

Semi-Circular Bunds in an Arid *Artemisia sieberi* Rangeland, Southeast Iran: Vegetation and Soil Contrasts with an Unbundled Area, and a Runoff-Capture Analysis of the Bund Design

S. Noori^{1✉}, M. Nikandish², Z.Noori kia³, S.Kherad narooi²

¹ Department of Range and Watershed Management, University of Zabol, Zabol, Iran

² Master's degree in Rangeland Management, Faculty of Water and Soil, University of Zabol, Zabol, Iran

³ Member of Rangeland Affairs Department, General Directorate of Natural Resources and Watershed Management of Sistan and Baluchestan Province, Iran

⁴ Master's degree in Watershed Management, Faculty of Water and Soil, University of Zabol, Zabol, Iran

*Corresponding Authors: Email: (Snoori.327@uoz.ac.ir)

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Abstract: Semi-circular bunds are widely built to rehabilitate degraded drylands, but their performance in rangelands receiving only ~100 mm rain per year is poorly documented. We evaluated hand-built semi-circular bunds (3 m diameter, 30–40 cm deep, 70–80 bunds ha⁻¹) 11–12 years after construction (built in 2005; surveyed 2016–2017) in the Chahgurik rangeland, Mirjaveh, southeast Iran, an *Artemisia sieberi* steppe at 1800 m elevation. Canopy cover was measured in ten 2 m² plots in a bunded area and an adjacent unbundled control, and soil N, P and K were determined under shrubs and on bare soil at 0–10 and 10–40 cm. Mean canopy cover was 8.77% in the bunded area and 7.73% in the control, a difference of 1.04 percentage points (95% BCa bootstrap CI 0.21–1.99; exact permutation $p = 0.043$) or +13.5% relative (95% CI 1.1–27.5%). The standardised difference was large (Hedges $g = 0.93$) but imprecise, with power of only 0.51; about 19 plots per area would be needed for 80% power. Available P and K were lower in the bunded area at both depths and positions, whereas total N was higher only in the surface soil under shrubs. A runoff-capture analysis bund geometry showed a catchment-to-basin ratio of about 37:1, far above 1.4:1–3:1 of FAO reference designs. Under an assumed runoff coefficient of 0.10–0.50 (reference 0.25) and an assumed mean rain-event depth of 4–12 mm, neither measured at site, each catchment generates a runoff-equivalent depth of 10–50 mm yr⁻¹. Annual water depth entering each basin is estimated at 7.2 times 100 mm rainfall depth (median; 90% range 3.7–10.9 from Monte Carlo propagation), with runoff coefficient accounting for most uncertainty. The 0.7–1.0 m³ basin storage captures most run-on, but basins cover <3% of the land. The bunds thus redistribute water rather than add it, consistent with modest area-level vegetation difference. Because the comparison involves one bunded and one control area without pre-construction data, observed differences indicate an association with bunding rather than a demonstrated treatment effect. In such dry rangelands, bund density and basin size should be designed with area expected to respond, and monitoring should use replicated, baseline-referenced designs.

Keywords: Water harvesting; Semi-circular bund; Micro-catchment; *Artemisia sieberi*; Rangeland rehabilitation; Runoff coefficient

1. Introduction

Drylands cover about 41% of the land surface and are home to more than a third of the world's population, and land degradation in them is driven by the coupling of climate variability, grazing and the loss of the vegetation patches that retain water and soil (Reynolds et al., 2007). In semi-arid and arid landscapes, perennial plants and the bare soil between them function as sinks and sources of runoff, sediment and nutrients (Ludwig and Tongway, 1995; Ludwig et al., 2005), and soil nutrients concentrate under shrubs to form "islands of fertility" (Schlesinger et al., 1996). Rehabilitation techniques that rebuild this source–sink structure, for example branch piles laid on the contour, can restore soil carbon, nitrogen and infiltration even under continued grazing (Tongway and Ludwig, 1996).

Micro-catchment water harvesting pursues the same goal through engineering. Runoff from a small contributing area is led into a basin where it infiltrates and is stored for plants (Critchley and Siegert, 1991; Mekdaschi Studer and Liniger, 2013). The semi-circular

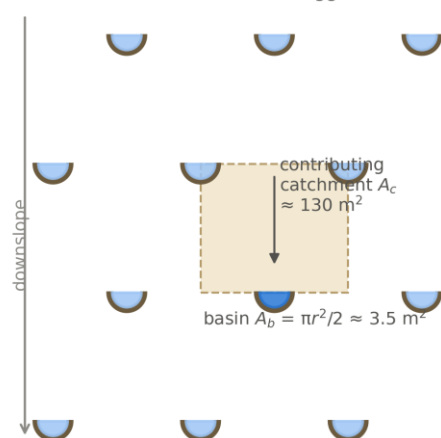
bund, or half-moon, is one of the most common designs: an earth ridge built as a half circle with its tips on the contour, open towards the upslope side. Semi-circular bunds are recommended for rainfall of 200–750 mm on slopes up to about 2%, mainly for rangeland rehabilitation and fodder production (Critchley and Siegert, 1991). Field studies in the Sahel report large increases in greenness and tree growth where semi-circular bunds were built (Mishra et al., 2023; Wourro et al., 2026), but also show that on crusted, nutrient-poor soils they do not increase yields unless organic amendments are added (Zougmore et al., 2003). In rangelands, fodder shrubs planted in semi-circular bunds established well in northern Afghanistan (Louhaichi et al., 2022), bunds increased soil organic carbon and improved soil structure in the Zagros (Heshmati et al., 2018), and micro-catchments in the Jordanian Badia raised soil moisture and microbial activity (Tatsumi et al., 2021). Benefits are not always lasting: in arid Australian rangelands the gains produced by pitting faded within a few years (Eldridge and Ding, 2023).

In southeast Iran, semi-circular bunds have been built on a large scale in *Artemisia sieberi* Besser (hereafter *Ar. sieberi*) steppes and other degraded rangelands of Sistan and Baluchestan Province, where annual rainfall is often around 100 mm. Earlier evaluations in the province reported higher vegetation cover and soil nutrients inside bunded areas (Khosravi et al., 2016), but they did not relate the observed response to the hydrology of the bund design, and effect sizes and their uncertainty were rarely reported. *Ar. sieberi* is the dominant shrub of the Iranian steppes; its cover responds to soil moisture, clay and nitrogen (Mirdavoudi et al., 2022), and it shapes the understorey around it (Bahalkeh et al., 2021).

This study combines field data from a bunded and an unbunded *Ar. sieberi* rangeland at Chahgurik, Mirjaveh, with a quantitative analysis of the bund design. Its objectives are (i) to quantify the difference in the canopy cover of *Ar. sieberi* between the bunded and the control area, with effect sizes, exact tests and a power analysis; (ii) to describe the associated differences in soil N, P and K under shrubs and on bare soil; and (iii) to quantify how much runoff the bund geometry concentrates and captures, and how uncertain these quantities are, in order to help interpret the magnitude of the observed difference and to derive design recommendations for very dry rangelands. Because the bunds were not allocated at random and no pre-construction measurements exist, the field comparison is observational; differences between the bunded and the control area are therefore interpreted as associations with bunding, not as demonstrated treatment effects.

2. Materials and Methods

a Plan view, 75 bunds ha⁻¹ (staggered)



2.1. Study area

The Chahgurik rangeland lies in Mirjaveh County, Sistan and Baluchestan Province, southeast Iran (29°01'–29°12' N, 60°40'–60°53' E), at about 1800 m above sea level in the Irano-Turanian region. Mean annual precipitation at the nearest rain gauge over a 20-year record (1997–2017) is about 100 mm, falling mainly in winter and early spring; the coldest month (January) has a mean temperature of 8.7 °C and the warmest (July) 30 °C. The climate is classified as arid by both the De Martonne and the Gaussen methods. The vegetation is an *Ar. sieberi* steppe; remnant almond and wild pistachio trees indicate that the site supported denser vegetation in the past.

2.2. Semi-circular bunds

Semi-circular bunds were built by hand with spades and picks, first in 2005 and then in 2014–2016, as part of a provincial range-improvement programme. All bunds in the sampled bunded area belong to the first phase and were built in 2005; the bunds built in 2014–2016 lie outside the sampled area and were not surveyed. The field survey was carried out in 2016–2017, when the sampled bunds were 11–12 years old. Each bund is a half circle of 1.5 m radius (3 m diameter), with a basin 30–40 cm deep and an earth ridge 40–50 cm high and 40–50 cm thick. Bunds are arranged in staggered rows along the contour at 70–80 per hectare, with the opening perpendicular to the slope, and each stores about 0.7–1.0 m³ of water (Figure 1). Construction guidelines excluded ephemeral channels, marly and saline soils, stony ground without soil, dense vegetation and steep slopes.

b Section along the flow line

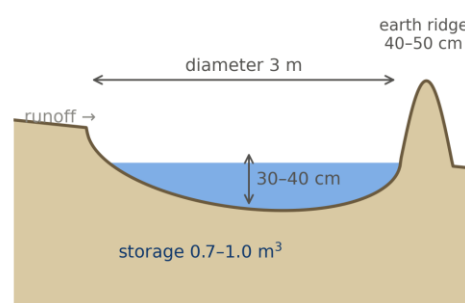


Figure 1. Geometry of the semi-circular bunds at Chahgurik: (a) staggered layout at 75 bunds per hectare with the contributing catchment of one bund; (b) section of a bund along the flow line.

2.3. Vegetation and soil sampling

A bunded area (bunds built in 2005, 11–12 years old at sampling) and an adjacent control area with similar soil, slope and aspect but no bunds were selected. In each area, four 100 m transects were laid out by systematic-random sampling and ten 2 m² plots were placed at

random along the transects, the plot size following earlier arid-rangeland surveys. In every plot the species present, the number of *Ar. sieberi* individuals and the canopy cover of *Ar. sieberi* (visual estimate, %) were recorded. Fifteen species were recorded in the study area (Table 1).

Table 1. Plant species recorded in the Chahgurik rangeland

Species	Growth form	Life span
<i>Alhagi camelorum</i>	forb	perennial
<i>Artemisia sieberi</i>	dwarf shrub	perennial
<i>Astragalus</i> sp.	dwarf shrub	perennial
<i>Cousinia stocksii</i>	dwarf shrub	perennial
<i>Echinops</i> sp.	forb	perennial
<i>Zygophyllum eurypterum</i>	shrub	perennial
Unidentified annual (Chenopodiaceae)	forb	annual
<i>Salsola</i> sp.	forb	annual
<i>Pycnocycla spinosa</i>	dwarf shrub	perennial
<i>Pteropryum aucheri</i>	dwarf shrub	perennial
<i>Fagonia indica</i>	forb	annual
<i>Ferula assa-foetida</i>	dwarf shrub	perennial
<i>Fortuynia bungei</i>	dwarf shrub	perennial
<i>Lycium</i> sp.	shrub	perennial
<i>Lactuca glaucifolia</i>	dwarf shrub	perennial

Growth forms as recorded in the field survey. Two taxa recorded under field names were entered at genus or family level pending herbarium verification.

Soil was sampled at the start and end of each transect, perpendicular to the dominant slope, at 0–10 and 10–40 cm depth, both at the base of *Ar. sieberi* shrubs and on bare soil between shrubs, in both areas. Total nitrogen was determined by the Kjeldahl method (Bremner and Mulvaney, 1982), available phosphorus by the Olsen method (Olsen et al., 1954) and available potassium by flame photometry.

2.4. Statistical analysis of the field data

Plot-level canopy cover was available for all twenty plots and was analysed in full. Normality and homogeneity of variance were checked with the Shapiro–Wilk and Brown–Forsythe (median-centred Levene) tests. The difference between the two areas was tested with Welch's *t*-test (Welch, 1947), with the exact Mann–Whitney *U* test, and with an exact permutation test of the difference in means that enumerates all 184 756 ways of splitting the twenty plots into two groups of ten. A 95% confidence interval for the difference was obtained from 20 000 stratified bootstrap resamples with bias-corrected and accelerated (BCa) limits (Efron and Tibshirani, 1993). Two effect sizes were computed: the bias-corrected standardised mean difference, Hedges *g* (Hedges and Olkin, 1985), and the log response ratio $\ln RR = \ln(\bar{x}_{\text{bund}}/\bar{x}_{\text{control}})$ with its large-sample variance (Hedges et al., 1999),

$$\text{Var}(\ln RR) = \frac{s_b^2}{n_b \bar{x}_b^2} + \frac{s_c^2}{n_c \bar{x}_c^2} \quad (1)$$

The achieved power of the two-sample comparison and the number of plots needed for 80% and 90% power were calculated for the observed *g* (Cohen, 1988). Because the bundled and the control area are each a single contiguous unit, plots are replicates of the area and not of the treatment, and the comparison is subject to the pseudoreplication caveat of Hurlbert (1984); this is discussed in Section 4.3. Accordingly, all results are reported as differences between the bundled and the control area. The term “effect size” is used in its statistical sense, as a standardised measure of the magnitude of this difference, and does not imply that the difference was caused by the bunds.

For the soil variables, only area means were available for re-analysis. Soil differences are therefore reported descriptively, as the log ratio of the bundled to the control mean for each nutrient, depth and position, and as a fertility-island ratio (under-shrub mean divided by bare-soil mean) within each area. No inferential statistics are reported for the soil data.

2.5. Runoff-capture analysis of the bund design

The hydrological function of the bunds was analysed with a simple micro-catchment water balance. For a bund of radius *r* the basin (cultivated) area is $A_b = \pi r^2/2$ and, for *N* bunds per hectare, the contributing catchment is $A_c = 10^4/N - A_b$ (m²). The catchment-to-cultivated-area ratio $C:CA = A_c/A_b$ is the design variable of the FAO method (Critchley and Siegert, 1991). Rain events were represented as a marked Poisson process with exponentially distributed depths of mean α , as in stochastic ecohydrology (Rodriguez-Iturbe et al., 1999). An event of depth *h* produces a runoff volume $RC \cdot A_c \cdot h$ from the catchment, where *RC* is the runoff coefficient, and the basin overflows when this exceeds the storage *S*. The event depth that fills the basin is

$$h^* = \frac{S}{RC A_c} \quad (2)$$

and, for exponentially distributed event depths, the expected fraction of the runoff that the basin captures is

$$\eta = \frac{E[\min(RC A_c h, S)]}{E[RC A_c h]} = 1 - \exp\left(-\frac{h^*}{\alpha}\right) \quad (3)$$

The annual depth of water entering the basin, *W* (direct rainfall plus captured run-on, expressed as a depth over the basin area), and the water concentration factor $F = W/P$ then follow from

$$W = P \left(1 + EFF \cdot RC \cdot \frac{A_c}{A_b} \cdot \eta\right) \quad (4)$$

where *P* is the mean annual rainfall and *EFF* the efficiency factor that accounts for losses in the basin. The reference case uses the dimensions of the Chahgurik bunds ($r = 1.5$ m, $N = 75$ ha^{−1}, $S = 0.85$ m³), $P = 100$ mm, $RC = 0.25$ and $EFF = 0.75$, the values recommended by Critchley and Siegert (1991) for short micro-catchment slopes, and $\alpha = 8$ mm. Uncertainty was propagated by Monte Carlo simulation with 2×10^5 samples from uniform distributions over the ranges given in Table 2, and the influence of each input was measured with standardised rank regression coefficients (SRRC).

Three water depths are distinguished throughout this study (Table 5). (i) The rainfall depth, *P*, is the depth of rain falling on any point of the hillslope, bundled or not. (ii) The runoff-equivalent depth, $RC \cdot P$, is the annual runoff generated per unit area of the contributing catchment, i.e. the run-on volume produced by the catchment of one bund, $RC \cdot P \cdot A_c$, divided by A_c . (iii) The depth of water entering the basin, *W*, is the total annual volume received by the basin (direct rainfall on A_b plus the captured run-on reduced by the efficiency factor) divided by the basin area A_b . Equation (4) can therefore be read as $W = P + EFF \cdot \eta \cdot (A_c/A_b) \cdot (RC \cdot P)$: the runoff-

equivalent depth is multiplied by the catchment-to-basin ratio and reduced by the captured fraction and the efficiency factor. W is a cumulative annual supply to the basin floor, not a ponding depth; water arrives in discrete events, and the depth ponded in any single event cannot exceed S/A_b (about 0.24 m for the reference basin). The concentration factor $F = W/P$ therefore compares the water supplied to the basin floor with the rainfall received by unbunded ground.

F depends directly on the runoff coefficient and, through η , on the distribution of rain-event depths, and neither was measured at Chahgurik. RC was taken from the FAO guidance for short micro-catchment slopes (Critchley and Siegert, 1991), and $\alpha = 8$ mm, which corresponds to about 12 rain events per year for $P = 100$ mm, was assumed rather than estimated from daily records. All values of W and F reported below are therefore conditional on these two assumptions; their sensitivity to RC and α is reported explicitly in Table 5 and Figures 5 and 6.

Parameter	Symbol	Reference	Range	Source
Bund density (ha^{-1})	N	75	70–80	field design
Basin storage (m^3)	S	0.85	0.70–1.00	field design
Runoff coefficient	RC	0.25	0.10–0.50	Critchley and Siegert (1991)
Efficiency factor	EFF	0.75	0.50–0.75	Critchley and Siegert (1991)
Mean event depth (mm)	α	8	4–12	assumed; see Sections 2.5 and 4.3
Mean annual rainfall (mm)	P	100	fixed	20-year station record

3. Results

3.1. Canopy cover of *Artemisia sieberi*

Canopy cover of *Ar. sieberi* ranged from 7.50 to 10.50% in the unbunded area and from 5.65 to 9.25% in the control area (Figure 2a). Mean cover was 8.77% (SD 0.96) in the unbunded area and 7.73% (SD 1.17) in the control area. Both samples were compatible with normality (Shapiro–Wilk $p = 0.80$ and 0.72) and with equal variances (Brown–Forsythe $p = 0.54$). The difference of 1.04 percentage points was significant with Welch's test ($t = 2.18$, $df = 17.3$, $p = 0.043$) and with the exact permutation test ($p = 0.043$, Figure 2b), but not with the rank-based Mann–Whitney test ($U = 73.5$, $p = 0.089$). The 95% BCa bootstrap interval of the difference was 0.21–1.99 percentage points and the Welch interval 0.04–2.05; both exclude zero, but only just.

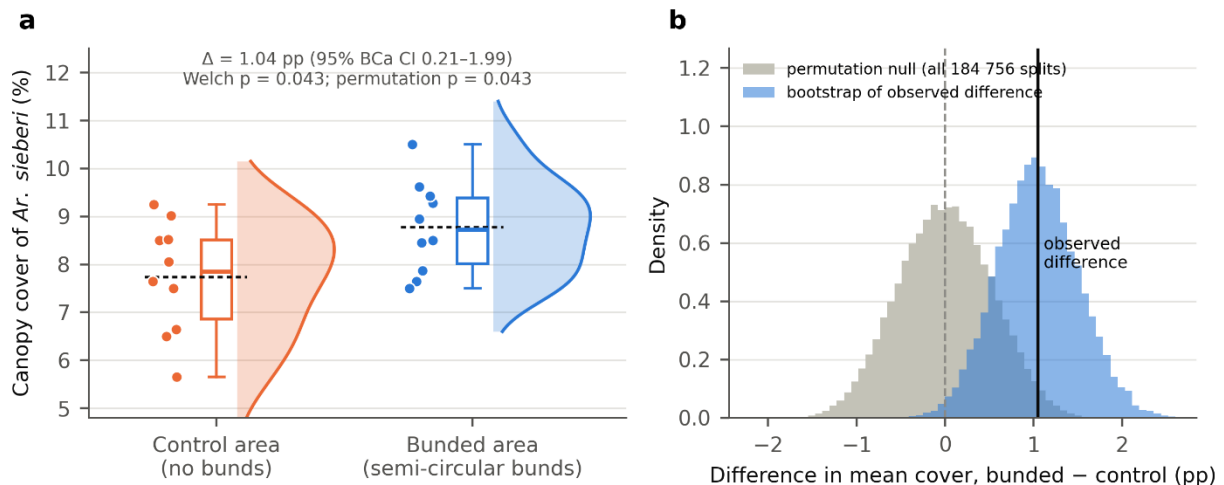


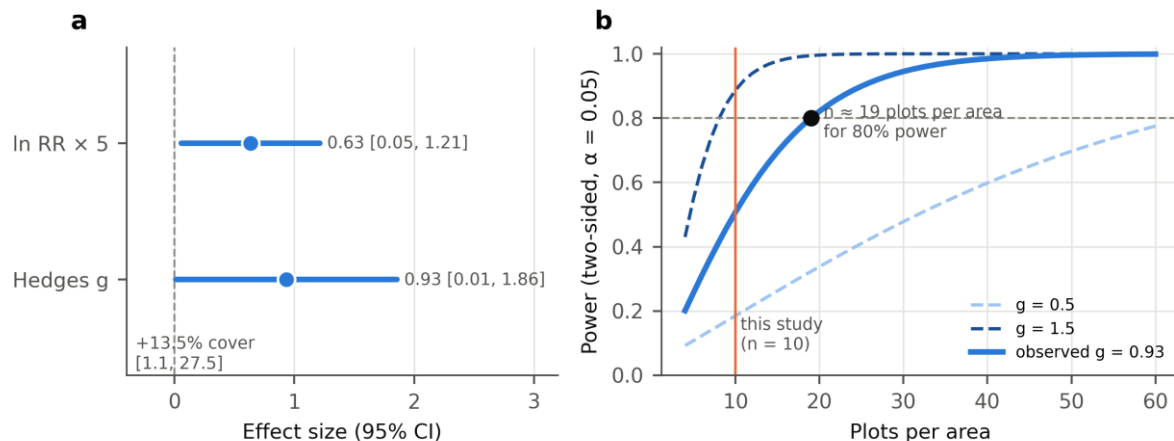
Figure 2. Canopy cover of *Ar. sieberi* in the control and the unbunded area: (a) plot values, box plots and kernel densities (dashed lines are means); (b) the observed difference in means against its exact permutation distribution and its bootstrap distribution.

Expressed as effect sizes (Table 3, Figure 3a), cover in the unbunded area was 13.5% higher than in the control area ($\ln RR = 0.127$, 95% CI 0.011–0.243). The standardised difference, Hedges $g = 0.93$, is large by conventional standards, but its confidence interval (0.01–1.86) spans everything from a negligible to a very large difference. With ten plots per area the comparison had a power of 0.51 to detect a difference of the observed size (Figure 3b); 19 and 26 plots per area would be needed for 80% and 90% power, and the minimum

standardised difference detectable with 80% power at $n = 10$ is $g = 1.32$. The number of *Ar. sieberi* individuals per plot was reported to be roughly twice as high in the unbunded area, but plot-level density values were not available for a formal analysis.

Table 3. Canopy cover of *Ar. sieberi* in the banded and the control area: tests and effect sizes ($n = 10$ plots per area)

Statistic	Value	95% interval
Mean cover, banded / control (%)	8.77 / 7.73	–
Difference in means (pp)	1.04	0.21 to 1.99 (BCa)
Welch t (df)	2.18 (17.3)	$p = 0.043$
Exact permutation test	184 756 splits	$p = 0.043$
Mann–Whitney U	73.5	$p = 0.089$
Hedges g	0.93	0.01 to 1.86
Log response ratio	0.127	0.011 to 0.243
Relative change (%)	+13.5	+1.1 to +27.5
Achieved power	0.51	–
Plots per area for 80% / 90% power	19 / 26	–

**Figure 3. Difference in *Ar. sieberi* cover between the banded and the control area: (a) Hedges g and the log response ratio (scaled $\times 5$ for display) with 95% confidence intervals; (b) power of a two-area comparison against the number of plots per area.**

3.2. Soil nitrogen, phosphorus and potassium

Differences in soil nutrients between the two areas were not uniform (Table 4, Figure 4a). Available potassium was lower in the banded area in every combination of depth and position, by 7–21%, and available phosphorus was lower by 24–49%. Total nitrogen was higher in the banded area under shrubs, markedly so in the surface layer (0.180% against 0.076%), but lower on bare soil at both depths. Ten of the twelve comparisons therefore show lower values in the banded area.

The fertility-island ratios (Figure 4b) show a consistent pattern. In the control area the under-shrub to bare-soil ratio was below or close to one for all nutrients (e.g. 0.80 for surface N), whereas in the banded area surface N was 3.6 times higher under shrubs than on bare soil and the ratios for K and P also increased. The banded area was therefore characterised by a stronger contrast between shrub patches and inter-shrub soil rather than by higher nutrient levels across the area; whether the bunds caused this contrast cannot be established without baseline data.

Table 4. Soil nutrients in the banded and the control area (area means)

Variable	Depth (cm)	Banded	Control	ln RR	Change (%)
Under shrub					
Total N (%)	0–10	0.180	0.076	+0.86	+137
Available P (mg kg ⁻¹)	0–10	1.24	1.98	–0.47	–37
Available K (mg kg ⁻¹)	0–10	162.7	175.1	–0.07	–7
Total N (%)	10–40	0.018	0.016	+0.12	+12
Available P (mg kg ⁻¹)	10–40	1.50	1.98	–0.28	–24
Available K (mg kg ⁻¹)	10–40	175.6	194.1	–0.10	–10
Bare soil					
Total N (%)	0–10	0.050	0.095	–0.64	–47
Available P (mg kg ⁻¹)	0–10	1.00	1.98	–0.68	–49
Available K (mg kg ⁻¹)	0–10	190.7	240.1	–0.23	–21
Total N (%)	10–40	0.050	0.150	–1.10	–67
Available P (mg kg ⁻¹)	10–40	1.50	2.80	–0.62	–46
Available K (mg kg ⁻¹)	10–40	165.4	205.2	–0.22	–19

Means of the samples collected in each area; sample-level values were not available, so no inferential tests are reported.

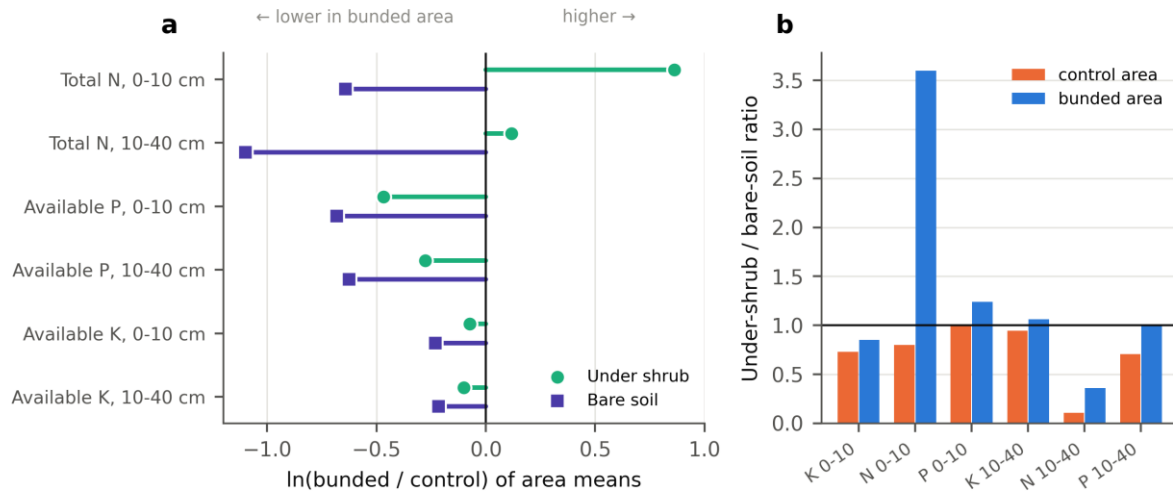


Figure 4. Soil nutrients: (a) log ratio of the banded to the control mean by nutrient, depth and position; (b) fertility-island ratio (under-shrub / bare-soil mean) in each area.

3.3. Runoff capture by the bund design

For the reference case each semi-circular bund has a basin of 3.53 m² and a contributing catchment of 130 m², giving C:CA = 36.7:1. The basins occupy only 2.7% of the banded land. An event of 26 mm fills a basin; with $\alpha = 8$ mm such events occur on average 0.47 times per year, so the basin captures 96% of the runoff it receives. Table 5 separates the water depths involved. With the reference runoff coefficient (RC = 0.25), the catchment generates a runoff-equivalent depth of 25 mm yr⁻¹, i.e. 3.2 m³ of run-on per bund per year. After the captured fraction and the efficiency factor are applied, this run-on adds 663 mm yr⁻¹ over the basin floor, which, together with 100 mm of direct rainfall, gives a depth of water entering the basin of $W \approx 763$ mm yr⁻¹, i.e. $F = 7.6$ (Figure 5a). This value is conditional on the assumed RC and α : for RC = 0.10 and 0.50, W is 375 and 1209 mm yr⁻¹ ($F = 3.8$ and 12.1), whereas varying α from 4 to 12 mm at RC = 0.25 changes F only from 7.9 to 7.1. The storage needed to capture 90% of the runoff at RC = 0.25 is 0.60 m³, below the 0.7–1.0 m³ that was built (Figure 5b); for runoff coefficients above about 0.35, however, the built storage captures noticeably less.

Monte Carlo propagation over the ranges in Table 2 (Figure 6) gives a median concentration factor of 7.2 with a 90% range of 3.7–10.9, corresponding to a depth of water entering the basin of 371–1093 mm yr⁻¹ (Table 5). The overflow threshold has a median of 22 mm (90% range 13–55 mm) and the captured fraction a median of 0.95 (0.74–1.00). The runoff coefficient dominates the uncertainty of the concentration factor (SRRC = 0.91), followed by the efficiency factor (0.30) and the mean event depth (−0.16); bund density and storage have little

influence within their built ranges. The rank regression explains 96% of the variance of F . When RC is fixed at its reference value, the 90% range of F narrows from 3.7–10.9 to 5.4–7.6, whereas fixing α at 8 mm leaves it almost unchanged (3.7–10.7); the uncertainty in the water supplied to the basins is therefore essentially the uncertainty in the runoff coefficient.

Table 5. Water depths in the runoff-capture analysis: rainfall depth, runoff-equivalent depth and depth of water entering the basin

Quantity	RC = 0.10	RC = 0.25 (reference)	RC = 0.50	Monte Carlo median (90% range)
Rainfall depth, P (mm yr ⁻¹)	100	100	100	100 (fixed)
Runoff-equivalent depth over the catchment, $RC \cdot P$ (mm yr ⁻¹)	10	25	50	30 (12–48)
Run-on volume per bund, $RC \cdot P \cdot A_c$ (m ³ yr ⁻¹)	1.30	3.24	6.49	3.89 (1.55–6.25)
Overflow threshold, h^* (mm)	65	26	13	22 (13–55)
Fraction of run-on captured, η	1.00	0.96	0.81	0.95 (0.74–1.00)
Captured run-on after losses, as depth over the basin (mm yr ⁻¹)	275	663	1109	617 (271–993)
Depth of water entering the basin, W (mm yr ⁻¹)	375	763	1209	717 (371–1093)
Concentration factor, $F = W/P$	3.8	7.6	12.1	7.2 (3.7–10.9)

Deterministic columns: $N = 75$ ha⁻¹, $S = 0.85$ m³, $EFF = 0.75$, $\alpha = 8$ mm. Monte Carlo: median and 5th–95th percentiles over the ranges in Table 2 (2×10^5 samples); percentiles are computed row by row and are not additive. The runoff-equivalent depth refers to the catchment area A_c ; the last three depths refer to the basin area A_b . The maximum depth ponded in a single event, S/A_b , is 0.24 m.

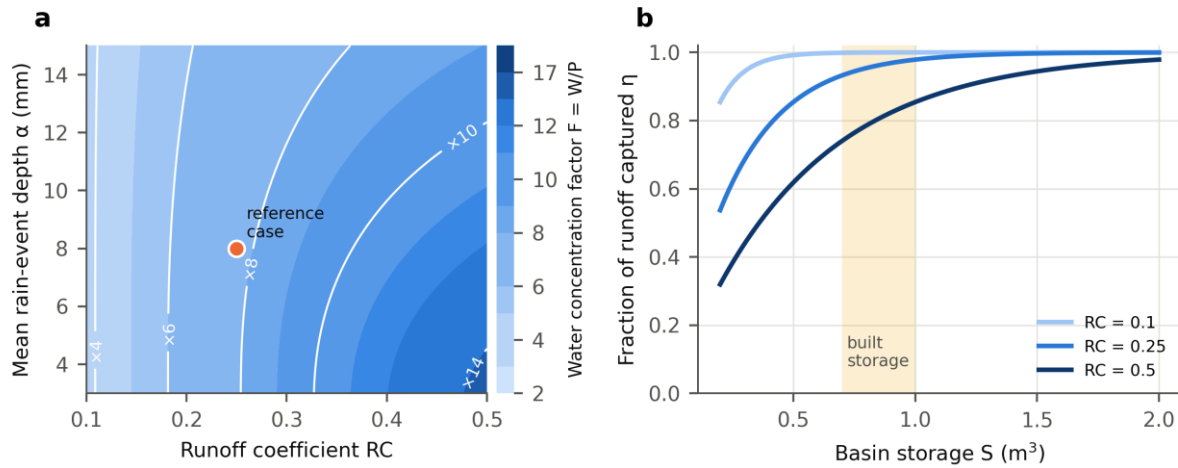


Figure 5. Design space of the Chahgurik semi-circular bunds: (a) water concentration factor $F = W/P$ (depth of water entering the basin divided by the rainfall depth) as a function of the runoff coefficient and the mean rain-event depth ($N = 75 \text{ ha}^{-1}$, $S = 0.85 \text{ m}^3$, $EFF = 0.75$); (b) fraction of runoff captured as a function of basin storage for three runoff coefficients ($\alpha = 8 \text{ mm}$).

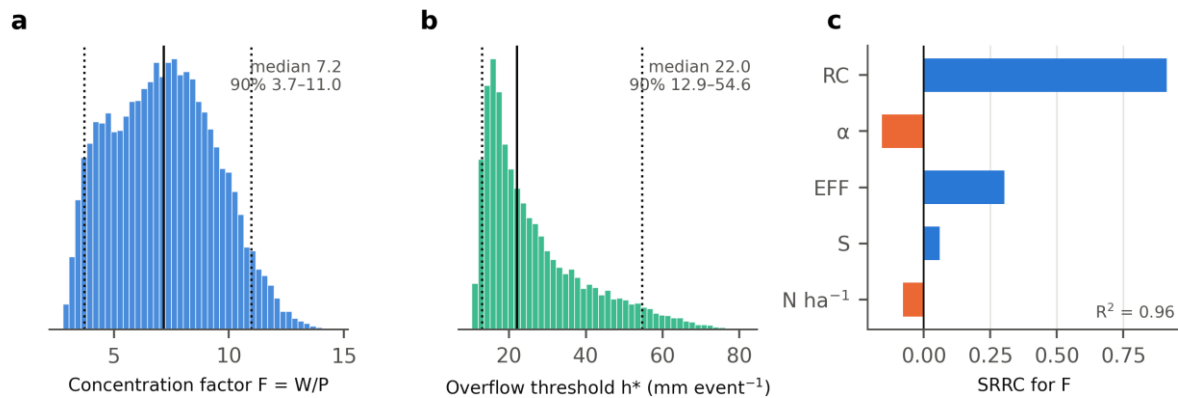


Figure 6. Monte Carlo propagation of design uncertainty: distributions of (a) the water concentration factor and (b) the overflow threshold, with the median (solid) and the 5th and 95th percentiles (dotted); (c) standardised rank regression coefficients of the inputs for the concentration factor.

4. Discussion

4.1. Why the vegetation difference was modest

Eleven to twelve years after construction, the banded area carried about 14% more *Ar. sieberi* cover than the control area. This is a smaller difference than the large increases in cover, production and nutrients reported for bunds elsewhere in Sistan and Baluchestan (Khosravi et al., 2016) or for Sahelian semi-circular bunds (Mishra et al., 2023). The design analysis offers a plausible, although untested, explanation. The Chahgurik bunds have a radius of 1.5 m, so at 70–80 bunds per hectare their basins cover less than 3% of the land and each basin drains a catchment about 37 times its own area. Within the basin, the depth of water received (direct rainfall plus captured run-on) is estimated at about seven times the rainfall depth, i.e. several hundred millimetres per year. This estimate is conditional on the assumed runoff coefficient and rain-event depth, but even its lower bound (about 370 mm yr^{-1} at $RC = 0.10$; Table 5) is far above the rainfall of about 250 mm at which *Ar. sieberi* cover peaks in the Iranian steppes (Mirdavoudi et al., 2022). Outside the basins, which is where most of the

randomly placed plots fell, the bunds redistribute water away from the catchment. The net area-level difference is therefore expected to be diluted: a potentially strong local effect on a small area and little or no effect on the rest. Because plots were not stratified by position relative to the bunds, this explanation remains a hypothesis to be tested by sampling basins, ridges and catchments separately. The FAO reference designs for semi-circular bunds use a radius of 6 m or more and C:CA ratios of 1.4:1 to 3:1 (Critchley and Siegert, 1991), which treat a much larger fraction of the land; they are, however, intended for rainfall of at least 200 mm, twice that at Chahgurik.

The soil results are consistent with this interpretation. Nutrient levels in the banded area were mostly lower than in the control area, but the contrast between shrub patches and bare inter-shrub soil was stronger, especially for surface N. Concentrated runoff moves fine sediment and organic matter from the catchment into the basins and towards established shrubs, which reinforces fertility islands (Schlesinger et al., 1996; Ludwig et al., 2005) while depleting the source areas. Without sample-

level soil data and without soil samples from inside the basins themselves, however, the soil differences cannot be separated from pre-existing differences between the two areas, and they should not be read as an effect of the bunds on area-wide fertility. Zougmore et al. (2003) showed that semi-circular bunds on nutrient-poor soils do not raise productivity unless nutrients are added; the low P values at Chahgurik ($1\text{--}3\text{ mg kg}^{-1}$) suggest that phosphorus may limit the response even where water is concentrated.

4.2. Design implications for very dry rangelands

Three practical recommendations follow. First, in rangelands receiving about 100 mm of rain, the bund design should be chosen from the area that is expected to respond, not only from the number of structures per hectare. Larger bunds or a lower C:CA would spread the harvested water over more land, at the price of more earthwork and lower concentration per basin; the water-balance relations of Section 2.5 make this trade-off explicit. Second, the storage of the existing bunds is adequate for typical runoff coefficients, and the uncertainty of the design is dominated by the runoff coefficient. Measuring runoff from a few instrumented micro-catchments would therefore narrow the design uncertainty more than any other field measurement. Third, the basins should be seeded or planted with the target shrubs, and organic amendments or phosphorus should be considered where soils are as poor as at Chahgurik (Zougmore et al., 2003; Louhaichi et al., 2022).

4.3. Limitations and recommendations for monitoring

The field comparison has the structure of a single bunded area and a single control area, without pre-construction data. Plots are therefore replicates of the areas, and any pre-existing difference between the areas is confounded with any effect of the bunds (Hurlbert, 1984). The reported differences and effect sizes should therefore be interpreted as a site-specific association with bunding rather than as a causal or generalisable treatment effect. The power analysis shows that ten plots per area give only a coin-flip chance of detecting even a large effect; future evaluations should use at least 20 plots per area, several paired bunded and control blocks, and separate sampling inside basins, on ridges and in the catchment. Remote-sensing time series of vegetation indices before and after construction offer a low-cost way to add a baseline, as done for Sahelian semi-circular bunds (Mishra et al., 2023). Finally, the design analysis uses a runoff coefficient taken from design guidance rather than measured at the site and a mean event depth that was assumed rather than estimated from daily records, and it treats events as independent; with daily rainfall from the local gauge both assumptions can be replaced by observed event statistics. Gains from micro-catchments in arid rangelands can also fade as basins fill with sediment (Eldridge and Ding, 2023), so repeated

surveys are needed to judge the long-term benefit. The results also refer to a single cohort of bunds, built in 2005 and 11–12 years old at sampling. Vegetation and soil responses may change with time since construction, as shrubs establish in the basins and the basins fill with sediment, so the results should not be extrapolated to younger or older bunds; the bunds built in 2014–2016 in the same rangeland offer an opportunity for a chronosequence comparison.

5. Conclusions

(1) Eleven to twelve years after construction, the canopy cover of *Ar. sieberi* at Chahgurik was 1.04 percentage points (13.5%, 95% CI 1.1–27.5%) higher in the bunded area than in the adjacent control area; the difference is statistically significant with parametric and permutation tests but imprecise; the study had a power of only 0.51 and, without replicated areas or pre-construction data, the difference can be interpreted only as an association with bunding.

(2) Available P and K were lower in the bunded area, while total N was higher under shrubs in the surface soil. The bunded area showed stronger fertility islands rather than higher nutrient levels across the area.

(3) The bund geometry concentrates water strongly: C:CA $\approx$ 37:1, and the annual depth of water entering each basin (direct rainfall plus captured run-on) is estimated at 3.7–10.9 times the rainfall depth (median 7.2), but on less than 3% of the land. This estimate is conditional on the assumed runoff coefficient and rain-event depth. The built storage captures most of the runoff; the runoff coefficient controls the design uncertainty.

(4) In rangelands with about 100 mm of rain, bund size and density should be chosen from the area expected to respond, basins should be planted and possibly amended, and evaluations should be replicated, baseline-referenced and adequately powered.

Data availability

The plot-level canopy data, the area-mean soil data, the analysis and figure scripts, the Monte Carlo outputs and the water-depth decomposition of Table 5 are provided as supplementary material.

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