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Factors Influencing the Spatial Variability of Runoff at Differing Scales in the Jornada Basin

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ABSTRACT—Factors that cause high spatial variability of water in arid regions include precipitation, soil, physiographic, and vegetation characteristics. The inherent heterogeneity of arid lands causes areas of runoff and run-on at the individual plant scale as well as in large area patterns of banded vegetation and beaded drainage networks where run-on and infiltration spur vegetation growth. To rehabilitate degraded rangeland, it is wise to mimic nature by diverting water to target areas to create islands of hydrologically enhanced productivity or by installing structures, such as water ponding dikes, to promote a landscape change to resemble natural vegetation patterns.

Note: This paper is an executive summary of the full length manuscript: Rango, A., S.L. Tartowski, A. Laliberte, J. Wainwright, and A. Parsons. 2006. Islands of hydrologically enhanced biotic productivity in natural and manged arid ecosystems. *Journal of Arid Environments* 65(2):235-252.

In order to produce runoff and areas of excess water, variations in atmospheric, land surface, and subsurface characteristics are necessary. Temporal and spatial discontinuities in precipitation must exist along with distinct boundaries and transition zones between soil, physiographic, and vegetation types that support discontinuous areas of increased vegetation production. Several investigators have documented the presence of "islands of fertility" or "resource islands" in the Chihuahuan Desert and other deserts (Schlesinger et al. 1990; Noy-Meir 1985).

In addition to the increased nutrient availability in "islands of fertility" or "resource islands," a low annual average precipitation requires certain hydrological discontinuities to promote enhanced vegetation production, whether it is shrub or grass growth. In this paper, we will refer to the availability of runoff water or excess water in certain areas as "islands of hydrologically enhanced productivity" and discuss how these hydrological islands can be produced. The presence of the resource islands and hydrological islands are not only observed in the Jornada Basin of southern New Mexico but are characteristic of other desert regions. Although resource islands occur only at the plant scale, the islands of hydrologically enhanced productivity occur at a range of scales.

Spatial Heterogeneity Characteristics Affecting Runoff Generation in Arid Regions—*Precipitation*—Various characteristics of precipitation interact with the infiltration rate of the soil to determine the amount of surface runoff that will occur. The precipitation characteristics that must be considered are amount, intensity, pattern and extent, type of storm event, duration, and seasonality. Thunderstorms in the Southwest are the primary runoff generators and are typically of short duration (1 to 2 hours), high intensity (up to 250 mm/h for 5 minutes is common), and over a very limited areal extent (Renard 1988).

Precipitation characteristics are the determining factors in generating runoff but additional factors affect the runoff after it is generated. Because the desert environment is so dry and precipitation so spotty, runoff generated at a site can become run-on for a nearby site that may not have received any precipitation at all. The hydrological effects of the run-on process are very important in the vegetative productivity and landscape function of desert regions (Tongway and Ludwig 2001).

Evapotranspiration—Evaporation from a free water surface in the Jornada Basin, as recorded by an evaporation pan, averages about 246 cm/y or about 10 times the average annual precipitation (Gile and Grossman 1979). The average annual potential evapotranspiration in the south-central New Mexico part of the Chihuahuan Desert is about 169 cm/y or about seven times the average annual precipitation (Whitford 2002). This great discrepancy between available water (free-standing and in the soil) and available energy assures that any excess water is quickly depleted by evaporative processes.

Soils—In the Southwest, soil formations reflect the persistent absence of moisture. Infiltration rates are controlled by soil type, but overall the rate and amount of infiltration is low (Renard 1988). The low infiltration amounts are due to short periods of precipitation, relatively shallow soil depths that limit the soil reservoir, the common occurrence of impervious caliche layers, and presence of impeding layers like surface crusts (Renard 1988). One underlying soil property in arid regions that affects runoff is the generally large percentage of bare soil (from about 65 to 90% or more). The infiltration rate of bare soil is much less than the same soil covered by vegetation, thus increasing surface runoff (Schlesinger et al. 1999).

Physiography—In many arid regions, the topography is dominated by rolling hills or outwash from mountain systems. In many of these arid regions, land gradients are steep and slopes can commonly exceed 50% (Renard 1988). A large amount of surface runoff can be produced in the areas near the mountains, for example, along the eastern flank of the Jornada Basin and, at times, along the southwestern part of the basin. This can be significant because precipitation is increased in these same areas because of orographic lifting.

It is not unusual to see large flows in channels be completely lost through infiltration in a reach of less than (16 km) (Branson et al. 1981). Sediment yields are very high in these arid regions with a maximum occurring at about 300 mm annual precipitation (Langbein and Schumm 1958) putting the Jornada Basin near the peak in sediment production.

Vegetation—Associated with precipitation, evapotranspiration, soils, and physiography are various vegetation characteristics that influence the generation of runoff. Vegetation type, canopy areal cover, and canopy structure all determine the amount of water that can be lost to the atmosphere through the leaf stomata in the various seasons. This vegetative loss in turn influences the moisture remaining in the soil which influences the infiltration rate and the amount of surface runoff to be generated. Old vegetation root channels and other macropores can be a cause of increased infiltration as they can serve as large voids that can rapidly transport water from the soil surface to depth faster than the normal infiltration-percolation process.

ISLANDS OF HYDROLOGICALLY ENHANCED PRODUCTIVITY AT DIFFERENT SCALES ON THE LANDSCAPE—*Plant Scale*—On the scale of individual plants, the hydrological islands are similar to the previously mentioned resource islands. For the individual plant, interception of precipitation reduces raindrop impact of the soil surface and promotes throughfall and stemflow. When the intercepted water retained in the plant canopy is evaporated, soil moisture is conserved as the energy is used for evaporation and not transpiration. Infiltration rates are greater under the plant canopy, allowing more water to enter the soil. Although the greater amount of evapotranspiration occurring over plants as compared to over bare soil reduces the soil moisture reservoir beneath the plant, the plant root system can exploit soil moisture available in the plant interspaces (bare areas). At this plant scale the resource islands and the hydrologic islands co-occur and are complementary to each other.

Rainfall intensity is reduced and controlled by the density of the vegetation canopy and results in an enrichment of the coincident hydrologically-enhanced islands and resource islands. The enrichment results from (1) a slower rate of soil surface sealing under shrubs than in adjacent intershrub areas, and (2) a greater plant litter accumulation under shrubs. Both effects promote infiltration and enhance moisture status under the shrub canopy while the increased litter enriches the under-canopy nutrient level (Abrahams et al. 2006).

Medium-to-Large Patches—Once one moves from the individual plant or small patch scale to medium-to-large patch scale, it is necessary to consider how the plant-bare soil complex pattern relates to runoff generation and vegetation production. Across the Jornada Basin the maximum area of the surface covered by vegetation that we have observed with remote sensing data is about 35%, except in very small areas such as playettes. Because we are considering an interrelated matrix of vegetation and bare soil, the concept of runoff/run-on must be considered. Where precipitation intensity exceeds the infiltration rate (both of which will vary during a storm event), excess water initially fills surface depressions and then flows downslope over the ground surface. For the same precipitation intensity, more surface runoff is generated in bare interspaces than under shrub (or grass) cover for reasons previously stated. About 65 to 90% of the vegetation-bare soil matrix is producing increased runoff while the 10 to 35% of the matrix covered by vegetation is producing less runoff during a storm event. The results of experiments over the bajada indicate that the most important control of water yield is the proportion of the soil surface covered by plant matter (ground vegetation or litter) (Abrahams et al. 2006). As a result, more runoff is produced as vegetation interspaces or bare areas increase. The main reason that bare areas produce so much runoff is that their soils are susceptible to the development of physical crusts (Greene et al. 2001). When compared to grassland measurements at Jornada, shrubland produces more frequent and larger runoff events. Investigations have shown that the mean runoff coefficients for grassland and shrubland are 6% and 19%, respectively (Abrahams et al. 2006).

At the Jornada Experimental Range (JER) approximately 92% of the 783 km^2 is now dominated by shrubland. Therefore, the runoff generation processes active in these shrubland areas are dominant on the JER. Runoff produced becomes run-on for areas downslope from the runoff-producing area. If the runoff reaches a rill system or a stream channel then, as in other parts of the Southwest, infiltration into the bed of the channel is common and the increase in soil moisture causes a type of riparian vegetation to grow along the channel. When something obstructs the surface runoff from reaching the channel or even after the water reaches the channel, a hydrologic discontinuity results by slowing down the surface runoff allowing more time for infiltration.

A common obstruction to the surface runoff (in some cases a homogenous sheet flow rather than flow in distinct channels) is vegetation. The vegetation slows the runoff and allows the water to infiltrate while, at the same time, any sediment being carried is deposited, thus allowing a small increase in elevation enhancing the vegetation barrier. The vegetation barrier can consist of herbaceous plants followed by woody plants in a band (Greene et al. 2001). As viewed from above, a relatively bare band where the surface runoff is generated is followed by a vegetation band where the run-on infiltrates into the soil. The vegetation bands are essentially the islands of hydrologically-enhanced productivity.

Where surface runoff has made its way into small channels in the Jornada Basin, the water can often discharge into sinks in upland areas. These areas are small playas, or playettes, and can occur in clusters across the landscape. Because of the increase in soil moisture in these playettes, vegetative ground cover can approach 100%, similar to ground cover amounts in the vegetated bands.

Catchment Scale—Although the Jornada Basin is a closed drainage, there are several features at the catchment scale related to hydrologic discontinuities. One feature is the way ephemeral stream channels are organized on the bajada slopes leading from the mountains to the valley bottoms. At the top of the bajada slope runoff/run-on is due to infiltration-excess precipitation and from sandbedded streams issuing onto the head of the bajada from the mountains. The smaller streams terminate near the top of the bajada, the larger ones survive to the lower part of the bajada. These larger streams have alternating single-channel and multichannel reaches. At times, the multichannel reaches are replaced by reaches with no clearly defined channelized flow that are termed beads because they are reminiscent of beads spaced out along a necklace (Fig. 1). At the downstream end of a bead the flow coalesces into a single channel as a result of a concentration of excess runoff downslope of the bead (Abrahams et al. 2006). The beads appear to be important sinks for water on the bajada.

Rehabilitation of Degraded Rangeland—It seems that in order to rehabilitate rangelands it would be wise to mimic nature when water is one of the key factors in the rehabilitation. Various types of structural features have been employed to change the flow of water over the surface with only a few providing positive results. Additionally, the use of impoundments to store water might eventually be used to produce an effect similar to beaded drainage networks if this pattern proves to be desirable.

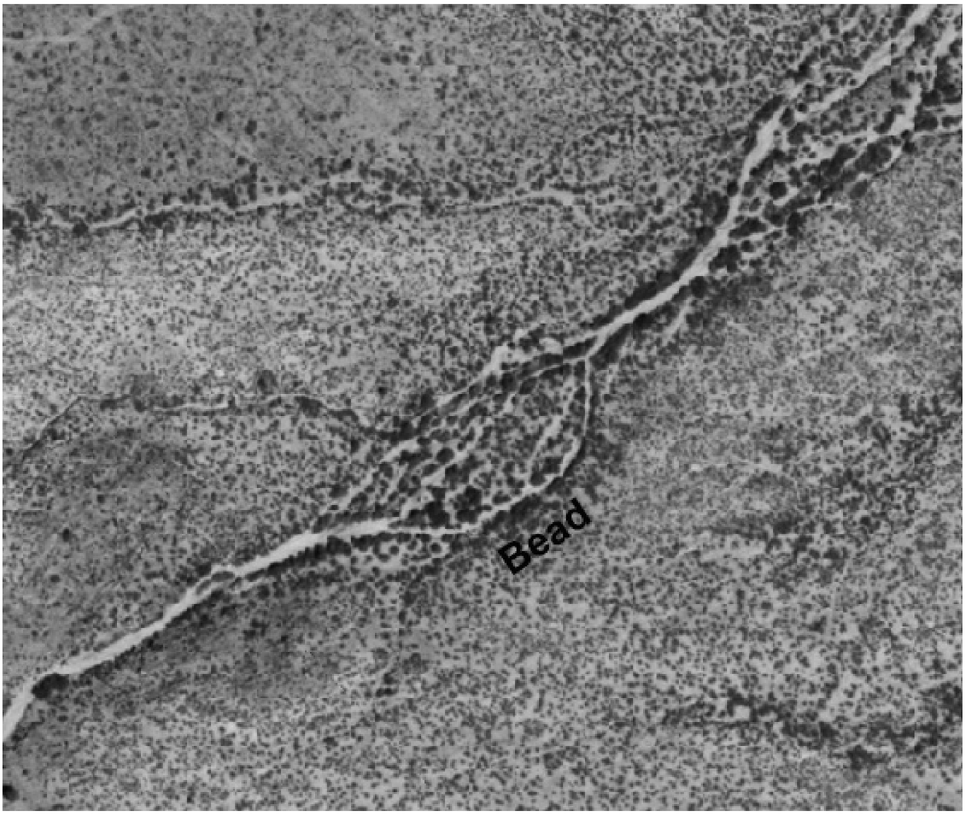

FIG. 1—Channel and bead drainage networks on the Summerford Mountain bajada slope on the Chihuahuan Desert Rangeland Research Center in the Jornada Basin as imaged by QuickBird on 27 September 2003.

Water ponding (or retention) dikes have been used on arid and semiarid rangelands to slow surface runoff, reduce soil erosion, increase soil moisture, and increase forage production. Experiments with the water ponding dikes have indicated that they work most efficiently on medium and fine-textured soils rather than on coarse-textured soils in areas with annual precipitation exceeding 200 mm and in areas with sufficient rainfall intensities leading to significant overland flow.

Dikes laid out on the JER were of a relatively simple construction and inexpensive to install. The water ponding dikes installed from 1975 to 1981 were of three heights: 7.5 cm, 15 cm, and 30 cm. The dikes were designed to be crescent shaped so that any excess water would overflow around the end of the dikes. With no maintenance, however, breaches in the dikes have developed and water flows through the breaches and around the dikes. In the mid-1980s, the dikes were left unattended due to retirement of the principal investigator and not maintained because of lack of manpower. It was

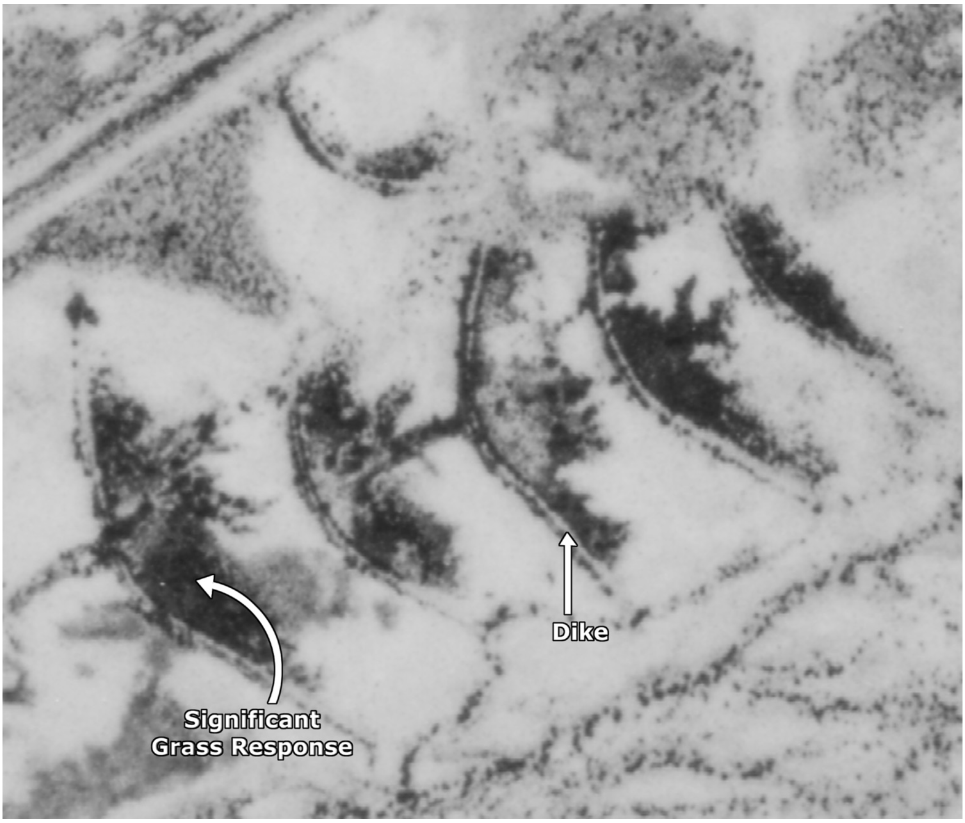

FIG. 2—Aerial photograph of water ponding dikes established in 1975 on the Jornada Experimental Range near Ace Tank. This 1994 photo indicates a positive response to treatment.

not until the late 1990s that interest in the dikes was revived and analysis of historical aerial photos and field measurements were initiated.

When the dike measurements were terminated in the mid-1980s some positive results were already evident for the Taylor Well and Ace Tank dikes. On average, four times the forage was available behind the 7.5-cm dikes compared to the control areas (Tromble 1984). An important limiting factor for forage production is a lack of available soil water. The effectiveness of 7.5-cm and 15-cm, water-ponding dikes for increasing available soil water was also investigated by Tromble (1982). The 7.5-cm dikes showed increased soil water near the surface and then slowly decreasing down to 180 cm. The 15 cm dikes had nearly uniform increased soil water down to 180 cm (Tromble 1982).

Fig. 2 shows a 1994 aerial photograph of the 15-cm Ace Tank dikes indicating a positive vegetation response to treatment. It is interesting to note that a very similar response was found on the 30 cm Dona Ana dikes, despite the fact that they were constructed in medium- to coarse-textured soils. Additionally, the pattern of dike vegetation is similar to naturally occurring banded vegetation where slight increases in elevation due to vegetation and sediment deposition cause runoff water to infiltrate. It seems that significant rainfall events producing surface runoff are necessary in order for a positive vegetation response. One may have to wait several years before these events occur in an arid environment.

Conclusions—In order to produce any significant surface runoff in areas of the Southwest, like the Jornada Basin, there needs to be variability in atmospheric, landscape, surface, and subsurface variables and parameters. Generally, by slowing down surface runoff, water will infiltrate into the soil and vegetation productivity will be increased. These areas of hydrologically enhanced productivity occur at all scales from the plant to the basin. At the plant scale, islands of fertility and islands of hydrologically enhanced productivity coincide, particularly the areas under shrubs. Vegetation bands (and bare areas) occurring at the medium-to-large patch scale have alternating areas of runoff production and infiltration. Larger catchments sometimes feature a beaded drainage network related to hydrologic discontinuities as well as sinks for water to accumulate in, such as playettes and playas. In order to rehabilitate rangelands it is wise to mimic the natural processes by providing time for surface runoff to infiltrate, thereby creating areas of potentially high vegetation productivity. The most successful treatments so far have been water-ponding dikes. These results pertain to not only deserts of the Southwest, but also to worldwide arid and semiarid regions.

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