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# Review of Water-Harvesting Techniques to Benefit Forage Growth and Livestock on Arid and Semiarid Rangelands

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## 1. Introduction

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 utilized, water harvesting is normally found in irrigated agriculture and domestic water supply applications, usually in less developed and impoverished regions of the globe. It has been found (Boers & Ben-Asher, 1982) that literature for water harvesting applied to crop production was sparser than expected. 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 or degraded resource conditions. Although applications in irrigated agriculture and domestic water supply are similar, this chapter focuses on the documented rangeland water harvesting approaches, which are even less common than those applications for crop production. (e.g., Frasier & Myers, 1983, Hudson, 1987, Critchley, et al., 1991, and Renner & Frazier, 1995).

The percentage of the world's total land surface area occupied by rangeland is between 40% to 70% depending on the definition used by the author (Branson, et al., 1981; Heady & Child 1994; and Holechek et al., 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 U.S. are good examples. The Jornada Experimental Range (Jornada) in south central New Mexico is representative of both the southwestern U.S. 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 et al., 2006).

There are a number of unanswered questions that will be addressed in this chapter. Specifically, why haven't water harvesting techniques been used more frequently in arid and semiarid rangelands, and where they have been used, what problems have been encountered and what gaps in our knowledge still exist? Briefly, water harvesting has been used on rangelands but the documentation of the results are widely scattered. No insurmountable problems have been encountered, but a synthesis of existing results in one chapter should provide easier access to the existing literature for informed decisions on where and how to employ various water harvesting approaches. The authors have reviewed

and assembled key water harvesting documentation which indicates that the techniques are easily used with the most effective approach for enhancing soil moisture and forage growth coming from constructing shallow water ponding dikes across known overland flow paths. For livestock watering, the construction of dirt stock tanks in established water channels provides valuable water sources for domestic animals as well as wildlife resulting in a complementary source of water to well water that may otherwise be wasted through the normal rainfall – evaporation cycle.

The authors have examined the positive and negative aspects of the water harvesting results. Surprisingly, there are few noted disadvantages. One disadvantage is a lack of evidence that shallow water ponding dikes have a capability to be self propagating in regards to vegetation growth. One distinct advantage is that simple traditional treatments are easy and inexpensive to install. Interestingly, historical and ancient methods are timeless. Infiltration of water into rangeland soils results in increased soil moisture and resulting associated forage growth. Still, future research is required over areas larger than those documented in the literature to see if results will vary based on differences in spatial scale. There will be a challenge in doing treatments as well as conducting measurements of soil moisture and forage over much larger areas than those used in the past. However, research at appropriate spatial scales should lead to more comprehensive recommendations of how to proceed in water harvesting in arid and semiarid rangelands around the world.

## **2. Historical applications**

### **2.1 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 et al., 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 & Neely, 2006). Water collecting structures were also found in the Negev Desert dating back at least 2,700 years and probably longer (Evenari et al., 1982). Water harvesting for irrigation has been practiced in the desert areas of Arizona and northwest New Mexico for at least the last 1,000 years (Zaunderer & 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 et al., 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 et al., 1982). This allows 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 & Malik, 2002, as adapted from French & Hussain, 1964). These types of water spreaders are typical of those used in arid regions around the world. However, as reported in Fedelibus & 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.”

## 2.2 Recent History

The availability of relatively inexpensive labor in the period 1934-1942 through Civilian Conservation Corps (CCC) personnel working at the direction of U.S. Government scientists produced a large number of land treatment measures throughout the western U. S. drylands. Peterson & Branson (1962) report that 899 water conservation 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 were assessed in terms of vegetation improvement, longevity, and quantities of sediment retained by the structures. More than half of the structures were breached by water within several years after construction and were not functioning as planned. However, the most effective water applications 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.



Fig. 1. Aerial photograph of a farm unit near Shivta in the Negev Desert. A terraced wadi and stone conduits leading runoff from hillsides to terraces are visible (after Evenari et al., 1982)

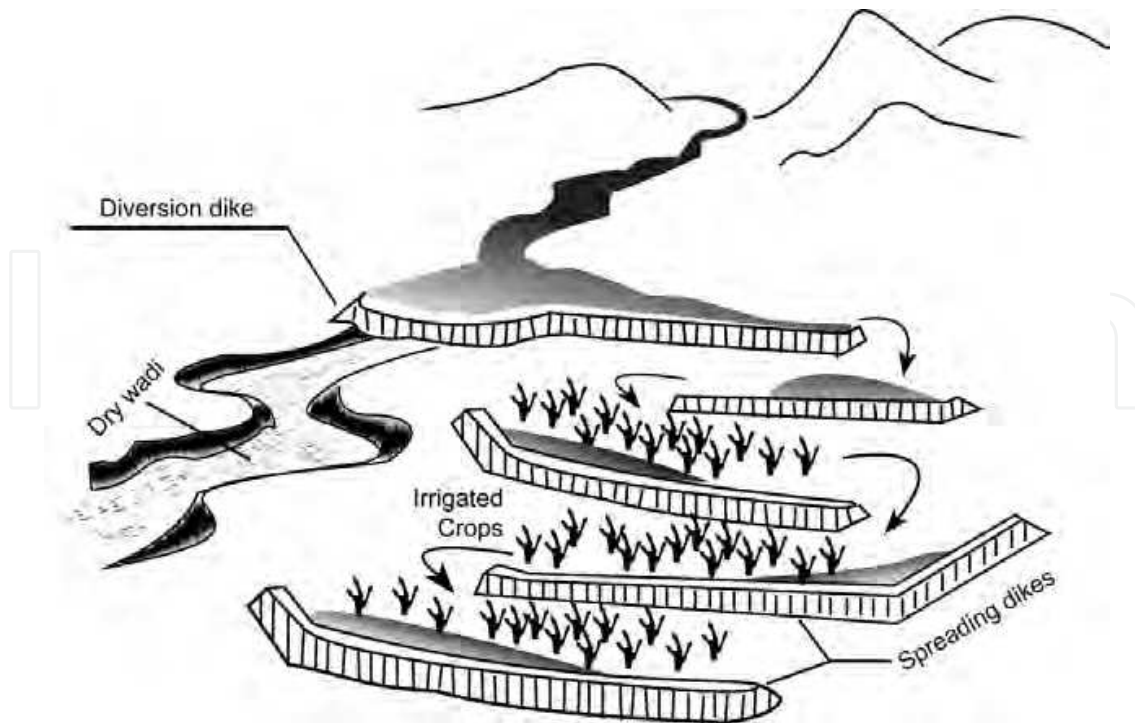


Fig. 2. Water spreading system in Pakistan to divert excess flood water ponding dikes (after Prinz & Malik, 2002, as adapted from French & Hussain, 1964).

Another study (Miller et al., 1969) of water spreader effectiveness 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 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 & Gardner (1950), Hubbard & Smoliak (1953), Branson (1956), Houston (1960), and Hadley & McQueen (1961) showed increases in yield of forage grasses from small to large amounts (Miller et al., 1969). Forage production occurred only on those sites that received a minimum of at least one flooding event per year. The amount of soil moisture in the soil profile had more influence than 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 et al. (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 (Warren, 1965; Cunningham et al., 1974). Soil berms of 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 event.

Some of the most recent water ponding dikes constructed in the United States were on the Jornada to evaluate the efficiency of the shallow structures to increase forage. Twenty-five dikes in four separate areas of the Jornada were installed between 1975-1981 (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).



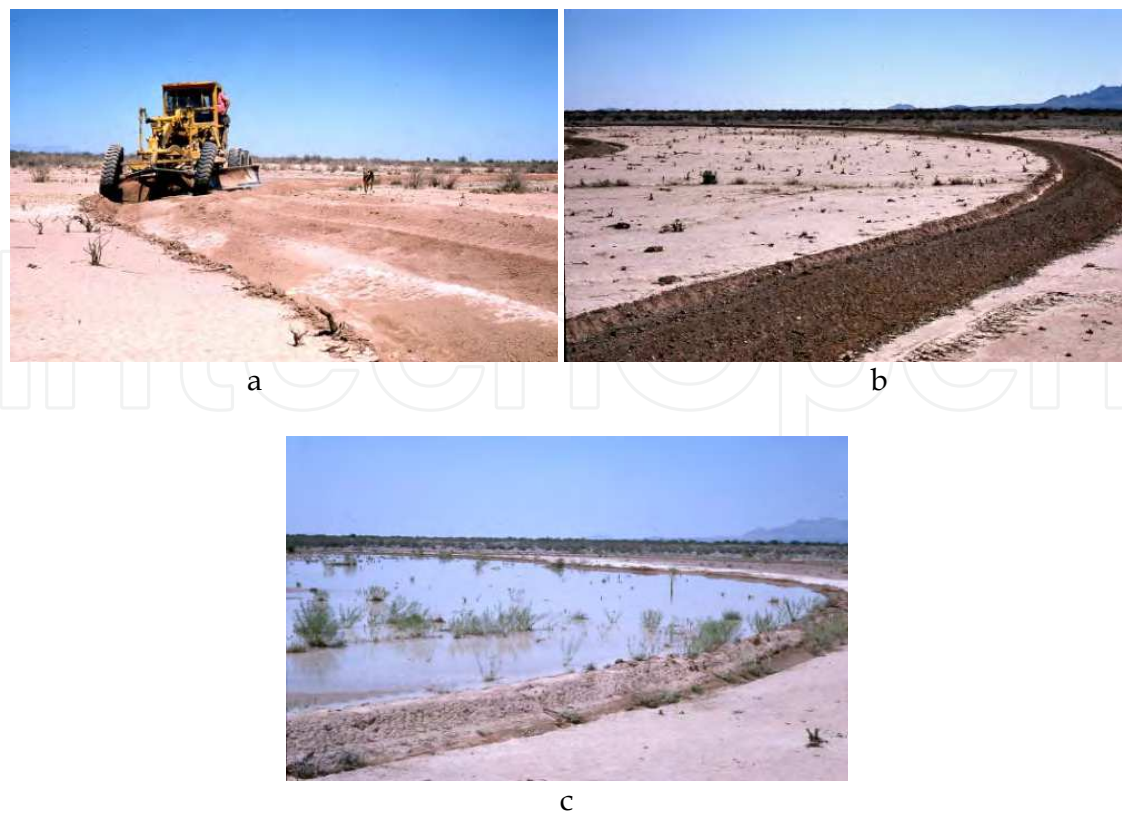


Fig. 3. Development of water ponding dikes at the Jornada showing a) 15cm dikes at the Ace Tank during construction with a road grader in 1975; b) 7.5cm dikes at Taylor Well during construction (accomplished using a mold board plow); and c) water ponding behind a 7.5cm dike at Taylor Well.

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 are 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 shape dike was usually employed to gather the water into a shallow pond. The resulting pattern of the dikes and vegetation growth approximate the pattern of natural banded vegetation which serves a similar function, namely, slowing down overland flow over bare areas, allowing the water to infiltrate into the soil moisture reservoir, and a resulting increase in vegetation growth (Tongway et al., 2001).

Location	Date Installed	Height	Number of Dikes	Soil Texture
Taylor Well	1975	7.5 cm	5	Fine
Ace Tank	1975	15 cm	5	Fine
Brown Tank	1978	15 cm	3	Fine
Dona Ana Exclosure	1981	30 cm	12	Medium-Coarse

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

Design criteria used when installing the water ponding dikes at the Jornada are specified by Tromble (1983). These criteria varied 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 on a scald area (Tromble, 1983), but other authors cite values of 5:1 to 25:1 depending upon local conditions (Vallentine, 1989).

Compared to the shallow water ponding dikes, much deeper ponds or lakes are also necessary in rangelands for watering livestock as well as for providing fringe benefits to wildlife. Placement of these water sources depends not only upon water availability, but also on animal numbers, available forage, soil properties, and abiotic factors. Many approaches to providing water have been tested on rangelands. The two most usual developed water sources are from drilled, deep water wells and earthen dams that cause the formation of stock ponds. Early in the 20<sup>th</sup> century, it was recognized that competition to use reliable well water would become intense and that earthen dams to capture surface runoff would help reduce the pressure on well water utilization (Talbot, 1926). Simple, small earthen dams placed across drainage ways can provide open water storage during the rainy season and sometimes year round. This ancient technique has been used ubiquitously in arid regions and continues to be used throughout the world today. The ponds formed behind these earthen dams are, obviously, much deeper than behind shallow water ponding dikes.

In times of drought, stock ponds can dry up and the more reliable water source from deep wells is commonly relied upon. But for large portions of the year, especially in average to wet years, it is best to restrict deep well pumping to conserve the limited groundwater resources. In the same general water harvesting family that includes water ponding dikes and water spreaders, livestock water supply schemes can be very simple and are generally referred to as dirt tanks, stock tanks, or stock ponds.

In sparsely settled rangeland, especially in arid and semiarid regions where vegetation cover is limited, arguments for expensive solutions to make water available are usually difficult to justify. Reasons for deciding on earthen dam stock ponds are numerous, but the primary reason is that they are affordable to construct. Stock tanks are especially suitable in closed drainage, arid basins where flow in channels never leaves the basin, except by infiltrating into the stream channel bed and subsequently evaporating. By concentrating the flow behind earthen dams, the surface water area is small, thereby reducing both infiltration and evaporation. When surface soils in a watershed (and also used in construction) have a high percentage of clay and silty loams, infiltration rates tend to be low and surface runoff is increased. The use of stock ponds as the primary source of surface water reduces the use of well water with a more expensive infrastructure required for establishment. In most arid regions today, the natural recharge by precipitation is unable to provide replenishment of ground water because of an increasing deficit between recharge and pumping, both historic and present day (Giordano, 2009). Also, simple earthen dams and ponds last a long time with minimal maintenance. At the Jornada 77 stock ponds exist over the 783 km<sup>2</sup> area, most of which were constructed by Civil Conservation Corps labor in the 1930s (see Figures 4 and 5).



Fig. 4. Construction of stock water storage tanks at the Jornada Experimental Range using three-horse Fresno teams on Big Meadows tank by the Civilian Conservation Corps (CCC) in April 1934.



Fig. 5. Use of mechanized earth moving equipment during construction of Big Meadows tank at the Jornada Experimental Range in 1934. New equipment and the availability of the CCC labor force were some of the reasons for the revitalization of water harvesting on rangelands.



Fifty-five percent of these stock ponds had to be renovated approximately 50 years later in 1984. Maintenance costs for the original stock ponds during the 50 year period before renovation was minimal due to limited erosion of structures and slow sedimentation rates behind the earthen dams.

### 3. 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 southwest U.S. as well as other arid to semiarid regions of the world. These reasons include: 1) a perceived notion that installation of water harvesting infrastructure is too expensive in relation to the resultant benefits, 2) legislative restrictions and their associated costs for applications in the public land ownership landscapes of the western U.S., 3) a persistent belief that large spatial scale installations are too difficult to implement and maintain, or 4) 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 can be 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 is also the possibility that there are falsely held ideas that these methods are only suitable 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. As water scarcity continues to pressure our increasing population, the importance of water conservation through water harvesting will be much more relevant (Giordano, 2009).

To some degree, arid land water managers may have overlooked the fact that there were installations of numerous rangeland water harvesting treatments in the western U. S. and other parts of the world in the 1930-1970s. Results from these applications are useful in improving the understanding of the advantages of employing water harvesting technologies. 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 United States, has already experienced warmer temperatures (+1° C in winter and +2° C in summer) as a result of the ongoing climate change (Watkins, 2006). Diffenbaugh et al. (2008) also noted that the southwestern U.S. stands out as a regional hot spot for 21<sup>st</sup> Century climate change. It is possible that certain locations of the arid southwestern U. S. will not only experience warming temperatures, but also declining rainfall amounts, thus, greatly increasing the relevancy of water harvesting approaches. Although some areas of the West may receive reduced annual rainfall, they could also experience increases of convective rainfall events. As a result, the water harvesting approaches which are effective during intense rainfall can be used to offset the effects of warmer temperatures and increased evaporative losses that would be expected.

### 4. 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 use of earthen dikes, berms or dams has been most popular because of

simplicity, effectiveness, and relative low cost of both installation and subsequent maintenance. The concept of water ponding is to use a dike or berm to hold the water in such a manner 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 time period to operate and replenish the soil moisture reservoir. Furthermore, by slowing down the flow of water, the amounts of infiltration and soil moisture are increased. Because of the increase in soil moisture, plant growth can be enhanced, either from existing plants, germination and resulting establishment, 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 also installed across large areas upslope of downstream areas that are prone to flooding. The purpose of these berms is to slow down surface runoff, promote infiltration, control erosion, reduce flash flooding peaks, and even out the flows reaching the stream channel so that adverse impacts on downstream reservoirs are minimized (Caird & McCorkle, 1946; Baquera, 2010).

Water spreaders used on rangeland usually cover larger areas than 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 storage reservoir that retains water during storm runoff events. When a certain volume of water has been stored, the entire stored volume is released in a quick burst to run 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 the natural arroyo channel. The resulting larger volume of water has a greater length to follow while infiltrating into 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 produce an increase in forage for livestock and wildlife.

To increase the water volume available for release, flow in stream channels of adjacent watersheds can be diverted to the storage reservoir to more rapidly increase the stored water volume. The soil berms are sometimes reinforced with concrete, especially at bends in the sinuous channel, to prevent bank erosion due to the transport of high flows over a short period of time.

Although the concept of shallow water ponding dikes to enhance soil moisture and, subsequently, increase ground cover and forage for livestock and wildlife is simple in concept, many factors enter into their exact placement 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 events, but this requires on-the-ground observations during what may be rare runoff events. It may be more useful to employ remote sensing data either by observing the evidence of overland flow immediately after a rainfall event, or by recognition of overland flow paths during post-rainfall dry periods that remain highlighted for several weeks because of remnant surface soil moisture patterns.

Figure 6 is an aerial photograph at the Jornada in southcentral New Mexico in October 2006 which shows runoff flow paths through the desert (after rainfall events) as darker areas where surface soil moisture is greater. From a landscape perspective, the use of remote sensing allows a more complete understanding of the landscape units generating surface runoff. This more detailed spatial analysis improves the actual placement of individual dikes.



Fig. 6. Aerial photograph over the Jornada 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 following overland flow.

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 texture 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 installation of dikes. Clay, silty-clay, or silty loam soils are generally suitable soil types for water ponding dikes. Once the pond is formed behind a dike, it is important to have the water infiltrate into the soil and be stored in the soil moisture reservoir for plant uses. Water harvesting dikes also promote sediment deposition in the ponding area. Generally, this can result in increases of 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), if the mean annual rainfall is from 200-355 mm, the conditions are ideal for plant growth for rangelands using water ponding. If a large portion of the rainfall occurs in



convective rainfall 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 southwest U.S. as well as in the vast arid to semiarid regions of the world.

When completed, the actual water ponding dike should have a round rather than a V-shaped top because the rounded crest is less affected 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. Dike lengths at the Jornada ranged from 50-150 m (Rango et al., 2006).

Periodic maintenance to repair breaches in dikes is recommended (Stokes et al., 1954). For a variety of non-technical reasons, the Jornada 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.

The soil type where a stock pond is to be constructed should possess silt and clay components, if possible, because of the capability of these soil textures to be compacted to increase the stock pond bottoms resistance to infiltration. However, construction on sandy soils is even possible. The USDA Forest Service (1939) suggested a way to make stock pond bottoms more impervious without using fine grain soils or other construction techniques. Salt was placed on the dry bottoms of the stock ponds to attract cattle. In a short time, the cattle would trample the soil of the future pond bottom into a hard compact state, and the stock pond would be nearly water tight when filled.

At the Jornada, when the first of the CCC stock tanks was built, the construction was accomplished using both five teams of three horses each with one Fresno plow (see Figure 4) and one of the first motorized caterpillars (see Figure 5). Today earthen dams used to form stock ponds are constructed around the world using anything from modern earth moving equipment to a large number (133) of men and women working with handheld tools (Botts, 2009).

## 5. Discussion

### 5.1 Water ponding dikes

Figure 7 shows a temporal sequence of vegetation growth behind the a) Ace Tank dikes and b) the Taylor Well dikes at the Jornada. When records were being kept of ponding events behind the dikes (1978-1981), 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 events typical of the southwest U.S. These delayed responses are to be expected in dry regions whereas in more humid regions, the response times may be 1-2 years. A similar delayed response was detected by Peterson & 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 subsequent surveys 12 years later revealed that vegetation growth was substantially improved. In the arid Southwest, it will take longer for the characteristic rainfall events (high intensity but widely distributed storms) to occur in the vicinity of the collecting area for water ponding dikes and still longer for extensive vegetation growth to occur.



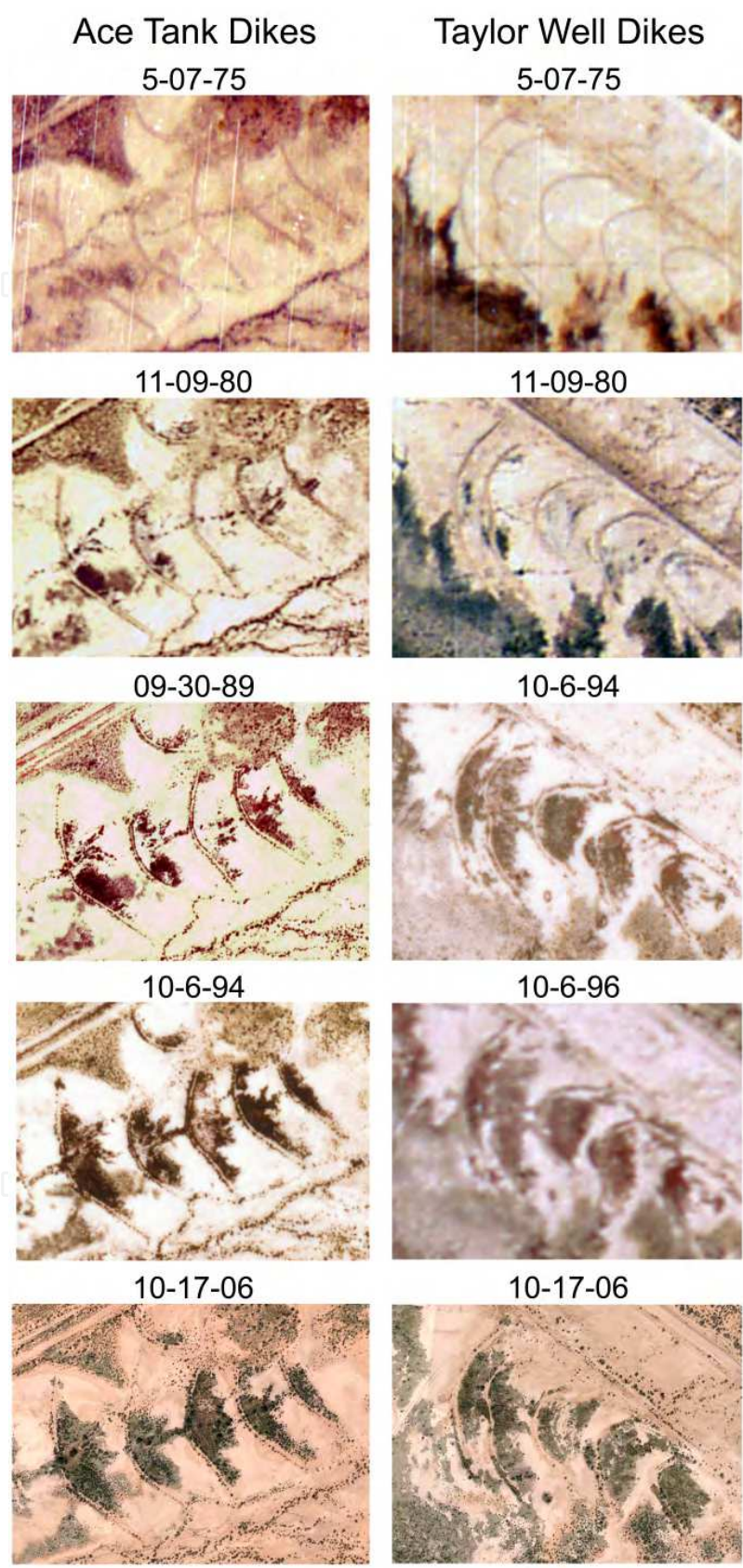


Fig. 7. A sequence of vegetation growth from construction in 1975 to 2006 using aerial photography for a) the Ace Tank dikes and b) the Taylor Well dikes at the Jornada.

Soil moisture was measured from the time of installation of the Jornada 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 similar for the Ace and Taylor dikes, the greater water ponding depth of Ace (due to the higher dikes) has produced a soil moisture profile difference. Figure 8 shows that 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).

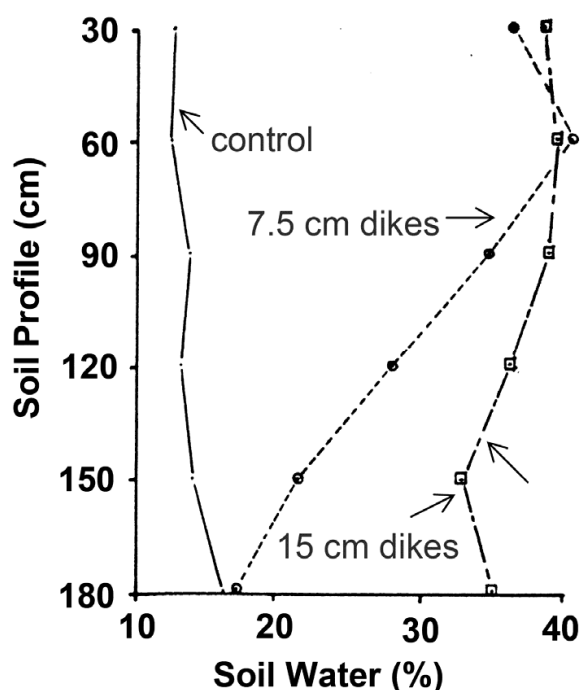


Fig. 8. Soil water profiles for control, 7.5-cm dikes, and 15-cm dikes on the Jornada Experimental Range on July, 1979 (from Tromble, 1982)

Associated with increases in soil moisture, Miller et al., (1969) have reported increased forage yields exceeding 1 ton/acre (2240 kg/ha) in response to water spreading treatments. Yields were reduced if water ponded without infiltrating for long periods of time. Branson (1956) reported 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 & Gardner (1950), experimenting in New Mexico, reported herbage yields increased by water spreading by 4-9 times and Hubbard & Smoliak (1953) reported herbage increases exceeding these yields. In the more recent water ponding experiments at the Jornada, Tromble (1984) reported that the 7.5 cm dikes resulted in a 2.4 - 6.0 fold increase in forage production over controls, depending on year and the location behind the dike. In all the water ponding or spreading experiments, it seems that increases in soil moisture and forage yield are consistent across the western U.S.

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 costs but less so about the benefits. Investigators generally state that the costs are out-weighed 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 (in U.S. \$, for 2010) associated with installation of dikes or spreaders. Generally, the cost of construction of water ponding dikes is less than construction of water spreaders. The dikes used in water spreaders by Hubbard and Smoliak (1953) and Monson & Quesenberry (1958) range from 1.5-2.5 ft. (46-76 cm) high, whereas dikes employed at the Jornada ranged from 3-12 in. (7.5-30 cm) high. In order to estimate the costs of the Jornada 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 [ $0.5 \times \$32.48 = \$16.24/\text{acre}$  ( $\$40.10/\text{ha}$ )] in U.S. dollars) because the Jornada [average dike height = 7 in (18cm)] required much less construction effort than the ones reported in Table 2. To estimate the cost of installing dikes over a much larger area, eleven pastures at the Jornada have been identified as potentially feasible for trapping and ponding surface runoff because of favorable soil type and evidence of overland flow after convective storms. About 20% of the area in those pastures would be treated or about 3,641 acres (1,473 ha). The cost for water ponding dike installation would be approximately \$59,000. Unfortunately, as with other analyses of the benefits and practices which can enhance goods and services from rangelands, we lack sufficient economic data for further cost/benefit calculations of the potential water ponding treatments.

Investigators	Cost/ acre (1 ac = 0.405 ha)		Benefit
	Cost When Installed	Converted to 2010 \$	
Mooney & Martin (1956)	\$6.70	\$53.13	% Increase hay
Hubbard & Smoliak (1953)	\$0.36	\$2.90	% Increase herbage
Monson & Quesenberry (1958)	\$1.38	\$10.29	% Increase herbage
Houston (1960)	\$2.35	\$17.10	Monetary increase of herbage/acre
Branson (1956)	\$9.96	\$78.99	Increased herbage/acre
Average		\$32.48	

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

5.2 Stock ponds

The number of stock ponds to be constructed depends upon the type of livestock to be grazed because of the distance that specific breeds of cattle typically graze away from a water source varies. For example, comparison studies using Global Positioning System (GPS) collars have shown that Mexican types and breeds of livestock such as the Criollo are willing to travel longer distances (5.8 km vs 2.2 km) from water than British breeds (Angus) when forage availability is limited. The Criollo will also travel to higher elevations than the Angus to seek out forage (Peinetti et al, 2011). Results from these studies indicate that the lighter, smaller Criollo breeds (~400 kg/animal) would probably be matched better than the



Angus breeds (~700 kg/animal) to the characteristics of desert rangelands (Peinetti et al, 2011). Designing stock water infrastructure for livestock breeds better suited to arid environments will result in reduced operational costs and reduced environmental impacts. For example, earlier studies by Herbel & Nelson (1966) found that Santa Gertudis cattle with a heritage from a hot, arid environment traveled 4.7 km a day further than Hereford breeds in search of forage. These cattle would seem to similarly disperse across the landscape like the Mexican breeds and reduce severe impacts around water sources as well as in areas with abundant forage.

When most of the stock ponds were constructed back in the 1930s at Jornada, a combination of manpower, horsepower, and mechanized vehicles were used (see Figures 4 and 5). The most usual stock tank is an earthen dam in a crescent shape that is constructed across an established drainage way. When original construction was done in 1934, the average time required for construction (with a crew of seven men, five Fresno teams of three horses each and one plow team) was two working days of eight hours each (USDA Forest Service, 1939). At that time the average cost of construction was \$90 per stock tank (\$1,450 in 2010). This value is considered to be on the low end of the range of construction costs because of the subsidized nature of using CCC labor. Construction costs in the same area of New Mexico before CCC labor was available averaged \$157 (\$2,529 in 2010) (Talbot, 1926). This was for a dirt tank that would store an average capacity of 220 m<sup>3</sup> of water. It is assumed that the same basic stock tank would be constructed today but with more modern earth moving equipment. The cost of the equipment would be higher, but the time for construction would be reduced. In 1935, the cost of drilling a deep well needed to yield this amount of water would be \$2,833 (\$44,524 in 2010 or more because the water table has continued to drop since the 1930s resulting in the need for deeper wells).

## 6. Conclusions

Water harvesting is a methodology that has been used for over 9 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 numerous positive results. It is possible that the technique may 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 effects of a growing population, increased pressure on existing groundwater supplies, 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 (sometimes delayed for years because of the type and distribution of rainfall experienced across an area) is enhanced. The advantages of water ponding dikes are that they are simple to install, cost effective, and make use of water that would be lost to evaporation.

The use of water ponding dikes also mimics nature in the way that banded vegetation is arranged on the landscape: bare soil producing surface runoff after a storm, vegetation



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

The use of stock tanks as water sources on rangeland for cattle grazing is a traditional method that has one of the least expensive construction costs amongst a variety of possible methods. In arid regions, it places reliance on trapping surface runoff that will otherwise be lost back into the atmosphere through evaporation. By confining this surface runoff in a pond with small surface area, and water depth of up to 2m, evaporation and infiltration losses are both reduced over what would normally occur if the water was spread out and infiltrated into a stream bed. The groundwater reservoir is not depleted until necessary, e.g., when severe drought years are encountered, and then well pumping would only be relied upon when the pond becomes dry.

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