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Contour-Based Trenches as a Nature-Based Solution for Soil Restoration and Potential Managed Aquifer Recharge in Guerrero, Mexico

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Abstract

Land degradation and declining groundwater availability threaten the sustainability of rural livelihoods across semi-arid regions. This study evaluates the hydrological performance of contour-based trenches as a low-cost and replicable nature-based solution (Nbs) for soil restoration, runoff regulation, and potential distributed managed aquifer recharge (MAR) in Guerrero, Mexico. The structures were installed on 12% slopes and designed using a simplified water balance criterion based on trench storage capacity, runoff coefficient, and representative rainfall events. Each trench was constructed along contour lines with overflow notches and connecting micro-trenches to improve hydraulic continuity, reduce erosion, and enhance infiltration opportunities under degraded field conditions. After one year of field monitoring, the trenches reached an average filling efficiency of approximately 90% per effective rainfall event, with estimated infiltration rates ranging from 0.0069 to 0.011 $L \cdot s^{-1}$. Soil moisture in the upper soil layer showed a relative increase of approximately 10–18% compared to adjacent untreated areas, while visible reductions in runoff velocity, sediment transport, and surface erosion were observed across the treated plot. Based on trench storage capacity, observed infiltration behavior, and assumed deep percolation fractions, the potential induced recharge was estimated between 216 and 360 $m^3 \cdot yr^{-1}$ (43–72 $mm \cdot yr^{-1}$). These values represent indicative plot-scale estimates rather than direct measurements of aquifer recharge, since no tracer studies or piezometric validation were performed. The results demonstrate that contour-based trenches contribute not only to infiltration enhancement and runoff control, but also to short-term soil restoration and improved water availability in rainfed agricultural systems. Their low-cost implementation, combined with community-based maintenance and adaptation to local environmental conditions, makes them a viable complementary strategy for strengthening decentralized water management, soil resilience, and climate adaptation in semi-arid rural landscapes. However, long-term effectiveness remains dependent on maintenance continuity, institutional support, and local governance conditions. Further multi-year monitoring and direct hydrogeological validation are recommended to improve the design and replicability of decentralized MAR systems.

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Keywords: nature-based solutions; contour-based trenches; soil restoration; runoff regulation; managed aquifer recharge; distributed infiltration; rural water security; watershed restoration

1. Introduction

Land degradation, declining soil fertility, and seasonal groundwater scarcity are among the main environmental constraints affecting rural livelihoods in semi-arid regions of southern Mexico and other tropical dryland systems worldwide. In sloping agricultural landscapes, the reduction in vegetation cover, soil compaction, and uncontrolled surface runoff accelerate erosion processes, reduce infiltration capacity, and limit groundwater recharge, directly affecting rainfed agricultural productivity and local water security [1,2].

Nature-based solutions (Nbs) have emerged as an important strategy for restoring degraded hydrological functions while improving ecosystem resilience under climate variability. These approaches seek to recover natural ecological processes through low-cost and adaptive interventions that enhance infiltration, reduce runoff, improve soil moisture retention, and strengthen local water regulation [3,4].

Among these strategies, contour-based trenches, infiltration ditches, and micro-catchment systems have been widely implemented as decentralized runoff harvesting practices in semi-arid agricultural landscapes. Their effectiveness has been associated with reduced runoff velocity, sediment retention, improved infiltration, and increased short-term soil moisture availability [5–7]. In some cases, these systems have also been discussed within the framework of distributed managed aquifer recharge (MAR), particularly where infiltration enhancement may contribute indirectly to groundwater replenishment [8,9].

However, most previous studies have focused either on large-scale engineered MAR infrastructure such as recharge wells, infiltration basins, and percolation ponds or on controlled experimental infiltration systems with limited integration of community-managed field conditions [10,11]. Fewer studies have evaluated small-scale contour trench systems operating under real rural management conditions, particularly in tropical sub-humid regions of Mexico where seasonal groundwater dependence and land degradation occur simultaneously.

Additionally, several studies report infiltration benefits but provide limited field-based evidence regarding the relationship between runoff control, gradual deep percolation, and practical recharge estimation at the plot scale. Uncertainty commonly remains regarding the contribution of distributed infiltration systems to actual aquifer recharge, especially where direct hydrogeological validation through tracers or piezometric monitoring is not available [12,13].

In Mexico, contour-based trenches have been widely promoted by CONAFOR and other watershed restoration programs for erosion control and soil conservation. Nevertheless, scientific evaluations of their hydrological performance, infiltration efficiency, and potential contribution to distributed MAR under field conditions remain limited, particularly in the community-managed rural systems of the Costa Chica region of Guerrero.

The novelty of this study lies in the integration of field-based hydrological monitoring, simplified recharge estimation, and community-managed implementation of contour-based trenches as a practical Nbs under semi-arid rural conditions. Unlike studies focused exclusively on engineering design or theoretical recharge modeling, this research evaluates the real operational performance of approximately 400 contour-based trenches installed in a 0.5 ha degraded agricultural plot under active community participation.

The study contributes quantitative evidence on trench filling efficiency, infiltration behavior, soil moisture improvement, and indicative plot-scale recharge estimates, while also discussing the limitations, uncertainty, and governance conditions that influence long-term functionality. This approach provides added value by linking hydrological restoration with feasible local implementation, offering a replicable framework for decentralized water management in regions where conventional MAR infrastructure is technically or economically inaccessible (Table 1).

Table 1. Summary of previous studies on nature-based solutions, infiltration systems, and managed aquifer recharge (MAR).

Authors	Study Area	System Evaluated	Main Contribution	Main Limitation Identified
[5]	Semi-arid agricultural regions	Infiltration trenches and runoff harvesting systems	Improved runoff interception and soil moisture retention	Limited direct evidence of groundwater recharge
[14]	Sloping dryland farming systems	Distributed infiltration structures	Increased infiltration and erosion control	Lack of long-term hydrological monitoring
[8]	Global MAR systems	Managed aquifer recharge (MAR) infrastructure	Conceptual framework for MAR and recharge pathways	Focused mainly on engineered recharge systems
[15]	Semi-arid watershed restoration	Recharge basins and infiltration ponds	High recharge potential and hydrogeological monitoring	High financial and technical requirements
[16]	Agricultural hillslopes	Micro-catchments and contour systems	Reduction in runoff velocity and sediment transport	Limited evaluation under community-managed conditions
[17]	Rural participatory water systems	Community-managed MAR practices	Importance of local participation and maintenance	Limited hydrological quantification
[12]	Mexico	Distributed infiltration systems	Field evidence of infiltration enhancement	Limited recharge validation through direct monitoring
Present study	Las Ánimas, Guerrero, Mexico	Contour-based trenches as NbS for distributed MAR	Field-based hydrological monitoring + simplified recharge estimation + community-managed implementation	No direct tracer validation; one-year monitoring period

Therefore, the objective of this study was to evaluate the hydrological performance of contour-based trenches as a nature-based solution for soil restoration, runoff regulation, and potential distributed managed aquifer recharge in Las Ánimas, Guerrero, Mexico, under community-managed field conditions.

Research-hypotheses:

H1. *Contour-based trenches designed using a simplified water balance criterion can achieve high filling efficiency (>80%) under representative effective rainfall events in semi-arid rural conditions, contributing to runoff regulation and improved infiltration.*

H2. *Community-managed contour-based trenches can enhance soil moisture retention and promote potential groundwater recharge at the plot scale through increased infiltration and gradual deep percolation.*

2. Materials and Methods

2.1. Study Area

The study was conducted in the rural locality of Las Ánimas, Municipality of Tecoanapa, located in the Costa Chica region of Guerrero, southern Mexico (16°44′ N, 99°15′ W). The experimental plot, locally known as "El Sitio", is situated at an elevation ranging from approximately 180 to 220 m above sea level. The regional climate is tropical sub-humid, with a mean annual temperature of approximately 31 °C and an average annual precipitation of nearly 1200 mm, concentrated mainly during the rainy season from June to October, as can be seen in the Figure 1 using the ArcGIS 10.3 software (Esri, Redlands, CA, USA).

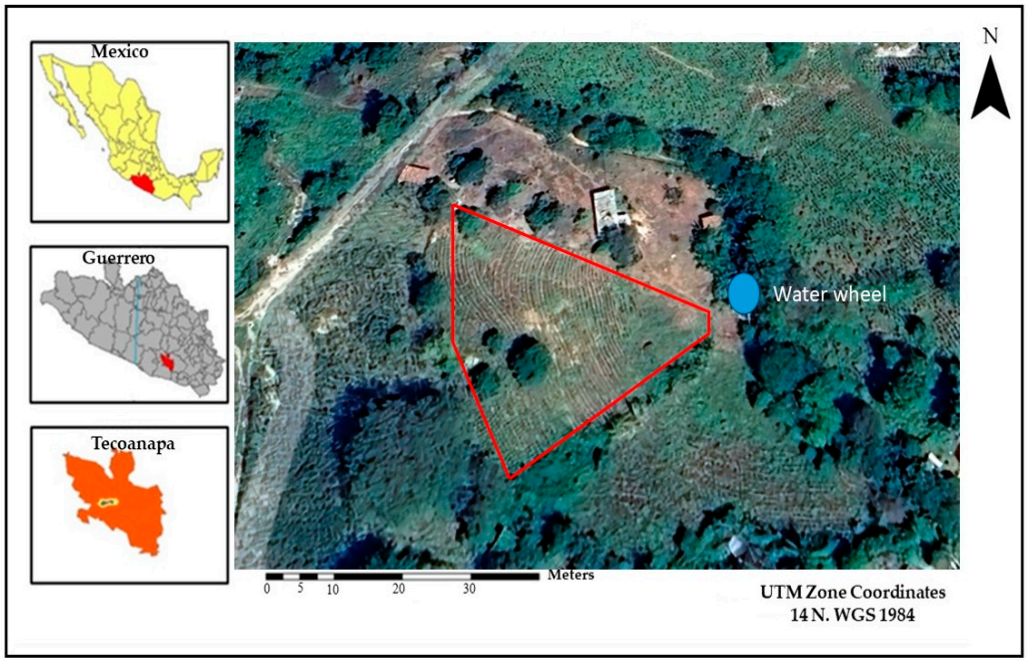


Figure 1. Geographic location of the experimental plot "El Sitio" in Las Ánimas, Municipality of Tecoanapa, Guerrero, Mexico.

The topography of the study area is characterized by moderate to steep slopes ranging from 10 to 15%, with the experimental plot presenting an average slope of 12%, which favors rapid runoff generation during intense rainfall events. The soils are shallow, compacted, and predominantly clay-rich, with reduced vegetation cover as a consequence of long-term agricultural expansion, deforestation, and continuous land-use pressure.

Field observations identified surface crusting, rill erosion, sediment displacement, and concentrated runoff pathways, all of which indicate limited infiltration capacity and significant soil degradation. These conditions contribute to reduced natural groundwater recharge and increased vulnerability of local agricultural systems.

Local livelihoods depend primarily on rainfed maize cultivation and small-scale livestock production. Domestic and agricultural water supply relies mainly on shallow wells and norias, which commonly experience seasonal declines in water levels during the dry season. This dependence on rainfall and shallow groundwater makes the community highly vulnerable to hydrological variability and reinforces the need for low-cost strategies that improve soil moisture retention, runoff regulation, and local water security.

In this context, contour-based trenches represent a practical intervention that integrates traditional land management knowledge with hydrological restoration, offering a feasible alternative for improving infiltration processes and reducing land degradation under smallholder farming conditions.

2.2. Design and Construction of Trenches

The intervention consisted of the construction of contour-based trenches designed to intercept, retain, and gradually infiltrate surface runoff under sloping agricultural conditions. These structures were established following technical criteria commonly used in soil and water conservation programs promoted by CONAFOR, particularly for hillside restoration, runoff control, and infiltration enhancement in degraded rural landscapes.

Each trench was prismatic, with dimensions of 2.00 m in length, 0.50 m in width, and 0.50 m in depth, corresponding to an effective storage volume of 0.50 m^3. These dimensions were selected based on field conditions, local slope characteristics, and practical recommendations adapted from technical manuals used in watershed restoration programs. Trenches were excavated manually by local community members following contour lines to reduce runoff velocity, minimize erosive flow concentration, and facilitate gradual infiltration (Figure 2).

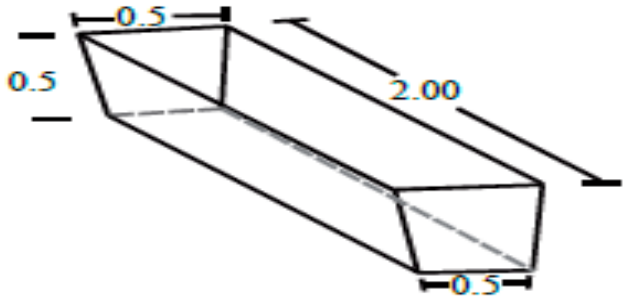


Figure 2. Dimensions of the trenches.

A freeboard equivalent to 10% of the trench depth was incorporated to prevent overtopping during high-intensity rainfall events. Overflow notches were constructed at one end of each trench to allow controlled discharge toward adjacent micro-trenches located downslope. These connecting micro-trenches ensured hydraulic continuity between structures while preventing uncontrolled erosion, sediment displacement, and structural failure.

The dimensions illustrated in Figures 2 and 3 were adapted from technical guidelines developed by CONAFOR for contour trench systems used in soil restoration and water harvesting programs in Mexico. Therefore, the figures should be cited as adapted technical references rather than original schematic designs.

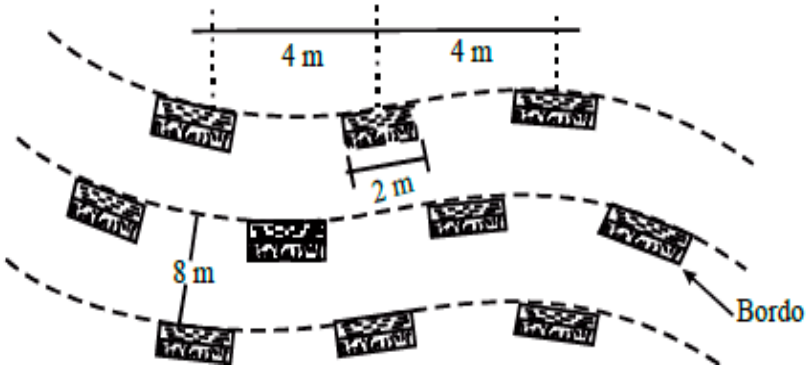


Figure 3. Distribution of the ditches on the plot.

The spatial arrangement and density of the trenches were determined using a simplified water balance criterion expressed as:

$$Acapt = \frac{V}{C \cdot P}$$

where Acapt is the contributing catchment area required per trench (m^2), V is the effective storage volume of the trench (m^3), C is the runoff coefficient (dimensionless), and P is the design rainfall depth expressed in meters (m).

A methodological clarification was necessary regarding the rainfall unit because part of the original manuscript reported the precipitation value as P = 40 mm, which could generate confusion if directly substituted into the equation without unit conversion. For the hydrological calculation, rainfall was converted as follows:

$$P = 40 \text{ mm} = 0.04 \text{ m}$$

Using this corrected unit:

For C = 0.30, the contributing area was approximately 41.6 m^2.

For C = 0.40, the contributing area was approximately 31.3 m^2.

These values are physically consistent and correspond to the reported contour spacing between 5.6 and 6.5 m for the average slope of 12% observed in the study area.

The runoff coefficient (C = 0.30–0.40) was selected considering compacted, partially bare, and predominantly clay-rich soils with reduced vegetation cover, which are typical of the experimental plot. This range is consistent with values reported for degraded rural hillslopes under similar runoff conditions.

The design rainfall (P = 40 mm) was selected based on local precipitation records and corresponds approximately to the median of effective rainfall events observed during field monitoring. It was considered representative because it generates visible runoff and measurable trench filling without representing extreme storm conditions, allowing a practical and conservative design criterion for community-level implementation.

From this balance, the optimal contributing area per trench ranged from 31.3 to 41.6 m^2, equivalent to contour spacing between 5.6 and 6.5 m for a 12% slope. Following the vertical interval method, trenches were distributed downslope every 4.17 m to maintain hydraulic uniformity and maximize runoff interception efficiency. For the 0.5 ha experimental plot, approximately 400 trenches were installed.

This design allowed the system to function not as isolated structures, but as an integrated network of distributed micro-catchments that enhance runoff regulation, sediment retention, infiltration, and potential deep percolation under field conditions.

2.3. Spatial Distribution of Trenches

Based on the simplified water balance criterion, the calculated contributing area required for each trench ranged from 31.3 to 41.6 m^2, depending on the assumed runoff coefficient and the representative rainfall event used for design. For the average slope of 12% observed in the experimental plot, this resulted in a recommended horizontal contour spacing between 5.6 and 6.5 m, which allowed effective runoff interception without excessive overlap between adjacent structures.

To maintain hydraulic continuity and slope stability, trench distribution was also evaluated using the vertical interval method commonly applied in hillside soil conservation practices. Under this criterion, the vertical spacing between contour lines was established at approximately 4.17 m, which corresponds to the topographic conditions of the site and ensures gradual runoff interception downslope.

This distinction between horizontal spacing (5.6–6.5 m) and vertical interval (4.17 m) is important to avoid confusion, as both parameters describe different components of trench layout. The horizontal spacing refers to the contributing runoff area per trench, while the vertical interval defines the elevation difference between consecutive contour lines.

This clarification responds directly to the reviewer's observation regarding the apparent inconsistency between Figure 3 and the text.

A total of approximately 400 contour-based trenches were installed within the 0.5 ha experimental plot, creating a high-density distributed infiltration system adapted to the slope configuration and local hydrological conditions. The trenches were arranged following contour lines across the plot to maximize runoff retention, reduce erosive flow concentration, and improve infiltration opportunities throughout the treated area.

The spatial distribution was documented using annotated aerial imagery and field verification, showing trench orientation, spacing, slope position, and hydraulic connectivity between adjacent structures. Figures 2 and 3 were adapted from technical guidelines of CONAFOR and adjusted to local field conditions, ensuring transparency, reproducibility, and methodological consistency.

This design allowed the system to function not as isolated structures, but as an integrated network of distributed micro-catchments that enhance runoff regulation, sediment retention, and potential deep percolation at the plot scale.

2.4. Field Monitoring and Data Collection

Field monitoring was conducted over a one-year period, from June 2023 to May 2024, covering the complete rainy season and the subsequent dry season. During this period, four main effective rainfall events were selected for detailed hydrological evaluation. These events were defined as effective rainfall events because they exceeded 40 mm of precipitation, generated visible surface runoff, and produced measurable water accumulation inside the contour-based trenches. This threshold was established based on local precipitation behavior and field observations, ensuring consistency with the design rainfall criterion used in the study.

Following each rainfall event, trench filling percentages were recorded using graduated rulers installed at the center of representative trenches distributed across the experimental plot. Measurements were taken within the first 12 to 24 h after rainfall cessation to minimize the influence of evaporation and ensure reliable estimation of retained water volumes.

Although approximately 400 trenches were installed in the 0.5 ha plot, detailed monitoring focused on representative sections located across upper-, middle-, and lower-slope positions to evaluate spatial consistency in filling behavior and infiltration performance. This approach allowed comparison of runoff capture efficiency and infiltration behavior along the slope profile.

No independent control plot without trenches was available because the intervention was implemented directly under community management conditions across the restoration area. Therefore, the study was designed as an applied field evaluation rather than a controlled experimental comparison. This limitation was considered in the interpretation of results and partially addressed by comparing soil moisture conditions with adjacent untreated areas.

Infiltration rates were estimated by measuring the decline in water level inside the trenches after rainfall events, considering the retention period and excluding periods with direct precipitation input. This procedure allowed estimation of infiltration behavior under field conditions without disturbing the natural functioning of the system. Measurements were repeated during the first 12–24 h after rainfall cessation to reduce bias associated with evaporation losses.

Sediment accumulation, structural stability, overflow behavior, and signs of erosion or overtopping were visually inspected after each event. Minor sediment retention was

observed inside several trenches, while no significant structural failures or uncontrolled overflow were detected during the monitoring period.

Soil samples were collected at depths of 0–30 cm and 30–60 cm both inside the trench influence zone and in adjacent untreated areas to compare infiltration-related properties. Laboratory analyses included soil texture, bulk density, and qualitative infiltration behavior. Results confirmed predominantly clay-rich soils with moderate compaction and reduced infiltration capacity, supporting the hydrological assumptions used for recharge estimation.

Rainfall data were obtained from the nearest official climatological station located in Tecoanapa, approximately 8 km from the study site, and were cross-validated using manual rain gauges installed within the experimental plot. This local validation improved confidence in rainfall representation and allowed adjustment of event-specific field observations, particularly regarding rainfall intensity and runoff generation.

Groundwater levels were monitored monthly in a local community well approximately 2 m in diameter and 10 m in depth, located near the intervention area. These observations were exploratory and were used only to identify temporal correspondence between rainfall, infiltration events, and seasonal water level fluctuations, rather than as direct quantitative validation of aquifer recharge.

Additionally, a descriptive survey was conducted with participating community members involved in trench construction and maintenance to document local perceptions regarding soil moisture improvement, vegetation recovery, sediment accumulation, and maintenance requirements. Although qualitative in nature, this information complemented the hydrological observations and strengthened the interpretation of community-managed implementation feasibility.

2.5. Estimation of Induced Recharge and Sensitivity Analysis

The potential induced groundwater recharge (Rind) was estimated using a simplified plot-scale water balance approach based on trench storage capacity, observed filling efficiency, and the fraction of infiltrated water assumed to contribute to deep percolation. The estimation was expressed as:

$$Rind = n \times N \times V \times \phi$$

where n is the number of installed trenches, N is the number of effective rainfall events per year, V is the effective storage volume per trench (m^3), and ϕ is the fraction of infiltrated water that potentially contributes to deep percolation beyond the active root zone.

This simplified criterion was adapted from approaches commonly used in distributed runoff harvesting and infiltration studies [12,14,18], where direct aquifer measurements are not available and recharge must be inferred from hydrological field observations. The model was selected because it provides a practical estimation framework for rural field conditions and supports community-level implementation without requiring complex hydrogeological instrumentation.

For the implemented configuration, approximately 400 trenches were installed within the 0.5 ha experimental plot, each with an effective storage volume of 0.50 m^3. Based on field monitoring, four effective rainfall events per year (N = 4) were considered representative of runoff-generating precipitation conditions.

The percolation fraction (ϕ = 0.30–0.50) was assumed based on soil texture analysis, observed infiltration behavior, and values reported in previous studies under similar clay-rich and moderately compacted soil conditions. This parameter represents the proportion of infiltrated water that potentially moves beyond the active root zone and contributes to gradual deep percolation, excluding water retained in the upper soil layers or lost through evapotranspiration.

The values of ϕ were not directly measured through tracer studies, deep percolation sensors, or piezometric monitoring. Instead, they were estimated using three complementary criteria.

First, soil texture analysis confirmed predominantly clay-rich soils with moderate compaction, which favor partial infiltration but also limit rapid deep percolation.

Second, field infiltration behavior showed gradual infiltration and temporary water retention inside the trenches after rainfall events, suggesting that part of the stored water could move below the active root zone.

Third, the selected range is consistent with values reported in distributed infiltration systems and small-scale managed aquifer recharge (MAR) studies under similar environmental conditions, particularly under degraded hillslope conditions with seasonal runoff concentration.

Potential evaporation losses were considered qualitatively during field interpretation. Because infiltration generally occurred within 12–24 h after rainfall events and water retention inside the trenches was temporary, evaporation was considered secondary compared to infiltration. However, under prolonged dry conditions or slower infiltration rates, evaporation may represent an important component of the local water balance.

Similarly, possible lateral subsurface flow and downslope return flow were recognized as processes that may reduce the fraction of water contributing to deep percolation. For this reason, the reported recharge values should be interpreted as indicative plot-scale estimates of potential recharge rather than direct measurements of aquifer replenishment.

Under these assumptions, the estimated potential recharge ranged between 216 and 360 $m^3 \cdot yr^{-1}$, equivalent to approximately 43–72 $mm \cdot yr^{-1}$ when normalized to the plot area.

To reduce uncertainty and improve the robustness of the analysis, a sensitivity analysis was performed by varying the deep percolation fraction (ϕ) between 0.20 and 0.60 and the number of effective rainfall events (N) between 3 and 5 per year. Under these scenarios, the estimated recharge ranged from approximately 180 to 450 $m^3 \cdot yr^{-1}$.

Although variability was observed across scenarios, the order of magnitude remained consistent, indicating that the system maintains similar hydrological behavior within realistic parameter ranges. This sensitivity analysis supports the interpretation that contour-based trenches can provide stable infiltration benefits under field conditions, while also reinforcing the need for cautious interpretation of recharge estimates.

It is important to emphasize that no direct tracer studies, piezometric analyses, or aquifer response measurements were conducted in this study. Therefore, the reported recharge values should be understood as indicative estimates of potential groundwater contribution at the plot scale rather than definitive quantification of aquifer recharge.

3. Results

3.1. Hydrological Performance of Contour-Based Trenches

The contour-based trenches exhibited stable and consistent hydrological performance throughout the monitoring period. Field observations conducted after four effective rainfall events during the 2023 rainy season indicated that the trenches reached an average filling level of approximately 90%, supporting the adequacy of the design spacing and storage capacity derived from the simplified water balance criterion (Figure 4).

Trench filling percentages ranged from 78% to 100%, with a mean value of 90% ± 6%. Measurements were obtained from representative monitored sections distributed across approximately 400 installed trenches, including upper-, middle-, and lower-slope positions, allowing the assessment of spatial consistency in runoff capture and infiltration behavior throughout the experimental plot.



Figure 4. Average filling level and infiltration rate per rainfall event for contour-based trenches during the 2023 monitoring period.

No overtopping, structural collapse, or significant lateral erosion was observed, even during rainfall events exceeding 40 mm·h^{-1}, indicating that the freeboard and overflow notch design effectively controlled excess runoff and maintained hydraulic stability.

Estimated infiltration rates, derived from post-rainfall water level decline inside the trenches, ranged from 0.0069 to 0.011 L·s^{-1}, with a mean value of 0.0091 ± 0.0014 L·s^{-1}. Minor variability among monitored sections was associated mainly with antecedent soil moisture conditions, sediment accumulation, and slope position. Slightly higher infiltration rates were observed in upper-slope trenches where runoff concentration tended to be greater (Table 2).

Table 2. Hydrological and design parameters of contour-based trenches.

Parameter	Symbol	Value Range	Units	Description
Slope	S	12	%	Average slope of the study area
Runoff coefficient	C	0.30–0.40	–	Based on soil compaction and reduced vegetation cover
Representative rainfall event	P	40 (0.04 m)	mm (m)	Design rainfall used in the simplified balance
Trench dimensions	–	2.00 × 0.50 × 0.50	m	Length × width × depth
Effective trench volume	V	0.50	m^3	Effective storage volume
Contributing catchment area	Acapt	31.3–41.6	m^2	Area contributing runoff to each trench
Deep percolation fraction	ϕ	0.30–0.50	–	Estimated fraction of infiltrated water contributing to deep percolation
Number of trenches	n	400	units·0.5 ha^{-1}	Installed contour-based trenches
Effective rainfall events	N	4	events·yr^{-1}	Representative runoff-generating rainfall events
Potential induced recharge	Rind	216–360	m^3·yr^{-1}	Indicative plot-scale recharge estimate
Infiltration rate	Q	0.0069–0.011	L·s^{-1}	Estimated infiltration flow

Overall, infiltration performance remained within a relatively narrow and stable range across rainfall events, suggesting that the system maintained consistent hydrological behavior under varying precipitation conditions.

In addition to quantitative measurements, qualitative field observations indicated a visible reduction in surface runoff velocity and sediment transport within the treated plot. Fine sediments were retained inside the trenches, contributing to improved soil moisture conditions in the upper soil layers and reducing erosive processes downslope.

Soil moisture content in the topsoil layer (0–30 cm) increased by approximately 10–18% compared to adjacent untreated areas during the monitoring period. This value corresponds to a relative percentage increase rather than an absolute percentage point increase, which improves the interpretation of the hydrological effect of the contour-based trenches. This improvement was particularly evident after consecutive rainfall events, suggesting that the trenches contributed not only to infiltration but also to short-term soil water retention, which is relevant for rainfed agricultural systems.

Community observations supported these findings. After the first rainy season, the treated area showed noticeable vegetation recovery, particularly in herbaceous cover, which further contributed to reducing surface erosion and improving soil stability. Maintenance requirements were limited mainly to minor sediment removal and occasional reinforcement of overflow notches, confirming the low operational demand and practical feasibility of community-managed implementation.

These results indicate that contour-based trenches function effectively as distributed runoff regulation structures that enhance infiltration and soil moisture while reducing degradation processes. However, given the one-year monitoring period and the absence of a control plot, the long-term hydrological performance and broader recharge effects should be interpreted cautiously and remain dependent on continued maintenance and local environmental conditions.

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Overall, infiltration performance remained within a relatively narrow and stable range across rainfall events, suggesting that the system maintained consistent hydrological behavior under varying precipitation conditions. Figure 4 illustrates the filling percentages and estimated infiltration rates recorded for each rainfall event, highlighting the reproducibility of trench performance under field conditions.

In addition to quantitative measurements, qualitative field observations indicated a visible reduction in surface runoff velocity and sediment transport within the treated plot. Fine sediments were retained inside the trenches, contributing to improved soil moisture conditions in the upper soil layers and reducing erosive processes downslope.

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3.2. Estimated Induced Recharge

Based on the monitored trench filling efficiency and estimated infiltration behavior, the potential induced groundwater recharge was calculated using the parameters described in the previous section. For the implemented setup, consisting of approximately 400 contour-based trenches distributed across a 0.5 ha experimental plot and four effective rainfall events per year, the estimated potential recharge ranged from 216 to 360 $m^3 \cdot year^{-1}$, which corresponds to approximately 43–72 $mm \cdot year^{-1}$ when normalized to the plot area.

These values represent indicative plot-scale estimates derived from trench storage capacity, observed infiltration performance, and assumed deep percolation fractions (ϕ), rather than direct measurements of aquifer recharge. The results therefore reflect the potential hydrological contribution of the trench system to groundwater replenishment under the specific environmental and management conditions of the study area.

Groundwater level observations conducted in a nearby community well were exploratory in nature and were used only to examine temporal correspondence between rainfall events, infiltration processes, and seasonal fluctuations in shallow groundwater levels. These observations were not intended to serve as quantitative validation of aquifer recharge, since no tracer experiments, piezometric monitoring, or direct hydrogeological measurements were performed.

To evaluate the sensitivity of recharge estimates to uncertainty in key parameters, a sensitivity analysis was performed by varying the deep percolation fraction (ϕ) between 0.20 and 0.60 and the number of effective rainfall events (N) between 3 and 5 per year. Under these realistic scenarios, the estimated potential recharge ranged from approximately 180 to 450 $m^3 \cdot yr^{-1}$.

Although this range reflects variability associated with climatic conditions, soil infiltration behavior, and rainfall distribution, the overall order of magnitude remained relatively stable, suggesting that the system provides a consistent hydrological contribution under field conditions. However, these estimates should be interpreted cautiously, as local factors such as evaporation losses, sediment accumulation, lateral subsurface flow, and maintenance conditions may influence actual recharge outcomes over time.

Accordingly, the recharge values reported in this study should be understood as indicative estimates of potential groundwater contribution at the plot scale rather than definitive quantification of aquifer replenishment. This distinction is particularly important for avoiding overestimation of MAR performance and for supporting more realistic application of small-scale infiltration systems in rural water management strategies.

The findings suggest that contour-based trenches can play a relevant complementary role in improving local infiltration processes and enhancing water availability under degraded semi-arid conditions, especially where conventional recharge infrastructure is technically or economically unfeasible. However, they should be interpreted as supportive decentralized interventions rather than direct substitutes for formal hydrogeological recharge systems [19,20].

3.3. Comparison with Similar Distributed MAR Systems

The potential recharge values obtained in Las Ánimas fall within the range commonly reported for distributed managed aquifer recharge (MAR) practices implemented in semi-arid and tropical environments, where recharge contributions generally vary between 30 and 80 mm·yr^{-1} depending on soil conditions, rainfall intensity, slope characteristics, and maintenance practices [5,12,14].

In the present study, contour-based trenches generated estimated recharge values between 43 and 72 mm·yr^{-1}, which are consistent with those reported for infiltration trenches, micro-catchments, and percolation basins used for runoff harvesting and soil moisture improvement in degraded agricultural landscapes.

However, unlike many engineered MAR systems that depend on mechanized construction, imported materials, or permanent hydraulic infrastructure, the contour-based trenches evaluated here operate through manual construction, low-cost maintenance, and direct adaptation to local topographic conditions. This makes them particularly suitable for smallholder farming systems and rural communities with limited financial and technical resources.

Compared with other small-scale MAR systems implemented in agricultural landscapes, the trenches demonstrated comparable infiltration behavior while operating over relatively small contributing areas, suggesting high functional efficiency per unit surface. In addition to infiltration benefits, the trenches also contributed to sediment retention, runoff reduction, and short-term improvement of soil moisture conditions, reinforcing their multifunctional value as nature-based solutions.

Nevertheless, the effectiveness of these systems should not be generalized without considering environmental and hydrological context. Factors such as rainfall distribution, soil texture, slope gradient, vegetation cover, sediment accumulation, and maintenance frequency strongly influence long-term performance. Therefore, the hydrological efficiency observed in Las Ánimas should be interpreted as site-specific evidence rather than universally transferable performance.

These results highlight the potential of contour-based trenches as an accessible and complementary MAR strategy for rural water management, particularly where large-scale recharge infrastructure is not feasible. Their value lies not only in potential groundwater contribution, but also in their capacity to strengthen local soil resilience, improve water retention, and support decentralized climate adaptation strategies.

4. Discussion

4.1. Hydrological Performance of Contour-Based Trenches

The results indicate that contour-based trenches function as an effective hydrological intervention for reducing surface runoff and enhancing infiltration under degraded semi-arid rural conditions. The observed average filling efficiency of approximately 90% per effective rainfall event supports the adequacy of the simplified water balance criterion used for trench design, confirming that substantial runoff capture can be achieved without relying on complex hydrological modeling or high-cost infrastructure.

This finding is consistent with previous studies reporting similar performance for small-scale infiltration structures operating in sloping agricultural landscapes, where runoff interception and temporary water retention improve infiltration opportunities and reduce erosive processes [12,20]. The relatively stable filling percentages observed across monitored events suggest that the system performs consistently under recurrent rainfall conditions, particularly when design parameters are adapted to local slope and soil characteristics.

The narrow range of estimated infiltration rates (0.0069–0.011 $L \cdot s^{-1}$) also indicates relatively stable hydrological behavior across rainfall events and trench positions. Minor variability was associated mainly with antecedent soil moisture, sediment retention, and runoff concentration in upper-slope areas, which is consistent with observations from other distributed infiltration systems implemented on sloping terrain [14,16].

Rather than demonstrating direct aquifer recharge, these findings provide evidence of improved infiltration processes and enhanced opportunities for gradual deep percolation at the plot scale. This distinction is important because the study focuses on field-based estimation of hydrological performance rather than direct quantification of aquifer replenishment. Therefore, the contribution of the trenches should be interpreted primarily as improved runoff regulation and soil water retention, with potential indirect effects on groundwater recharge.

In addition to hydrological performance, the trenches contributed to improved soil moisture conditions, sediment retention, and visible vegetation recovery, highlighting their multifunctional role in soil restoration. The increase in topsoil moisture observed during the monitoring period is particularly relevant for rainfed agricultural systems, where short-term water availability strongly influences crop productivity and resilience during irregular rainfall periods.

These co-benefits have been widely documented in micro-catchment systems and runoff harvesting structures in semi-arid environments, where infiltration enhancement and erosion control are closely linked processes [1,21,22]. In this sense, contour-based trenches should not be understood solely as recharge structures, but as integrated landscape management interventions that improve hydrological regulation and land restoration simultaneously.

However, long-term hydrological performance remains dependent on continued maintenance, sediment removal, vegetation dynamics, and local climatic variability. Without periodic maintenance, trench storage capacity may decline due to sediment accumulation, reducing infiltration efficiency over time. This reinforces the need to interpret the observed effectiveness within the temporal scale of the study and under the specific environmental conditions of the monitored site [23].

Likewise, the absence of a control plot and the limited monitoring period of one hydrological year restrict the possibility of extrapolating these results to broader spatial and temporal scales. For this reason, the findings should be interpreted as strong field evidence of local effectiveness rather than universal hydrological performance applicable to all semi-arid landscapes [24].

4.2. Comparison with Other Managed Aquifer Recharge Practices

The estimated potential recharge values obtained in Las Ánimas (43–72 $mm \cdot yr^{-1}$) fall within the range reported for other distributed managed aquifer recharge (MAR) practices in semi-arid and tropical regions, including infiltration trenches, micro-catchments, percolation basins, and runoff harvesting systems [9,14,20]. These values suggest that contour-based trenches can contribute meaningfully to local infiltration processes under degraded rural conditions.

However, it is important to emphasize that the values reported in this study represent potential recharge contributions inferred from trench storage capacity, observed infiltration behavior, and assumed deep percolation fractions, rather than direct measurements of aquifer replenishment. This distinction is essential for avoiding overinterpretation of MAR performance and for maintaining consistency between the methodological scope and the conclusions drawn [25,26].

Large-scale MAR infrastructures such as recharge wells, infiltration ponds, or engineered recharge basins often generate higher absolute recharge volumes and can provide direct hydrogeological monitoring opportunities. Nevertheless, these systems usually require substantial financial investment, mechanized construction, specialized technical knowledge, and sustained institutional support [15,27,28].

In contrast, the contour-based trenches evaluated in this study operate through manual construction, low-cost maintenance, and adaptation to local topographic and soil conditions. Their implementation does not depend on sophisticated infrastructure, which makes them particularly suitable for smallholder farming systems and resource-constrained rural communities where formal water management infrastructure is limited or absent [29–31].

This comparison highlights the relevance of decentralized MAR strategies as complementary solutions rather than substitutes for centralized recharge systems. Their contribution is especially valuable in contexts where improving infiltration, reducing runoff losses, and strengthening short-term soil water availability are as important as long-term aquifer recharge itself [32–35].

Additionally, the multifunctional character of contour-based trenches—including erosion control, sediment retention, soil moisture improvement, and vegetation recovery—provides benefits that extend beyond conventional MAR objectives. These co-benefits are particularly relevant in rural landscapes where land degradation and water scarcity occur simultaneously, reinforcing the value of nature-based solutions as integrated watershed restoration strategies [36–38].

Nevertheless, the effectiveness of these systems remains highly dependent on environmental context, including rainfall distribution, slope conditions, soil texture, vegetation cover, and maintenance frequency. Therefore, extrapolation of the results to larger spatial scales or different hydrogeological settings should be approached cautiously.

Rather than presenting contour-based trenches as universally applicable recharge systems, the findings support their role as site-specific, low-cost interventions that can strengthen integrated watershed management and community-based adaptation strategies under semi-arid conditions [39–41].

4.3. Role of Community Participation and Implementation Feasibility

Beyond hydrological performance, the effectiveness of contour-based trenches is strongly influenced by community participation and local management capacity. In the study area, local farmers actively participated in trench construction, basic field monitoring, sediment removal, and periodic maintenance, which facilitated local ownership, practical knowledge transfer, and long-term operational feasibility.

Although the primary focus of this study was hydrological evaluation rather than social organization, community involvement proved to be a critical factor for implementation success. Manual excavation, routine inspection of overflow notches, and minor reinforcement of trench walls were carried out using locally available labor and without dependence on external mechanized resources, significantly reducing implementation costs and increasing local adaptability [42,43].

Participatory approaches have been widely recognized as essential for the long-term sustainability of soil and water conservation interventions, particularly in smallholder farming systems where technical maintenance and institutional support are often limited [27,44,45]. In this context, community-managed MAR practices can improve not only hydrological performance, but also social acceptance and continuity of intervention over time.

The low maintenance requirements observed during the monitoring period—mainly limited to minor sediment removal and occasional reinforcement of overflow

structures—support the practical feasibility of these systems under resource-constrained rural conditions. Similar findings have been reported in participatory MAR initiatives where local involvement reduced operational costs and increased system longevity [17,46–48].

However, sustainability should not be assumed solely from initial implementation success. Long-term persistence depends on continued collective organization, local incentives for maintenance, and institutional recognition of these practices within broader watershed management programs. Without periodic maintenance, sediment accumulation may reduce trench storage capacity and hydrological efficiency, eventually limiting system performance [49,50].

For this reason, the community dimension should be understood not simply as labor participation, but as a governance condition necessary for the continuity of decentralized water management strategies. In rural contexts such as Las Ánimas, where water security is closely linked to agricultural productivity and seasonal groundwater availability, the social viability of these interventions becomes as important as their hydrological effectiveness.

Likewise, the absence of formal technical assistance or continuous institutional support may compromise long-term maintenance, even when local participation is initially strong. This reinforces the importance of linking community-based implementation with broader watershed restoration programs and public policy support mechanisms.

Thus, contour-based trenches represent not only a technical solution for infiltration enhancement, but also a practical example of how locally managed nature-based solutions can support climate adaptation, soil restoration, and water resilience under conditions of limited institutional and financial resources.

4.4. Institutional, Governance, and Scalability Considerations

Although contour-based trenches are technically simple, low-cost, and feasible for smallholder implementation, their long-term success and broader scalability are not determined solely by hydrological performance. Institutional support, local governance structures, land tenure arrangements, and collective coordination among landholders play a fundamental role in sustaining these systems over time.

In rural landscapes such as Las Ánimas, land fragmentation and differences in property boundaries can limit the continuity of contour-based interventions across larger areas. Since the hydrological benefits of distributed infiltration systems often depend on connectivity across slopes and watershed sections, isolated implementation at the individual plot level may reduce overall effectiveness.

Likewise, the availability of communal labor and the continuity of local organization are essential for maintaining trench functionality. Even when construction costs are low, long-term performance requires periodic sediment removal, reinforcement of overflow notches, vegetation management, and basic field monitoring. Without collective maintenance, the storage capacity and infiltration efficiency of the trenches may gradually decline [49].

Previous studies have shown that institutional support—including technical assistance, inclusion in watershed restoration programs, and formal recognition within local land-use planning frameworks—is necessary to improve the permanence of nature-based solutions and decentralized MAR systems [3,4]. In the absence of such support, small-scale interventions may be abandoned or lose effectiveness regardless of their initial technical performance.

From a policy perspective, the results of this study support the integration of community-managed Nbs into broader soil and water conservation strategies, particularly in regions affected by land degradation and seasonal groundwater scarcity. However, these systems should be understood as complementary interventions rather than replace-

ments for larger-scale water infrastructure such as recharge wells, reservoirs, or centralized watershed management projects.

This distinction is important for avoiding unrealistic policy expectations and for promoting balanced water management strategies that combine local infiltration practices with broader institutional planning. The hydrological effectiveness of contour-based trenches, like their social sustainability, remains highly context-dependent and influenced by both environmental and governance conditions [20].

Therefore, scaling these systems requires more than technical replication; it demands coordination between communities, local governments, environmental agencies, and watershed management programs capable of supporting long-term maintenance, monitoring, and adaptive decision-making.

Under these conditions, contour-based trenches can contribute meaningfully to rural climate adaptation, soil restoration, and decentralized water security strategies, particularly where conventional infrastructure is economically or technically inaccessible. Their greatest value lies not only in potential groundwater contribution, but also in strengthening local resilience and improving watershed functionality under increasingly variable climatic conditions.

4.5. Limitations and Future Research Directions

Despite the field-based evidence provided, this study presents several methodological and temporal limitations that should be considered when interpreting the results. The monitoring period covered only one hydrological year, which limits the evaluation of interannual variability in rainfall patterns, infiltration behavior, sediment accumulation, and long-term trench performance.

In addition, groundwater response was inferred indirectly through trench filling efficiency, infiltration estimates, and assumed deep percolation fractions rather than through direct hydrogeological measurements. Although groundwater levels were observed in a nearby community well, these observations were exploratory and were not intended to provide quantitative validation of aquifer recharge processes.

The absence of an independent control plot without trenches also represents an important limitation. Because the intervention was implemented directly under community restoration conditions, the study was designed as an applied field evaluation rather than a controlled experimental comparison. Although comparisons with adjacent untreated areas were used to support qualitative interpretation of soil moisture differences, causal attribution should be interpreted cautiously.

The simplified water balance criterion used in this study was designed to provide practical applicability under rural field conditions and to facilitate community-level implementation. However, this approach does not fully capture important hydrological processes such as lateral subsurface flow, delayed percolation, evapotranspiration losses, sediment-induced reduction in storage capacity, or spatial heterogeneity in soil infiltration behavior. As a result, the recharge estimates should be interpreted as indicative plot-scale approximations rather than definitive measurements of aquifer replenishment.

Similarly, the assumption of a constant deep percolation fraction (ϕ) introduces uncertainty, since this parameter may vary seasonally depending on antecedent soil moisture, rainfall intensity, vegetation cover, and local soil structure. Although sensitivity analysis was performed to address part of this uncertainty, longer-term monitoring would provide more robust estimates of system behavior.

Future research should incorporate multi-year hydrological monitoring, tracer experiments, and piezometric analyses to better characterize the temporal relationship between in-

filtration processes and aquifer response [50]. These methods would allow direct validation of recharge pathways and improve the precision of MAR estimates under field conditions.

In addition, watershed-scale assessments are needed to evaluate cumulative hydrological effects when multiple contour-based trench systems operate simultaneously across larger landscapes. Understanding how distributed infiltration structures interact across slope networks is essential for scaling these interventions beyond the plot level.

Further research should also explore the long-term effects of sediment accumulation, vegetation succession, and maintenance frequency on trench efficiency, as well as the institutional and governance conditions required for sustained community management. These aspects are critical for strengthening both the hydrological and social sustainability of decentralized nature-based solutions.

Addressing these limitations will improve the scientific basis for integrating contour-based trenches into formal watershed restoration strategies and climate adaptation policies in semi-arid rural regions.

5. Conclusions

Contour-based trenches represent a practical and low-cost nature-based solution (Nbs) for improving runoff regulation, soil moisture retention, and supporting potential distributed managed aquifer recharge (MAR) in the semi-arid rural landscapes of Guerrero, Mexico. Their implementation contributes to reducing surface runoff, controlling erosion, retaining sediments, and improving short-term water availability in agricultural soils, which are critical processes for land restoration and local water security.

Beyond their hydrological function, these structures provide important environmental and social co-benefits. The improvement of soil moisture conditions and vegetation recovery, and the reduction in erosive processes reinforce their multifunctional value as integrated watershed restoration strategies rather than isolated recharge structures. Their low-cost construction and adaptation to local topographic conditions make them especially suitable for smallholder farming systems and communities with limited access to conventional water management infrastructure.

The study also highlights that the effectiveness and long-term sustainability of contour-based trenches depend not only on technical design, but also on continued maintenance, community participation, institutional support, and local governance conditions. For this reason, these systems should be understood as complementary interventions within broader watershed management and climate adaptation strategies, rather than as stand-alone solutions for aquifer recharge.

Although the findings support the relevance of contour-based trenches as decentralized water management practices, caution is necessary when interpreting their contribution to groundwater recharge. The absence of direct hydrogeological validation means that their role should be considered primarily in terms of infiltration enhancement and improved opportunities for gradual deep percolation rather than confirmed aquifer replenishment.

Future research should focus on long-term monitoring, direct hydrogeological validation, and watershed-scale evaluation to better understand the cumulative effects of distributed infiltration systems and strengthen their integration into public policies for rural water security, soil restoration, and climate resilience.

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