other simple engineering changes to affect drainage, the area of road surface within the effective watershed could be increased from 1.4 acres (.58 ha) to 3.3 acres (1.2 ha) with a concomitant increase in runoff. One long section of road surface that could easily be added would feed directly into the proposed storage reservoir immediately up gradient from the road-fill "dam". The runoff efficiency of this section would approach that for a compacted earth catchment and thus significantly increase total runoff.

RECOMMENDATIONS FOR WATER SUPPLY DEVELOPMENT

Further investigation of this smaller drainage to the south of Cottonwood Canyon confirmed the existence of two potential reservoir sites. With slight modifications, the site above the road-fill "dam" could store about one million gallons (3,788 m^3). A second reservoir capable of storing about 0.5 million gallons (1,893 m^3) could be created by constructing a 25 foot (7.6 m) high dam several hundred feet downstream from the road-fill "dam". Bedrock outcrops and a narrow "v"-shaped cross-section at this location make it an attractive site for a lower dam.

In light of these excellent reservoir sites, and the ease with which the road system within this drainage could be developed as a water harvesting system, the options being considered for Cottonwood Canyon and for a paved catchment near the summit were abandoned. It was recommended that the two above-mentioned storage reservoirs be constructed, with the upper reservoir serving both for water storage and for trapping the inevitable sediment load. The spillway for this reservoir would completely bypass the lower reservoir. In addition, a pumping system was recommended to enable water from the upper reservoir to be trickle-filtered down the slopes into the lower reservoir or be pumped back up into the upper reservoir if infiltration past the upper dam should prove excessive during extended low-runoff periods.

To reduce evaporation losses, it was recommended that the lower reservoir be covered with a monolithic sheet of floating foamed butyl rubber and that the upper reservoir be covered with 2x2 foot (.61 x .61 m) squares of wax-impregnated polystyrene foam (Cluff, 1977b).

In order to create an adequate water harvesting system for these reservoirs, recommendations were made for closing off some culverts, equipping others with simple control structures, enlarging the ditch at the foot of the cut slope in order to accomodate increased runoff and paving certain sections of the road. Also included in the system would be the necessary pumps and distribution lines to move water from the lower reservoir up to a nearby storage tank and then on up to the facilities on the ridge.

RESERVOIR OPERATION BASED ON COMPUTER MODELING

A computer model (Cluff, 1977a) was used to simulate the operation of the proposed system over a 12 year period. This was done to confirm that the proposed storage capacity would be adequate to meet projected weekly demand over the long term and would be able to normalize the expected variation in runoff with an acceptable amount of spillage out of the system.

The limited daily precipitation data base collected during the study for the Cottonwood Canyon watershed was first used to calibrate the model. Parameters in the daily rainfall-runoff relationship were adjusted to optimize the correlation between measured runoff and simulated runoff, both on a storm-by-storm basis and for total runoff for the period. Once the model was calibrated for the Mt. Hopkins data, a 12 year daily precipitation record from Kitt Peak was used to estimate the runoff from the proposed, modified watershed over a similar period. The Kitt Peak record was chosen because it matched the Mt. Hopkins annual precipitation data for 1970-77 well in terms of average annual rainfall (20.26 for Mt. Hopkins versus 22.55 inches for Kitt Peak, 51.5 cm versus 57.3 cm) and because its variation from year to year closely paralleled that for the Mt. Hopkins data.

Using the Kitt Peak data for the 12 year period 1965-76, a storage capacity of 1,100,000 gallons (4,166 m^3) for the upper reservoir and a projected weekly demand of about 9,600 gallons (36.4 m^3), the model generated a spillage of 106,660 gallons (404 m^3) and a minimum storage of 77,000 gallons (293 m^3). As 100 percent storage would not be cost-effective, the size of the upper reservoir was deemed to be adequate to normalize expected variations in runoff. The lower reservoir could then be used solely to store potable water infiltrating from or transferred by pump from the upper reservoir. Its size could also be considerably less than originally determined as the maximum potential storage. An engineering consulting firm is presently comparing the cost for a dam at the lower site with that for a steel storage tank or tanks.

CONCLUSIONS

Several conclusions of a practical nature can be drawn from the situations and data described above:

1. Despite the existence of steep slopes and rather extensive bedrock outcrops, mountain watersheds characterized also by dense oak woodland and significant amounts of exposed talus may have surprisingly low rainfall-runoff relationships.

2. In calculating the area of small, steep-sloped watersheds whose boundaries are crossed by roads, the location of culverts should be taken into account when determining the boundary of the effective watershed.

3. For such watersheds, the road surface may contribute a very large percentage of the surface flow and may be easily modified to create an effective water harvesting system.

4. When conducting hydrologic studies in order to size culverts for mountain roads containing several switchbacks, the contributing road-surface area should be considered, since it could well be the major source of storm runoff.

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