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Evaluating the Hydrological and Erosional Benefits of Afforestation Interventions in Ayubia National Park, Pakistan: Implications for Groundwater Recharge and Sediment Yield Reduction

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Abstract. *The effects of deforestation on hydrological services and stability of soil are a major concern in the mountain areas. This study quantitatively evaluates the benefits of afforestation interventions on groundwater recharge and sediment yield in the sensitive ecosystem of Ayubia National Park, Pakistan. A comparative watershed study was used, evaluating four watersheds (two afforested "treated" and two degraded "untreated"). Field measurements were made of infiltration capacity (double ring infiltrometer), stream discharge (velocity-area method), and sediment yield (fixed area plots). Findings showed treated areas yielded significantly higher infiltration capacity (up to 40 mm/h) as compared to untreated ($p < 0.001$). The average stream discharge after rainfall in vegetated watersheds increased moderately by 25% as compared to a 92% increase in an untreated watershed indicating great flood-mitigating ability of vegetated watersheds. In addition, sediment yield was about 50% lower in treated areas. Vegetation cover (trees, shrubs, grass) was determined to be the most significant determinant of improved soil porosity and infiltration by multivariate regression analysis. The conclusion drawn by the findings is quite clear and as per the requirements, afforestation is found as one of the key nature-based solutions for managing water resources sustainably and improving groundwater recharge, mitigating floods and reducing erosion in the vulnerable watersheds of the Himalayan region.*

Keywords: *deforestation, watershed management, nature-based solutions, land use change, infiltrometer and discharge flow*

Introduction

Forest resources are crucially important and essential contributors to a wide range of ecological functions that are vital for life, such as controlling hydrology, conserving soil, preventing erosion and preserving biodiversity. Forests that exist on earth are approximately 3870 million hectares, 95% of them are natural forests and 5% plantations (Sousson et al., 1995).

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27% of the planet's entire forests are in Europe, 5% in Latin America and the Caribbean 19% in Asia and Pacific, 17% in Africa and the remaining 12% in North America (FAO, 2001). The forest areas account for 5.2% in Pakistan which represent 4.606 million hectares, with a high proportion (17%) of forest lands in KP province (Ali et al., 2020).

During the last decade of the 20th century, the world lost nearly 14.6 million ha of forest per year and forests were converted to agriculture or urban land use. Even though 5.2 million ha of forests were naturally regenerated through forest expansion and that were added during that period, still the net loss is 9.6 million ha of forests per year (FAO, 2001). Despite their importance, global deforestation continues at an alarming rate, leading to the degradation of critical services. Forest cover in Pakistan is one of the lowest in the region with a high deforestation rate and is linked with increased risks of flooding, sedimentation and water scarcity (Khan & Khan, 2009).

The Himalayan region is a critical zone of global biodiversity and is particularly vulnerable. Ayubia National Park, situated in the Western Himalayas of Pakistan, is a protected national land whose ecologic values are very high. It is subjected to extreme pressure from surrounding human settlements and historical deforestation, which have altered its hydrological properties and accelerated soil erosion. It is therefore important to quantify the benefits of interventions such as afforestation for assisting in the formulation of effective watershed management strategies in such sensitive areas (Qasim et al., 2017; Nurrochmat et al., 2024). Watershed restoration projects have shown tangible improvements in the ability to control the hydrology and resilience of the ecosystems in mountain areas (Berke et al., 2003).

The effects of land use and rainfall on sediment loss and annual runoff were studied in eight land use cases in the north Mediterranean and in the Atlantic coastline in Portugal, Spain, France, Italy and Greece (Moore & Wondzell, 2005). Groundwater recharge to an aquifer is simply the water which enters the aquifer in any direction. Recharge to a groundwater flow system is normally assumed to be the height of the water column that enters in the groundwater zone divided by the time. Despite being a fundamental aspect in hydrological cycle, recharge cannot be measured directly due to the difficulty of measurement at the spatial level, where most of the processes occur (Mirzezadeh & Mammadova, 2026; Jafarova, 2026). Therefore, recharge rate has been calculated from indirect sources using climatic, spatial scale and temporal scale. Groundwater is a valuable, hidden, yet replenishable resource that exists beneath the surface of the ground. Headwater hillslopes generate runoff and contribute to groundwater flow (Manna et al., 2016).

Groundwater is an important resource that is often out of sight and out of mind. In Ireland, about 25% of total water is supplied by groundwater, although in most rural settings, groundwater supply forms a much larger share and in some regions of the country, is nearly the only supply (Allen & Chapman, 2001).

The whole process entails an increase in sediment yield through runoff. The increased runoff is correlated with increased rainfall and subsequently with increased kinetic energy utilized in the initial erosion of hill slopes and also in the transportation of the eroded silt in streams. Conspicuous differences exist, though, in the percentage of annual runoff increase in rates of sediment yield. With resulting changes in average cover between forest and rangelands, there is more sensitivity of the sediment loss to changes in runoff (Thomas Dunne & Leopold, 2016).

Various landscape types are subject to a variety of land uses common to the Mediterranean area such as agricultural land where cereals are grown rain-fed, vines, olives, eucalyptus plantation or natural vegetation. Land use was found to have very significant impacts on runoff and soil erosion. Hilly slopes with vines had average sediment loss of 142.8 tonnes per km² per year (Kosmas & Danalatos, 1997).

The changes in watershed hydrology are the major factors related to land use and land cover change. Vegetation cover directly affects infiltration, generation of surface runoff, and detachment and transport of sediment. The previous research in the other watersheds (Ayubia & adjoining Himalayan watersheds) also showed decrease in infiltration capacity and spring discharge after deforestation and overgrazing (Kamran, 2003; Kamran, 2005; Kamran, 2007). Though forests provide overall benefits, there is limited quantitative data to prove their effectiveness at the site-level in the Western Himalayas. This is especially important for validating management actions and optimizing future investments in nature based solutions.

This study aims to fill this knowledge gap by conducting a comparative analysis of treated (afforested) and untreated (degraded) watersheds in Ayubia National Park. The specific objectives are:

1. To quantify the impact of afforestation on soil infiltration capacity and its implications for groundwater recharge.
2. To assess the effect of plantations on sediment yield in local streams.
3. To develop a multivariate model relating vegetation cover to soil hydrological properties.

Materials and Methods

The study sites included peripheral sites of Ayubia National Park which are Namli Maira (1,800–2,980 m elevation; 250 ha) and Lundi Mandri (1,860–2,650 m elevation; 43.26 ha), Mohra (1,980–2,680 m elevation; 35.99 ha), and Arifabad (1,800–2,480 m elevation; 20.22 ha) under a temperate monsoon climate. A comparative design included treated and untreated areas (planting species such as *Pinus wallichiana*).

Figure 1

Collective map of study area showing all sites

Experimental Design and Field Measurements

Infiltration Capacity: Soil infiltration capacity was measured using a double-ring infiltrometer (fig. 2). The inner ring had a diameter of 21.5 cm. A constant head of 4 cm was maintained. Readings were taken at 1, 2, 3, 4, 5, 10, 20, 35, 55, and 85 minutes until a steady-state rate was achieved. Three replicates were taken per site. The infiltration capacity (Ic, mm/hr) was calculated as:–

$$Ic = D / T$$

Where, D is the depth of water added (mm) and T is the time interval (hours). The use of infiltration-based approaches for evaluating watershed restoration effectiveness has been widely reported in hydrological studies (Itsukushima et al., 2016).

Figure 2
Double ring infiltrometer

Stream Discharge and Sediment Load: Stream discharge (Q, m^3/s) was measured at predetermined GPS-marked points using the velocity-area method as following:

$$Q = V \times A$$

Where, V is flow velocity (m/s) and A is the cross-sectional area (m^2). Measurements were taken both before and after rainfall events. Water samples were collected simultaneously to determine sediment concentration (mg/L).

Sediment Yield from Plots: Sediment yield was quantified using fixed-area research plots of 8.93 m^2. Runoff was channeled into collection drums (Fig. 3). The settled sediment volume in the drum (radius = 25 cm) was measured and converted to a volume (cm^3). This volume was then extrapolated to a per-hectare basis (m^3/ha) to standardize the yield.

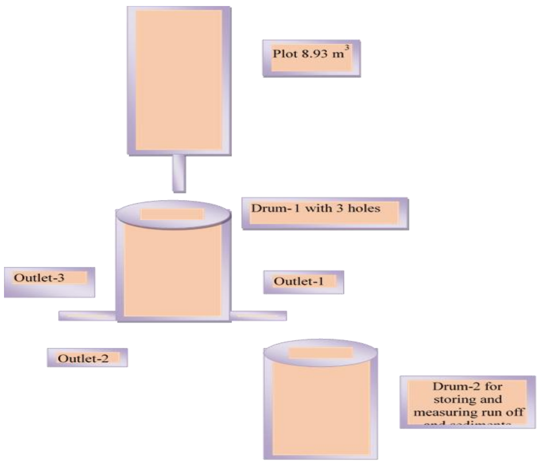

Figure 3
Rectangular fixed research plot

Ancillary Data
Vegetation surveys were conducted to record species composition, density and canopy cover percentage at each site (Fig. 4). Soil samples were collected for texture analysis using the USDA classification system.

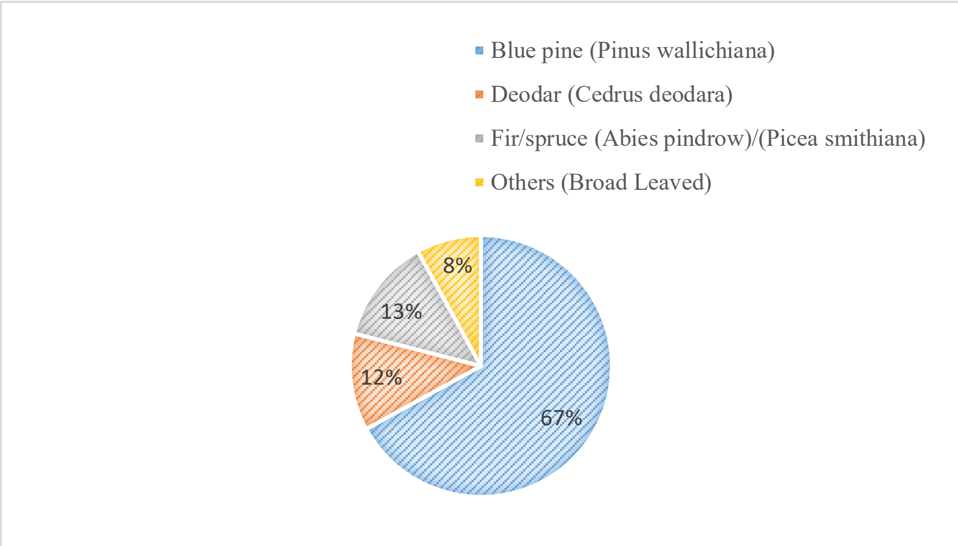

Figure 4
Floral diversity in the study area

Statistical Analysis: Statistical procedures followed standard biometric approaches described by Steel et al. (1997). Data analysis employed ANOVA and t-tests ($\alpha = 0.05$); multivariate regression (Infiltration Rate = $\beta 0 + \beta 1$Vegetation Density + $\beta 2$Slope + ε) using R software; ArcGIS for spatial analysis (Madnee et al., 2025a).

Results

Discharge Rate of Water in Streams
To determine the rate of discharge, two streams, one each from protected and unprotected watersheds were examined. The discharge rates for both the streams were calculated before and after rainfall in different seasons of the year. The resultant values of discharge rates of both streams examined in different months are given in table 1. It should be noted that Stream I and Stream II represents streams at protected and unprotected sites respectively. The average difference in discharge rate (before and after rainfall) for Stream I was almost double that of Stream II. The watersheds of the stream I located at the protected forestland have dense vegetation; on contrast stream II being feed by watershed of open forestland have sparse vegetation. Dense vegetation at the watershed area means high evapotranspiration rates after rainfall and less change in the water discharge, similarly sparse vegetation means minimal evaporation rates and high discharge rates, especially after rainfall.

The data analysis clearly reveals that the variation in the discharge rates of stream I before and after rain is quite less than stream II. The maximum increase in the discharge rate after rainfall at stream I was found to be 38%, and 25% on average. On the other hand, at stream II the maximum recorded change in discharge rate was 160% in the month of September, with average increase of 92% in discharge rate after rainfall. This means that the effect of rainfall on stream flow is much higher for Stream II compared to Stream I. Therefore, we can conclude that vegetation regulates the flow of water from the watersheds of these streams and thus protect the downstream areas from floods during heavy rainfall mentioned in figure 5.

Sediment Yield

Comparative analysis of the sediment yield in the two streams show that there is a close relation between density of vegetation in the watersheds of a stream and the amount of sediment (eroded soil particles) in that stream. The resultant values of sediment concentration before and after rainfall at both streams in various months are given in table 2.

Stream I having good vegetation on its watersheds have low concentrations of sediment before rainfall with small amount of increase in sediment concentration after rainfall. On the other hand, stream II having poor vegetation on its catchment area have high concentration of sediment before rainfall but the increase in sediment concentration on stream II after rainfall as given in the table 2. The average increase in the sediment concentration after rainfall in stream II was 100% more than that of stream I as shown in figure 6. The maximum sediment concentration in both the streams was recorded in the month of July after heavy rainfall, but still the increase in the sediment load in stream I was only 61ppm compared to 120 ppm increase in the sediment load of stream II. This is inversely related to total suspended sediment. The greater the amount of vegetation in the watershed, the lower the sediment load will be and vice versa. So, the conclusion is that vegetation of the upstream watershed is a filter and it intended to get fresh water from upstream to the downstream watershed.

The fixed area method was used to determine the sediment yield from various sites. The results are expressed in table 3. Results reveal that treated area has less sediment yield than untreated area. The most vulnerable is degraded soil because it has the maximum sediment yield or soil losses. The difference can be attributed to covered soil in treated area (planted area) than denuded soil in untreated area (unplanted area). More the plantation lesser will be the soil erosion and vice versa.

Infiltration Capacity

The p-value of 0.001 is lower than 0.05, proving that the difference between the infiltration capacities of both watersheds are significantly different. The mean infiltration rate at each time interval was highest at Spot 1, i.e., 40 $mm^3$and gradually started to decrease linearly and reached its minimum point at the last interval in both watersheds at all spots. While, the horizontal mean values describe that the infiltration rate was highest at the Spot 1 i.e. a bit lower in Spot 2 and further lower at Spot 3 in the treated area, which may be due to the difference in vegetation density and vegetation type but further lower at Spot 4 and minimum at Spot 5 in the untreated watershed, which are definitely due to the absence of management practices (Table 4).

Table 1

Discharge rates of streams

	Protected stream discharge rate (m^3/S)			Unprotected stream discharge rate (m^3/S)		
	B. Rain	A. Rain	Difference	B. Rain	A. Rain	Difference
April, 16	0.073	0.094	0.021	0.044	0.093	0.049
July, 16	1.573	1.963	0.39	1.03	1.94	0.91
September, 16	0.059	0.082	0.023	0.033	0.086	0.053
November, 16	0.046	0.061	0.015	0.039	0.085	0.046
Average	0.43775	0.55	0.11225	0.2865	0.551	0.2645

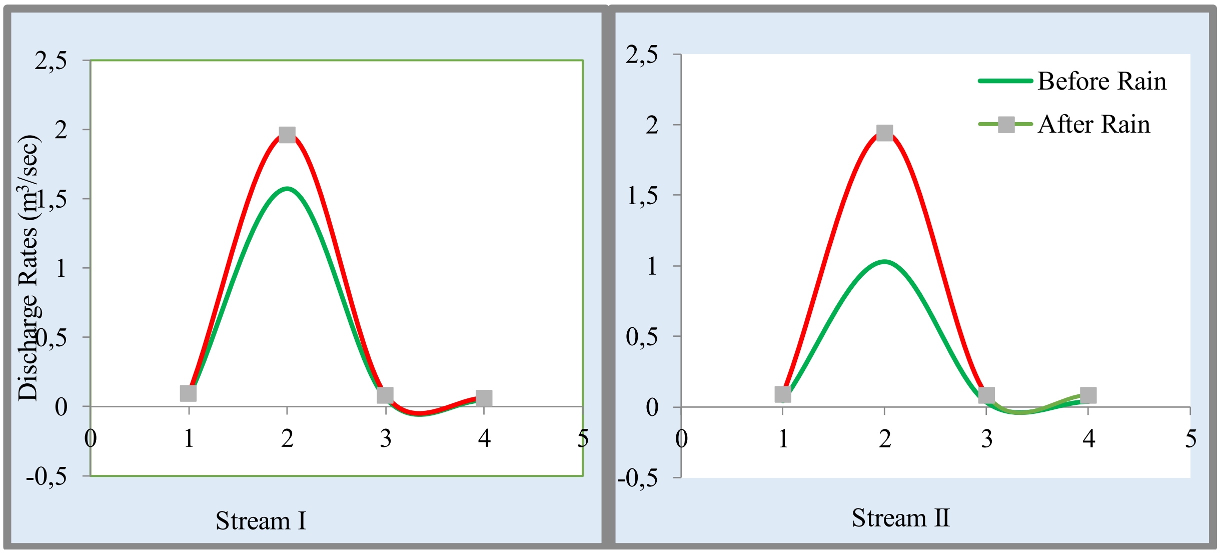

Figure 5

Discharge rate of water flow in the streams of both study sites (m^3/sec)

Table 2

Sediment concentration at protected and unprotected streams

	Sediment load in stream I(ppm)			Sediment load in stream II(ppm)		
	B. Rain	A. Rain	Increase	B. Rain	A. Rain	Increase
April, 16	114	144	30	117	177	60
July, 16	136	197	61	177	297	120
September, 16	110	131	21	138	210	72
November, 16	100	132	32	138	175	37
Average	115	151	36	142.5	214.75	72.25

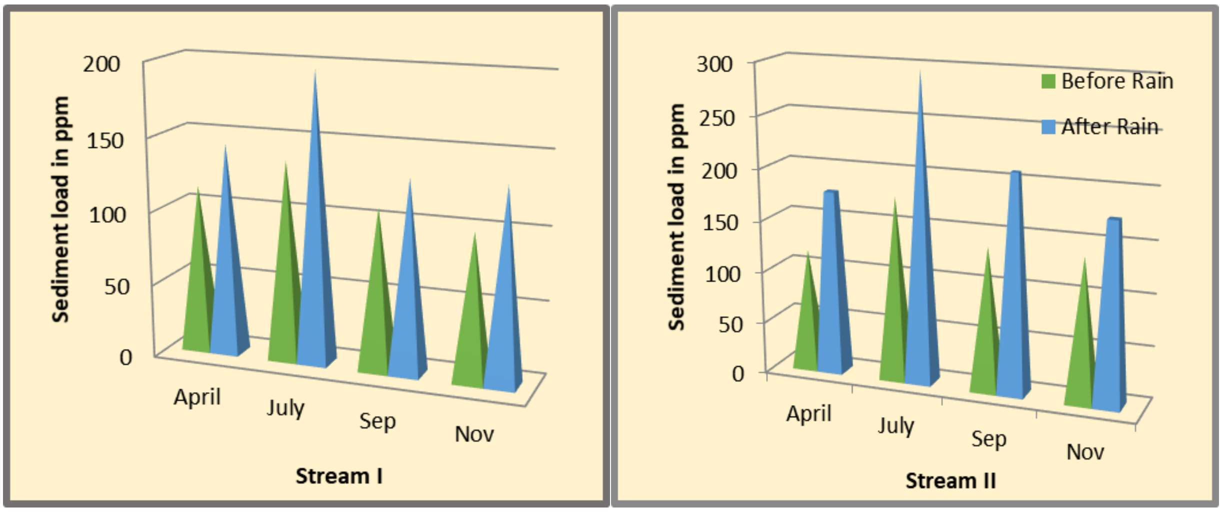

Figure 6
Sediment concentration before and after rainfall in both the streams

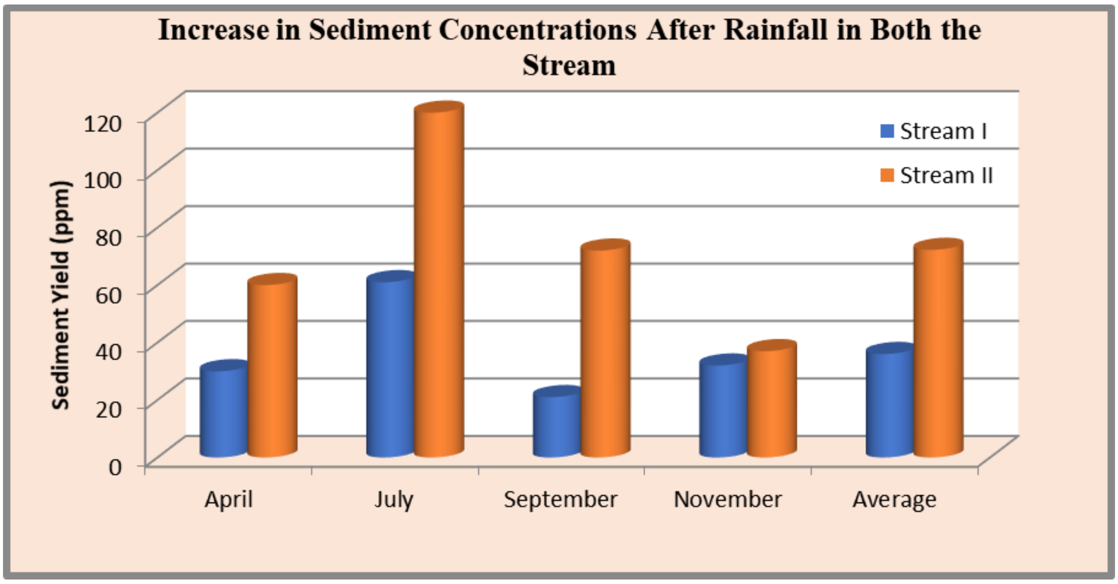

Figure 7
Increase in sediment concentrations after rainfall in both streams

Table 3
Sediment yield at various sites

Site locations of the research plot	Sediment yield in plot size of 8.93 m^2 (cm^3)	Sediment yield m^3/ha
Treated	46560	52.13
Untreated	47347	53.02
Improved agricultural land	51522	57.69
Conventional land	55459	62.10
Degrades soils	62332	69.80

Table 4
Infiltration capacity of all study sites around Ayubia National Park

Time taken (min)	Amount of Water Infiltrated (mm^3)					Mean
	Spot 1	Spot 2	Spot 3	Spot 4	Spot 5	
1	150	133.3	127.66	111.3	83	121.08
2	48	45	37.2	33.6	22.2	37.20
3	44.2	37.6	31	27.3	19.5	31.92
4	34.1	30.2	28.8	22	16	26.22
5	31.8	30.1	26.7	21.9	14	24.90
10	28.7	24.7	25	14	8.9	20.26
20	26.7	23.6	24.6	12.3	7.3	18.90
35	15.8	11.4	11.3	7.7	6.3	10.50
55	11.6	7.6	6.2	5.7	3.5	6.92
85	9.4	6.4	5	3.8	2.5	5.42
Mean	40.030	34.990	32.346	25.975	18.320	

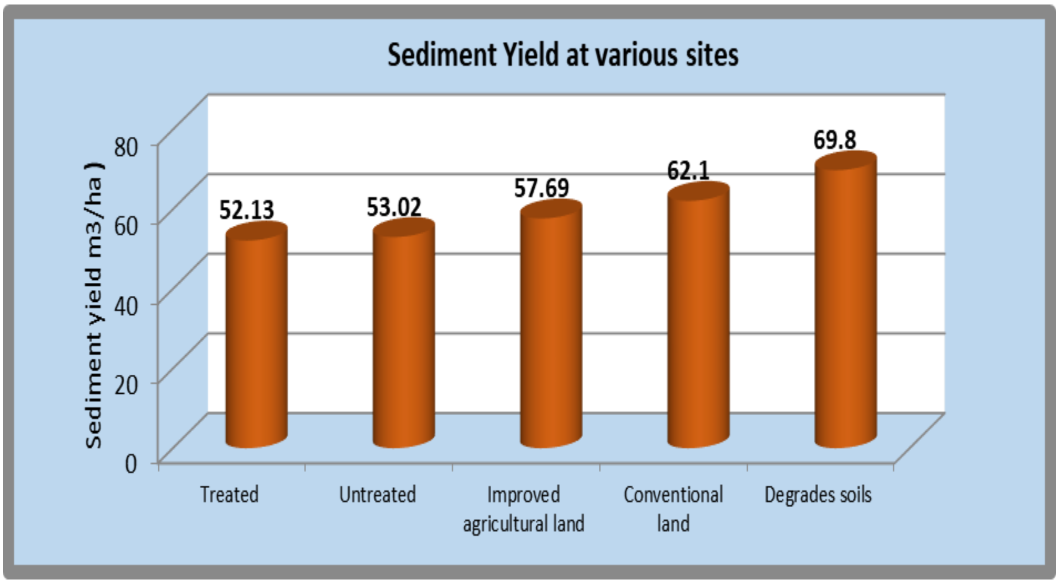

Figure 8

Sediment yield at various sites around Ayubia National Park

Discussion

The findings of this study supports the effectiveness of nature-based solutions in sustainable water resources management with empirical evidence. Afforestation interventions on the sensitive Himalayan ecosystem of Ayubia National Park positively influenced the hydrological functions. There is marked difference in infiltrative capacity for afforested and non-afforested watersheds, as seen in our comparative study. We observed a significant difference in the infiltration capacity of degraded versus afforested watersheds, and to regulate and control streamflow as well as sedimentation. An important result of this work is the significantly higher infiltration capacity for treated areas than for degraded areas, up to 40 mm/h. This enhancement can be directly attributed to the re-establishment of vegetation, because it enhances soil structure through several mechanisms (Makki et al., 2025; Madnee et al., 2025b). Tree roots create macropores and channels in the soil that facilitate rapid water movement through the soil profile (Ilstedt et al., 2007). At the same time, organic matter added with litter fall increases soil water-holding capacity, porosity, and aggregation (Bargués-Tobella et al., 2014; Bari et al., 2026), minimizing surface crusting and runoff initiation. This is consistent with the global average of above average infiltration rates found in forests compared to disturbed or non-forested sites (Zhou et al., 2022).

The effects on aquifer recharge in this hilly area are serious. Afforestation allows more rainwater to infiltrate underground by reducing runoff and is therefore likely to lead to increased aquifer renewal. This is not only an environmental benefit, but also a critical water security measure for communities that are highly reliant on springs and shallow groundwater. The results of the study indicate that watershed restoration could be an anticipatory step towards abating the growing water scarcity occurring in the Western Himalayas and driven by climate change and population pressure (Rasul, 2014; Safeer et al., 2025).

Vegetated watersheds' feedback to rainfall events is much more moderate, thus highlighting the flood mitigation service of afforestation. An untreated watershed had a very large change when it rained (the average change was 92%), while a treated watershed had a smaller change (25%). This differential response is an immediate result of the enhancement of infiltration capacity, a 'sponge' that reduces and delays the amount of surface runoff to stream channels. This buffering capacity is an essential ecosystem service. It can modify the intensity of flood peaks, decreasing the potential for flash floods in steep, mountainous areas prone to intense rainfall. These findings reflect similar results from other montane sites that have shown a strong reduction of the peak flow and an increase in the lag time between the rainfall and the runoff due to the forest cover (Bruijnzeel, 2004). Given that downstream areas, including the city of Abbottabad, are susceptible to flooding; the investment in afforestation upstream makes it a direct and cost-effective natural infrastructure for disaster risk reduction.

Another key benefit is the approximately 50% reduction in sediment yield, demonstrating effective control of soil erosion and improvement of water quality (fig. 8). Vegetation cover reduces the direct effect on the soil surface of rainfall, and root systems act to promote soil cohesion and to reduce the erosive forces acting on the soil (Gyssels et al., 2005). A dense canopy and understorey structure, also found in afforested areas, is also associated with reduced velocity of overland flow, resulting in reduced sediment transport capacity. Reductions in soil erosion and sediment export with improved vegetation cover have also been reported in Ethiopian watersheds using GIS-based soil loss assessment (Gelagay & Minale, 2016).

Afforestation helps in maintaining the precious thin top soil in the mountainous terrain, thereby retaining their fertility and eco-function. Second, it drastically reduces the sediment load to downstream reservoirs and rivers. Reservoirs that receive a high amount of sediment silt up, lose storage capacity and life, and stress aquatic ecosystems as well through turbidity (Syvitski et al., 2005). The lower sediment concentration in streams from treated watersheds, as documented in our study (Fig. 6), indicates a clear pathway to safeguarding downstream water infrastructure and biodiversity, aligning with the findings of Madnee et al. (2025) on the role of vegetation in stabilizing soil systems even in arid climates.

The multivariate regression model verified that vegetation cover is the most important factor affecting soil hydrological responses, consistent with studies showing strong relationships between vegetation cover, soil protection, and ecosystem productivity (Zafar et al., 2026). This study significantly reinforces WWF-Pakistan's afforestation efforts and serves as a solid scientific basis for advocating policy changes. Our findings indicate that forest rehabilitation in the degraded watersheds of the Himalayas is not just conservation but investment towards the management of water resources. The findings are validated by the recommendations of broader climate smart ecological interventions recommended for dryland and mountain ecosystem of Pakistan (Qureshi et al., 2024).

This study finds that afforestation and integrated watershed management are crucial elements for strategic scaling-up endeavours for adaptation to climate change as a policy issue and as a water management tool for policy makers (Ali et al., 2026) These interventions deliver three benefits: increased water security through groundwater recharge, safe communities through flood risk reduction and longer water infrastructure life through reduced sedimentation. Future research needs to quantify the economic value of these hydrological services to enhance the rationale for investments in nature based solutions.

Conclusion

The significance of plantations in improving hydrological services and soil resource protection in the Rawal and Abbottabad watersheds in Ayubia National Park, Pakistan is emphasized in this study. Field data from treated (planted) and untreated areas reveal that afforestation significantly mitigates flood risks and frequencies through improved water retention and reduced sediment yields. Results showed that infiltration capacities were much higher (up to 40 mm/h) and sediment loads were much lower for the treated areas compared to the untreated areas and the finding resulted from the use of the statistical analysis (p<0.001). Stream discharge following rainfall significantly increased in unprotected areas (92%), suggesting vegetation stabilizes the flow of water that generates flooding downstream, while being moderated in vegetated watersheds (25%). WWF-Pakistan's conservation initiatives not only protect nature but also socio-economically support the livelihoods of communities. This study therefore strongly suggests that the application of watershed integrated management practices should be promoted in order to facilitate sustainable use of land and water resources within environmentally vulnerable areas such as Ayubia National Park.

Declaration of Competing Interests

The authors declare that they have no competing interests. M.M. is a member of the Editorial Board of the journal and was not involved in the editorial evaluation or publication decision concerning this manuscript.

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