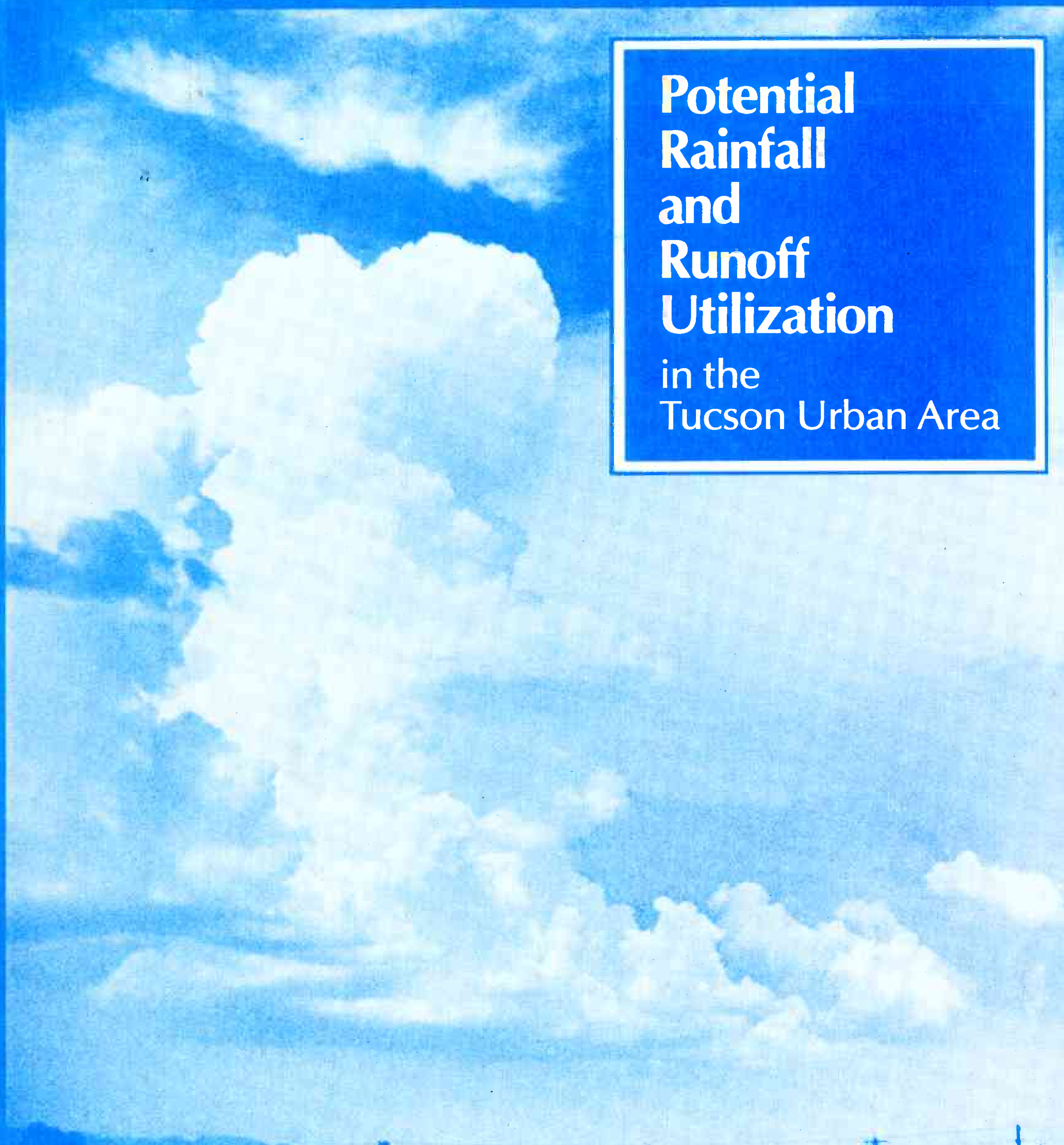
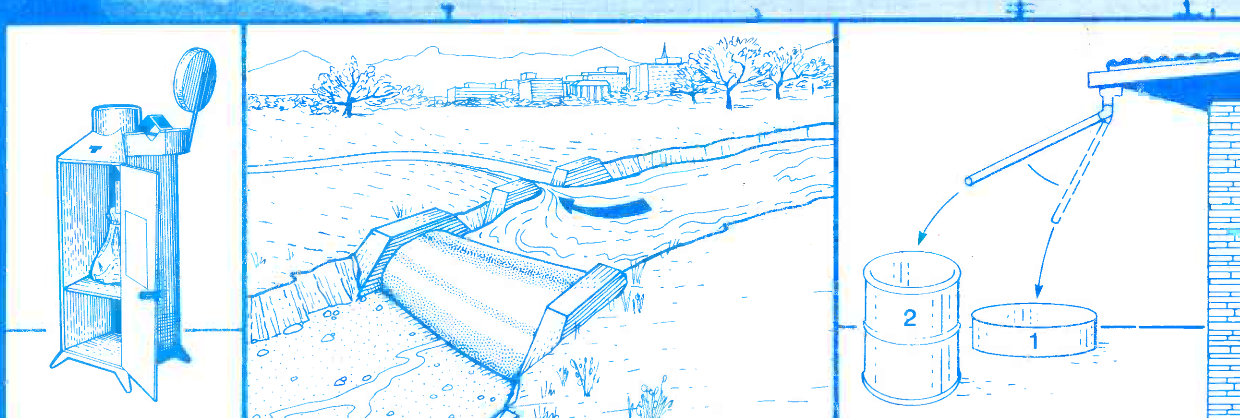


Potential Rainfall and Runoff Utilization

in the Tucson Urban Area



Office of Arid Lands Studies • University of Arizona • Tucson
September 1983

POTENTIAL RAINFALL AND RUNOFF UTILIZATION IN THE TUCSON URBAN AREA

An Office of Arid Lands Studies Report to the
City of Tucson
Real Estate Division
Contract No. 0255-83

Prepared by
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Note: This report represents one of two parts of the project "Evaluation, Monitoring and Operation of Existing City Water Harvesting System and Expansion Plan for Future Development of Rainfall Utilization," funded by the City of Tucson during the period November 1982 to June 1983.

September 1983

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ACKNOWLEDGMENTS

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INTRODUCTION

This report deals with the potential harvesting of rainfall and runoff in the Tucson urban area, as distinguished from the rural (farmland) setting that is discussed separately. The principal differences are that 1) rainfall catchment surfaces like rooftops and pavement already exist in the urban area, and 2) harvested rainwater in the urbanized area can be put to a variety of beneficial uses.

Purpose and Scope of Report

The purpose of this study was to make a preliminary assessment of the possibilities for harvesting rainfall in the Tucson urban area. Whereas a rural water-harvesting demonstration site has been built on retired farmland in Avra Valley and currently is being evaluated and expanded, the urban area is now under only the first phase of study. The objectives of this phase are as follows:

1. To review existing published reports of investigations by others in the field of rainfall/runoff harvesting in Tucson and similar urban areas, and to identify gaps in existing knowledge or data;
2. To explore the site potential for rainfall harvesting and utilization in the Tucson urban area, in the context of local hydrological conditions;
3. To describe the physical design components of systems for rainfall harvesting, and to illustrate them with preliminary design drawings, sketches and photographs; and
4. To prepare a report on the above findings and to make recommendations for further study, site development, or other action related to urban rainfall/runoff harvesting.

The results presented here relate primarily to the technical aspects. Some cost figures are included, but economic feasibility and certain institutional and legal questions concerning rainfall/runoff harvesting remain to be analyzed.

Study Area

The geographic area considered in this study is the Tucson metropolitan area. Varying degrees and types of urbanization have taken place within the downtown-university area, the older neighborhoods or barrios, the newer (post World War II) suburbs, and the surrounding foothills areas. In all of these, the natural conditions affecting runoff from rainfall have been altered in some way, and opportunities exist for improving the beneficial use of rainfall and runoff. Precise geographic boundaries have not been delineated; this report deals generally with urban-suburban Tucson.

Previous Research

Data on rainfall and runoff on small urban watersheds in Tucson have been collected by the University of Arizona Water Resources Research Center since 1968. A number of technical papers, graduate theses and dissertations have reported various aspects of hydrologic data, field experiments, and project formulation for runoff control, diversion and use. Much of this work has been summarized in recent reports by Resnick and DeCook (1980) and Resnick, DeCook and Phillips (1983). Concurrently, various reports were prepared under the Tucson Urban Study. Investigations of sites and criteria for runoff diversion-detention and recharge enhancement were reported by Resnick, DeCook and Wilson (1981). Also, summaries of the 1981 and subsequent studies are on file as Working Papers of the U.S. Corps of Engineers (1982).

In the area of direct rainfall harvesting, recent attention has been directed to quality changes in precipitation due to atmospheric contaminants. Wisniewski and Kinsman (1982) have documented 71 precipitation monitoring studies nationwide. In the southern Arizona region, Dawson (1978) analyzed the ionic composition of rainfall during convective showers at the University of Arizona. Osborn, Cooper and Billings (1981) studied rainwater quality near Tombstone. Frasier (1983) reported on three years of observations of water quality from a water-harvesting system near Mesa, Arizona. Quantitative studies on rooftop runoff and rainfall harvesting system design have been published by Ree (1976) and Ree et al.(1971), respectively.

A detailed feasibility study of rainwater collection systems in California was made by Jenkins and Pearson (1978). A comprehensive volume on residential water reuse was published through the California Water Resources Center by Milne (1979).

The above reports and related research have been used to further an evaluation of rainfall/runoff harvesting potential in the Tucson region.

RAINFALL HARVESTING

Direct, on-site collection and use of rainfall can occur in several urban settings: 1) residential sites — primarily the single-family residence, duplex, or apartment where individuals can use water catchment surfaces, principally rooftops; 2) institutional and commercial sites, like an office-building complex or a suburban shopping center where the property owner-manager can use water shed by rooftops, paved parking areas, and walkways; or 3) industrial sites, like aircraft-component or electronics plants, where the corporate developer can integrate plant design, construction, and operational features for water collection, treatment, storage, distribution, use or reuse.

Before any rainfall harvesting system, either simple or complex, can be efficiently designed and effectively operated, it is necessary to determine the local characteristics of the rainfall that constitutes the supply for the system. Some of the important characteristics are the amount and variation of annual rainfall, monthly rainfall distribution, rainfall frequency, intensity, and duration, and the rainfall quality in relation to its intended use.

Rainfall Characteristics in the Tucson Region

Most locations within the Tucson urban area receive a long-term average of approximately 11 inches of precipitation annually. Table 1 indicates values of mean annual rainfall for four stations in urban-suburban Tucson, in Cortaro and at the Arizona-Sonora Desert Museum, for similar periods of record. The average amount, as well as the year-to-year variation in amount received, is relevant to design considerations. Table 1 shows the relatively wide departure from mean values at these stations, during approximately the same time period. Generally it can be expected that, at any place in the city during an extended period of time, the annual rainfall may vary from less than 6 inches to more than 16 inches.

The seasonal and monthly distribution of rainfall is critically important in the design of a system for collecting, storing and using rainwater. The monthly distribution for Arcadia and High School watersheds is illustrated in Table 2. The

Table 1. Mean and Extreme Values of Annual Rainfall at Various Points In and Near Tucson (NOAA, National Weather Service, 1981; and Sellers and Hill, 1974)

Location	Rainfall Mean (Inches)[1]	Extremes[2]
Tucson International Airport	11.05	5.34-17.99
Tucson Magnetic Observatory	10.85	5.59-16.36
Tucson, University of Arizona	10.73	5.72-16.26
Tucson, Campbell Ave. Exper. Farm (1949-1970)	11.13	5.58-15.47
Cortaro 3 SW (1945-1970)	11.07	6.27-18.47
Arizona-Sonora Desert Museum (1943-1970)	9.62	5.05-17.05

[1]Period of record 1941 to 1970 unless otherwise indicated.

[2]Extremes are for periods ranging from 1931-1972 to 1949-1972.

Table 2. Monthly Precipitation Data For Two Urban Watersheds in Tucson (Resnick, DeCook and Phillips, 1983)

	Mean No. of Rainfall Events		Mean Values of Rainfall Depth per Rainfall Event (inches)[3]		Mean Monthly Rainfall (inches)		
Month	Arcadia[1]	High School[2]	Arcadia	High School	Arcadia[3]	High School[3]	Tucson Airport[4]
Jan.	3.0	2.6	0.34	0.30	0.95	0.84	0.76
Feb.	2.6	2.6	0.31	0.26	0.76	0.67	0.75
March	3.1	2.8	0.27	0.25	0.76	0.69	0.83
April	1.5	1.5	0.14	0.13	0.20	0.24	0.28
May	1.5	1.5	0.17	0.15	0.22	0.23	0.19
June	2.7	2.3	0.11	0.16	0.29	0.36	0.20
July	9.2	8.9	0.18	0.20	1.68	1.72	2.06
Aug.	8.3	7.8	0.23	0.23	1.94	2.03	1.57
Sept.	4.5	4.6	0.25	0.21	1.13	1.00	1.41
Oct.	3.2	3.2	0.29	0.34	1.16	1.11	1.14
Nov.	2.0	2.1	0.38	0.32	0.76	0.73	0.69
Dec.	3.3	3.3	0.26	0.26	0.88	0.87	0.76
Year	44	44	0.24	0.23	10.73	10.49	10.64
Summer Season	26	26	0.18	0.19	5.26	5.34	5.43
Winter Season	18	18	0.28[5]	0.27[5]	5.47	5.15	5.21

[1]Period of Record July 1968 to December 1980.

[2]Period of Record March 1968 to December 1980.

[3]Average of All Gages Within Each Watershed.

[4]Period of Record 1968 to 1980.

[5]Calculated from Monthly Averages.

general location of these watersheds is shown in Figure 1; more detailed maps of each, showing raingage locations, are presented in Figures 2 and 3. Table 2 lists the average monthly rainfall values for these two watersheds and for Tucson Airport for the 13-year period 1968 to 1980. This period was chosen because it is the period for which runoff and other data are available for comparison, as discussed in a later section.

The quality and quantity of harvested rainwater are relevant for determining how the water can be used. When examining quality for residential, recreational or other water applications, the starting point for analysis is where the rainfall arrives at the earth surface. In its descent to earth, rainwater collects various substances from the atmosphere. In recent years much of the concern about this process has been centered in the problem of "acid rain," although a considerable body of data has resulted from various other kinds of meteorological and hydrological investigations.

The effects of acid rain and other atmospheric contamination phenomena have been studied more intensively in the highly industrialized regions, but currently the air quality monitoring network extends nationwide. Within Arizona, analyses of rainwater at Tombstone and elsewhere have indicated that contaminants originate from terrestrial sources, including copper smelters (Osborn et al., 1981). In general, the ionic concentration, such as that of sulfate, decreased with increasing storm rainfall amount, illustrating a "washout" effect.

The pH of "pure" rainfall would be approximately 5.6 in an unmodified state of equilibrium with atmospheric CO_2 (Dawson, 1978). Concentrations of the ammonium, nitrate and sulfate ions and pH typically decreased with accumulated rainfall during storm events. At Tombstone the measured pH of rainfall during 1975 to 1978 ranged from about 4.0 to 7.6. The greatest acidity occurred during the summer season; about one-half of the August samples were below 5.0, whereas during the rest of the year all samples had pH >5.0 and most were >6.0.

In a study of harvested rainfall quality at several test sites in Arizona, Frasier (1983) found that 12 out of 112 water samples had concentrations of chromium,

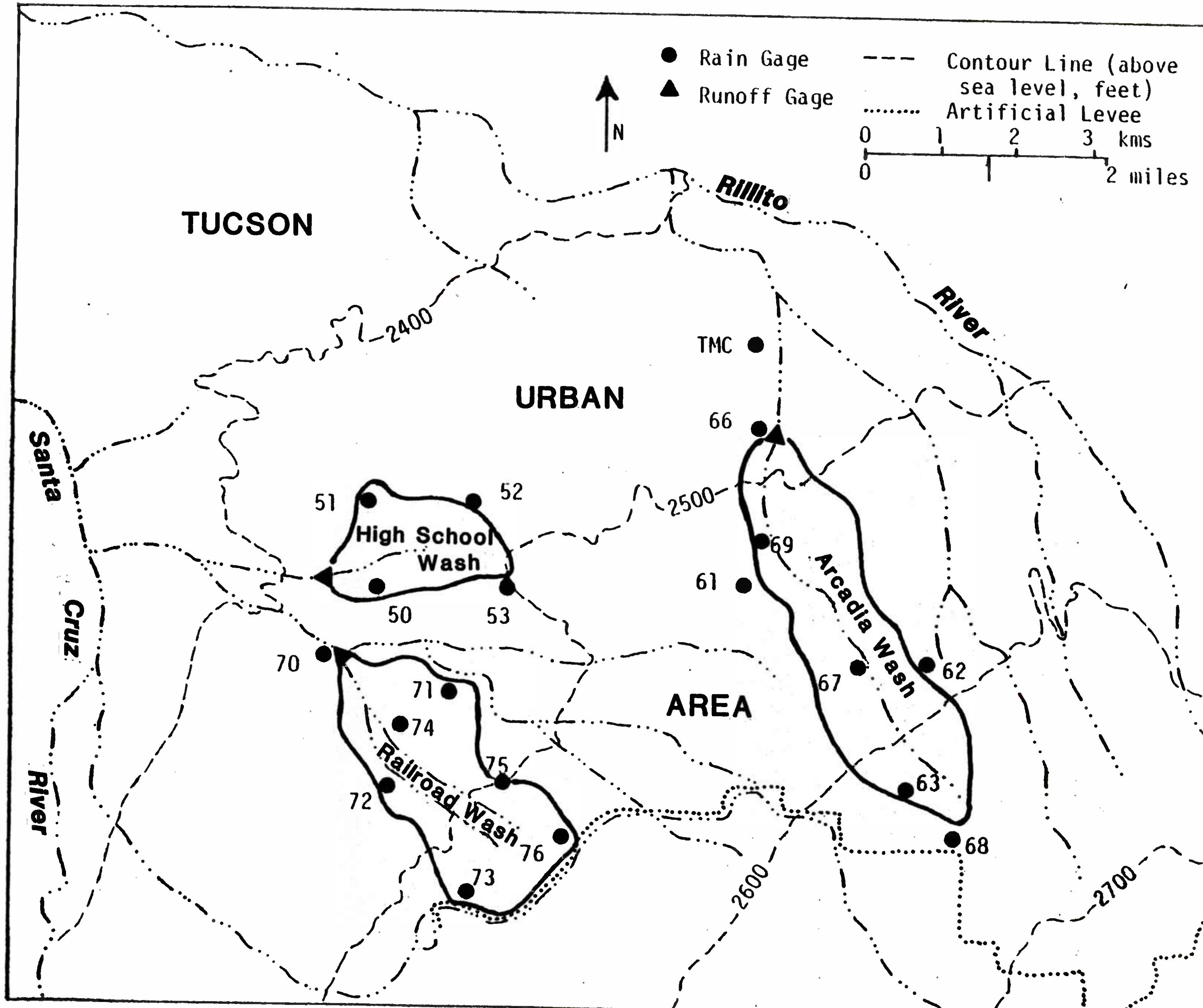


Figure 1. Experimental Urban Watersheds in the City of Tucson, Arizona, 1971

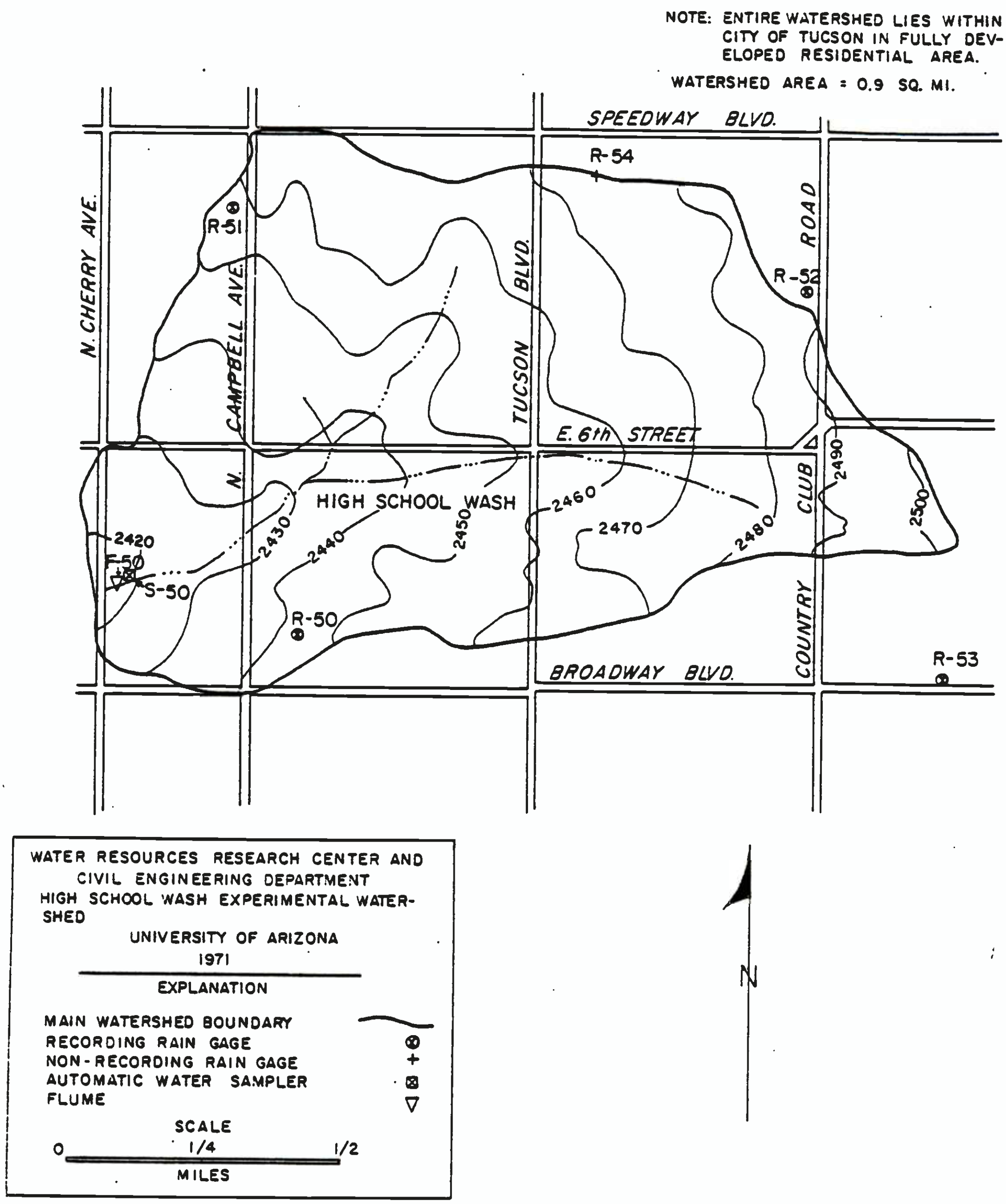


Figure 2. High School Wash Experimental Watershed

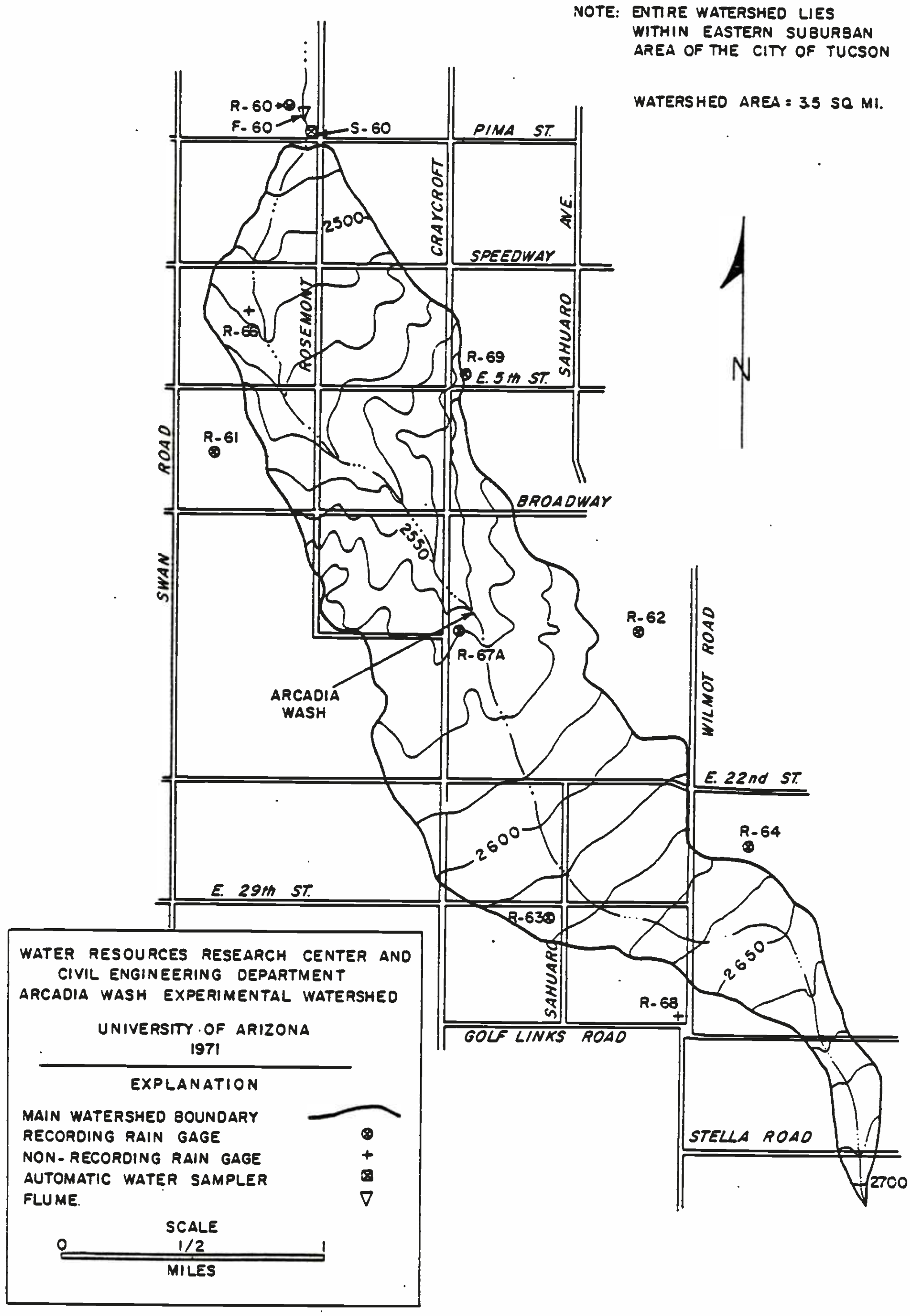


Figure 3. Arcadia Wash Experimental Watershed

cadmium, lead and/or mercury that exceeded standards for drinking water supplies. Only arsenic, however, was found consistently in potentially hazardous concentrations for drinking water. Arsenic content increased with increasing time between rainfall events, and decreased with greater precipitation quantity during a single event.

In a study of 13 localities in California, Jenkins and Pearson (1978) determined that the ". . . concentration of lead in rainwater near urban areas frequently exceeds the recommended limit for drinking water, which would imply that rainwater supply systems are feasible only in rural areas." That finding would suggest that a similar condition may exist in the Tucson urban area. Therefore, with the cooperation of the USDA-SEA office in Tucson, arrangements were made in April 1983 to collect direct rainwater samples for analyses of lead and possibly other constituents (see Figure 4). From April through June only one rainfall event yielded sufficient sample for analysis. That sample showed lead content of 1.0 micrograms per milliliter, which is 20 times the recommended limit of 0.05 milligrams per liter. The rainfall, however, was relatively light (< 0.10 inches) and occurred during or immediately after a period of atmospheric stability. These factors may have contributed to an unusually high reading. In any event, though conclusions cannot be drawn from one sampling, the high lead content suggests that additional analyses should be made before recommending rainwater for human ingestion. The USDA personnel have agreed to continue collecting rainfall samples for this purpose.

Residential Sites

The residential setting offers a unique opportunity for individual citizens to participate actively in rainfall harvesting, to their own benefit and that of the community. Collectively, the beneficial use of rainfall by individuals can contribute significantly to a municipal program of water conservation. Moreover, it is likely that the residential consumer's water bills will be reduced.

Whether motivated by increasing water costs or by an awareness of resource conservation, the residential water user must have acquired an attitude conducive to a more careful water-using lifestyle before he or she is apt to initiate a real water-

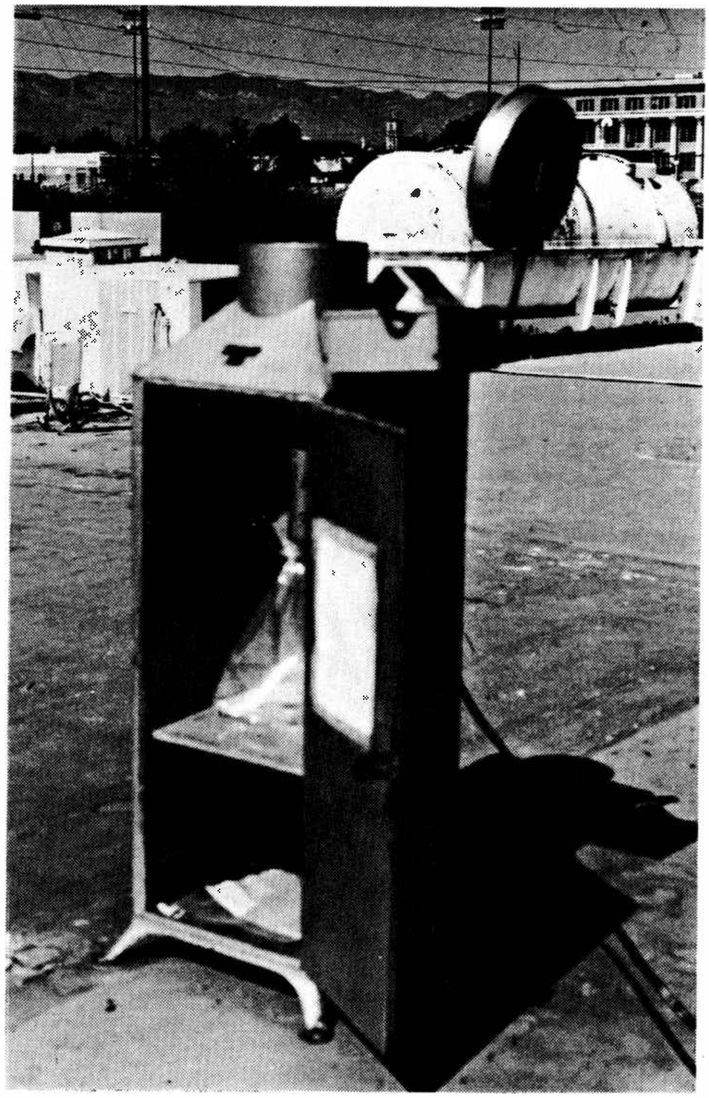


Figure 4. Wet-Deposition Rainfall Sampler, USDA-SEA, Tucson.

saving effort in the home. Such efforts require some degree of initial expense, inconvenience, and modification of lifelong habits of excessive water use.

It should not be expected that rainfall harvesting alone will provide an ample supply for domestic needs and that it will allow one to declare independence from the public water system, because rainfall in the Sonoran Desert is not plentiful. To achieve water self-sufficiency, the householder may have to combine several activities like rainfall harvesting, recycling of grey water, and use of an alternative toilet fixture design with a generally more frugal use of water. Nonetheless, direct use of rainfall can provide a substantial portion of water for indoor or outdoor use.

In the residential setting, whether it is a single-family residence, duplex, condominium, or other unit, a rainfall harvesting system contains five basic elements (Figure 5):

1. Rainfall catchment surface;
2. Rainwater collecting/concentration components;
3. Rainwater separation and treatment units;
4. Rainwater storage facility; and
5. Water distribution capability.

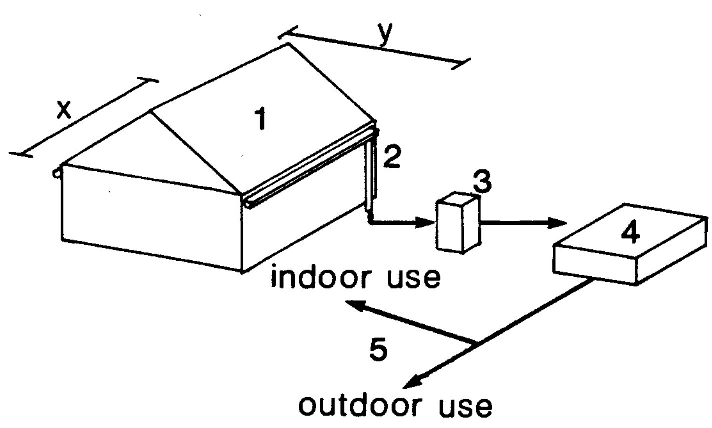


Figure 5. Elements of a Residential Rainfall Harvesting System.

The performance of the system is a function of two of the above elements — available catchment surface area and storage capacity — combined with the amount and time distribution of rainfall and the amount and time distribution of water demand. Functional relationships can be established considering all these factors for use in the hydraulic and physical design of rainfall harvesting systems (Jenkins and Pearson, 1978). The five physical elements listed above can be considered in terms of their geometry, material composition, and cost.

Rainfall Catchment Surface

In the residential setting, the primary impact surface and catchment area is the rooftop. Other, supplementary catchment surfaces may be hard-surfaced (concrete, brick, tile, or flagstone) terraces or open porches, walkways and driveways. These surfaces can be used most readily for landscape watering. Rainwater collected from rooftops can be directed to either outdoor or indoor use.

The area and form of roof affect the amount of rainwater that can be collected efficiently. The type of roof covering material also can affect the water-collecting characteristics, but more importantly, it can affect the quality of water collected. This and other factors affecting quality will be discussed later. The rooftop area of the single-family residence in Tucson may range from less than 1,000 to more than 2,500 square feet. We may assume that a typical structure including carport would have a covered area of 1,700 square feet. (For rainfall collection, the area is measured as a horizontal projection; see Figure 5, the X-Y plane). Assuming an average annual rainfall of 11 inches and a collection efficiency of 90 percent (Ree, 1976), each square foot of roof would yield approximately 6.25 gallons annually. The 1,700-square-foot rooftop, for example, would yield about 10,625 gallons annually. With totally efficient storage to provide for daily and seasonal variations, this would be equivalent to roughly 29 gallons per day. Clearly, this source of supply is sufficient for only a fraction of the residential water demand at present rates of use. If the average number of persons per household is 2.5, the above quantity would supply only 12 gallons per capita per day (gpcd) or about 11 percent of the current municipal input for residential water consumption (SAWARA, 1983a). Harvested rainwater, therefore, must be directed toward selective uses, and the per-capita or per-family rates of use must be sharply reduced, if rainwater is to be an effective factor in the water-supply equation.

The type of roofing material also affects both the quantitative and qualitative characteristics of rooftop runoff. Material that is smoothest and least absorptive will yield water at rates most consistent with maximum rainfall intensities, while rough surfaces like unsealed gravel will tend to retard flow and will retain some of the rainfall in surface irregularities and interstices.

Specific quality effects of roofing material have not been analyzed for this study, but should be considered if the harvested rainfall is to be used for drinking water. The following list illustrates the most common kinds of roof surface materials in the Tucson area (each roof type may be associated with various water quality concerns, depending upon age, maintenance, type of finish or coating, and other variables):

- Red clay tile;
- Galvanized sheet metal;
- Baked enamel sheet metal;
- Cedar shakes or shingles;
- Gravel;
- Asbestos paper;
- Asphalt roll roofing;
- Asphalt shingle roofing; and
- Urethane insulation (foam).

Large trees or other overhanging vegetation near the roof can cause deposition of bird litter and leaf debris, which deteriorates roofing by holding moisture and also may plug rain gutters and drain spouts. The level of maintenance of the roof also will affect water collection efficiency and quality.

Rainfall Collection and Concentration

The collection and concentration of rainwater from the rooftop is accomplished principally through eave gutters and downspouts. The configuration depends on the form of roof. The traditional form is the flat roof, inherited from Indian and Spanish/Mexican styles (Figure 6). The territorial period brought the hip roof (Figure 7). Today the simple gable (Figure 8), pitched and flat roof styles are popular in modern Tucson architecture.

The so-called flat roof usually is built with just enough slope to drain rainwater to one or more canales or spouts protruding through a parapet wall (Figure 6), or to one edge (Figure 9). In the first case, the point or points of water concentration from a flat roof are fixed; in the latter, water can be directed to one of two corners by installing an eave gutter and sloping it toward one end or the other.

The gable style allows roof runoff to be collected at various desired points that can be determined by the slope of the eave gutter and placement of the downspouts. Figure 10 illustrates one possible arrangement for consolidating the runoff from the two sloping sections of a single gable roof. The metal (aluminum or steel) sections and hardware can be shaped to a particular style and colored to harmonize with the eave, fascia, and siding or stucco of the house. Gutters and spouts should be appropriately sized to handle the heavier rainstorms, as indicated by the long-term maximum 5-minute intensity of rainfall. Milne (1979) tabulated a desired size for California conditions, in terms of the range of roof areas and gutter slopes. In general, a 6-inch rectangular width or diameter of gutter and a 4- to 6-inch diameter of downspout will serve the average single-family Tucson residence, depending upon the length, location, and slope of the gutter. If desired, a spatially varied flow concept can be used to size the gutter with increasing capacity toward the discharge end.

Cost information on collection systems was requested from eight firms in the Tucson area, and in most instances the dealers did not have a pre-calculated standard design; rather, the standard procedure is to make estimates for fabricating

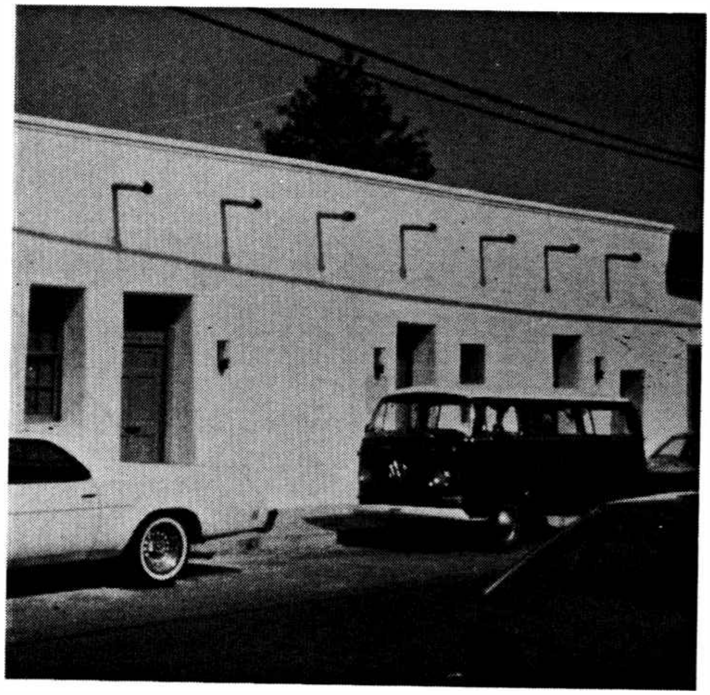


Figure 6. View of Flat Roof with Full Parapet Wall.

Figure 7. View of Hip Roof Style.

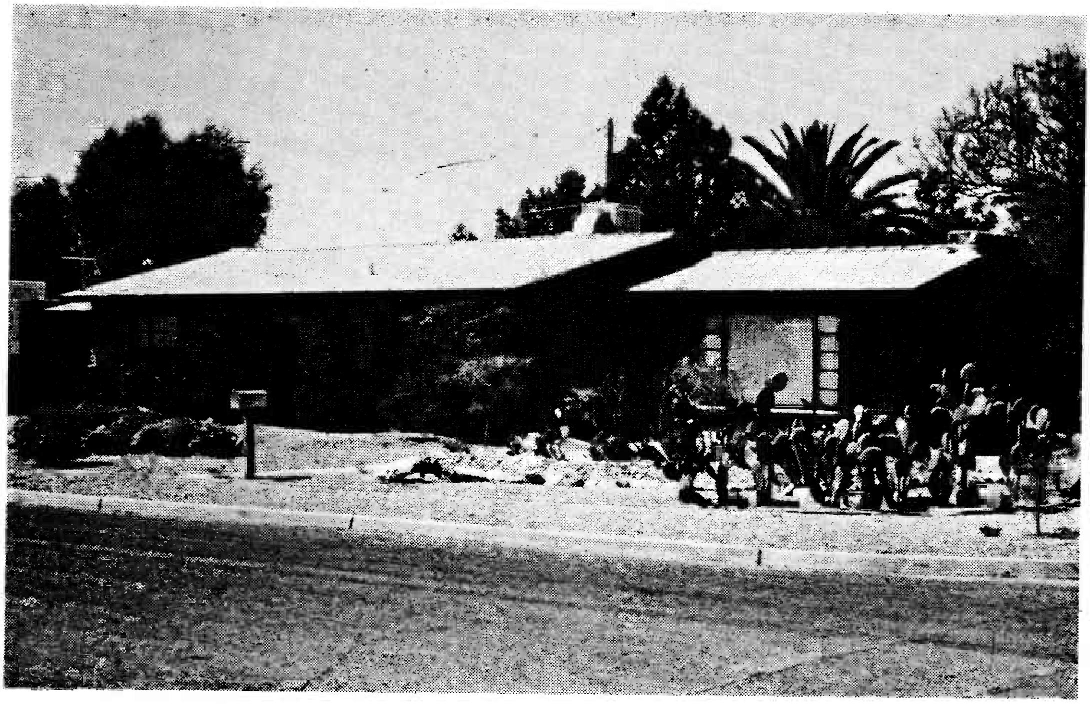


Figure 8. View of Gable Roof Style.

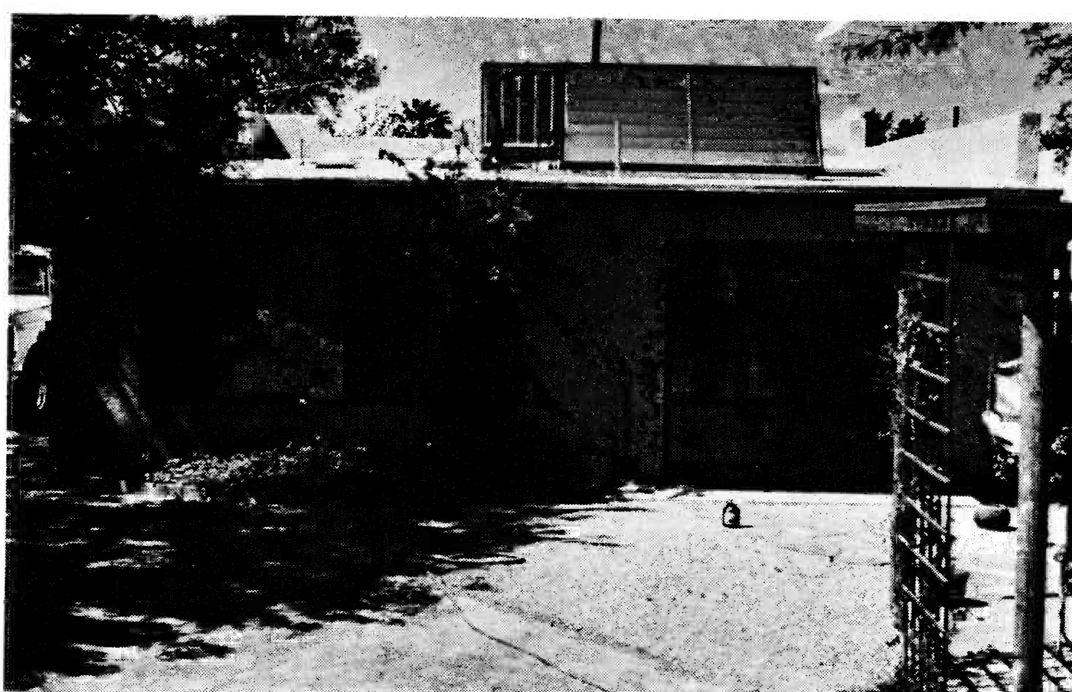


Figure 9. View of Flat Roof with Partial Parapet Wall.

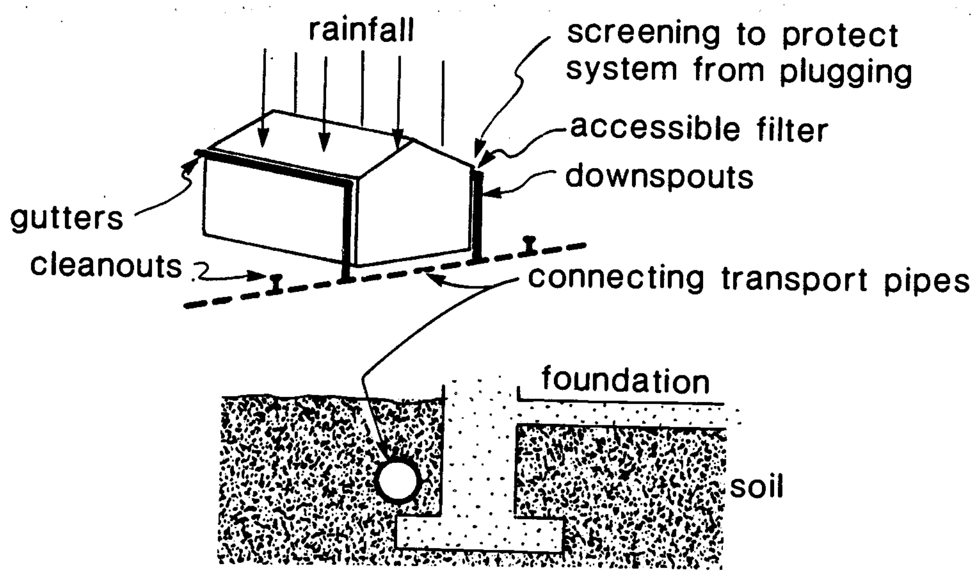


Figure 10. Method of Collecting Rainfall From Gable Roof.

and installing the needed components for an individual job. As an example, one estimate of $2.65 per linear foot of roof edge included gutters and downspouts, elbows, pipe bands, end caps, dropouts and hangers, plus installation labor. Another example illustrating actual costs, with all the necessary components and do-it-yourself labor, is the Papago Baboquivari District Office collection system which would cost $150 for 100 feet of eave, or about $1.50 per linear foot, for materials only.

These devices for collecting and concentrating rooftop runoff can be added to the existing building easily and with relatively modest expense by the individual homeowner.

Separation and Treatment

The degree of clarification and treatment of the collected rainfall depends on quality desired, which, in turn, depends on the intended use of the water. If water is intended for drinking and culinary uses, it may require screening, coagulation and sedimentation, filtration and disinfection. On the other hand, if it is to be simply an auxiliary supply for landscape watering, it may require only a screening to separate solids. In any event, it is usually desirable to separate or split out the "first flush" of runoff from the roof catchment, especially when a substantial period of time has elapsed since the last rainfall. Between rains, materials like leaf litter, bird droppings, dust and other particulates collect on the surface, and it is well to divert and dispose of the first flush of roof runoff carrying the bulk of these materials. Several devices have been conceived for this purpose. One simple method is to install a movable (rotating) downspout section (Figure 11) that can be directed to a disposal container, then moved manually after the first few minutes of rain to discharge into the treatment or storage system. Self-actuated devices include one described by Hall (1982) and another by Vale (1975).

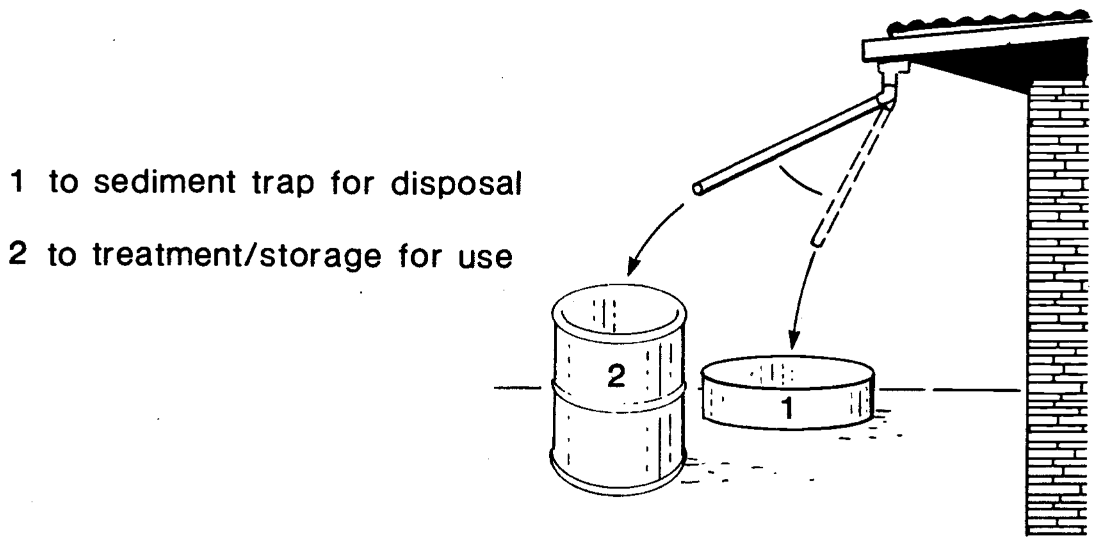


Figure 11. Device for Disposing First Flush of Rainfall from Rooftop.

Once this early, most contaminated flow has been diverted, the continuing flow will be directed into the treatment system or the storage tank. The sequence of treatment or storage depends upon the individual system and the use of the water. In general, it is recommended that primary screening and settling should be applied to all the collected water, in conjunction with storage. Then, as the stored water is withdrawn for use, that portion intended for drinking can receive appropriate treatment as needed, and those portions used for other purposes can receive the necessary treatment, if any, for their particular uses.

In the most stringent case, the drinking water supply, quality considerations include: 1) potentially toxic atmospheric contaminants in solution, like lead; 2) contaminants from roof surface and guttering materials (see earlier section; 3) suspended particulates derived from the atmosphere or the collecting surface that cause turbidity; and 4) microorganisms like fungi and coliform bacteria, derived largely from bird droppings. Removal of dissolved toxins may not be economical on the household scale, except possibly through distillation. In this case, solar distillation of the drinking-water fraction may be an attractive option. Suspended matter can be removed economically by settling, followed by alum coagulation and/or sand filtration. Such removal of solids also achieves a reduction in bacteria, which commonly adhere to solids and are removed with them. The disinfection process is then completed by chlorination or other methods. Procedures adding alum and chlorine dosages are outlined by Jenkins and Pearson (1978) and others.

The practical feasibility of these treatments depends upon the aptitude and motivation of the individual homeowner. These systems require an initial expense for installation and some time and effort for operation and maintenance. In addtion, periodic testing of the treated water, to evaluate process effectiveness, would be desirable. Chlorination, for example, should be followed by periodic testing to maintain residual chlorine.

Some fairly simple and successful treatment systems for drinking water have been employed by various cultures in remote or undeveloped areas. Many of these systems rely upon an effective combination of a settling chamber and a slow sand filter, both of which work best in a continuous-flow system. Even where a system like this is operating well, it is recommended that the water be further purified before drinking. On the domestic scale, boiling requires considerable energy, and chlorination requires considerable attention to detail. Solar distillation for purifying the drinking-water fraction is a possible alternative. A solar still of moderate size can be incorporated into residential design; this method has the additional advantage of removing bacteria and heavy-metal contaminants like lead, which may present a health hazard in the urban area (see earlier section).

Storage Tanks

Water storage tanks or "cisterns" are required to hold harvested rainwater until needed. Conceivably, storage tanks could be formed with any of the following materials or types of containers: steel tanks; fiber glass or concrete septic tanks; water bags or water beds; pressure-treated plywood; reinforced concrete block with standard mortar and grout or with a surewall surface bonding of stacked block with grout; poured-in-place reinforced concrete; ferrocement; rammed earth with portland stabilizer; or above or below ground swimming pools.

The first three types listed above are manufactured or prefabricated, while the remainder are constructed in place. Manufactured tanks are presumed to be watertight. The principal concern about material is that the tank or its inner lining should not be harmful to water quality, especially if the water is intended for human consumption. In the case of built-in-place tanks, some form of lining is required to ensure watertightness and durability. Such lining material may be of plastic,, butyl rubber or a special synthetic like Chevron Industrial Membrane (CIM). Again, the lining material should be chemically compatible with the intended use of the water.

Traditionally, in the more humid regions, the rain barrel was used to store rainwater for some domestic uses, and cisterns were dug for water storage, and were commonly lined with brick or rock masonry. "Soft rainwater was considered especially suitable for laundry and personal hygiene, particularly hair washing" (Milne, 1979). More recently, and with expanded urbanization, a vast majority of the populace is served by a public or private water supply and distribution system, and residential storage systems are virtually obsolete. A revival of interest in individual systems arises from the currently growing need for conservation or augmentation of the piped-in supply.

Now that residential-scale storage tanks are again receiving more attention, advantage can be taken of recent advances in construction materials, like fiber glass, inert plastic coatings and bonding agents. For example, an inner lining can be applied to a concrete or masonry storage container with CIM, which has outstanding tensile strength, durability, and elongation properties and is not prohibitively expensive. It has been tested and found safe and acceptable as a potable water storage membrane. Price catalogs for CIM materials are available, and there are numerous dealers throughout southern Arizona that handle various types of preconstructed tanks.

Storage tanks, whether above or below ground, should be covered, for several reasons: 1) an open tank would encourage photosynthesis and plant growth; 2) evaporation losses from an uncovered tank would appreciably reduce the stored water supply; 3) an open tank can represent a safety hazard for small children; and 4) breeding mosquitoes in an uncovered tank may pose a health hazard.

Location of the storage tank at an appropriate place within the residential property is an important consideration, and will vary with each situation. Generally, however, it should be centrally located between the catchment area and the point of water use. It can be either inside or outside the building and above or below ground. It is assumed here that the storage tank would be constructed below ground level, to lower visibility and to moderate water temperature. Other necessary features of the storage tank are 1) an entrance pipe from the outer source and an easily accessible screening device; 2) a screened overflow pipe; 3) an outlet pipe, with pump, to the point of use; and 4) a drain and sump for cleaning, with access hole.

The desired volume of storage can be estimated in various ways. The calculation must begin with the expected rainfall and the available catchment area, which in combination will comprise the upper limit of annual water input to the system. Within those limits, the storage tank can be sized according to the anticipated water demand and the desired degree of reliability. An equation developed by Jenkins and Pearson (1978) expresses the relation among all these factors except reliability:

$$Q = 0.002\, A^{0.2}\, R^{0.2}\, V^{0.8}$$

where Q = system yield, in gallons per day
A = catchment area, in square feet
R = annual rainfall, in inches
and V = storage volume, in gallons.

This expression is considered valid for all locations in California, including some with approximately the same annual rainfall as Tucson, e.g., Fresno (10.69 inches per year) and Los Angeles (11.14 inches per year). Inserting the Tucson value for average or anticipated annual rainfall would enable one to approximate a storage requirement.

The foregoing equation, however, would not predict system performance or reliability for a Tucson site, because the storage required for a certain reliability depends on the manner of operation of system output (withdrawals), and on the storm-to-storm or month-to-month pattern of incremental input (rainfall) to storage. In California, for example, most of the annual precipitation occurs during the winter; in Tucson, it occurs almost equally in the summer and winter seasons. This variation, of course, affects the requirements for holdover storage.

A simple way to approximate needed storage volume is to use an iterative process, starting with an estimated storage that would contain all the expected rainfall in a "wet" year. Then construct a table that will display the operation of the storage system assuming a given month-by-month water demand, a given catchment area, and the historic mean monthly rainfall for that location. Such a method was suggested by Milne (1979), using a constant monthly demand. This could apply directly to indoor household uses, which do not change greatly throughout the year, but it can be modified to reflect a variable monthly demand that better fits outdoor water use patterns. In a sample tabulation (Table 3), collected rainfall supplied 39 percent of the annual demand. The remaining 61 percent would have to be supplied from other sources. Also, storage volume evidently could have been less than that assumed, without an appreciable loss of efficiency.

Table 3. Sample Calculation of Monthly Rainwater Storage System Performance (after Milne, 1979)

Month	Rainfall[1] (inches)	Net Rainfall[2] (gallons)	Monthly Demand[3]	Net Change in Storage	In Storage From Prior Month[4]	Deficit (From Other Sources)
Jan.	0.77	735	1,800	-1,065	4,800	4,800
Feb.	0.70	668	1,800	-1,132	3,735	0
March	0.64	611	1,800	-1,189	2,603	0
April	0.35	334	1,800	-1,466	1,414	0
May	0.14	134	2,400	-2,266	0	52
June	0.20	191	3,000	-2,809	0	2,266
July	2.38	2,271	3,600	-1,329	1,991	4,800
Aug.	2.34	2,232	3,000	-768	662	0
Sept.	1.37	1,307	2,400	-1,093	0	106
Oct.	0.66	630	1,800	-1,170	0	1,093
Nov.	0.56	534	1,800	-1,266	0	1,170
Dec.	0.94	897	1,800	-903	0	1,266
						(+903)
Annual	11.05	10,544	27,000			16,456

[1]Based on 1941-1970 record, Tucson International Airport.

[2]Assumptions are roof area = 1,700 square feet; catchment efficiency = 90 percent.

[3]Assumes 30 gallons per capita per day demand for each of two people, 30 days per month for indoor use, plus summer season outdoor use.

[4]Storage tank 8 x 10 x 8 feet depth = 4,800 gallons. Assumes refilling tank from other sources on January 1 and July 1.

Distribution System

The final part of the total system is the facility for delivering stored water to the point of use. For outdoor use only, a small sump pump can deliver water from the tank to the various key points to irrigate a garden or shrubbery. Or, if the tank is located at a high point on the property, a manual outlet valve can be opened to drain water by gravity to the points of use, where the water can emerge through a bubbler or alfalfa valve.

If indoor household use is the objective, a standard shallow-well pump system can deliver water from the storage tank to the internal plumbing system to serve the showers, sink faucets, toilets and washing machine. These uses generally will require a pressure of 20 to 40 psi, which can be provided by the pump system. However, the pump should not be required to start every time water is used, because of pump noise and excessive wear. Therefore, a good option may be to install an intermediate elevated holding tank as shown in Figure 12. Ideally, from the standpoint of energy consumption, it would be desirable to place the entire storage facility at an elevated level (near the rooftop collection point) and thus obviate the need for much pumping. It may be expensive, however, to construct the elevated tank support and, even so, it may not be high enough to provide adequate pressure to operate fixtures. The aesthetic appearance of such a tank also must be taken into account when a system is constructed in a residential neighborhood.

Integrating the Parts

The resurgence of interest in water and energy conservation has given birth to a number of new ideas and has given a re-birth to some old methods for drinking-water self-sufficiency. The trend has been toward "appropriate technology," or simplicity of design and operation.

A real-life example exists near Tucson at the home of Mrs. Jones (a fictitious name for a real person with a real, practical rainwater harvesting system). Her system has provided an adequate domestic supply for one or two people and occasional visitors since 1941. A distinct advantage is the location, close to the

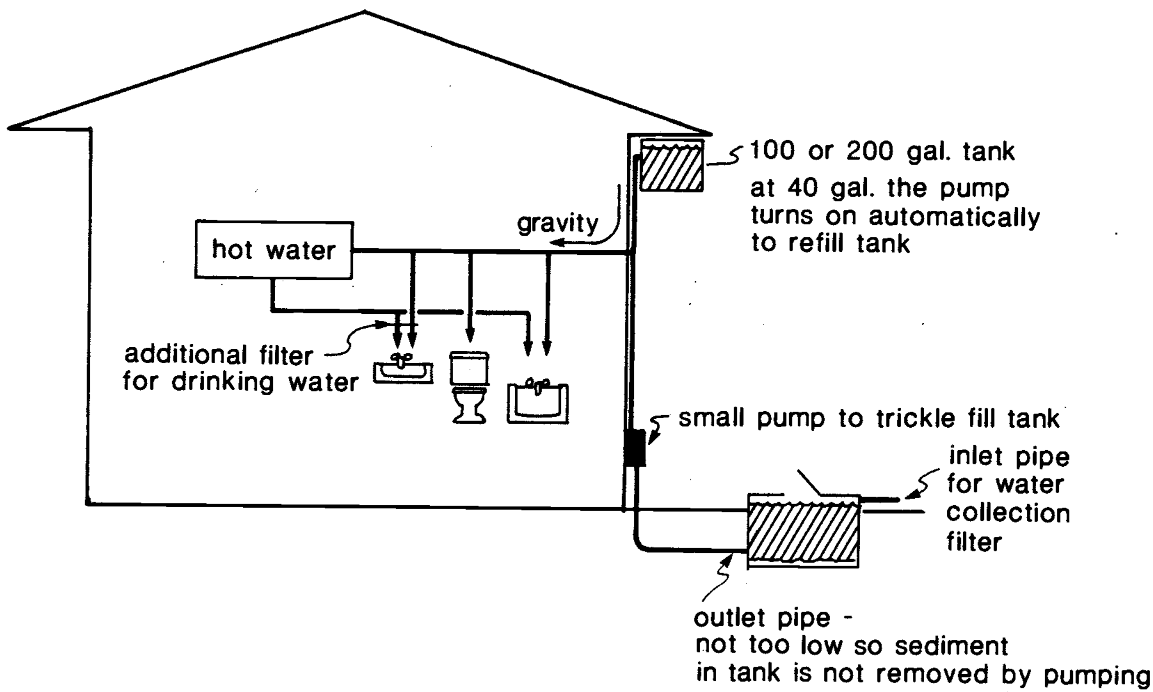


Figure 12. System With Intermediate Holding Tank for Indoor Water Uses.

Santa Catalina Mountains, where the average annual rainfall exceeds 19 inches. Another advantage is that the roof surfaces of the home and an adjacent structure have a total area of about 2,700 square feet. Water treatment is done solely with a filtration box containing muslin cloth and metal mesh screen filters (Figure 13). Storage is provided by a main and an auxiliary cistern, both constructed of reinforced concrete, that provide a storage capacity of 13,670 gallons. This example is not typical of urban Tucson, since Mrs. Jones' water supply is greater in quantity and possibly better in quality, but it illustrates the extreme simplicity that is possible for self-contained systems.

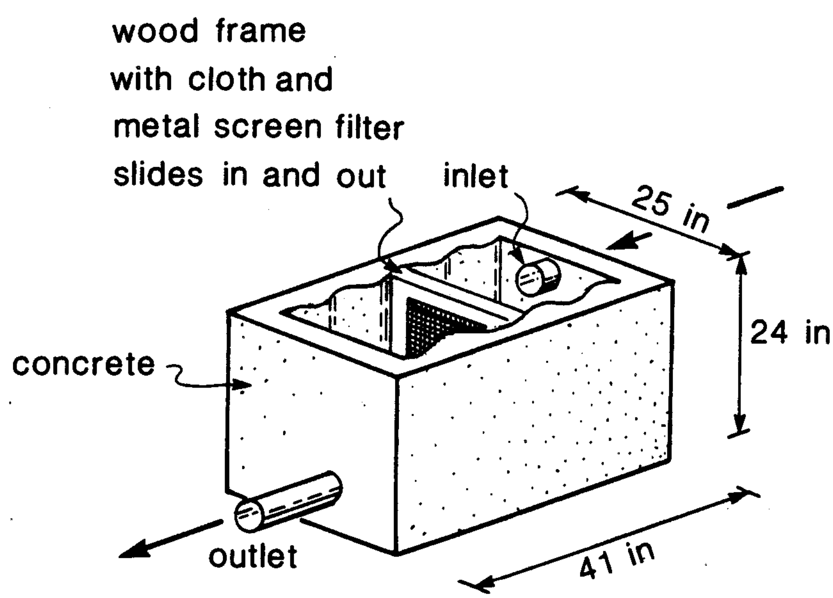


Figure 13. Simple Water Treatment Device for Domestic Use

In other regions, numerous residential water conservation systems have been designed or are in operation. For many years, harvested rainfall has provided the sole water source for residents in localities like Bermuda and the Virgin Islands. In the United States, Milne (1979) has described 14 home-built systems and seven operating experimental systems, including the widely known Farallones Integral Urban House in Berkeley, the Hawaiian Energy House, and the Miraflores Development in Tiburon, California. Many of these systems use some form of greywater recycling. In addition, a number of designs (Table 4) have been prepared for integrated water and energy conservation or even self-sufficiency.

Table 4. Designs for Residential Water and Energy Conservation (Milne, 1979)

Design	Location	Principal Features
Living Lightly	California	Rainwater collection, greywater recycling, solar distillation. Self-sufficient five family unit.
Key Largo	Florida	Rainwater collection, greywater reuse, solar distillation.
Morrison-Jaconi	California	Greywater recycling, landscape watering.
Eco-Unity	California	Greywater and blackwater treatment and recycling.
Malibu	California	Rainwater collection, cistern, solar distillation, greywater treatment and use for plant watering.
Rainwater Storage Roof	England	Rooftop rainfall collection and storage.
Autonomous House	Cambridge Univ.	Rainwater collection, cistern, ceramic candle filtration, solar collector, greywater reuse.
Ecol House	McGill Univ.	Rainwater collection, solar distillation, greywater recycling.

These examples illustrate the widespread diversity in applying simple principles for water conservation. Many of the designs have been developed in coastal or temperate zones where temporary droughts or water shortages may occur. In desert-like regions of perennial water scarcity, these systems can be even more valuable.

Institutional, Commercial and Industrial Sites

The foregoing discussion of the residential setting was confined to situations where the individual home owner or renter has control of the entire site and can harvest and use rainfall on the residential property. The following section covers the larger setting where property ownership may be corporate or public and the implementation of water conservation measures involves group decisions generally on a larger scale.

Concept

There are numerous situations in urbanized areas where a distinct parcel of land contains a concentration of buildings and adjacent paved areas like parking lots, driveways and walkways. Some examples are shopping centers, government centers, schools, libraries, hospitals and medical centers, and industrial complexes. These represent one to several acres of rainfall catchment surfaces (rooftops and pavement), from which the concentrated rainfall runs off to a low point on the property boundary. At this point, if some means of control is established, the runoff can be collected, treated, stored and used for landscape watering on the property where it originated. Alternatively, if contained or controlled, the flow can be directed into a "dry well," for underground disposal.

On a still larger scale, runoff use or disposal can be expanded to include wastewater reuse, desert landscaping, and other water conservation measures and can be integrated into the design and construction of a major industrial complex.

Examples of institutional, commercial, and industrial sites in the Tucson area are cited below.

Public Buildings

A public building that could be used for rainfall harvesting in urban Tucson is the Tucson House. The Tucson House is a high-rise apartment building owned and administered by the City of Tucson and provides housing for the elderly and handicapped (Figure 14). Rainfall catchment, collection, and detention storage components aready exist on the site. Only additional storage volume and water treatment are needed, depending on the type of water use, to complete the system.

The roof area of the Tucson House main building is 21,700 square feet. The roof area of attached buildings (beauty shop and disco lounge) is 4,100 square feet. Paved area on the surrounding property is about 50,000 square feet. The total catchment area is approximately 75,800 square feet, which, with 11 inches of annual rainfall, would yield about 474,000 gallons of runoff. Of this amount, 161,000 gallons from the rooftop currently is collected by downspouts and is discharged to a sump behind the patio area. There it is pumped to a point of discharge to Linden Wash, which passes beneath the property through a box culvert. The 313,000 gallons of runoff from the paved areas drains by gravity flow into Linden Wash behind the property.

If plans are developed requiring outdoor water use on the property, this harvested rainfall can be clarified and used instead of being discharged. Development of a water/energy conservation and greenhouse project for Tucson House tenants is now being considered. With such a project, the collected rainfall could be used to augment the water supply, and is recommended for further investigation as project plans evolve. An opportunity exists here for the City of Tucson to show by example how rainfall harvesting can be integrated with other activities.

Commercial Centers

Concentrated storm rainfall and runoff also occurs at various commercial sites in the city, notably at suburban shopping centers or shopping plazas. Preliminary field data have been collected at several sites by the University of Arizona Water

Figure 14. The Tucson House, a Public Building with Rainfall Harvesting Potential.

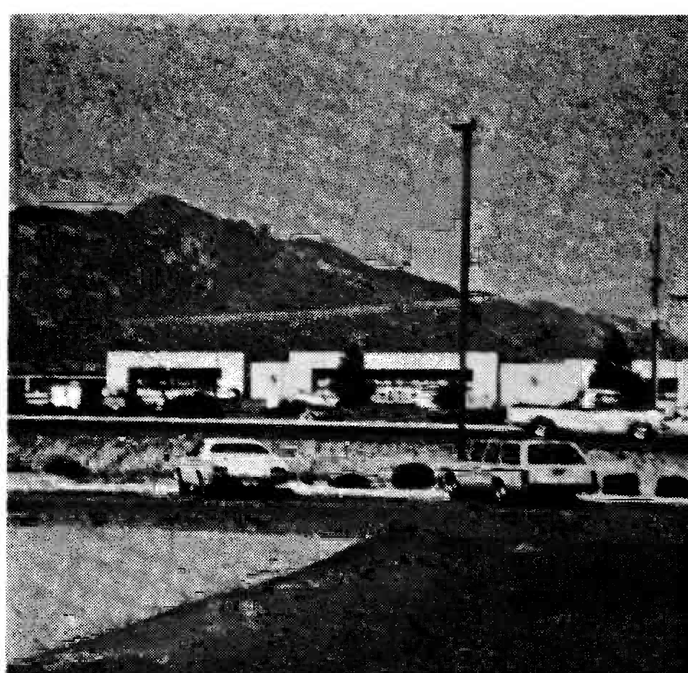


Figure 15. Plaza Escondida, a Neighborhood Shopping Center with Concentrated Runoff.

Resources Research Center staff, as reported by Resnick et al.(1983). Plaza Escondida, located at the intersection of Oracle and Magee roads, is an example.

Plaza Escondida (Figure 15) contains a supermarket, department stores and shops, fronted by a parking lot and paved entrance roads. The composite area of rooftop and pavement is 141,600 square feet, or about 3.4 acres — much smaller than the major shopping malls. Plaza Escondida is representative of many neighborhood centers. Rainfall and runoff at this site were measured throughout one season; however, quantitative results are incomplete because the 6-inch Parshall flume, which was set in place at each storm event to measure runoff, was repeatedly overtopped because of fast runoff concentration time and high peak flow. Further measurements are needed to calculate the capacity required to measure or control the total runoff from the property.

Runoff quality also is important, whether the flow is to be contained for disposal or treated for use. Table 5 shows the results of analyses from storm events at Plaza Escondida. The parameters showing relatively high readings (in terms of human-contact uses) are suspended sediment, chemical oxygen demand and some of the trace minerals. Of significance, however, is the extreme variability in concentrations of these contaminants from one storm event to another. Additional qualitative measurements are needed to assess more accurately the possible hazards of underground disposal or the treatment requirements for landscape irrigation or other use of the runoff.

Some sites like Plaza Escondida are not within the city limits, but are located in Pima County. The 1982 amendment (Ordinance 1974-86, Book 4925, Pages 256-286 of County Records) to the Floodplain Management Ordinance addresses on-site detention/retention requirements for storm waters in County areas with severe flooding problems. The purpose there is not beneficial use of the storm runoff but on-site control to reduce downstream flood hazard. The possible use of dry wells (Figure 16) for gravity disposal in the vadose zone (the unsaturated zone between land surface and water table) is within the provisions of the ordinance. A similar ordinance in the Phoenix area has resulted in the construction of hundreds of such devices for on-site disposal (see Appendix).

Table 5. Statistical Values of Water Quality Parameters
for Runoff from Plaza Escondida Commercial Center, Summer 1978
(Resnick, DeCook and Phillips, 1983)

Quality Indicator*	Mean	Maximum	Minimum	Standard Deviation
Flow (CFS)	0.67	1.17	0.16	0.37
Temperature (°C)	29	34	24	4.1
Suspended Sediment	1.1×10^5	5.1×10^5	0.17	2.0×10^5
Specific Conductance (m mho)	120	190	< 90	30
Chemical Oxygen Demand	320	800	28	251
Ca^{++}	8.6	22	2	5.3
Mg^{++}	0.4	1.4	0.1	0.4
Na^+	1.5	6.3	< 1	1.3
HCO_3^-	15.4	38	3.4	9.6
Cl^-	< 2	< 2	< 2	0
$SO_4^=$	15	66	0	16
NO_3^-	1.12	2.21	0	0.7
Fe	0.59	2.99	<.02	0.76
Cu	< .05	< .05	<.05	0
Mn	0.12	0.45	<.02	0.13
Pb	0.19	0.55	<.05	0.17
Cr	< .04	< .04	< .04	0
Cd	< .005	< .005	<.005	0
Co	<0.02	< .02	<.02	0
Ni	<0.04	< .04	<.04	0
K^+	0.9	2.7	0.2	0.6
NH_4^-	1.74	3.38	0.49	0.83
pH	5.4	6.4	4.4	0.6
Total Coliform (per 100 ml)	560	<1000	<10	450
Fecal Coliform (per 100 ml)	540	<1000	<10	430
Fecal Streptococci (per 100 ml)	590	<1000	<10	590

*All units are mg/l except pH and others as noted.

Note: Samples taken from 18 storm events.

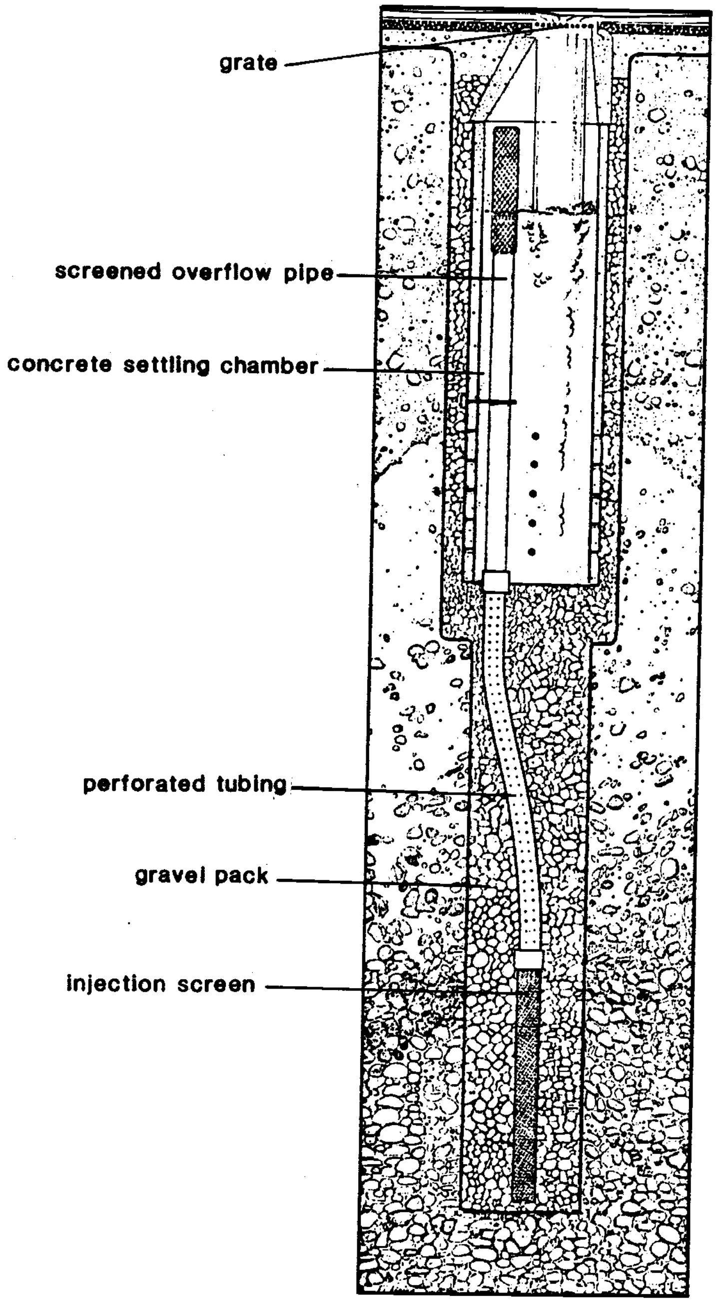


Figure 16. Cross-Section of Maxwell® Type III Dry Well
(Courtesy of McGuckin Drilling Co., Phoenix, Arizona)

Industrial Sites

An increasing number of light industrial plants are being located in the Tucson area by major corporations. A number of them have included water conservation features and practices in their plant design and operation. At the International Business Machines (IBM) plant, for example, floodwater control and use, wastewater recycling, and water-saving landscape designs have been integrated into the total plant layout (SAWARA, 1983b). The City of Tucson and Pima County governments could encourage other companies who are relocating in the area to adopt similar plans.

RUNOFF CONTROL, DIVERSION AND USE

The foregoing sections have discussed the collection of rainfall/runoff on specific sites, and the containment or use of the water on the local site. Where the waters are not contained, they continue their movement by overland flow into streets and gutters and eventually become concentrated into natural or modified watercourses within the urban/suburban region. At various points along these channels, a portion of the runoff could be diverted or detained for use in parks, boulevard medians or other landscaped areas requiring supplemental irrigation. This diverted water also could be controlled and managed to enhance recharge to groundwater reservoirs.

As with direct rainfall harvesting, site design for runoff control must be based on the quantitative and qualitative characteristics of the storm runoff itself. These characteristics reflect the combined interaction of the "storm variables," described earlier, and the "watershed variables," like soils, topography, vegetation and degree of urbanization.

Runoff Characteristics in the Tucson Region

Measurements of runoff quantity and quality characteristics have been made in the Tucson urban area since 1968 by the University of Arizona Water Resources Research Center. Results have been presented in a number of published reports, theses and dissertations and have been summarized recently in reports by Resnick and DeCook (1980) and Resnick, DeCook and Phillips (1983). These data have been collected at gaging points that represent the "lumped parameters," or combined characteristics, of the runoff from small watersheds with areas of less than 20 square miles, mostly within the range of 1 to 10 square miles.

Two gaging points, Arcadia Watershed and High School Watershed (Figure 17, locations 7B and 19C), are representative of the Tucson urban/suburban region for the 13-year period of data collection. Of the two watersheds, High School is smaller and also has a higher imperviousness ratio, resulting in greater unit volume of runoff and greater peak runoff rates per unit area (Table 6). According to Table 7, Arcadia

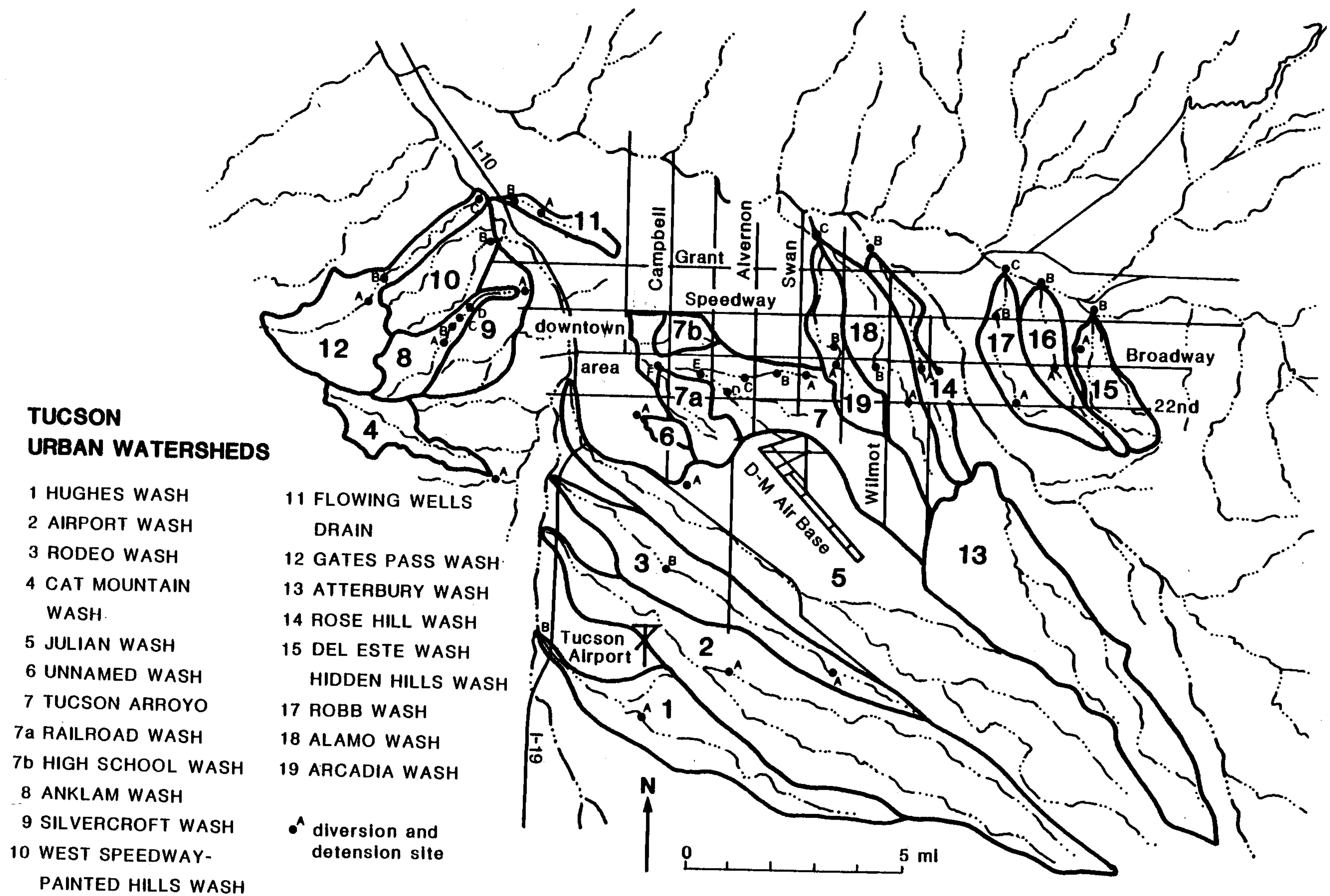


Figure 17. Minor Drainages — Diversion and Detention Sites, Tucson Urban Area

Table 6. Hydrologic Characteristics of Two Watersheds in Urban Area (Resnick, DeCook and Phillips, 1983)

Characteristic	Watershed: Arcadia	Watershed: High School
Watershed Area (square miles)	2.72	0.90
Imperviousness Ratio[1]	0.24	0.30
Mean Annual Rainfall (acre-feet per square mile)	572	558
Mean Annual Runoff (acre-feet per square mile)	59	78
Mean Annual Runoff/Rainfall Ratio	0.102	0.140
Mean Annual Peak Discharge (cubic feet per second per square mile)	192	359

[1]Defined as the proportion of total watershed area represented by the sum of all paved streets and parking lots, plus 70 percent of the commercial and industrial areas, plus 10 percent of the net residential areas.

Table 7. Runoff Frequency and Amount by Months, Arcadia and High School Watersheds (Resnick, DeCook and Phillips, 1983)

Month	Mean Number of Runoff Events		Mean Monthly Runoff (inches)	
	Arcadia	High School	Arcadia	High School
January	0.92	1.31	0.045	0.087
February	0.92	1.15	0.077	0.072
March	1.77	1.46	0.042	0.056
April	0.15	0.77	0.000	0.010
May	0.15	0.31	0.005	0.013
June	0.54	0.92	0.027	0.034
July	2.85	5.15	0.142	0.254
August	3.00	4.31	0.324	0.445
September	1.69	2.31	0.138	0.129
October	1.69	2.15	0.136	0.177
November	1.00	1.15	0.104	0.072
December	0.92	1.46	0.060	0.119
Year (Sum of Monthly Means, Rounded)	16	22	1.10	1.47
Summer Season (Sum of May-September Means)	8	13	0.64	0.88
Winter Season (Sum of October-April Means)	8	9	0.46	0.59

Note: Period of record July 1968 to December 1980 for Arcadia and March 1968 to December 1980 for High School Watershed.

Watershed, with mean annual precipitation of 10.73 inches, yielded about 1.10 inches of runoff annually at the gage, while High School Watershed, with 10.49 inches of annual rainfall, yielded about 1.47 inches of annual runoff.

Table 7 also illustrates the monthly and seasonal distribution of runoff for the same period of record. (Recall from Table 1 that both watersheds recorded 44 rainfall events per year, including 26 in the summer season and 18 in the winter.) Arcadia Watershed recorded 16 runoff events per year, 8 in each season. High School Watershed experienced 22 runoff events annually, probably indicating a lower runoff threshold, that is, less rainfall is required in a given storm, to initiate measureable runoff. The fewest number of runoff events generally occur in May, and the greatest number occur in August on Arcadia and in July on High School Watershed. As for monthly runoff volumes, the smallest amount occurs in April on both watersheds. The greatest amount occurs in August. For the year, about 58 percent of the runoff occurs in the summer season on Arcadia, and about 60 percent is summer runoff on High School Watershed.

Another practical factor to consider is the unit volume of runoff to be anticipated per storm event. According to Table 8, the smallest amounts of runoff per storm occur in April and the greatest amounts occur in August on both watersheds. As a general average for the entire year, one may expect runoff of approximately 0.06 inches per storm, at either location; it is important for planning, however, to consider the monthly variations described above.

The quality of urban storm-water runoff from several small watersheds in Tucson has been sampled intermittently since 1968 by investigators at the University of Arizona Water Resources Research Center. An intensive sampling program was conducted from 1969 to 1971. Results have been reported in a series of graduate theses. Much of the information on quality of runoff has been summarized by Resnick and DeCook (1980) and Resnick, DeCook and Phillips (1983).

Table 9 illustrates the mean values of 22 quality indicators, as shown by analyses of runoff samples from Arcadia and High School Watersheds in the urban area and from Atterbury Experimental Watershed, which was largely unaffected by

Table 8. Mean Values of Runoff Depths per Runoff Event, Arcadia and High School Watersheds (Resnick, DeCook and Phillips, 1983)

Month	Mean Values (inches)	
	Arcadia	High School
January	0.049	0.067
February	0.083	0.063
March	0.024	0.039
April	0.003	0.013
May	0.034	0.042
June	0.050	0.037
July	0.050	0.049
August	0.120	0.103
September	0.070	0.056
October	0.080	0.082
November	0.104	0.063
December	0.060	0.081
Year (Average of Monthly Means)	0.061	0.058
Summer Season (May-September)	0.065	0.057
Winter Season (October-April)	0.058	0.058

Note: Period of record July 1968 to December 1980 for Arcadia and March 1968 to December 1980 for High School Watershed.

Table 9. Summary of Mean Values of Runoff Analyses
(Resnick, DeCook and Phillips, 1983)

Quality Indicator[1]	Watershed		
	Arcadia	High School	Atterbury
Turbidity (JCU)	1167	531	2424
Suspended Solids	1762	769	3003
Volatile Suspended Solids	216	148	328
Specific Conductance (m mho)	202	238	180
Total Dissolved Solids	174	185	169
Chemical Oxygen Demand	263	226	157
COD Filtrate	66	67	—
Ca^{++}	36	37	33
Mg^{++}	3.0	3.3	3.1
Hardness (mg/l as $CaCO_3$)	101	106	94
Na^+	3.3	6.6	3.1
$CO_3^=$	0	0.05	0.05
HCO_3^-	105	104	102
Cl^-	6.9	10	5.3
$SO_4^=$	17.5	26	15
NO_3^-	2.6	3.8	4.7
F^-	0.25	0.34	0.20
$PO_4^=$	0.38	0.58	0.51
pH	7.7	7.5	8.0
Total Coliform[2]	1.6×10^6	6.6×10^6	6.1×10^5
Fecal Coliform[2]	2.9×10^5	8.1×10^5	1.6×10^5
Fecal Streptococci[2]	7.8×10^4	1.1×10^5	9.3×10^4

[1]All units are mg/l except pH and others as noted. [2]Density per 100 ml

Note: Includes results of all sampling during period 1969 to 1975, except Atterbury Watershed 1971 to 1975.

urbanization during the sampling period. Generally, the concentrations of mineral ions and total dissolved solids are relatively low and should not be troublesome in most uses of the runoff. High values, however, generally prevail in the concentrations of suspended solids, bacterial density, and chemical oxygen demand (COD), which is an indicator of organic contaminant materials. Samples from Atterbury Watershed commonly contain more suspended solids than those from the urban areas, but display a lower order of bacterial density and COD.

These results refer to mean values of all runoff samples, regardless of time of collection. Resnick et al. (1983) have pointed out that content of COD and bacteria commonly is lower in winter than in the summer. Also, during a specific storm event, suspended sediment and COD content may rise and fall in accordance with rate of runoff, whereas the pH values and phosphate content tend to increase with elapsed time throughout the runoff period.

On the basis of the hydrologic record, which provides knowledge of the quantity and quality of runoff that will occur at various points along the urban arroyos or channels, it is possible to select sites where the diversion or detention of runoff could provide various benefits. The benefits can be derived from any or all of the following uses or control measures: 1) to irrigate parks, playgrounds or other landscaped areas; 2) to create recreational uses like park lakes; 3) to enhance ground-water recharge; and 4) to reduce flood hazard.

These measures in their varied aspects have been examined previously by DeCook (1970), Resnick and DeCook (1980) and Resnick, DeCook and Phillips (1983). Some points relevant to the present study are summarized below. Potential sites for design and possible demonstration then will be described under "Discussion."

Diversion and Detention for Landscape Irrigation and/or Recreational Use

Under the concept of diversion and detention, runoff in urban stream channels following storm events (Figure 18) would be:

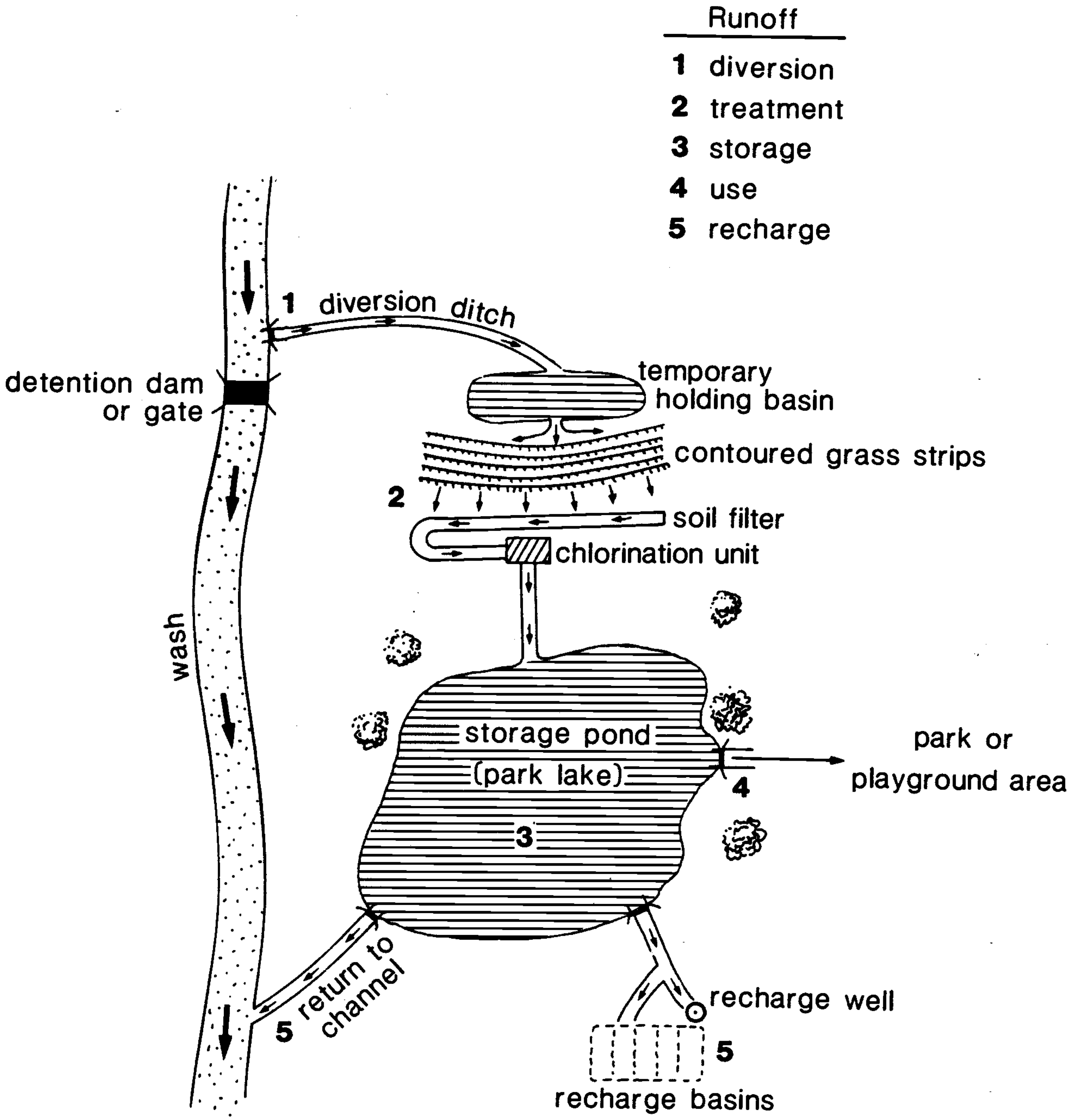
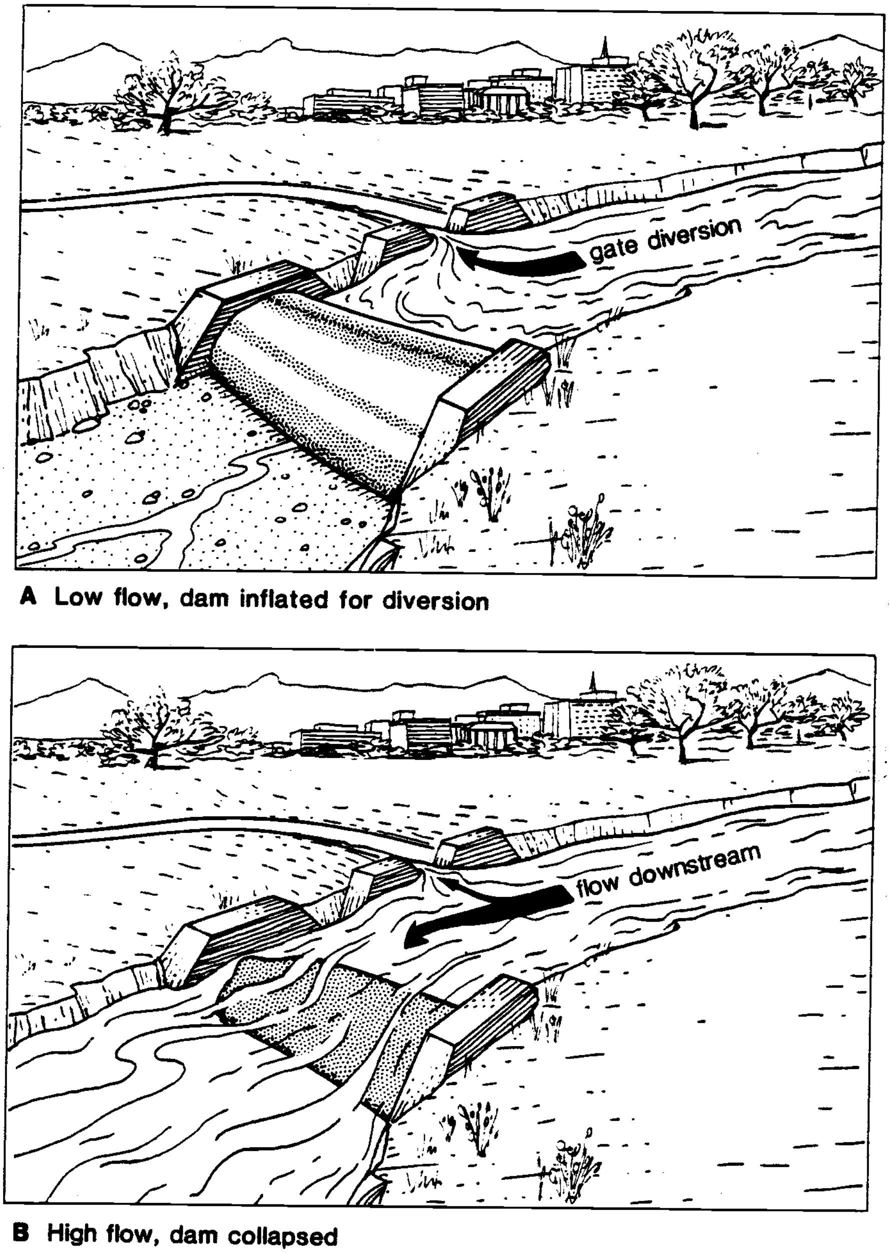


Figure 18. Schematic Diagram of Facility for Harvesting and Using Ephemeral Flow from an Urban Wash.

1. detained in-channel, or diverted and detained off-channel, with a low-head collapsible dam (or gate) at sites near or adjacent to parks or other points of water use;
2. directed through contoured grass strips and/or soil filters for sediment filtration, possibly augmented by alum coagulation and settling, and chlorination; and
3. held in a storage pond (which can serve simultaneously as a recreation lake) until desired for landscape irrigation, recreational uses or recharge.

The temporary detention of runoff in-stream can be accomplished by installing either collapsible inflated dams or gates. The main purpose is to provide sufficient head so that the flow can be pumped or, preferably, diverted by gravity flow toward the treatment or storage area (Figures 18 and 19). A more detailed sectional view of the side diversion over or through the stream bank is shown in Figure 20. The fabric inflatable dam (one trade name is Fabridam) is a rubberized, sausage-shaped tube, which can be inflated by water or air and set in place on a concrete apron in the channel. When flow begins, it will be headed up by the dam, but if upstream head continues to build up past a predetermined level, the dam will begin to deflate through a pressure-sensitive siphon tube. When the dam is completely deflated, the streamflow will pass over it in a normal manner, and will be essentially unobstructed. The deflation process can be preset mechanically and does not need an external power source or drive mechanism.

Another device for detaining flow for diversion is the horizontal steel "gate," which is actually a series of steel plates set upright and side-by-side across the width of the channel. Two varieties of this structure are used. The simplest is a series of flat plats. Each plate is spring-loaded to remain upright until the upstream water pressure forces it to rotate on its lower edge and lie down flat on the channel surface. If flow continues to increase to a high level, all the plates eventually will be forced down, and the flow will pass unobstructed as in the case of the Fabridam. The other variety consists of a side-by-side series of steel sections rotating on a horizontal trunnion axis. Each section is actuated by hydraulic pressure on a buoyant compartment adjoining the upstream face. (A trade name for this device is AMIL Gate). This gate maintains a constant upstream water level. If excessive



A Low flow, dam inflated for diversion

B High flow, dam collapsed

Figure 19. Collapsible Dam for In-Channel Detention and Diversion.

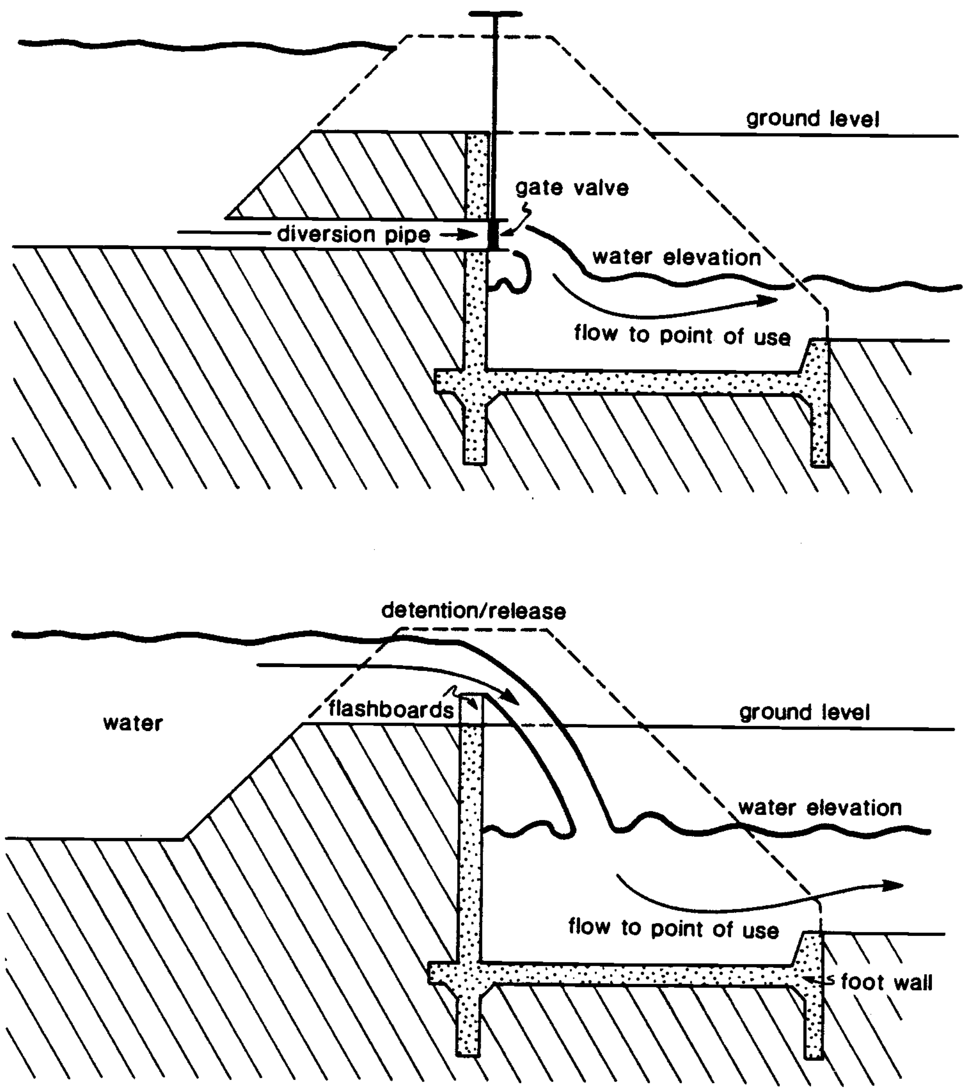


Figure 20. Sectional View of Simple Overshot and Undershot Diversion Structures.

upstream head builds up, the gate rotates to a more open position and allows more flow to pass by. If upstream head decreases, the gate closes a bit and again detains more flow. This type of structure, unlike the others, never reaches a totally collapsed or prostrate position where there is no impedance to flow. More detail in these types of structures is given in U.S. Corps of Engineers Working Papers (1982).

Cost estimates for materials and installation of fabric dams and steel gates can be made for specific site designs. The cost calculations should be made in the context of a total project installation, so that costs of detention and diversion can be figured with other cost items and in the perspective of anticipated project benefits.

Once the runoff is diverted from its watercourse, treatment and storage must be provided (Figure 18). A low-cost field treatment process for urban storm runoff has been evaluated by Popkin (1983). In that process, runoff diverted from Arcadia Wash was passed over common grasses and through a profile of native soil. A plan view of the facility is shown in Figure 21, and a typcial cross-section of the filter is shown in Figure 22. Samples of the diverted and treated water were analyzed following eleven storm runoff events during a one-year period. The principal water-quality constitutents of concern, and the average change in each following grass and grass-soil filtration are shown in Table 10.

Table 10. Changes in Water Quality Following Grass and Grass-Soil Filtration

Constituent	Average Reduction in Concentraton (%)	
	Grass	Grass-Soil
Chemical Oxygen Demand (COD)	62	99
Suspended Solids (SS)	35	99.6
Volatile Suspended Solids (VSS)	26	97
Turbidity	97	99.8
Total Coliforms	84	98
Fecal Coliforms	87	99.8

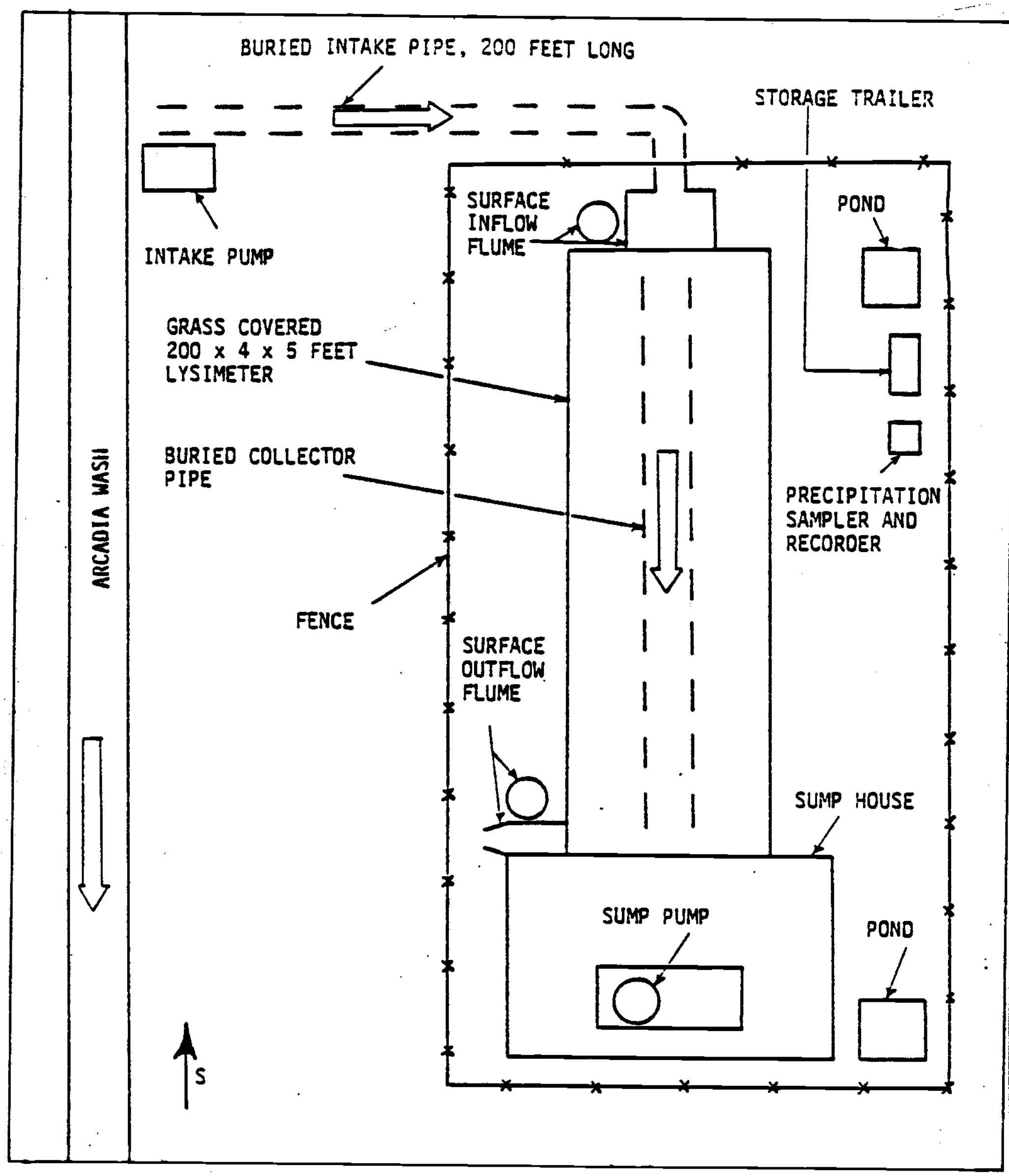


Figure 21. Design of Grass and Soil Filter Water Treatment Pilot Plant in Tucson, Arizona (Resnick, DeCook and Phillips, 1983)

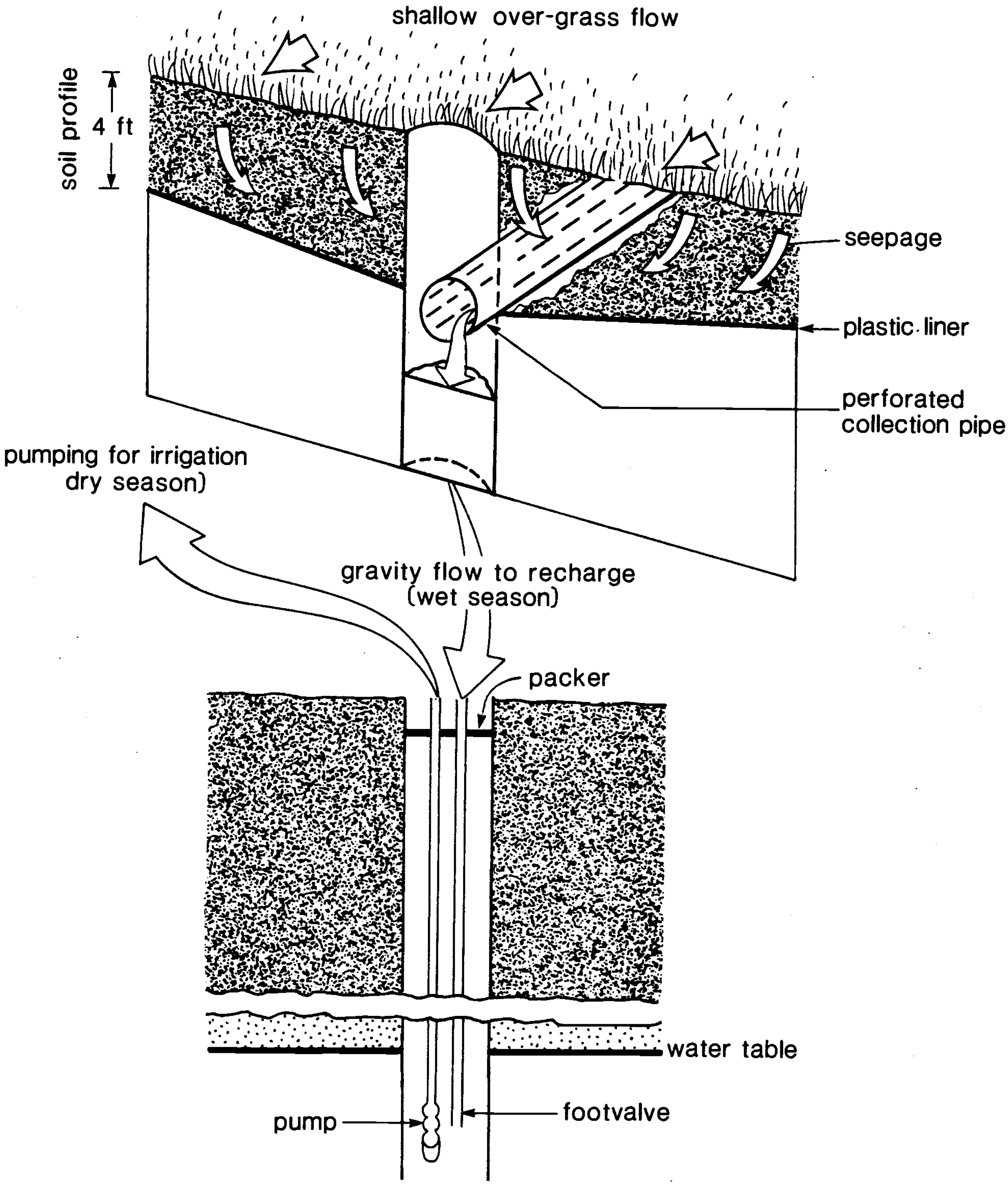


Figure 22. Cross-Sectional View of Grass and Soil Filter and Recharge-Discharge Well

A sediment trap or settling tank should precede the filtration treatment. Chlorination should follow the treatment, especially if the product water is destined for recreational uses. Grass-soil filtering, as indicated, yields a higher quality of water than simple grass filtering; however, the grass filtration is generally adequate for recreational uses, and it may be preferred because of lower costs, faster treatment rates and other factors.

Cost estimates for the treatment processes, presented by Popkin and updated to reflect 1981 costs, are shown in Table 11.

Table 11. Cost of Water Treatment Processes

Type of Treatment[1]	Cost (dollars per acre-foot)[2]
Grass Filtration	12
Grass-Soil Filtration	29
Chlorination	5

[1]Based on 10 storm events per year for a 10-year period, at a treatment volume of 10 acre-feet per event.
[2]Costs may be reduced by almost 100 percent for grass filtration, and by 10 percent to 75 percent for grass-soil filtration, if grass cover, earthmoving and grading are considered part of general landscaping.

The treated runoff then may be held in a storage pond until needed for its intended use (Figure 18). If the pond serves also as a recreational lake (for scenic value, fishing or water sports), the losses incurred by seepage and evaporation must be assigned as a cost to the recreational use. (The annual evaporation of perhaps 7 acre-feet per acre may be reduced by half by using evaporation suppressants, but only at an additional cost. Seepage losses can be minimized by lining with clay, bentonite or plastic liners, but the cost would be determined by the design of each individual project). If the stored water is to be pumped from the pond to irrigate turf grass or other landscape vegetation, the consumptive use rate for year-round mixed grass under efficient application would be approximately 5 acre-feet per acre. Another alternative is to use the treated and stored water to enhance ground-water recharge, as discussed in the following section.

Enhancement of Ground-Water Recharge

Portions of diverted and treated storm runoff that may not be needed for seasonal landscape watering or recreational uses can be directed toward enhancing ground-water recharge. Generally, this can be accomplished by either returning the water to its channel of origin, or by injecting the water to the subsurface through a recharge well, basins or pits. Recharge in the channel, under a controlled rate of release, will occur at a faster rate than it would have as storm runoff, because it is clarified of sediment and because slow releases to the larger and more permeable channel sections downstream can be prolonged for more extended periods of time. This provides better opportunity for recharge to occur. Further enhancement can be provided by a series of baffles in the channel (Figure 23), which extend the flow path and flow time of the recharge water.

Alternatively, the stored water can be delivered 1) to pits or basins for recharge if the water table is relatively shallow and near-surface sediments are relatively permeable, or 2) to one or more recharge injection wells where the water table is deeper. The latter is likely to predominate in Tucson.

Injection through wells requires that the recharge water be treated to a high quality. Grass-soil filtration and chlorination, and perhaps alum coagulation, would be needed. A schematic set-up for injection and later pump-back is shown in Figure 22. Recharge through basins or pits ordinarily would require less treatment.

Popkin (1983) has estimated the range of costs for recharge, by various processes, at a complete facility for recharge only, accounting for costs of the diversion works, the water treatment and the recharge facility (Table 12).

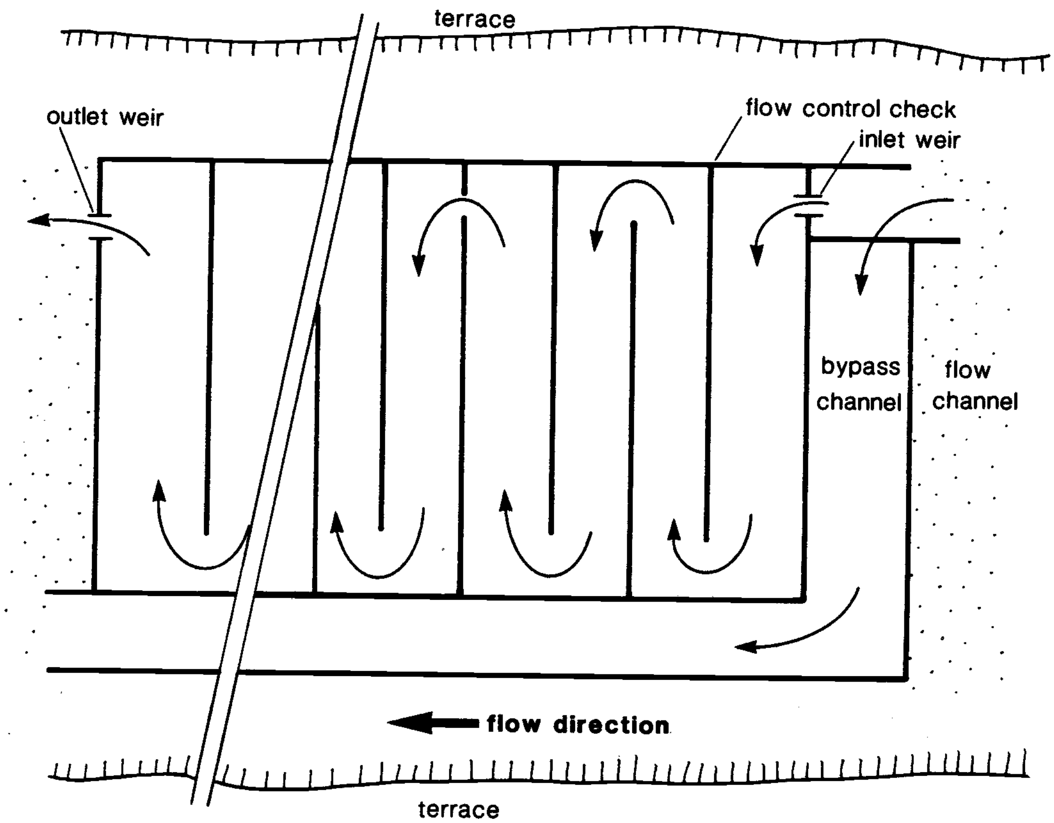


Figure 23. In-Channel Recharge Enhancement by Flow Extension

Table 12. Cost of Various Recharge Processes

Method of Recharge*	Total Cost ($)	Total Recharge (acre-feet)	Cost Per Acre-Foot of Recharge** ($)
Spreading in Channel	17,600 - 58,655	240 - 5,000	12 - 73
Pits in Channel Bank	23,100 - 86,155	240 - 1,200	72 - 96
Injection by Wells	48,400 - 89,455	240 - 1,200	75 - 200

*Figured for various rates and frequencies of runoff, during a 10-year period.

**Based on 1981 costs.

In Resnick et al. (1981), 68 potential sites were surveyed for possible runoff diversion/detention or recharge enhancement. Three of those sites were selected by the Corps of Engineers for a more detailed study to evaluate technical, economic and institutional feasibility of recharge only (U.S. Corps of Engineers, 1982).

Concurrent Reduction of Flood Hazard

To whatever extent storm runoff is diverted from an urban watercourse, the rate of flow will be reduced accordingly downstream. By diverting a relatively small volume of runoff, the peak flow for a local runoff event may be reduced by an appreciable percentage, since runoff in small urban watersheds is generally flashy and of short duration. If the diversion structure were designed to divert peak flows from the low-frequency extreme runoff events, the design capacity of downstream culverts and control structures could be reduced, resulting in a construction cost savings and reduced flood damage. A comparative benefit/cost evaluation for a multiple-purpose facility (including flood control) versus a single-purpose facility has been presented by Bennett (in Resnick et al., 1983). For the present study, reduction in flood peaks or flood hazard will not be further evaluated but will be considered an incidental benefit to other measures.

Discussion: Potential Demonstration Sites

As indicated in the preceeding sections, a hydrologic data base exists and several preliminary studies of the feasibility of controlling and using increments of urban runoff in the Tucson area have been completed. The next step is to locate and evaluate physical sites where runoff could be diverted and used. One or more demonstration facilities then should be designed and constructed. A demonstration site permits a realistic assessment of actual costs and benefits and the resolution of practical problems before attempting a large-scale program.

In the aforementioned U.S. Corps of Engineers Working Paper (Resnick, DeCook and Wilson, 1981), prepared in conjunction with the Tucson Urban Study, 68 potential sites (24 on major streams and 44 on minor streams) were identified and evaluated by applying technical and engineering criteria for runoff diversion, detention and recharge.

For this report, 44 potential small-watershed sites and others that were field-checked during the present study were reviewed to identify and further describe the more favorable ones. They were evaluated for recharge and for use of the diverted or detained runoff for landscape irrigation or recreation. From those sites, one or more will be recommended for development as a demonstration project.

The following criteria were used to select favorable sites:

1. opportunity for multiple uses of runoff, and recharge potential, at larger sites;
2. adequate supply of runoff for intended uses;
3. high recommendation based on technical criteria in Tucson Urban Study;
4. minimal land purchase, earthmoving and construction requirements; and
5. presence of an existing park or other water-using facility, to which diverted runoff could be applied.

Additionally, the array of potential sites was categorized by watershed area, on the premise that drainage area would determine the range of magnitude of annual runoff available at a site and, accordingly, the scope of facility construction needed for diversion or use. For sites with an upstream drainage area of less than 1 square mile, annual runoff probably would be less than 100 acre-feet. For those with areas of 1 to 10 square miles, annual runoff would be 100 to 500 acre-feet. For sites receiving flow from areas of more than 10 square miles, annual runoff would likely exceed 500 acre-feet. (Some degree of urbanization is assumed in all cases.)

The candidate sites that appear to have the best potential according to the criteria are listed in Table 13 and are grouped according to the size categories described above. Many of these sites have been identified in the U.S. Corps of Engineers Working Papers. It was not intended to duplicate that effort but to take advantage of the previous site evaluations and to refine them where appropriate.

The 17 sites listed in Table 13 have been reduced, by closer field examination, to four sites, which should be given first consideration for further development. These include one in the smallest watershed grouping, two in the middle range, and one in the larger watershed category. These four sites and some of their pertinent characteristics are listed in Table 14. Three of the sites — one in each watershed-size category — are shown in Figures 24 to 26.

To retain simplicity and to incur minimal expense in the demonstration sites, it seems best to proceed first with the smallest facility (Linden Wash) in design work and site development. If desired, other small sites then can receive additional attention, or larger-scale facility plans can be implemented.

Table 13. Selected Potential Sites for Demonstrating Runoff Diversion and Use

Location	Drainage Area (square miles)	Previous Ident. No.[1]
Sites with Drainage Area <1.0 Square Mile		
1. Mirasol Wash, at E. 29th St. and S. Mountain Ave.	0.44	6A
2. Arroyo Chico, at S. Desert Ave.	0.75	7B
3. Linden Wash, at N. 15th Ave.	0.9+	—
Sites With Drainage Area Between 1.0 Square Mile and 10 Square Miles		
1. Rodeo Wash at Ajo Way	6.1	3C
2. Cat Mountain Wash above La Cholla Blvd.	2.6	4A
3. Arroyo Chico at Randolph Municipal Golf Course	2.0	7C
4. Arroyo Chico at Treat Ave.	4.5	7E
5. Arroyo Chico at Campbell Ave.	6.0	7F
6. Flowing Wells Drain at Fairview Ave.	4.8	11A
7. Rose Hill Wash at Grant Road	2.9	14B
8. Alamo Wash at Tucson Medical Center	4.9	18C
9. Alamo Wash at Fort Lowell Road	9.5	18,19D
10. Arcadia Wash at Woodland Vista Road	1.9	19B
11. Arcadia Wash at Tucson Medical Center	3.3	19D
Sites With Drainage Area >10 Square Miles		
1. Julian Wash (Tucson Diversion Channel) at Santa Cruz River	46	5B
2. Anklam Wash and Silvercroft Wash at Silverbell Rd. and West Speedway	11	8,9A
3. Silvercroft Wash near Grant Road	11+	9B

[1]As described for Tucson Urban Study by Resnick, DeCook and Wilson (1981).

Table 14. Characteristics of Selected Runoff Control Sites on Various Urban Watersheds

Characteristic	Linden Wash	Flowing Wells Drain	Alamo Wash	Anklam/ Silvercroft Wash
Watershed Area (square miles)[1]	0.9	4.7	9.5	11
Control Site Area (acres)	3	80	200	80
Ownership of Control Site Area	City	City	Private and County	Private, city, and federal
Present Land Use	Park	Park	Pasture	Park, boys club, and power easement
Proposed Design	Diversion gate and detention basin	Diversion dam and detention basin	Diversion dam and detention or recharge basin	Diversion dam and detention basin
Purposes	Park irrigation	Park irrigation, possible recreation and recharge	Recharge, possible park irrigation and recreation	Park irrigation and recreation

[1]Above diversion point

Note: Information derived in part from Resnick et al., 1981.

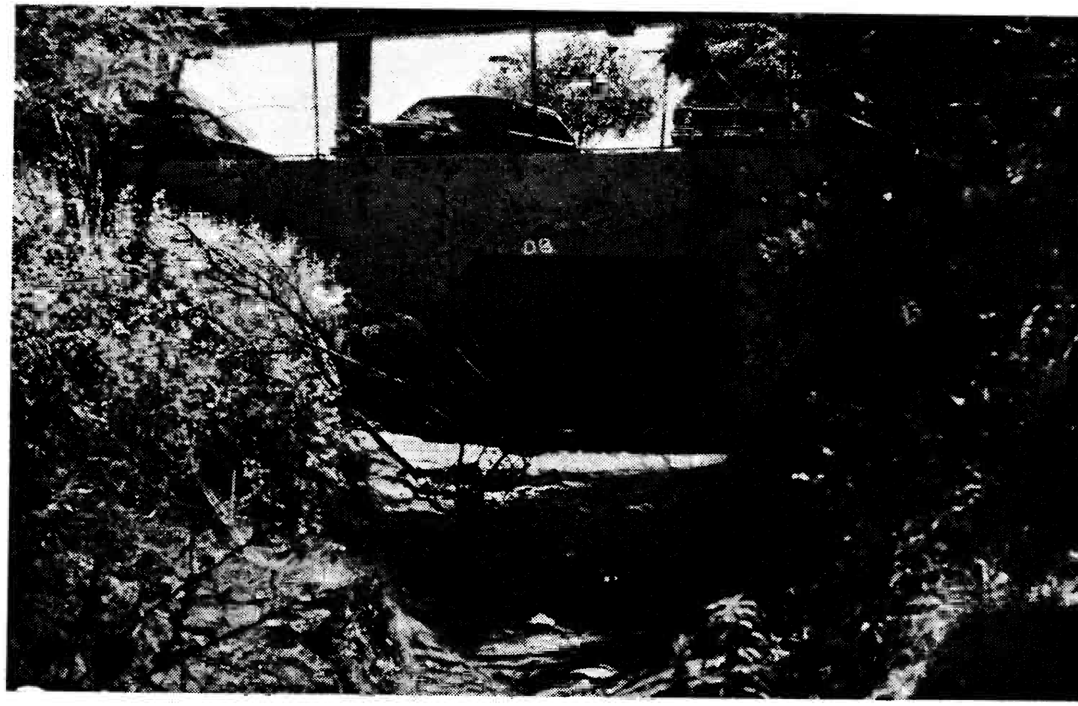


Figure 24. Linden Wash Just Below the Tucson House.

Figure 25. Flowing Wells Drain Above Fairview Boulevard.

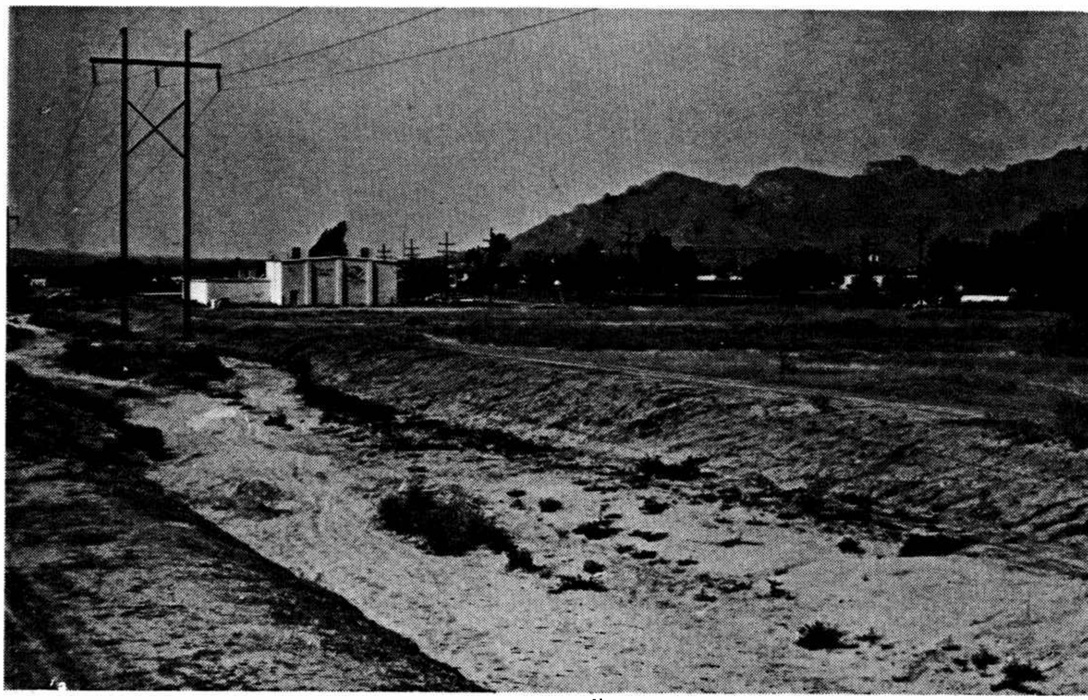


Figure 26. Silvercroft Wash Above Confluence with Anklam Wash, Near Speedway Boulevard.

CONCLUSIONS

1. The amount of precipitation in the Tucson urban area is sufficient to supply only a portion of residential household needs. Nevertheless, by providing holdover storage, harvested rainfall can provide a significant quantity of water that can augment or partially substitute for the piped-in supply. Moreover, in combination with other measures like water-saving plumbing fixtures, greywater recycling and outdoor water conservation, it may be feasible to provide minimal household needs. With average rainfall, rooftop catchments in Tucson will yield approximately 6.25 gallons of water per square foot per year. Further analysis is needed to quantify the relationship between harvestable rainfall supply and the variables of water demand, water storage and system reliability.

2. The quality of harvested rainfall in the Tucson urban area may not be suitable for all residential water uses, specifically drinking water. The concentration of lead derived from atmospheric contamination exceeds the commonly recommended limit for drinking water in many California communities. It must be considered a serious concern in the Tucson area until sufficient data are gathered with which to base a judgement. The only rainwater sample analyzed for the present study contained 1 milligram of lead per liter, or 20 times the recommended limit of 0.05 milligrams per liter. This is an indication of high levels of atmospheric lead, but is not conclusive without more testing.

3. The essential components of a residential rainfall harvesting system are the catchment surface, collection system, treatment facility, storage capability and a means of distribution. All the component parts can be purchased or fabricated in Tucson, although better prices for some elements can be found out-of-state. So many variations in design and materials are available, that a unit cost for a harvesting system can hardly be assigned. Typical sets of designs and specifications, documented and followed in actual construction of a harvesting system on a full-scale model home, would yield a realistic range of cost estimates for alternative designs.

4. The rooftops and paved parking areas of institutional settings, like government-building complexes, concentrate rainfall and yield high rates of storm runoff. Such settings represent an opportunity for city government to set an example for the public in the area of water conservation. At the Tucson House, the elements of rainfall catchment, collection and storage are in place; what remains is to assign the collected water to a beneficial use. This can be done as part of a proposed water-and-energy conservation demonstration.

5. Commercial shopping plazas also yield high rates of storm runoff in localized areas. Experiences in Phoenix and elsewhere have shown that street-flooding hazards can be reduced by total containment of on-site runoff. One method of containment is dry-well underground disposal, which apparently can be employed successfully if the water table is deep and the runoff water is not injected near the aquifer. More information is needed statewide to avoid ground-water pollution by subsurface disposal.

6. The annual yield of storm runoff from small urbanized watersheds in the Tucson area is about 50 to 100 acre-feet per square mile, depending upon the size and nature of the watershed and the characteristics of individual storm events. Increments of such runoff can be diverted and detained, treated and stored for beneficial use or the enhancement of ground-water recharge, with incidental reduction of urban flood hazards. Small-scale demonstration facilities are needed to evaluate operational costs and to broaden public awareness of the potential of these conservation measures.

RECOMMENDATIONS

Based on information summarized above and the evident lack of information in certain areas, the following recommendations are made for further consideration and action.

1. The quality of incipient rainfall should be monitored at one or more points in the Tucson urbanized area, for at least one year. Lead, pH, arsenic, and nitrogen species should be analyzed to evaluate quality for drinking water standards, and landscape irrigation and recreational uses. The USDA Agricultural Research Service near North Campbell Avenue, Tucson, plans to maintain a self-actuated rainfall sampler, from which the collected samples can be made available at no cost. The only expense to the City of Tucson would be the cost of water analysis and data handling.

2. A mathematical and graphical relationship should be developed, using Tucson rainfall records, incorporating the variables of catchment area, water storage volume, and water demand in a water-saving household.

3. The chemical composition of all the common types of roofing and roof-finishing materials should be documented more precisely for potential health hazards where collected rainfall may be used for human ingestion or skin contact.

4. A rainfall collection system should be installed in a residential building or model home to demonstrate rainfall harvesting materials, installation, operation and costs. A design manual for the construction or retrofitting of rainfall harvesting systems can be developed and would be useful to homebuilders and homeowners. When sufficient cost information has been developed, comparative cost estimates should be made for a) installing rainfall harvesting components in a new mobile home or conventional home, versus b) retrofitting a conventional or mobile home.

5. At the Tucson House, consideration should be given to integrating the existing rainfall harvesting system with proposed plans for solar heat collection and an enclosed greenhouse in the patio. Plans and specifications would be needed to enhance water storage and distribution facilities.

6. The operation of one or more dry wells in the urban area, preferably near a commercial shopping center, should be monitored to evalute and demonstrate its capacity and effectiveness in containing concentrated storm runoff.

7. A feasibility-grade engineering design, specifications and cost estimates should be prepared for installing a demonstration facility to divert, detain and use storm runoff at one of the sites described in this report. The site should be selected with the concurrence of representatives from the City Engineer's office and the Parks and Recreation Department. First priority should be given to the site at Linden Wash and 15th Avenue (Elias Park). If that site is deemed infeasible or undesirable in the view of any of the responsible parties, consideration should be given next to each of the other sites in the order named in Table 14.

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APPENDIX

Excerpt from City of Scottsdale Code, Concerning Retention of Storm Runoff on Private Property

g. <u>Retention areas</u>

In order to reduce the storm runoff as much as feasible in those areas where an adequate outfall does not exist, retention areas shall be used for local (on-site) storm water as per the following procedures:

(1) The design frequency shall be the fifty-year storm. If feasible, using the twenty-four-hour rainfall depth "D" as determined from the U.S. Weather Bureau Isopluvials (equal rainfall lines, in Arizona State Highway Department Standards).

(2) Determine a rational "C" factor as per Arizona State Highway Department Standards for the tributary area.

(3) Solve for volume required:

$$V_t = \frac{D}{12} AC$$

V_t = Volume required (acre-feet)
D = 24-hour rainfall depth (inch)
C = Rational runoff factor for tributary area
A = Tributary area (acre)

The retention area shall be drained within a 96-hour period by methods approved by the Engineering Services Director.

Note: The above paragraph "g" is a subparagraph of paragraph 5-614, E., 3. of the City Code.