

Water-Harvesting Applications for Rangelands Revisited

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Although water-harvesting techniques have been used effectively in irrigated agriculture and domestic water supplies, there seems to have been little continued exploitation of the same techniques in arid and semiarid rangeland water conservation. A review of the history of rangeland water harvesting allows identification of the methods that have been useful in the past and that would likely be effective in the future. It seems that relatively simple water-harvesting approaches work best on rangelands, particularly water-ponding dikes to stimulate vegetation growth. Experience from rangeland water harvesting in New Mexico and other locations in the Southwest indicates that the approach is a long-term solution that produces significant vegetation growth, but generally only 10–15 years after installation because of the sporadic and spatially distributed nature of the summer monsoon rainfall. Additionally, the use of water-ponding dikes seems to most reliably produce an “island” of enhanced soil moisture and increased habitat cover and forage. Water-ponding dikes are easy and relatively inexpensive to construct and produce a pattern of vegetation similar to naturally occurring banded vegetation. Even very shallow dikes (7.5 cm) have been shown to produce a significant vegetation response. As climate changes our water supplies, historical techniques of water harvesting used for over 9,000 years are viable rangeland water conservation alternatives now and in the future for adapting to such changes.

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The term *water harvesting* means the concentration, collection, and distribution of water that would naturally exit a landscape through other processes (runoff,

evaporation). Although very simple in concept and ancient in its history of application, it is surprising that this traditional water management approach is not more commonly implemented. When used, water harvesting is normally found in irrigated agriculture and domestic water supply applications, usually in less developed and impoverished regions of the globe. There have been applications on rangeland, particularly for desired management effects such as enhanced forage growth, landscape-level distribution of livestock water supply, and rehabilitation of deteriorated vegetation. Although applications in irrigated agriculture and domestic water supply are similar, this review focuses on the less common rangeland water-harvesting approaches, except when a particular cropland or domestic water supply harvesting technique can be applied directly to rangelands (e.g., Critchley et al., 1991; Frasier and Myers, 1983; Hudson, 1987; Renner and Frasier, 1995). Literature for water harvesting applied to crop production has been found to be sparser than expected (Boers and Ben-Asher, 1982). This lack of literature is even more pronounced when water-harvesting applications to rangeland are considered.

The rangeland percentage of the world's total land surface area is between 40% and 70%, depending on the definition used by the author (Branson et al., 1981; Heady and Child, 1994; Holechek, Pieper, and Herbel, 1995). Approximately 80% of all the world's rangeland is found in arid and semiarid regions (Branson et al., 1981), of which the rangelands in the southwestern United States (US) are good examples. The Jornada Experimental Range (JER) in south-central New Mexico is representative of both southwestern US and the world's arid-to-semiarid rangeland and is a long-term ecological research site that has produced almost a century of important rangeland research knowledge (Havstad, Huenneke, and Schlesinger, 2006).

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Historical Applications

Ancient Evidence

Investigators have found evidence in Jordan that water-harvesting structures were constructed over 9,000 years ago and in Southern Mesopotamia over 6,500 years ago (Bruins, Evenari, and Nessler, 1986). Water-harvesting structures used by the Phoenicians in the Negev Desert were found to date back 3,000–4,000 years (Lowdermilk, 1960). Water collection and irrigation structures in southern Mexico have survived in excellent condition for about 3,000 years (Caran and Neely, 2006). Water-collecting structures were also found in the Negev Desert dating back at least 2,700 years and probably longer (Evenari, Shanan, and Tadmor, 1982). Water harvesting for irrigation has been practiced in the desert areas of Arizona and northwestern New Mexico for at least the last 1,000 years (Zaunderer and Hutchinson, 1988).

The rainwater-harvesting approaches cited as used in the Negev Desert include terraces in wadis that are still under cultivation by local Bedouins and water-harvesting farms reconstructed as part of an experiment by researchers at local universities (Evenari, Shanan, and Tadmor, 1982). Figure 1 is an aerial photo showing a farm unit near Shivta in the Negev Desert that features terraces in the wadis that slow water flow

(Evenari, Shanan, and Tadmor, 1982). This enables infiltration and an increase in soil moisture, which enhances the success of cultivation behind the terraces. To increase the volume of water available for farming, stone-lined conduits from the surrounding hillsides collect and rapidly transmit rainfall runoff to the cultivated area. Figure 2 is a schematic of a water-spreading system illustrating floodwaters being delivered to a sequence of water-ponding dikes that have historically been used on rangelands in the Middle East (Prinz and Malik, 2002, as adapted from French and Hussain, 1964). These types of water spreaders are typical of those used in arid regions around the world. However, as reported by Fidelibus and Bainbridge (1995), “like many great solutions to environmental problems, rainfall catchments” (or water-harvesting methods) “are a reinterpretation of ancient techniques developed in the Middle East and Americas, but forgotten by modern science and technology.”

Recent History

The availability of relatively inexpensive labor in the period 1934–42 through Civilian Conservation Corps (CCC) personnel working at the direction of US government scientists produced a large number of land treatment measures throughout the western US drylands. Peterson and Branson (1962) report that 899 water conservation

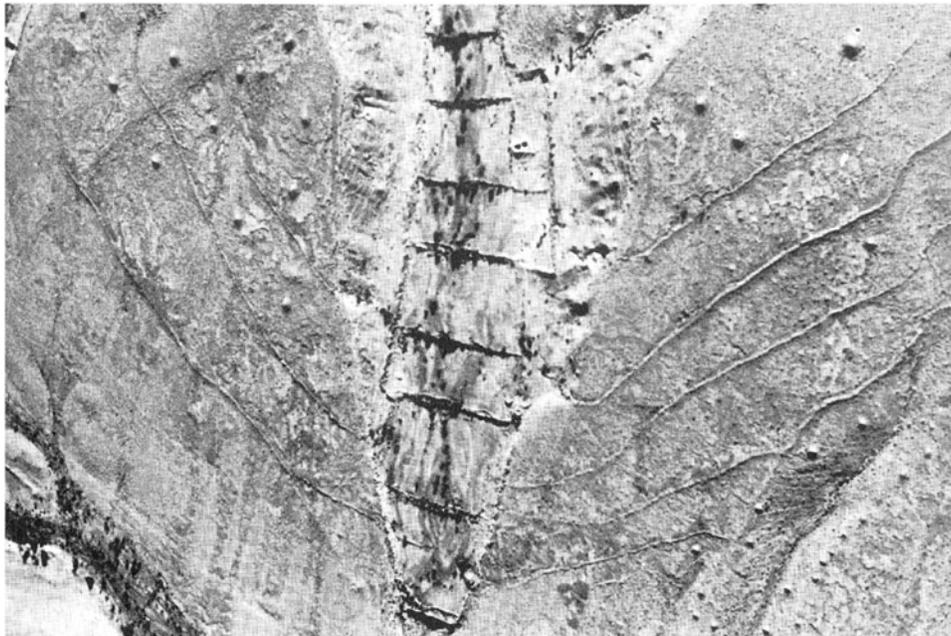


Figure 1. Aerial photograph of a farm unit near Shivta in the Negev Desert. Terraced wadi and stone conduits leading runoff from hillsides to terraces are visible After Evenari, Shanan, and Tadmor (1982).

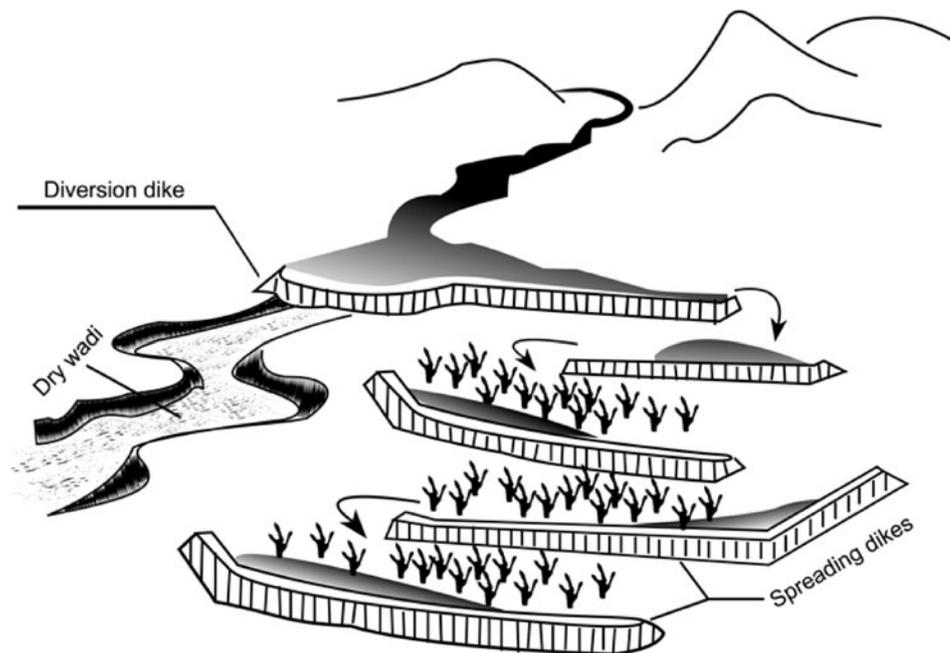


Figure 2. Water-spreading system in Pakistan to divert excess floodwater-ponding dikes. After Prinz and Malik (2002), as adapted from French and Hussain (1964).

structures established by the CCC were located and appraised in 1949 and 1961 in the Upper Gila and Mimbres River watersheds in Arizona and New Mexico. The effectiveness of the treatments was assessed in terms of vegetation improvement, longevity, and quantities of sediment retained by the structures. More than half of the structures were breached within several years after construction and were not functioning as planned. However, the most effective water-spreader systems were where earthen dikes were not breached and water was able to reach the spreader system, which resulted in vegetation improvement even in the driest areas of the region.

Another study of water-spreader effectiveness (Miller et al., 1969) found that the response of forage vegetation was dependent on rainfall characteristics, runoff production, and drainage of water detained in ponds behind dikes. If a site received less than 200 mm of annual precipitation or less than 100–130 mm during the growing season, it would typically not produce enough runoff to justify installation of a water spreader (Bennett, 1939). Results produced by Valentine (1947), Hubbell and Gardner (1950), Hubbard and Smoliak (1953), Branson (1956), Houston (1960), and Hadley et al. (1961) showed increases in yield of forage grasses from slight to large (Miller et al., 1969). Forage production occurred only on those sites that received at

least one flooding event per year. The amount of soil moisture in the soil profile had more influence than did soil texture on forage produced. More forage was also produced when ponded water could drain completely from the soil surface between rainfall events.

Similar work has also been done in other arid and semiarid regions of the world. As an example, Cunningham, Quilty, and Thompson (1974) have reported on the use of water-ponding dikes to reclaim extensive bare soil areas (*scalds*) in Australia. This water-ponding approach yielded almost double the amount of forage obtained from nearby non-scald areas with the same soil type. Scalds are formed through a combination of wind and water erosion removing surface soil to expose the subsoil, which subsequently becomes very impervious (Cunningham, Quilty, and Thompson, 1974; Warren, 1965). Soil berms 30–45 cm high were constructed using a road grader that allowed ponding of surface runoff that was trapped behind a berm after a rainfall.

Some of the most recent water-ponding dikes constructed in the US were on the JER to evaluate the efficiency of the structures to increase forage. In four separate areas of the JER, 25 dikes were installed between 1975 and 1981 (Rango et al., 2006). These types of dikes can be constructed with

a tractor and mold board plow or with a road grader as in this experiment (see Figure 3). The height of the dikes ranged from a low of 7.5 cm to a high of 30 cm (see Table 1). The orientation of the dikes is typically perpendicular to the general direction of the overland flow. Additionally, multiple dikes are often arranged so that dikes downslope can catch any overflow from the upslope dikes. A crescent-shaped dike is usually used to gather the water

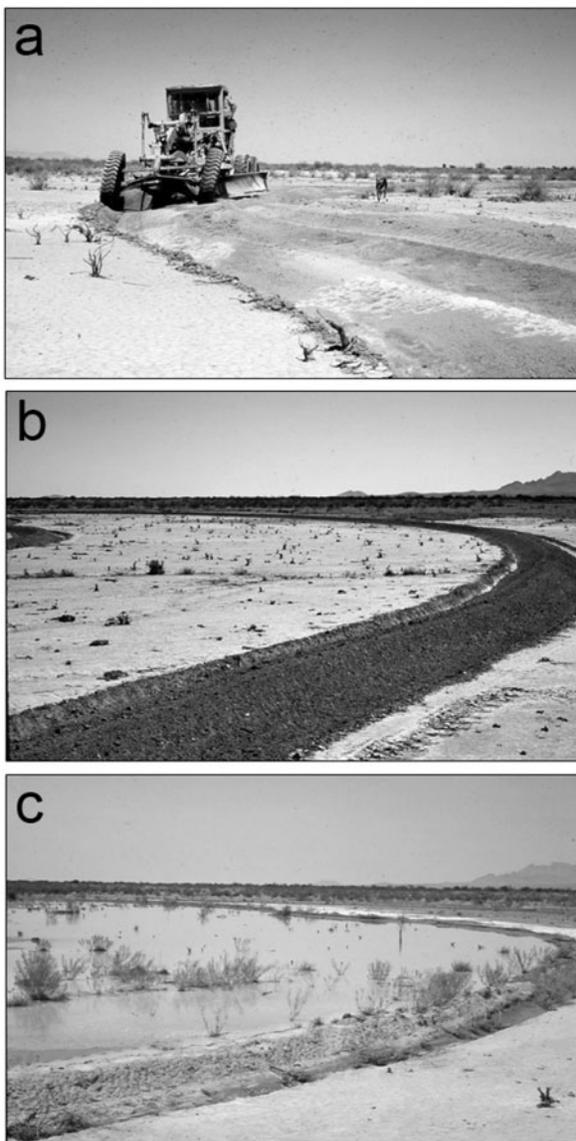


Figure 3. Development of water-ponding dikes at the Jornada Experimental Range showing (a) 15-cm dikes at the Ace Tank during construction with a road grader in 1975; (b) 7.5-cm dikes at Taylor Well during construction (accomplished using a mold board plow); and (c) water ponding behind a 7.5-cm dike at Taylor Well.

Table 1. Attributes of water-ponding dikes established on the Jornada Experimental Range in south-central New Mexico

Location	Year installed	Height (cm)	Number of dikes	Soil texture
Taylor Well	1975	7.5	5	Fine
Ace Tank	1975	15	5	Fine
Brown Tank	1978	15	3	Fine
Dona Ana Enclosure	1981	30	12	Medium-coarse

into a shallow pond. The resulting pattern of the dikes and vegetation growth approximates the pattern of natural banded vegetation, which serves a similar function; namely, slowing overland flow over bare areas, allowing the water to infiltrate into the soil moisture reservoir, and increasing vegetation growth (Tongway, Valentin, and Seghier, 2001).

Certain design criteria that were used when installing the water-ponding dikes at the JER are specified by Tromble (1983). These criteria vary because of the characteristics of the individual site. Dikes were installed on fine- to medium-textured soils where the soil sealed rapidly during rainfall events, thereby producing surface runoff. Furthermore, the dikes were placed in areas of “wasteland” supporting little or no vegetation (similar to the scalds in Australia). Dikes were placed starting at the highest place on the slope and working downslope. The direction of water flow from one dike to the next was regulated by locating one end of the dike higher than the other end so that water flowed out the lower end of the dike once it filled (Tromble, 1983). The distance between dikes was a function of the slope and expected water-ponding depth. Enough distance was left between dikes to provide a source area for surface runoff water. Usually a 1:1 or 2:1 ratio of water runoff area to ponding area is satisfactory in a scald area (Tromble, 1983), but other authors cite values of 5:1 to 25:1, depending upon local conditions (e.g., see Vallentine, 1989).

Rationale for Revisiting Use on Rangelands

Though an ancient practice, there are several reasons why water harvesting has been nearly abandoned as a management tool across most land areas of the southwestern US, as well as other arid-to-semiarid regions of the world. These reasons include (a) a perceived notion that installation of water-harvesting infrastructure is too expensive in relation to the resultant benefits, (b) legislative restrictions and their

associated costs for applications in the public land ownership landscapes of the western US, (c) a persistent belief that installations on large spatial scales are too difficult to implement and maintain, and (d) a lack of knowledge about the effectiveness of water harvesting as a legitimate management practice. In reality, installation of simple systems are not that expensive, minimal maintenance is all that is needed to maintain function, and water-harvesting works are effective if given enough time to be activated in regions of sparse, sporadic, and spatially widespread rainfall. Though there may be a lack of communication about the details of these structures, this could be rectified by more effective documentation and educational outreach programs. There also might be falsely held ideas that these methods are suitable only for areas of extreme poverty and with little access to more modern technologies. However, the water-conserving nature of these water-harvesting methods should dispel this idea, and, as water scarcity continues to pressure our increasing population, the importance of water conservation through water harvesting will be much more relevant.

To some degree, arid-land water managers may have overlooked that numerous rangeland water-harvesting treatments were installed in the western US and other parts of the world in the 1930s–70s. Results from these applications are useful in improving the understanding of the advantages of water harvesting. The desirability of these water-harvesting techniques should increase in the future under conditions of climate change and increasing climate variability. New Mexico, because of its southerly location in the US, has already experienced warmer temperatures ($+1^{\circ}\text{C}$ in winter and $+2^{\circ}\text{C}$ in summer) as a result of the ongoing climate change (Watkins, 2006). Diffenbaugh, Giorgi, and Pal (2008) also note that the southwestern US stands out as a regional hot spot for 21st-century climate change. Certain locations of the arid southwestern US might experience not only warming temperatures, but also declining rainfall, thus greatly increasing the relevancy of the water-harvesting approaches. Although some areas of the West may receive reduced annual rainfall, they could also experience increases in convective rainfall events. As a result, the water-harvesting approaches that are effective during intense rainfall can be used to offset the effects of warmer temperatures and increased evaporative losses.

Methods of Rangeland Water Harvesting

The basic goal of water harvesting on rangeland is to intercept the flow of surface water, either as overland flow or as channel flow. A variety of surface structures have

been used in the past, but the use of earthen dikes or berms has been most popular because of simplicity, effectiveness, and relative low cost. The concept of *water ponding* is to use a dike or berm to hold the water in so that it cannot flow off the surface of the soil unless the capacity of the dike is exceeded (Miller et al., 1969). When a pond forms behind the dike, the infiltration process has an extended period to operate and replenish the soil moisture reservoir. Furthermore, by slowing the flow of water, the amount of infiltration and soil moisture is increased. Because of the increase in soil moisture, plant growth can be enhanced, either from existing plants, native seed banks, or planting of seeds during construction of the dikes. Water-harvesting methods to supply livestock drinking water employ the same general techniques used in water-ponding dikes. In this case, the collected water is stored in tanks or ponds (Frasier, 2003).

Although not serving exactly the same function as water-ponding dikes, earthen berms are installed across large areas upslope of downstream areas that are prone to flooding. The purpose of these berms is also to slow down surface runoff, promote infiltration, control erosion, reduce flash-flooding peaks, and even out the flows reaching the stream channel so that impacts on downstream reservoirs are minimized (Caird and McCorkle, 1946).

Water spreaders used on rangeland usually cover larger areas than do water-ponding dikes and are generally of two kinds. The first is designed as a system of dikes or berms constructed to automatically divert storm flows in gullies and spread them over the adjacent rangeland to promote the growth of forage (Miller et al., 1969). Such water-spreading systems can also be used effectively with irrigated agriculture. The second type of spreader is more specific and requires a water-holding reservoir that retains water during storm runoff events. When a certain volume of water has been stored, the entire stored volume is released to flow down a restricted flow path like a modified arroyo system. Earthen berms are used to cause the discharged water to flow through a more sinuous channel, longer than a natural arroyo channel. The resulting larger volume of water has a greater distance to follow while infiltrating the channel bottom of the target area. This also promotes increased soil moisture, which can enhance plant growth. Useful forage plants can be seeded along the flow path to encourage an increase in forage for livestock. To increase the water volume available for release, flow in adjacent stream channels can be diverted to the storage reservoir to increase the stored water volume more rapidly. The soil berms are sometimes reinforced with concrete,

especially at bends in the channel, to prevent bank erosion caused by the transport of high flows over a short period. Water-ponding dikes are commonly included as part of a water-spreading system, and the remainder of this article focuses on water-ponding dikes.

Although the concept of shallow water-ponding dikes to enhance soil moisture and, subsequently, increase ground cover and forage for wildlife and livestock is simple, many factors enter into the exact placement of such dikes in arid and semiarid regions. The overriding purpose is to slow down surface runoff, and one consideration is to determine areas with significant overland flow. This can be done by observing such flows in the field during or after heavy rainfall, but this requires on-the-ground observations during what may be rare runoff events. It may be more useful to use remote-sensing data either by observing the evidence of overland flow after a rainfall event or by recognition of overland flow paths during dry periods. Figure 4, which is an aerial photograph at the JER in south-central New Mexico in October 2006, shows runoff flow paths through the desert (after rainfall) as darker areas where surface soil moisture is greater. From a landscape perspective, the use of remote sensing enables a more complete understanding of the landscape units generating surface runoff. This more detailed spatial analysis improves the actual placement of individual dikes.



Figure 4. Aerial photograph over the Jornada Experimental Range in October 2006 showing runoff flow paths after rainfall events at 25-cm resolution. Flow paths are darker because of an increase of surface soil moisture.

The type of soils where dikes are constructed needs to be considered because of the differential amounts of overland flow that can be generated by different soils. Fine- to medium-textured soils generally produce significant surface runoff from intense rainfall that can be intercepted by water-ponding dikes (Miller et al., 1969). Sandy soils allow higher rates of infiltration, generate too little surface flow, and are therefore unsuitable for producing enough water for the installation of dikes. Clay, silty-clay, or silty-loam soils are generally suitable for water-ponding dikes. Once a pond is formed behind a dike, it is important to have the water infiltrate the soil and be stored in the soil moisture reservoir for forage plants to use for growth. The water-harvesting dikes also promote sediment deposition in the ponding area. Generally, this can increase the clay, silt, and/or loam contents of the soil, which may allow more stored soil moisture and greater vegetation production.

Mean annual and seasonal rainfall and the type and intensity of storms are important rainfall characteristics for designing any water-harvesting system. According to Bennett (1939), a mean annual rainfall of 200–355 mm produces ideal conditions for plant growth for rangelands using water ponding. If a large portion of the rainfall occurs in convective events in summer, the chance of successful water ponding increases because rainfall rates are more likely to exceed infiltration rates and produce more runoff than areas with many low-intensity storms. If the mean annual rainfall exceeds 355 mm, then water harvesting for supplemental feed and cultivated crops also has a high probability of success (Bennett, 1939). These are characteristics present in the southwestern US, as well as in the vast arid-to-semiarid regions of the world. For example, at the JER, the long-term average rainfall from 1915 to 1995 was 245 mm, with about 55% of the annual total occurring in the three summer monsoon months of July, August, and September.

When completed, the actual water-ponding dike should have a round rather than a V-shaped top because the rounded crest is affected less by large-animal impacts, such as livestock trampling. Broad-based dikes with a bottom width of 2–3 m are more stable than narrow dikes. It is recommended to construct dikes with gentle curves as opposed to sharp curves that commonly result in V-shaped crests. The dike lengths at the JER range from 50 to 150 m (Rango et al., 2006).

Periodic maintenance to repair breaches in the dikes is recommended (Stokes, Larson, and Pearse, 1954). For a variety of nontechnical reasons, the JER dikes were not

originally thought to be effective, and the dikes have not received any maintenance since being constructed in 1975. Although this is not the optimum situation, the dikes are still performing their water-ponding and increasing vegetation functions despite the development of breaches through the earthen dikes.

Discussion

Construction of water-ponding dikes on rangelands has two major goals. The first is to increase soil moisture by slowing down surface runoff to promote ponding of water that would otherwise be lost to evaporation in some other location. The second goal is to increase plant growth where soil moisture has increased. Often, increased plant growth increases forage available for grazing animals, both domestic and wildlife. Figure 5 shows a sequence of vegetation growth behind the (a) Ace Tank dikes and (b) the Taylor Well dikes at the JER. When records were being kept of ponding events behind the dikes (1978–81), the Ace Tank dikes averaged 12 ponding events per year, whereas the Taylor Well dikes averaged 11 per year. In the case of both sets of dikes, the response of vegetation behind the dikes (shown in darker brown or red tones) to ponded runoff water was not immediate, taking about 10–12 years to react to sporadic precipitation typical of the southwestern US. These delayed responses are to be expected in dry regions. In fact, the delay was partially responsible for the dikes not being maintained or checked for many years. A similar delayed response was detected by Peterson and Branson (1962) on water-harvesting structures installed by the CCC between 1934 and 1942 in southwestern New Mexico and southeastern Arizona. Initial surveys of vegetation growth showed little response, but surveys 12 years later revealed that vegetation growth was much improved. In the arid Southwest, it just may take longer for appropriate rainfall to occur in the vicinity of water-ponding dikes and still longer for extensive vegetation growth. This seems to indicate that, in arid regions, these types of treatments are more long-term investments and cannot be depended upon for a response within 1–2 years, like water harvesting used for irrigated crops, because of the type of rainfall events commonly experienced (high-intensity but widely distributed storms).

Soil moisture was measured from the time of installation of the JER dikes in 1975 until when measurements were terminated in the mid-1980s. Tromble (1982) compared the soil moisture profile in July 1979 (after the dikes had been in place for four years) for the Taylor Well dikes (7.5 cm) and the Ace Tank dikes (15 cm). Although rainfall totals are

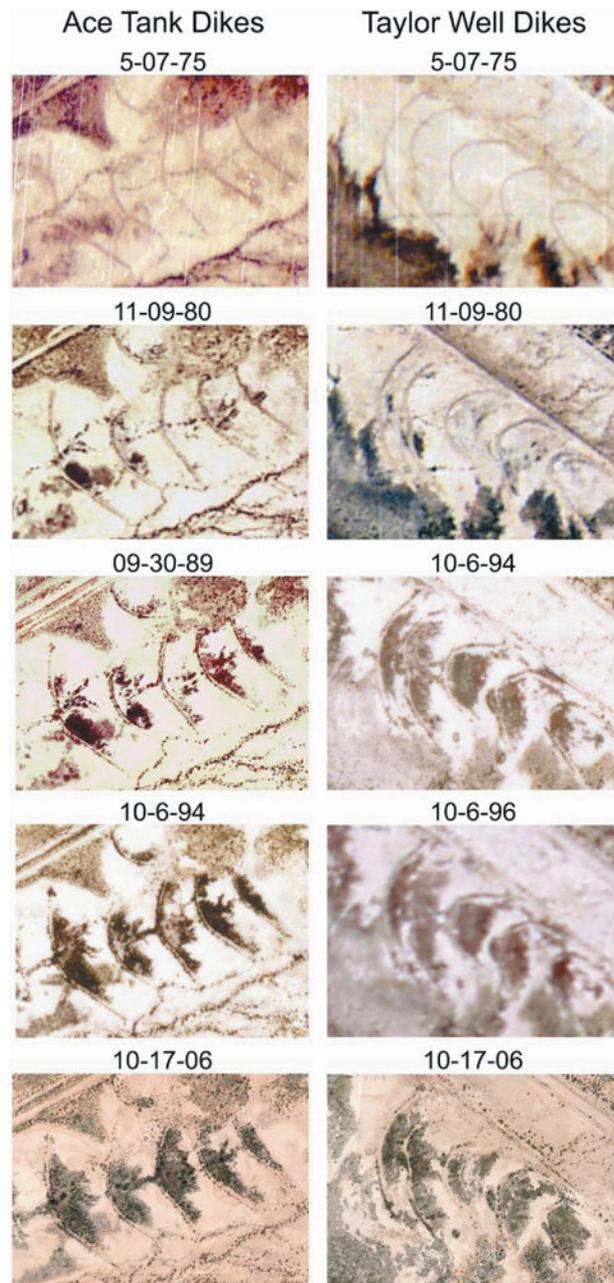


Figure 5. A sequence of vegetation growth from construction in 1975–2006 using aerial photography for (a) the Ace Tank dikes and (b) the Taylor Well dikes at the Jornada Experimental Range.

similar for the Ace and Taylor dikes, the greater water-ponding depth of Ace (because of the higher dikes) has produced a soil moisture profile difference. The control area was uniformly dry down to 180-cm depth, whereas the Taylor dikes were much wetter at the surface and gradually

dried out with depth. The Ace dikes had uniformly greater soil moisture down to 180 cm (Tromble, 1982).

Associated with increases in soil moisture, Miller et al. (1969) have reported increased forage yields exceeding 1 ton/acre in response to water-spreading treatments. Yields were reduced if water ponded without infiltrating for long periods. Branson (1956) reports that forage yields on water-ponding dikes (as part of a water-spreader system) were 2.6 times the yields on controls in a Montana experiment. Houston (1960), also working in Montana, reported an increase in herbage yields of 62% for water draining across rangelands, and a yield increase of 189% for rangeland where water was allowed to pond and infiltrate. Hubbell and Gardner (1950), experimenting in New Mexico, reported that herbage yields increased by water spreading by 4–9 times, and Hubbard and Smoliak (1953) reported herbage increases even in excess of this. In more recent water-ponding experiments at the JER, Tromble (1984) reports that the 7.5-cm dikes caused a 2.4- to 6.0-fold increase in forage production over controls, depending on year and the location behind the dike. In all the water-ponding or water-spreading experiments, it seems that increases in soil moisture and forage yield are consistent across the western US.

Disadvantages

To install water-ponding systems, detailed knowledge of the target areas is needed. Not all soils are suitable for the installation of water-ponding dikes, and a knowledge of soils accompanied by spatial soils maps is necessary. Additionally, to locate the site of dikes, an informational data base needs to include vegetation type, bare soil areas that may be producing surface runoff, and a method for distinguishing rills and overland flow areas. Access to high resolution (<1 m) remote-sensing data, as well as training in remote-sensing analysis techniques, can greatly enhance these landscape characterizations. Justification for using the old or traditional technology of water harvesting may be necessary in order to acquire installation funds, environmental or archaeological clearances, or permit approvals from the appropriate jurisdictions. Finally, much more deliberation is necessary in deciding to install water spreaders rather than the more simple water-ponding dikes. The complexity of the water-spreading system can result in more problems than with the simple water-ponding dikes.

Advantages

In hyperarid regions, much surface runoff is unusable following infiltration into the desert floor or an arroyo stream-

bed. The use of water-ponding dikes basically conserves this moisture and enables subsequent application to enhance vegetation growth. In most cases, because of the high infiltration rates of most desert surfaces, especially sandy arroyo bottoms, the surface runoff will be infiltrated and then evaporated into the atmosphere, not far from where the precipitation fell originally, thus never making it downstream to potential users. In the case of water-ponding dikes, the water can be more effectively used where it falls on rangeland. The dikes can be installed very simply without major effort compared with other types of rangeland remediation treatments. And, by selecting this approach, one is using a traditional and historical water conservation technique. The use of techniques that have been developed over long periods have known merits and typically produce a positive response.

Economic Considerations

Few investigators have documented quantitative results and the costs and benefits associated with water harvesting for rangeland. Where this has been done, the investigators are usually more specific about the costs but less so about the benefits. Investigators generally state that the costs are outweighed by the benefits, which are usually an increased amount of forage or increased plant species diversity and subsequent ground cover. Table 2 lists authors who have included costs (US\$, 2007) associated with the installation of dikes or spreaders. Generally, the cost of construction of water-ponding dikes is less than that of water spreaders. The dikes used in water spreaders by Hubbard and Smoliak (1953) and Monson and Quesenberry (1958) range from 1.5 to 2.5 ft. high (46–76 cm), whereas dikes employed at the JER ranged from 3 to 12 in. high (7.5–30 cm). To estimate the costs of the JER dike installation (because no records were kept during installation), the dikes would be expected to cost about 50% of the average cost in Table 2 ($0.5 \times \$31.41 = \$15.70/\text{acre}$ [$\$38.77/\text{ha}$]) in US dollars) because the JER (average dike height, 7 in. [18 cm]) required much less construction effort than the ones reported in Table 2. To estimate the cost of installing dikes over a much larger area, 11 pastures at the JER have been hypothetically identified as potentially feasible for trapping and ponding surface runoff because of soil type and evidence of overland flow after convective storms. About 20% of the area in those pastures would be treated: about 3,641 acres (1,473 ha). The cost for water-ponding dike installation would be approximately \$57,000. Unfortunately, as with other analyses of the benefits and practices that can enhance goods and services from rangelands, we lack sufficient economic

Table 2. Cost associated with installation of water-ponding dikes or water spreaders

Investigators	Cost/acre		Benefit
	Cost when installed	Converted to 2007 dollars	
Mooney and Martin (1956)	\$6.70	\$51.34	% Increase hay
Hubbard and Smoliak (1953)	\$0.36	\$ 2.78	% Increase herbage
Monson and Quesenberry (1958)	\$1.38	\$10.06	% Increase herbage
Houston (1960)	\$2.35	\$16.54	Monetary increase of herbage/acre
Branson (1956)	\$9.96	\$76.33	Increased herbage/acre
Average		\$31.41	

data for further cost/benefit calculations of the potential water-ponding treatments.

Banded Vegetation

There are striking similarities between the vegetation patterns caused by water-ponding dikes shown in Figure 5a and b and those of banded vegetation patterns in Australia and the US (Tongway, Valentin, and Seghieri, 2001) occurring in water-limited environments. The occurrence of vegetation bands in arid regions seems to be a landscape strategy for vegetation survival in areas normally lacking sufficient available soil moisture (Valentin, Tongway, and Seghieri, 2001). Vegetation bands accumulate water runoff from bare areas, and the biological systems within bands operate as though they were in an area of higher rainfall (Noy-Meir, 1973). Consequently, the vegetation bands serve as barriers to slow surface flow and therefore serve as natural water-harvesting systems (Valentin, Tongway, and Seghieri, 2001). Work regarding banded landscapes (Tongway, Valentin, and Seghieri, 2001) has substantiated the theory of Noy-Meir (1973) that, in environments with limited resources (e.g., water), vegetation productivity is greater if resources are concentrated into patches rather than being distributed uniformly over the landscape (Tongway and Ludwig, 2001; Valentin, Tongway, and Seghieri, 2001). The question that remains to be answered is whether water-ponding dikes are an effective management tool for eventually initiating a banded vegetation landscape. As far as length of time, the JER water-ponding dike vegetation required 10–15 years for a positive response and has survived for 21 years. Obviously, the status of this vegetation will continue to be monitored. A more important question that is harder to answer is whether the water-ponding dike-vegetation community will propagate itself to nearby bare portions of the landscape. So far, this has not been ob-

served, but it may be related to scale. Thus far, the vegetation and dikes cover relatively small areas.

Conclusions

Water harvesting is a methodology that has been used for over nine millennia to concentrate, collect, and distribute water that normally would be inaccessible for applications in irrigated agriculture, individual domestic water supply, and rangeland management. Although used widely for agriculture and domestic supplies, water harvesting is a management technique seldom used for rangeland applications despite many positive results. The technique might be overlooked for a variety of possible reasons, the least compelling being that it is an ancient method based on archaic technologies.

As more and more stresses are placed on our natural resources through the effects of a growing population and climate change, a renewed use of water harvesting would have positive outcomes. The simplest technique is to use water-ponding dikes, which slow down surface runoff, allow infiltration and increase soil moisture, and promote significant vegetation growth for habitat cover and forage. It is recommended to use water-ponding dikes because of the direct response: shallow water ponds form after high-intensity rainstorms, infiltration and soil moisture increase, and growth of native vegetation is enhanced (though sometimes delayed up to 10–15 years because of the type and distribution of rainfall across an area). The advantages of water-ponding dikes are that they are simple to install, cost effective, and use water that would be lost to evaporation.

The use of water-ponding dikes also mimics the way banded vegetation is arranged on the landscape: bare soil produc-

ing surface runoff after a storm, and vegetation bands downslope slowing and catching the surface runoff, increasing soil moisture and increasing vegetation growth as though it was located in an area with a higher rainfall. Future experiments are needed on larger areas to determine whether these rangeland treatments improve vegetation cover that can expand to (or at least be stable over) even larger spatial extents. If water can be supplied effectively, as through water harvesting, to the soil and vegetation complex, rangeland restoration projects will have an increased likelihood of success.

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