Quest For The Perfect Cap: The Prototype Hanford Barrier 15 Years Later-10419

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ABSTRACT

Engineered surface barriers are recognized as a remedial alternative to the removal, treatment and disposal of near-surface contaminants at a variety of waste sites within the DOE complex. One outstanding issue that has impacted stakeholder acceptance of this technology is the limited amount of performance data and the uncertainty in using them to predict long-term performance. In 1994, a 2-ha multi-component barrier was constructed over an existing waste disposal site using natural materials. The 4.5-m thick barrier includes a 1-m thick silt loam surface layer with 15% pea gravel to control erosion as well as a capillary break, an asphaltic concrete layer at the base, and two protective side-slope configurations. The cover was designed to meet a 0.5 mm/yr drainage criterion and is instrumented to monitor stability as well water balance components. A treatability test conducted from 1994-1998 included irrigation at a rate of 480 mm/yr including a simulated 1000-yr return storm each March, in which 68 mm of water was applied over an 8 hr period. Monitoring has been almost continuous for the last 15 yrs and has focused on barrier stability, vegetative cover, evidence of plant and animal intrusion, and the main components of the water balance, including precipitation, runoff, storage, drainage, and deep percolation. The total precipitation received from October 1994 through August 2008 was 3311 mm on the northern half (formerly irrigated), and 2638 mm on the southern, non-irrigated half. Water storage in the fine-soil layer shows a cyclic pattern, increasing in the winter and decreasing in the spring and summer to a lower limit of around 100 mm, regardless of precipitation, in response to evapotranspiration. The functional portion of the barrier and its side slopes are structurally stable. Over the 15 years, only three runoff events have been observed but the 600-mm design storage capacity has never been exceeded. Total percolation ranged from near zero amounts under the soil-covered plots to over 600 mm under the side slopes but an asphalt layer prevented any of this water from reaching the buried waste. A relatively high ground cover of native plants still persists after the initial revegetation although the number of species decreased from 35 in 1994 to 15 in 2009. The vegetative cover, in addition to the silt-loam-gravel admix, proved effective in minimizing erosion but a recent removal of vegetation from the north half resulted in significant soil movement. There is ample evidence of insect and small mammal use suggesting that the barrier is beginning to function like a recovering ecosystem. These data have proven useful in the development of more rigorous methods for evaluating long-term performance and quantifying associated risk and uncertainty using numerical models.

INTRODUCTION

Engineered surface barriers are an integral component of DOE's waste management strategy serving as a remedial alternative to the removal, treatment and disposal of near-surface contaminants at a variety of waste sites [1]. Over 200 barriers, with functional lives of 500 to 1000 yrs, are needed to remediate a variety of waste sites at Hanford alone [2]. Selecting the most appropriate design is therefore an important consideration. Barrier designs generally fall into two categories: (i) resistive, which are low-permeability structures that divert water away from the underlying waste, and (ii) capacitive or store-and-release covers ranging from monofill soil layers to multilayered designs incorporating capillary breaks. Evapotranspiration covers and multilayered designs with a vegetated evapotranspirative surface layer have proven to be effective alternatives in arid and semiarid climates [3]. However, the basis for selecting a particular barrier design and its constituents is still based on one of two approaches: (i) the use of numerical models, or (ii) expert judgment based on laboratory, lysimeter, and field tests [3].

Either approach requires high-quality, long-term data sets for validation. However, engineered barriers have not been in existence long enough to allow assessment of performance for the typical design lives. Furthermore, much of the available data have been derived from groundwater monitoring down-gradient of barriers rather than direct monitoring of the barriers themselves. Consequently, there is some uncertainty in selecting the optimal design of the functional barrier and this limits the ability to predict barrier performance beyond the accumulated knowledge of controlled tests. In addition to the functional portion, above-grade barriers must include side slopes to protect the functional portion from erosive forces. Although side slopes can occupy 30-70% of foot print of above-grade covers, no consistent design or practice exists for their construction and there is paucity of performance data. Increasing stakeholder acceptance of barrier technology requires demonstration of barrier longevity and the assurance of adequate performance over the design life. Implicit in the demonstration of adequate performance is an assumption of the necessity and sufficiency of performance testing.

In August 1994, a prototype Hanford barrier, a multilayered capillary barrier with an evapotranspiration surface layer, was constructed over the 216 B-57 liquid-waste disposal crib in Hanford's 200 East Area. This crib received in-tank solidification condensates that were low-level radioactive wastes from the 241-BY Tank Farm between February 1968 and June 1973. The barrier covers an area of 2.5 ha (6.2 acre) and was designed with objectives that included the ability to: 1) limit recharge to 0.5 mm/yr (1.6×10^{-9} cm/s); 2) be maintenance-free, 3) resist plant animal and human intrusion, 4) limit the exhalation of noxious gases, 5) minimize erosion, 6) meet or exceed RCRA cover-performance requirements, 7) be accepted by regulators and the public, and 8) isolate wastes for at least 1,000 years [4,5]. The barrier has been monitored almost continuously for the last 15 years to document structural stability, erosion, and components of the water balance including precipitation, surface runoff, water storage, percolation out of the root zone, and evapotranspiration. Ecological processes have also been monitored to document vegetation dynamics including plant floristics, ground cover by plant species, and indices of animal use. A treatability test conducted from 1994-1998 irrigated the north half at a rate of 480 mm/yr and included a simulated 1000-yr return storm each March in which 68 mm of water was applied over an 8 hr period. In September 2008, one half of the barrier was burned to gain an improved understanding of the response of engineered ecosystems to wild fire [1,6,7].

This paper provides a summary of performance data collected over the last 15 years to document barrier stability, hydrologic performance, and vegetation dynamics. The data set is unique owing to the length of the record and it being the only documented study of protective side slope performance. These data clearly show well-designed surface barriers can limit recharge to near zero amounts.

MATERIALS AND METHODS

Physical Setting

The prototype barrier is in 200 East central plateau of the Hanford Site in semiarid southcentral Washington State. The long-term average (LTA) annual precipitation from 1946 to the present is 6.85 in (174 mm) with almost half occurring in the winter (November through February). Temperature ranges from as low as -23 °F in the winter to as high as 113 °F in the summer. Actual evapotranspiration (AET) ranges from 4.4 in. (111 mm) to 6.3 in. (159 mm) whereas potential evapotranspiration (PET) ranges from 29.5 in. (750 mm) to 54.7 in. (1390 mm). The thick vadose zone on the central plateau (> 300 ft [100 m]) is comprised mostly of coarse glaciofluvial sediments ranging from loamy sand to sandy loam. The relatively deep vadose zone and the difference between AET and PET make this site ideal for use of engineered barriers for waste isolation.

The Prototype Hanford Barrier

The prototype barrier is similar in concept to the RCRA subtitle C design and consists of a 2-m thick silt-loam layer overlying other, coarser materials including sand, gravel, and basalt riprap with each layer serving a distinct purpose (Fig. 1). The silt-loam layer acts as a medium in which moisture is stored until the processes of evaporation and transpiration recycle any excess water back to the atmosphere [6,7]. The design storage capacity, the amount of water that can be stored before drainage occurs, is 600 mm (23.6 in) which is over three times the LTA precipitation for the site. The silt loam also provides a medium for establishing vegetation, which is necessary to recycle water to the atmosphere. In addition, the top 1 m (3.3 ft) of silt loam was amended with 15% by weight of pea gravel as a guard against erosion. The entire silt-loam layer is a medium for plant growth and therefore forms the evapotranspiration layer. Coarser materials (sand overlying gravel) placed directly below the silt-loam layer create a capillary break that inhibits the downward percolation of water through the silt and prevents fine soil from migrating into the coarser layers. The basalt riprap layer is intended to act as a biointrusion layer to deter root penetration, animal burrowing, and inadvertent human intrusion. An asphalt layer at the base of the barrier provides redundancy in infiltration and biointrusion control. The entire barrier was constructed with a 2% slope to promote movement of water towards the edges. Side slopes are required for above-grade barriers to protect the functional portion from erosion and collapse but have received little attention in barrier studies. The prototype barrier is unique in its incorporation of two side-slope configurations for evaluation of stability and hydrologic performance (Fig. 2).

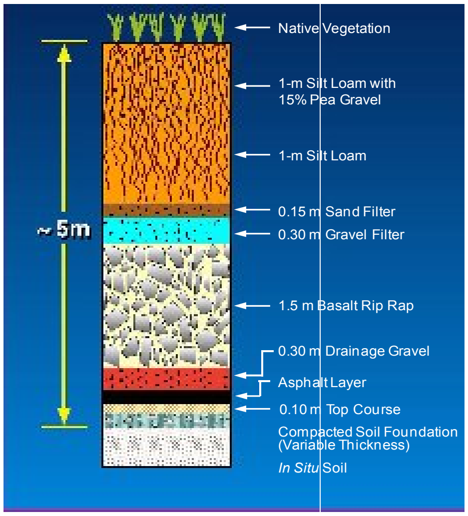


Fig. 1. Cross section of Prototype Hanford Barrier.

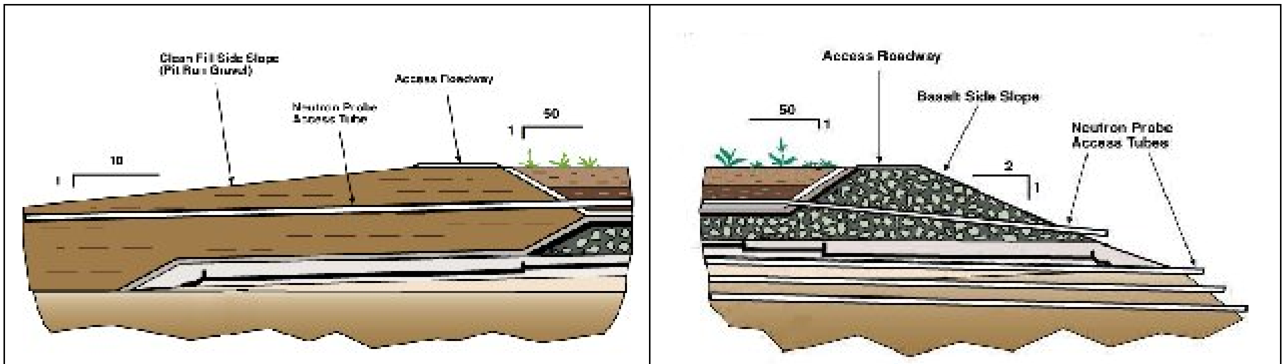


Fig. 2. Cross Section of the Two Side Slope Configurations, (a) west side pit run gravel with a 10:1 slope, and (b) east site fractured basalt riprap with a 2:1 slope.

The side slope on the east side of the barrier, which is constructed of 25-cm fractured basalt riprap, has a 2:1 (H:V) slope and occupies the smaller footprint. The side slope on the west side is constructed of pit run gravel with a 10:1 slope and occupies the larger footprint. Both side slopes are underlain by the asphalt layer and have drainage systems connected to the siphon monitors to record drainage.

Site Vegetation

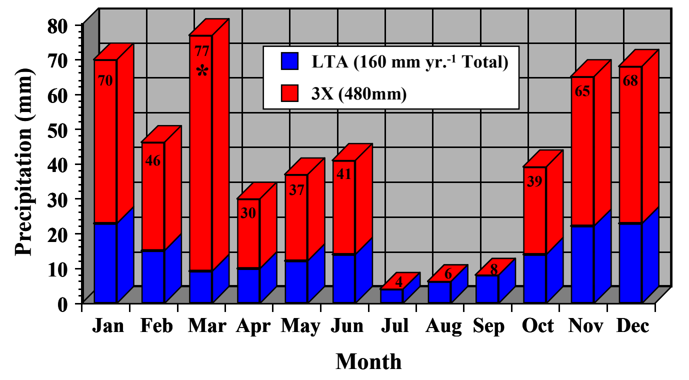
The native vegetation at the site prior to construction of the barrier was a mix of *Artemisia tridentata* (sagebrush), *Ericameria nauseosa* (gray rabbitbrush), and *Poa secunda* (Sandberg's bluegrass). The silt loam used to construct the barrier was obtained from the McGee Ranch where the vegetation is mostly shrubs (22%), with *A. tridentata* being dominant and grass (23%) with *Poa secunda* accounting for 15.4%. Following construction of the barrier, the surface was vegetated with a mixture of shrubs (*A. tridentata* and *E. nauseosa*) and grasses including *Agropyron dasystacyum* (thickspike wheatgrass), *Hesperostipa comata* (needle and thread grass), *Elymus elymoides* (squirreltail), *Elymus wawawaiensis* (Snake River wheatgrass), *Poa secunda* (Sandberg's bluegrass), and *Poa ampla* (Sherman big blue grass).

Performance Monitoring and Testing

The barrier is instrumented for monitoring structural stability, components of the water balance including precipitation, runoff, water storage, and percolation out of the root zone. Structural stability of the functional portion is monitored using elevation measurements on the surface and at two subsidence monitors anchored to the asphalt layer. One subsidence monitor, DSG1, is located near the crown of the barrier whereas the second, DSG 2, is located 14 m to the east. Stability of the side slopes is measured using a set of 14 creep gauges. Each of 14 monitoring stations is equipped with aluminum and PVC access tubes for measuring water content with neutron hydroprobe and capacitance probes, respectively. Independent automated water content measurements are made with vertically installed shorting-diode time domain reflectometry (TDR) probes. Matric potential and soil temperature are measured by heat dissipation units (HDUs). Percolation is monitored using a system of 12 concrete vaults located to the north and down-gradient from the asphalt layer where water is collected by gravity flow and the hydrograph recorded automatically using tipping buckets and pressure transducers [1,2]. Monitoring of deep percolation is facilitated by a 6.5 m × 6.5 m pan lysimeter installed under the northeast section of the asphalt layer [1,2]. A set of horizontally installed, 10-cm diameter aluminum access tubes facilitate monitoring of water content at the capillary break (1.95 m deep) and beneath the asphalt layer (1-, 2-, and 3-m depths) by neutron hydroprobe. Surface runoff from a 6.1 m-wide by 15.2 m-long runoff plot located in the northwest section of the barrier is monitored using a v-notch flume connected to automated water and sediment sampler. Evidence of erosion was derived from erosion pin measurements and from any sediment collected from the runoff plot. During the treatability test, dust traps on the surface were used to measure wind-blown sediment moving onto and the surface. Over the last 15 years, changes in the surface layer composition resulting from deflationary and inflationary processes have been documented by measuring the particle size distribution.

As part of a CERCLA treatability test, the north half of the barrier was irrigated from November 1994 through October 1997 to document performance under the stress of elevated precipitation [8]. The temporal distribution of irrigation water mimicked the distribution of the long-term annual precipitation for each month (Fig. 3). During this test, the south half received ambient precipitation only. Wind erosion monitoring also occurred during the treatability test and focused on wind characteristics, surface and near-surface gravel composition, surface layer deflation/inflation, saltation stresses, and sand drift rates. Since completion of the treatability test, performance monitoring has focused on stability, water balance, and vegetation dynamics.

Vegetation dynamics and ecological processes have been routinely monitored over the last 15 years. Measurements of plant species composition, including the occurrence of soil cryptograms, have been determined for the entire



*Simulated 1,000-yr. storm (68 mm in 8 hrs.)

Fig. 3. Distribution of Long-term Average Natural Precipitation and Irrigation Used During the Treatability Test.

barrier including the north and west side-slopes. Over the years, the occurrence and density of the dominant shrubs *A. tridentata* and *E. nauseosa*, have been determined by counting the number of shrubs in three age classes (new seedlings, midsize young, and old large). In addition, shrub height, greatest canopy diameter, and the diameter at the center of the plant perpendicular to the greatest diameter have been routinely measured on 25 shrubs each from the north and south sections of the barrier. Ground cover of grass, shrubs, forbs, litter, soil, and soil cryptogams have also documented on the functional portion of the barrier and the side-slopes by visual inspection according to Daubenmire [9]. Periodic measurements of leaf area index (LAI) have been made using an AccuPAR LP80 Ceptometer. Periodic measurements of pre-dawn xylem pressure potential have also been made with a Model 1005 pressure chamber instrument (PMS Instruments) on *A. tridentata*, *S. kali*, and *M. officinalis*. The barrier surface has been routinely examined for evidence of use and intrusion by insects and small mammals. Evidence sought included direct observation as well as the presence of droppings, tracks, nests, burrows, holes, and resting spots with gall formation on *A. tridentate* being indicative of insect use. Surveys for typically collected by careful inspection of a subset of 300 sample squares on the surface and in 2008 included the use of small mammal traps to allow identification of vertebrates.

RESULTS AND DISCUSSION

Barrier Stability

Fig. 4a summarizes the settlement gauge elevation between November 1994 and September 2009. Changes in elevation, Δz, were mostly within the range of measurement error of the instrument and there is no apparent trend. The large Δz in elevation in 2004 is due to a change in survey methods. Subsequent Δz are within the range of earlier measurements. However, some caution is needed in data interpretation as the sub-grade response data to distributed loads over large areas is generally a complex problem. The near-surface soils at the site are sands of fluvial and eolian origin which do not characteristically exhibit significant expansion or compression behavior. Proper compaction during construction would have eliminated the potential for settlement but some compression could be expected as the asphalt was loaded with barrier materials. The first measurements were taken in December 1994, after the placement of barrier materials, so it is likely that our measurements missed settlement that might have taken place. Nonetheless, these results show a stable barrier system after loading.

Fig. 4b is a polar plot of the resultant of changes in the x,y coordinates (r) as a function of angle for each creep gauge on the 2:1 riprap slope from 1994 to 2009. Immediately after construction, all gauges would have been located the center of the plot (r =0 m). Movement from year to year measurements appear quite random but over the 15-yr period. Overall, movement is mostly in an easterly direction with horizontal displacement ranging from 0.031 to 0.098 m and a mean of 0.056 ± 0.016 m with a mean orientation of 6.84 ± 1.29 radians. Elevations changes ranged from -0.06 m to 0.010 m with a mean of -0.012 ± 0.02 m. There small changes are not indicative of slope failure but do suggest some settlement of the riprap slope.

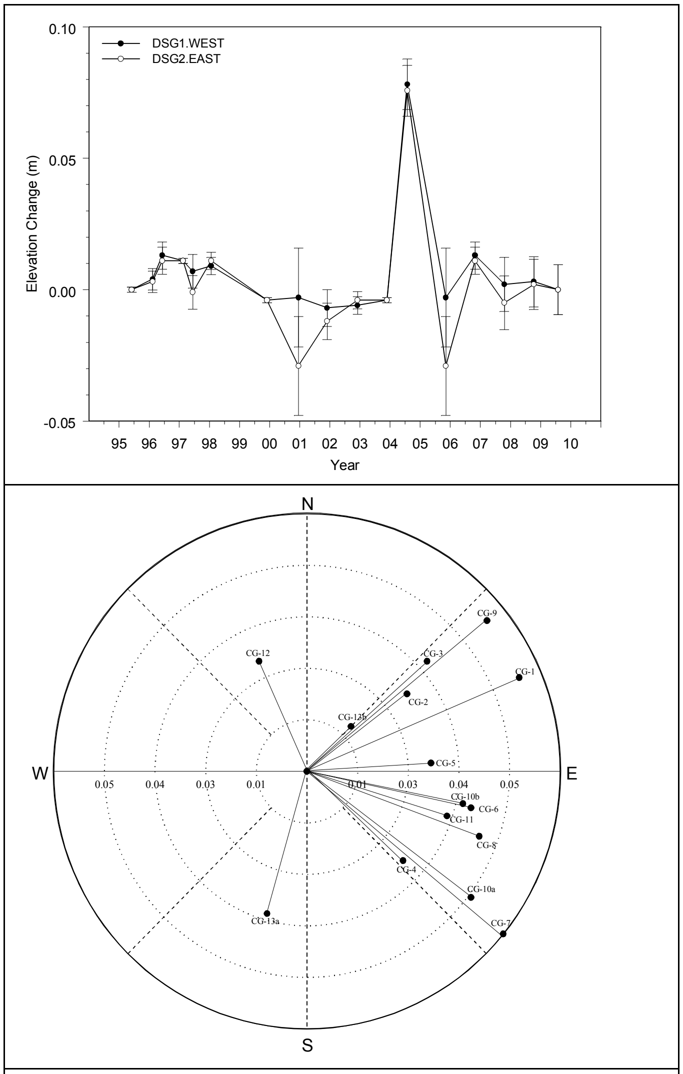


Fig. 4. Summary of Stability Measurements from 1994 through 2009, (a) settlement on functional portion, and (b) creep on riprap side slope.

Erosion

As part of the treatability test, the barrier was monitored to document the effects of water and wind erosion stresses on the silt-loam surface [8]. During the first simulated 1,000-year storm, runoff occurred in increasing amounts after 5 hr of irrigation with a total of 1.79 ± 0.11 mm being collected [10]. In the same runoff event, peak sediment collection was 7 g L^{-1} and decreased over time to 1 g L^{-1} by the end of the test. Field tests at Hanford show that unprotected silt loam is very susceptible to rain-splash erosion as it does not contain enough coarse material to initiate the development of surface armor [11]. Use of a gravel admix on unvegetated silt loam reduced, but did not eliminate, erosion [11]. After the first runoff event, none was observed until January 1997 when a combination of rain and snowmelt on a frozen surface-soil led to sporadic runoff events but without soil loss. This is consistent with the findings of Gilmore [11 who showed that a silt-loam-gravel admix, combined with a vegetative cover, such as used on the prototype barrier, can reduce sediment yields by a factor of 10 to 100. The only other runoff event from the original surface occurred in the winter of 1997 when Chinook winds on frozen soil resulted in 36.3 mm of runoff but there was no sediment loss as the surface was now vegetated. In January 2009, 4 months after the north half of the barrier was burnt as a part of a study of the effects of fire on barrier performance, 1.45 L (0.016 mm) of runoff was recorded from the burnt section [7]. Sediment yield was only 2.2 gm with a d_{50} of 0.085 mm. The yield of water and sediment, though quite small in comparison to previous events, are the first observed in 13 years and can be attributed directly to the effects of the fire, particularly the loss of the vegetative cover and an increase in hydrophobicity [12].

The response of the surface to aeolian stresses was monitored only during the treatability test with soil loss measurements limited to the first year [8]. Wind speeds on the elevated surface averaged about 20% higher than at ground level. The exposed, elevated, surface is therefore subjected to greater erosive stresses than the surrounding natural environment and quantifying the near-surface gravel composition provided insight into the inflationary and deflationary stresses. The only measurable loss of soil by wind occurred during the first 3 months when the surface was bare with estimates ranging from 7.4 to 744 mg/m^2. This loss of fine soil was sufficient to initiate the formation of gravel armor in some places, which coupled with establishment of vegetation on the surface, essentially eliminated further soil loss. Gravel content in the 0-2 cm layer initially decreased, especially during first 3 years of monitoring. Mean gravel content for the entire barrier in 1994 was 16.2 ± 3.0%; the 16.9 ± 4.0% on the irrigated side was not significantly different (α=0.05) from the 15.5 ± 1.0% on the non-irrigated. At the end of the treatability test in 1997, mean gravel content for the entire barrier was 13.4 ± 2.0%, a significant (α=0.05) decline from the

1994 value. After 15-years, mean gravel content in the 0-2 cm layer is now 20 ± 5.18%, which is significantly higher (α=0.05) than the mean content in 1994 and 1997. There was no significant difference (α=0.05) between the post-burn mean on the north half (21.8 ± 5.6%) and the pre-burn mean (20.8 ± 4.3%). Such large changes during a time when the surface was vegetated may be partly due to disturbance of the soil fabric by plant and animal activities as well as freeze-thaw cycles. Erosion pin measurements show clear evidence of soil movement, particularly after the burn. The greatest deflationary pressures were observed in the northwest through the center of the burned area with a maximum loss of 13.5 mm. Evidence of inflation greatest on the east side of the burned area with surface a maximum accumulation of 18.5 mm of soil. These changes are due to localized redistribution of soil from the burned area. Overall, the relatively small amount of soil loss from the surface is evidence that the prototype has performed according to design specifications.

Water Balance

Precipitation

For the period October 1994 through September 30, 2009 the prototype received a total of 3312.9 mm of water, of which 2640 mm came from natural precipitation and 672.87 mm came from irrigation during the treatability test. For the same period, seasonal distribution of precipitation has shown significant variability. The highest winter precipitation for the monitoring period, 138.4 mm, was observed in 1997 and over four times the low of 34 mm recorded in the winter of 2005 and some 211% of normal. Total precipitation has shown a general decrease from 1994 through 2009. A similar trend is obvious in the winter, except for 2003 and 2004, and spring although summer precipitation has been more erratic [13]. Seasonal variations in precipitation are important when evaluating cover performance and must be taken into consideration when selecting candidate barrier designs as composite and ET barriers are typically designed to store the expected winter precipitation.

Soil Water Storage

Fig. 5 compares the mean storage (*W*) on the north and south sections of the barrier. These plots represent the average of storage measured at 6 locations in each section, each at a different slope position on the silt-loam surface. Both sides show a well-defined annual cycle in *W* for the duration of monitoring. The temporal patterns in storage on the north and south sections of the barrier are similar but amplitudes in storage are very different, especially during the treatability test. The break in the water storage record observed from September 30, 1998 through May 05, 2000 was due to a hiatus in monitoring. Another break in the record occurred from December 08, 2004 through September 09, 2005 and no water storage data were recorded. The most striking observation is the elevated water storage on the north side between 1994 and 1999. The north half of the barrier was irrigated at a rate 480 mm/yr, three times the long-term annual precipitation for Hanford, 1994 through 1997 as part of a 3-yr CERCLA treatability test and showed the largest values of storage during this period and for almost two years after the cessation of irrigation.

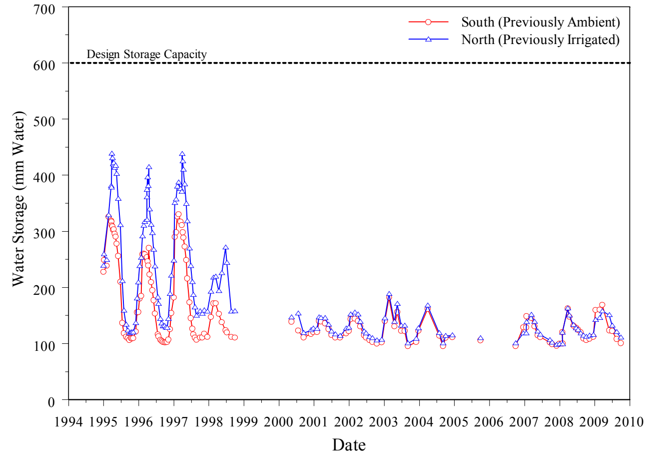


Fig. 5. Variation on Mean Water Storage on the North and South Plots from October 1994 through September 2009.

Although not obvious from these data, *W* also showed a strong spatial dependence with lowest values near the crown and W increase down gradient slope toward the edge. The barrier was constructed with a 2% slope from the middle towards the east and west edges so as to direct overland and interflow away from the crown. In 1997, the wettest year on record, *W* reached 554.6 m at the lowest slope position (S1), only 45 mm shy of the design capacity but there was no drainage. Storage at the mid-slope (S2) reached only 447 mm, whereas at the upper slope (S3), *W* reached a maximum of 377 mm. Larger *W* at the lower slope positions is implicated in the higher plant biomass observed along the edges where sagebrush and rabbit brush plants are significantly larger than the interior plants.

For the 15-yr period, *W* ranged from 97 mm to 438 mm with a standard deviation of 103 mm on the north side and 95 mm to 330 mm with a standard deviation of 69 mm on the south side. Since the completion of the treatability test, the once-prominent peaks have shown a progressive decline over time. In the 4 years immediately after the treatability test, *W* rarely exceeded 150 mm. During the last year *W* ranged from 110 mm to 157 mm with a standard deviation of 17.6 mm on the north compared to a range of 100 mm to 169 mm and a standard deviation of 25 mm on the south side. A divergence in the lower limits of storage at the end of each year is therefore evident and is attributed to inter-plot differences in the ability of the vegetation to recycle applied water. In the early stages of testing, the lower limits of storage between monitoring stations were quite similar but gradually diverged until 1999. Over the years, the discrepancy between the minimum *W* on the north and south sections, prominent during and immediately after the treatability test, has essentially disappeared. These results confirm the hypothesis that differences in the lower limit of water withdrawal may have developed as a result of stresses caused by irrigation. The eventual convergence of the minimum *W* suggests that the native species can easily recover from short-term stresses. In this case, stress due increased available water was present for the three years of the treatability test and two years after its completion. Optimizing performance will require close attention to the choice of plant species and perhaps allowance for maintenance to ensure that the right mix of plant species remains active.

Drainage

Fig. 6 shows a plot of the cumulative drainage from the side slopes and silt-loam plots. Any water passing through the fine-soil and rock layers is intercepted by the asphalt layer and diverted to the collection system where it is recorded and treated as drainage in the water balance. Results indicate a seasonal dependence with significant differences between precipitation treatments (north and south), and soil cover (rock and soil) from year to year and a strong correlation between drainage rates and winter precipitation. The effect of side slope configuration is evident from these data. During the treatability test, the irrigated riprap slope (4E) typically drained less than the gravel (4W), except in the winter and despite low drainage rates in the summer, cumulative drainage from the riprap generally exceeded that from the gravel for the duration of the treatability test. By the end of August 2009, the north

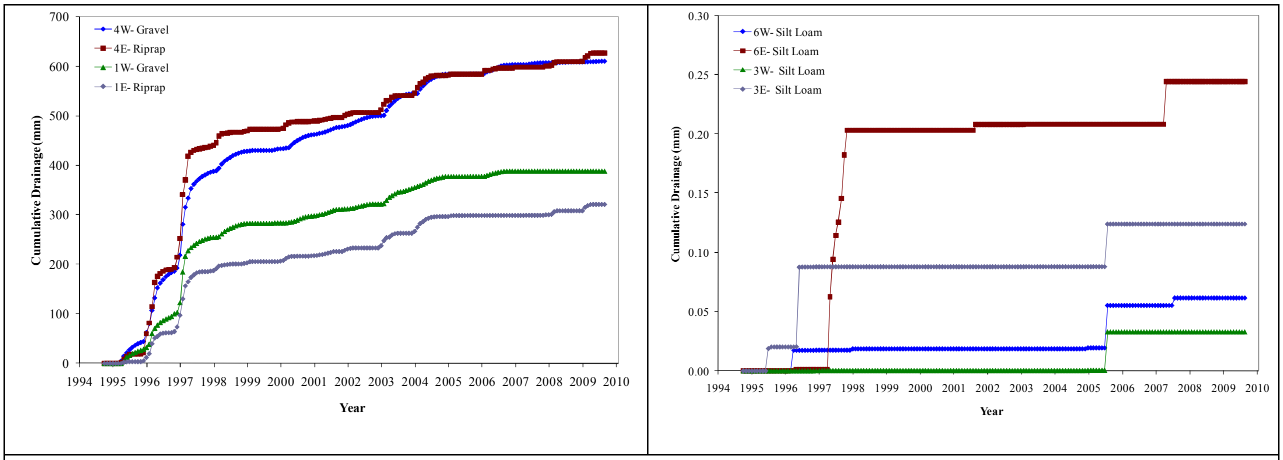


Fig. 6. Cumulative Amounts of Water Diverted by the Asphalt (Drainage) from (a) the Side-Slope Plots, (b) Silt-Loam Plots.

gravel slope (4W) had drained 611.1 mm or 17.8% of the intercepted precipitation whereas the north riprap slope (4E) had drained 627.29 mm or 18.3% of the intercepted precipitation. Interpretation of side-slope drainage from the north slopes is complicated by the use of irrigation during the treatability test. However, these effects are absent on the south side slopes. On the southern plots, drainage from the gravel slope (1W) consistently exceeded that from the riprap (1E). These differences have persisted throughout the monitoring period and by the end of August 2009, cumulative drainage from the non-irrigated gravel was 388.5 mm, or 14.1 % of total precipitation, whereas the south riprap slope (1E) had drained 321.2 mm, or 11.6% of intercepted precipitation. This represents a difference of 67 mm, but this difference appears to be declining over time, from over 90 mm in the early stage of monitoring to 80 mm in 2009. The discrepancy in drainage between two side-slope configurations exposed to the same climatic conditions, is due to the effects of advective drying. Wind pumping with air of low relative humidity causes evaporation of moisture from the riprap surfaces thereby reducing drainage from the riprap slopes, which coupled with the smaller footprint makes this a more efficient design.

In contrast, drainage from the soil-covered plots was quite small. Over the 15-yr period, these plots (6W, 3W, 3E, and 6E) have generated 0.062 mm, 0.033 mm, 0.124 mm, and 0.244 mm of drainage, respectively. There has always been some uncertainty about nature of the higher amounts from plot 6E. Verification studies in 1997 showed no significant differences in soil physical properties. However, visual inspection and vegetation surveys showed a significant difference in the ground cover composition on this plot with a larger percentage of grass, which is only active part of the year, and smaller than average shrubs that are active year round. Given that the 600-mm storage capacity of the 2-m thick silt loam layer has never been exceeded, the observed small amounts of drainage may be related to thermal effects exacerbated by differences in vegetative cover. Nonetheless, the mean drainage from the soil plots over the 15-yr monitoring period is only 0.116 ± 0.093 mm. This is equivalent to a percolation rate of only 0.0075 mm/yr or 1.5% of the design drainage criterion of 0.5 mm/yr. These results clearly illustrate the effectiveness of the capacitive barriers constructed of fine soil materials in minimizing percolation. The 2-m thick silt-loam cover essentially cut off percolation as these small amounts of water collected from under the silt loam has been attributed to condensation in the drainage system. Even at this low rate, none of this water would contribute to recharge as the prototype barrier includes low-permeability asphalt layer at its base.

Deep Percolation

Evidence of deep percolation is derived from drainage measurements in an under-asphalt lysimeter located in the northeastern corner of the barrier, from measurements of soil water content (θ) at the depth of the capillary break, and under the asphalt layer in horizontal neutron access tubes. After 15 years, there is no evidence of percolation through the asphalt layer from the pan lysimeter. Fig. 7 is a plot of θ at the capillary break (2-m depth) on the north half of the barrier from December 1994 through September 2009. The x-axis represents horizontal distance from the crown of the barrier with a positive ordinate representing to the east of center (toward the riprap side slope) and a negative ordinate to the west of center (toward the gravel side slope). Shortly after construction, variations in θ showed strong spatial and temporal dependence at the capillary break. Water content typically increased in the winter, reaching a maximum in late spring, and decreased over the summer. On the southern half, θ decreased within the first few months of revegetation and was invariant for most of the monitoring period except for 1997. Since the end of irrigation, θ at the capillary break has decline steadily except for a sharp drop in 2005. Under–

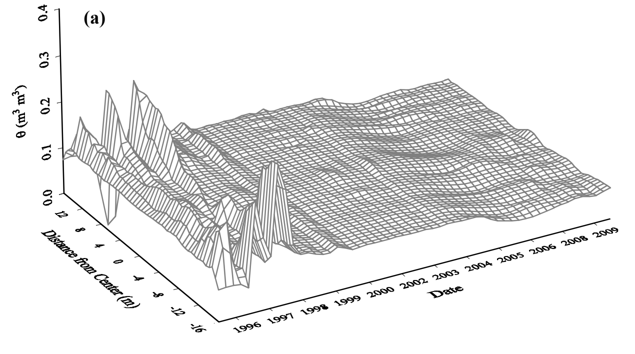


Fig. 7. Spatiotemporal Variations in Soil-Water Content at the Bottom of the Silt-Loam Layer from 1994 through 2009.

asphalt θ also show a general decrease over the last 15 years. However, there is no change in the spatial patterns except for small increases near the edge of the asphalt in the winter. The wetting front typically migrates about 1 m under the asphalt until it is halted by evapotranspiration, suggesting a potential for underflow.

Evapotranspiration

Fig. 8 shows a plot of ET from 1994 through 2009. During the 3-yr treatability test, calculated ET showed essentially no intra-plot difference but showed significant treatment differences with the highest amounts coming from the north (irrigated) plots. During the treatability test, calculated ET rates were not significantly different between plots on the two precipitation treatments. However, the difference between the north and south (irrigated and non-irrigated) sections is quite clear. In the early part of the treatability test through 1998, the average ET was almost twice as high on the north (744 mm) as on the south (396 mm). This can be expected because under wetter conditions, plants will transpire more water, within limits. During the treatability teat, all plots showed a general decline in ET, with the sharpest decline on the northern plots. The decline is due to partly to a disappearance of a large Russian thistle (*Salsola kali*) population initially present and perhaps to cessation of irrigation and hypothesized to reduce the efficiency of ET on the irrigated plots. Since the completion of the test, ET has closely followed precipitation but has shown a general decrease over time with a mean value of about 167 ± 40 mm each year. The fact that the actual ET exceeds the long-term annual average of 160 mm/yr for the site is evidence that vegetated capillary barriers will perform effectively at this and similar arid and semiarid sites where potential ET significantly exceeds precipitation.

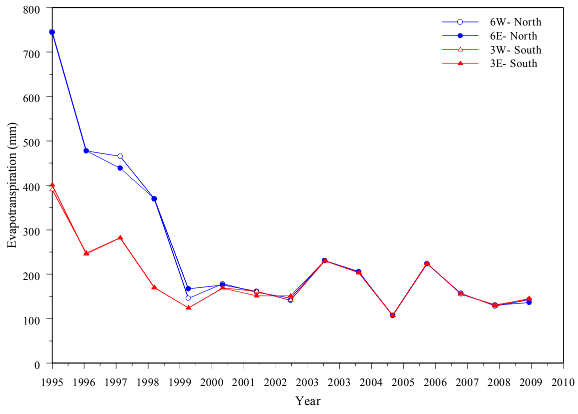


Fig. 8. Calculated ET for the Soil-covered Plots.

Ecological Processes

Species Composition

Over the last 15 years, information on plant species composition and canopy characteristics have been documented to better understand vegetation dynamics in this type engineered ecosystem. Fifteen years after vegetation was established, the surface is dominated by sagebrush. Rabbitbrush is sparse on the barrier surface, with relatively few plants in either treatment (formerly-irrigated, and non-irrigated). These were found near the edges of the surface. Fig.9a compares the total number of species on the barrier surface from 1995 through 2009. Species richness on the barrier has dropped from 35 in 1997 to 10 in 2008 just before the fire. One year after the fire, species richness increased to 15 in the unburned half of the surface and to 24 on the burned half of the surface. Species richness at the unburned McGee Ranch analog sites is essentially the same as on the unburned half of the barrier (

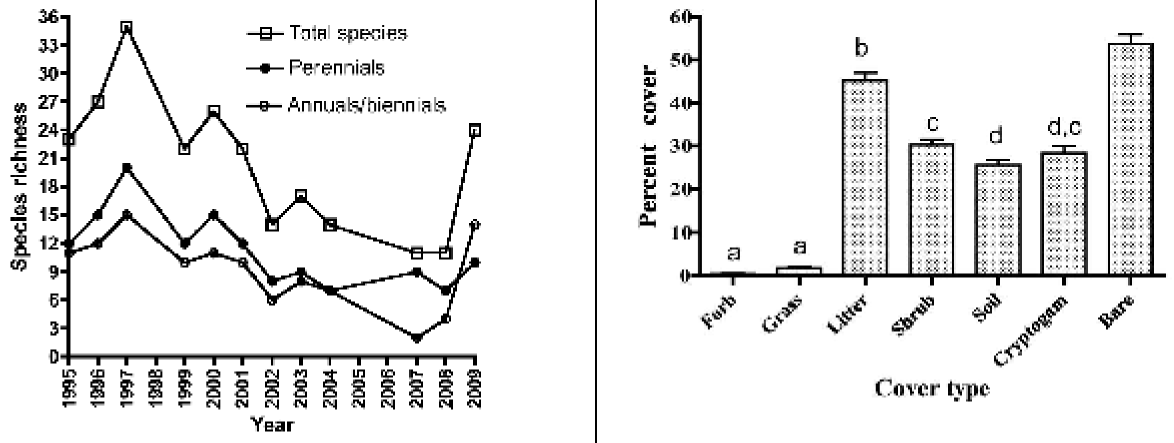


Fig.9. (a) Species Richness and Composition at the Prototype Barrier, (b) Mean Cover on South Half of the Barrier in 2009. Error bars of one standard error of the mean (n=144). Different letters indicate significant differences.

was modified by the controlled burn test in 2008 on the north half. Nonetheless, the unburned south half are reflective of the prototype 15 years later. On the south section, 53.8 ± 2.06% of the surface is bare; 1.86 ± 0.18% is covered with grasses; 30.3 ± 1.13% is covered by shrubs, whereas litter accounts for 45.3 ± 1.7 %. Ground cover at the prototype barrier is in sharp contrast to those observed at the two analog sites at McGee Ranch. Shrub cover in the McGee Ranch unburned area is lower (22 ± 2.57 %) than that in the unburned area on the barrier. Forb cover is similar in the two burned areas, 24.7 ± 0.97 % at the barrier and 19.8± 2.19 % at the McGee Ranch old burn site, and significantly greater than in the unburned barrier (0.4 ± 0.1 %) and unburned McGee Ranch (8.1± 1.4 %). There was no soil cryptogam on the burned half of the barrier, but low cover percentages were observed at the McGee Ranch burned area (6.79 ± 1.98 %) compared to those at the unburned barrier (28.3 ± 1.63 %) and unburned McGee Ranch (42.6 ± 3.57 %). Cryptogamic crust cover is now about 37.3 % of the surface with in the south (unburned half). The thallus of *Caloplaca tominii* was 60 mm in diameter. Assuming it initiated in 1994, its growth rate is about 4.6 mm y^{-1}. The western and northern (gravel) side slopes of the barrier showed less vegetated cover than the barrier surface. Cover was relatively uniform, thus data were combined. The gravel slopes has a large component of *E. nauseosa*. Rock cover was much greater than cover of other classes while cover of shrubs and grasses (mostly bunchgrasses) were similar. There was no growth on the riprap slopes.

Shrub Density

Vegetation was established on the barrier at a much higher density than the surrounding environment and observations over the years provide insight into optimal densities. Due to a combination of physiological and hydrological factors, shrubs at the fine-soil perimeter are more productive than interior shrubs [13,14]. Differences in cover are partly related to lower competition as plants along the barrier's edges receive competition from only three sides compared to those on the interior, which receive competition from plants on all four sides. Another contributor is the increased available soil water owing near the barrier's edge [8]. After 15 years, *Artemisia tridentata* dominates the south (unburned) section of the barrier with a density of 0.77 ± 0.012 plants/m^2. This is significantly higher than at the McGee Ranch unburned analog site (0.437 ± 0.033). Other shrubs were present but in low numbers with *Ericameria nauseosa* (0.00386 ± 0.002) and *Chrysothamnus viscidiflorus* (0.0107 ± 0.006) being the most dominant. While there are few *E. nauseosa* plants on the silt-loam surface, there are numerous plants on the adjacent side slopes that can be the source of the new recruits. Shrub density also varied by size/age class. On the south section of the barrier, 96% of the shrubs were old with a density of 0.743 ± 0.010 plants/m^2. Mid-size shrubs were present with a density of only 0.027 ± 0.007 plants/m^2. Most sagebrush shrubs had only a few flowering

Table 1). Annual and biennial species are 32% of the flora in the long-term undisturbed community at the McGee Ranch, 44% in the McGee Ranch old burn, 53% in the unburned barrier surface, and increasing to 58% on the burned half of the barrier. The dominance of *A. tridentata* on the unburned half of the barrier surface may contribute to continued reductions in species richness on the surface. Ward [7,14] reported surveys of cryptogram crusts at four study sites including two analog sites at the McGee Ranch with seven species present at the prototype barrier.

Ground Cover

The mean, median, and mode cover classes for each cover type have been recorded each year and are summarized for 2009 in Fig.9b. The ranges are the cover classes as defined by Daubenmire [9]. Ground cover distribution was modified by the controlled burn test in 2008 on the north half. Nonetheless, the unburned south half are reflective of the prototype 15 years later. On the south section, 53.8 ± 2.06% of the surface is bare; 1.86 ± 0.18% is covered with grasses; 30.3 ± 1.13% is covered by shrubs, whereas litter accounts for 45.3 ± 1.7 %. Ground cover at the prototype barrier is in sharp contrast to those observed at the two analog sites at McGee Ranch. Shrub cover in the McGee Ranch unburned area is lower (22 ± 2.57 %) than that in the unburned area on the barrier. Forb cover is similar in the two burned areas, 24.7 ± 0.97 % at the barrier and 19.8± 2.19 % at the McGee Ranch old burn site, and significantly greater than in the unburned barrier (0.4 ± 0.1 %) and unburned McGee Ranch (8.1± 1.4 %). There was no soil cryptogam on the burned half of the barrier, but low cover percentages were observed at the McGee Ranch burned area (6.79 ± 1.98 %) compared to those at the unburned barrier (28.3 ± 1.63 %) and unburned McGee Ranch (42.6 ± 3.57 %). Cryptogamic crust cover is now about 37.3 % of the surface with in the south (unburned half). The thallus of *Caloplaca tominii* was 60 mm in diameter. Assuming it initiated in 1994, its growth rate is about 4.6 mm y^{-1}. The western and northern (gravel) side slopes of the barrier showed less vegetated cover than the barrier surface. Cover was relatively uniform, thus data were combined. The gravel slopes has a large component of *E. nauseosa*. Rock cover was much greater than cover of other classes while cover of shrubs and grasses (mostly bunchgrasses) were similar. There was no growth on the riprap slopes.

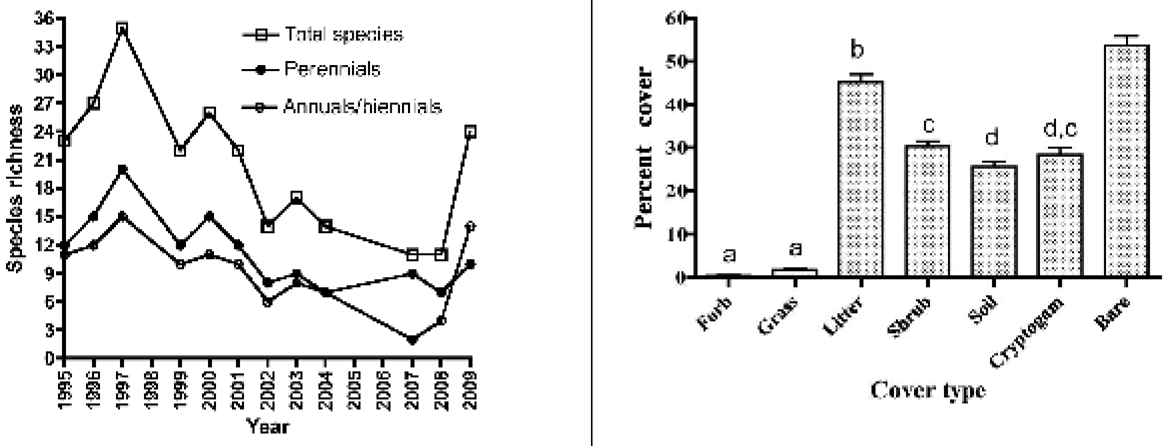


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Table 1. Species Observed in 2009 on the Unburned Section of the Barrier and the McGee Ranch Analog Site

Family	Species	Barrier	McGee Ranch
Asteraceae	*Artemisia tridentata*	X	X
	Centaurea diffusa	X	
	Chrysothamnus viscidiflorus	X	
	Crepis atribarba		X
	Ericameria nauseosa	X	
	Erigeron filifolius		X
	Erigeron piperianus		X
	Erigeron poliospermus		X
	Helianthus cusickii		X
	Machaeranthera canescens	X	X
Boraginaceae	*Amsinckia lycopsoides*	X	
Brassicaceae	*Descurainia pinnata*		X
	Sisymbrium altissimum	X	
Chenopodiaceae	*Grayia spinosa*		X
	Salsola kali	X	X
Geraniaceae	*Erodium cicutarium*	X	
Malvaceae	*Sphaeralcea munroana*		X
Poaceae	*Achnatherum hymenoides*		X
	Bromus tectorum	X	X
	Elymus elymoides		X
	Elymus wawawaiensis	X	
	Poa ampla	X	
	Poa bulbosa	X	
	Poa secunda	X	X
	Vulpia microstachys	X	X
	Total Number of Species Present	15	16

closer to that in natural areas. When density has been sufficiently reduced then it is likely that the *A. tridentata* population will achieve a more natural size/age distribution.

Leaf Area Index

The leaf area index (LAI) is the ratio of total upper leaf surface of the plant divided by the surface area of the ground occupied by the plant canopy. While there is an abundance of LAI data for crop plants, little information is available for the native species such as those used on engineered barriers. Data collected over the years have been used to develop a model for LAI based on measured shrub height, the greatest projected canopy diameter, and the diameter measured orthogonal to the greatest projected canopy diameter [15,16]. Measurements of LAI on the south half of the barrier (1.13 ± 0.087) was not significantly different from mean LAI in the McGee unburned plant community (0.692 ± 0.129).

Animal Use

Fig. 10. Evidence of Animal Use on the Barrier in 2009, (a) Rabbit Droppings in Area with Grass Cover and (b) Small Mammal Hole on the Barrier Surface, note recent digging activity in the upper left hand corner.

Over the years use of the barrier by animals has been wide spread. In the 2008 surveys, the most common mammals captured during a total of 50 trap nights were deer mice (*Peromyscus maniculatus*) and great basin pocket mice (*Perognathus parvus*). Adults and juveniles were captured, indicating that the small mammals were residents to the area, as opposed to dispersed migrants from other areas. In addition, a number of side-blotched lizards (*Uta stansburiana*) were observed during the trapping event. Over the years, cottontail rabbit (*Sylvilagus nuttallii*) use, as indicated by the presence of droppings, has been most evident in the northeast corner of the barrier where grass-cover was highest (Fig. 10a). Indirect indices of animal activity, such as evidence of use by rabbits, coyotes, lizards, and invertebrates (in addition to small mammals), is common across the entire surface. Coyote and rabbit feces were noted in numerous other locations across the surface.

A number of small, relatively shallow excavations were noted throughout. Based on the sample size, 70% of the surface had animal burrows. These holes, dug by insects and small mammals, were distributed throughout the surface with no obvious pattern that could be associated with disturbance, concrete, instruments, or other items on the surface (Fig. 10b). The average hole diameter was 3.9 ± 0.8 cm, the area was 13.8 ± 5.5 cm^2, the depth was 12 ± 2.6 cm, and the volume was 164 ± 75 cm^3 ($n = 11$). The bulk of these excavations were believed to be made by resident lizards, but there was some evidence that some of these excavations were also made by darkling beetles and small mammals. There is also evidence of underground small mammal burrow systems likely constructed by resident pocket mice. Based on several species of pocket mice, as much as 50% of the burrow system can be distributed within the top 0.5 m and up to 90% within the top 1 m [17]. Pocket mice typically construct burrows less than 2.5 cm in diameter, and other small mammal burrows common to the site are typically wider; for example, deer mouse burrows are up to 10 cm in diameter [18].

In the most recent survey conducted in September 2009, hole sizes were classed as large (> 2 cm diameter) or small (< 2 cm). Holes in each class were counted in each plot. Animal holes were significantly ($p < 0.0001$) more prevalent on the south (unburned) half (0.0414 ± 0.00737 holes m^{-2}) than on the burned half (0.0054 ± 0.002 holes m^{-2}). Of 61 holes found in all the plots 31 were large and 30 were small. Of 21 holes dug by rodents, 20 were large. Of 38 holes dug by insects, 9 (23.7%) were large. There were no significant ($p > 0.05$) linear relationships between location on the surface and hole density. Cottontail rabbit use, indicated by the % of plots with feces in each of 25 rows, was positively correlated with % cover of *E. wawawaiensis.* Most *E. wawawaiensis* plants had experienced herbivory, most likely by rabbits. Coyote feces were noted in two locations on the surface. Small mammal holes can potentially be a source of variation in soil-water patterns, but they are small and make up a very small portion of the surface. There are only about 1.55 holes in a sampling square (9 m^2) or an area of about 21 cm^2 in each 9-m^2 plot. This is only 0.0023 % of the surface and may not have a functional influence on the surface. It is likely that use will increase with time and may become more similar to use in natural ecosystems where burrows and mounds can be very common. As yet, there is little or no use of the surface by large burrowing animals such as badgers. A few mounds were observed on the north edge of the barrier surface. The only burrowing insects present were ants on the north edge of the barrier. Animal activity on the side slopes was restricted to the lower elevations where fine soils are more common. In these areas, there were numerous holes that were from small mammals or insects. There were large ant colonies in the fine soils.

Galls, likely due to flies or wasps, were found infesting a number of *A. tridentata* plants. The degree of gall formation and amount of animal feces were classed into high and low groups. A high degree of gall formation was noted when any shrub had numerous (> 50) galls. Some of the *A. tridentata* were heavily infested to the point of damaging the shrub. Of 144 plots in the unburned half of the barrier 102 (71%) had infested shrubs and 19% of the plots had heavily infested shrubs. This infestation will likely reduce the population density of *A. tridentata* in future years. Observations of insect and small mammal use suggest that the barrier is functioning like a natural ecosystem.

SUMMARY AND CONCLUSIONS

One outstanding issue that has impacted stakeholder acceptance of engineered barrier technology is the limited amount of performance data and the uncertainty in using them to predict long-term performance. In 1994, a 2-ha vegetated, multi-component barrier was constructed over an existing waste disposal site using natural materials. This barrier, which was designed to meet a 0.5 mm/yr drainage limit, has been monitored almost continuously for the last 15 years including the response to 3 annual 1000-yr return storms, giving rise to a unique dataset.

Stability of the barrier has been documented over the last 15-yrs by monitoring elevation on the functional portion of the barrier and creep on the riprap side slope. Annual surveys of two settlement gauges anchored to the asphalt layer show no evidence of subsidence. Over the years, small changes in elevation have been observed on the functional surface and a significant increase in near-surface gravel content. These changes can be attributed to disturbance of the soil fabric by plant and animal activities as well as freeze-thaw cycles. Erosion pin measurements show evidence of soil movement on the surface, particularly during the last fiscal year (Oct 2008 – Sep 2009) after the controlled burn. Creep gauges on the riprap moved 0.056 ± 0.016 m in an easterly direction and showed a mean elevation change of -0.012 ± 0.02 m. These small changes are not indicative of slope failure but do suggest some settlement of the riprap slope.

Hydrological performance exceeds design specifications. For the period October 1994 through September, 2009 the prototype received a total of 3312.9 mm of water, of which 2640 mm came from natural precipitation and 672.87 mm came from irrigation during the treatability test. Three runoff events have been observed over the life of the barrier, the first during the first simulated 1,000-year storm, in which 1.79 ± 0.11 of runoff with 7 g L^{-1} of sediment was collected from a vegetation-free surface; the second in 1997 when 36.3 mm of water without sediment was collected following a rapid snow melt on a frozen surface; and the third in 2009, 4 months after the north half of the barrier was burnt, in which 0.016 mm of runoff 2.2 gm of sediment was collected. The only measurable loss of soil by wind occurred during the first 3 months when the surface was bare with estimates ranging from 7.4 to 744 mg/m^2. Use of a silt-loam-gravel admix, combined with a vegetative cover, has proven effective in controlling soil loss. Soil water storage shows a well-defined annual cycle with qualitatively similar patterns on the different plots but significant differences in the maximum and minimum storage amounts. Water storage showed a strong dependence on precipitation, slope position, plant species composition. The optimal design will require close attention to the right mix of plant species. Drainage from the silt-loam plots has been small with a mean of 0.116 ± 0.093 mm or 0.0075 mm/yr, which is 1.5% of the design drainage criterion of 0.5 mm/yr. These results clearly show the effectiveness of the barrier in minimizing percolation. In contrast, the side slopes, which can occupy 30-70% of the barrier footprint, generated significant amounts of drainage. Under ambient precipitation conditions, the large-footprint gravel slope drained a total of 388.5 mm, or 14.1 % of total precipitation, whereas the small-footprint riprap slope drained 321.2 mm, or 11.6% of the intercepted precipitation. The discrepancy in drainage from the two side slope configurations, exposed to the same meteorological conditions, is due to the effects of advective drying. Horizontal water content measurements at the capillary break and below the asphalt layer show no evidence of deep percolation within the barrier. However they show increased accumulation of water along the edges and some potential for underflow beneath the asphalt under high precipitation conditions. Total evapotranspiration calculated by water balance show a decrease from a high of 744 mm/yr on the irrigated treatment and 396 mm/yr on the non-irrigated treatment, during the treatability test, to a mean of 167 ± 40 mm/yr in 2009. Actual ET in excess of the annual precipitation of 160 mm/yr is evidence that vegetated capillary barriers will perform effectively at this and similar arid and semiarid sites where potential ET significantly exceeds precipitation each year.

Over the last 15 years, information on plant species composition and canopy characteristics have been documented to better understand vegetation dynamics in this type engineered ecosystem. Species richness on the barrier has declined from a high of 35 in 1997 to 15 in 2009 with the current value being essentially identical to that observed at the McGee Ranch analog site. Sagebrush dominates at the barrier as well as the unburned analog site but the shrub density is quite different. Shrub cover in the McGee Ranch unburned area is lower (22 ± 2.57 %) than that in the unburned area on the barrier (30.3 ± 1.13%), a reflection of the higher density used in establishing vegetation at the barrier. Analysis of shrub density, by size/age class, shows that old shrubs had the highest density at the barrier with no new seedling. Although the shrubs are reproducing, they are doing so at very low rates so it likely they will die faster than they are recruited until the density of large shrubs is closer to that in natural areas.

There is widespread animal use of the barrier with numerous holes dug by insects and small mammals distributed throughout the surface. These holes can potentially be a source of variation in soil water patterns, but they are small and make up a very small portion of the surface. There is no evidence of burrowing by larger mammal badgers. Use of *E. wawawaiensis* by rabbits is substantial and herbivory is significant, which could potentially lead to a reduction in this species, especially if seed production is reduced. Insect galls on *A. tridentata* were significant with shrub damage under heavy infestation. This infestation will likely contribute to a reduction in *A. tridentata* populations. A recent control burn on the north half of the barrier will allow side-by-side comparison of the performance of an established barrier system and a recovering system as the burned side is revegetated.

The dataset generated by this study is unique and have already proven useful in the development of more rigorous methods for evaluating long-term performance and quantifying uncertainty using numerical models. Results will contribute to a better understanding of long-term barrier performance and the recovery of engineered ecosystems after major disturbances in a post-institutional control environment. Such an understanding is needed to enhance stakeholder acceptance regarding the long-term efficacy of engineered barriers.

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