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An overlooked sediment trap in arid environments: ancient irrigation agriculture in the coastal desert of Peru

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Abstract The fluvial transfer of sediment from the land surface to the ocean is a complex process, and in many regions of the world, this process has been strongly influenced by man. In humid regions, the onset and expansion of agriculture coincided with deforestation, accelerated soil erosion, and an increase in sediment yield. In arid regions, agriculture is based on irrigation and thus the withdrawal of water and sediment from the rivers. Several metre thick irragric anthrosols are evidence of the continuous and long lasting trapping of sediments on irrigated fields. Investigations of irragric anthrosols in the Palpa Valley, southern Peru, have shown that trapping of sediments started around 3000 cal BP. Based on these investigations and other published data, this paper assesses the amount of sediment trapped in the river oases of the Rio Grande de Nazca drainage basin (11 164 km^2) in the coastal desert of Peru.

Key words arid environments; sediment transport; irrigation agriculture; irragric anthrosols; human impact; Peru

INTRODUCTION

A widely used approach to reconstruct catchment-scale land surface and erosion dynamics over long time scales is based on the amount of sediment delivered by streams to the ocean or to interior basins and lakes. Changes in sediment transport rates, deposition rates or sedimentary characteristics can be related to changes in upland erosion or stream dynamics triggered by environmental change related to climatic change or human impact. It is well known that the reconstruction of landscape dynamics from sediment delivered to a depositional environment is hampered by several problems, including: (i) difficulties in quantifying the time lag between upland erosion and downstream sediment delivery due to temporary storage of sediment in the fluvial system (cf. Walling, 1990; Reid & Dunne, 1996); and (ii) complex responses of fluvial systems to external factors (Summerfield, 1991). In many parts of the world, the sediment yield-based approach has been complicated by the construction of dams and reservoirs in the past centuries. These features manipulate the hydrological regime and trap sediment, leading eventually to a situation where downstream sediment load is decreasing despite increasing upland erosion (cf. Milliman & Meade, 1983; Walling, 2006). At the same time reservoirs provide an opportunity to study upland erosion on the catchment scale and over a long time scale (cf. Van Rompaey *et al.*, 2003; Baade & Rekolainen, 2006; Verstraeten *et al.*, 2006).

This paper draws attention to an often overlooked factor in arid and semi-arid environments which has been effective for several millennia: the anthropogenic manipulation of runoff and sediment transport in rivers and streams caused by the diversion of water (and sediment) for irrigation purposes. It is based on field studies conducted in the Rio Grande de Nazca catchment, Peru, and provides a first detailed account of the amount of sediment trapped by irrigation agriculture in the river oases of this allogenic river system transversing the coastal desert of Peru.

STUDY AREA

The coastal desert of Peru is one of the driest regions on Earth. Nonetheless, it hosts impressive and widespread evidence of pre-Columbian cultures such as the ruins of Cerro Sechin in the north and the geoglyphs of the Nazca-Palpa area in the south, both dating back more than two millennia (Moseley, 2001; Reindel & Grün, 2006). Settlements and agricultural areas in the coastal desert are restricted to river oases in the valley bottom of allogenic rivers originating in the semi-arid to semi-humid upper slopes of the Cordillera Occidental.

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The study area, the Rio Grande de Nazca drainage basin (11 164 km^2), is located in the southern part of the coastal desert of Peru. It consists of eight intermittent rivers (Rio Santa Cruz, Rio Palpa, Rio Vizcas, Q. Ingenio, Rio Aja, Rio Tierra Blanca, Rio Taruga, Rio Las Trancas) and a few episodic headwaters (Q. Yapana, Q. Cinco Cruces, Rio Socos, Q. Chauchilla) joining the intermittent Rio Grande on its way to the Pacific Ocean (Fig. 1). In the western and middle parts of the drainage basin mean annual precipitation is about 10 mm/year and the potential evaporation rate is about 1600 mm/year. In the upper part of the catchment precipitation increases and reaches 200 mm/year above approx. 2500 m a.m.s.l. and 400 mm/year above approx. 3500 m a.m.s.l. (ONERN, 1971; Dornbusch, 1998; Hesse, 2008). At the crest of the Cordillera Occidental (approx. 4500 m a.m.s.l.) mean rainfall amounts to 670 mm/year. Mean annual runoff from the sub-basins measured at gauging stations located at the foot of the Cordillera Occidental just upstream of the major irrigation areas varies from 0.17 to 3.5 m^3/s (MINAG, 2007, cf. Table 1). Discharge is characterised by extreme inter-seasonal and inter-annual variability with average discharge season lengths of not more than 18 weeks and a ratio of maximum to minimum total annual discharge of about 60 (data for the Rio Grande gauging station, period 1975–2007, from Junta de Usuarios Palpa, 2007). Downstream of the major irrigation areas "the rivers are through-flowing only two years out of seven, on average" (Schreiber & Lancho Rojas, 1995). This is due to natural properties, i.e. the high infiltration capacity of the gravel river beds and to human impact, i.e. the diversion of water for irrigation purposes.

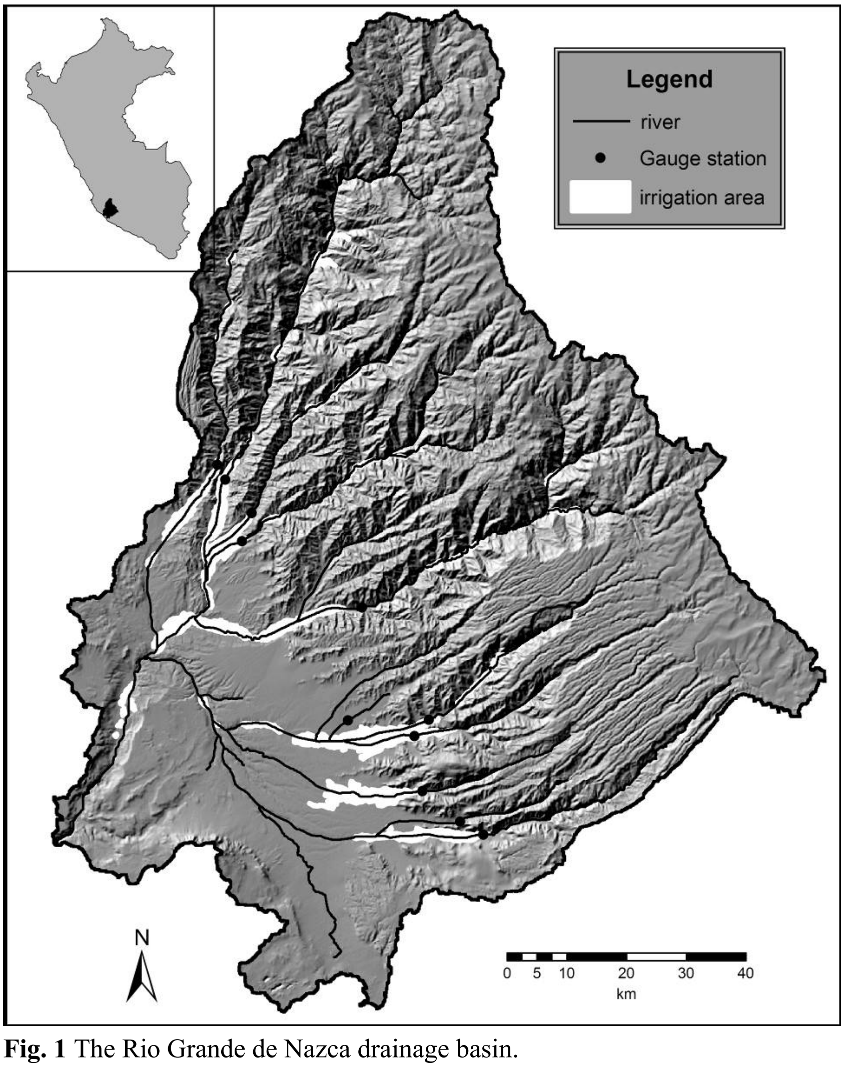

Fig. 1 The Rio Grande de Nazca drainage basin.

Table 1 Hydrological properties of sub-basins of the Rio Grande de Nazca drainage basin.

	Valley	Gauging station	Upstream catchment area(1) (km^2)	Rainfall(2) (mm)	Runoff(3) (m^3/s)	Runoff used for irrigation(4) (%)
North	Santa Cruz Valley	Rio Santa Cruz	414.5067	152	0.1670	95.4
	Rio Grande Valley	Rio Grande	1811.1753	315	3.5120	54.1
	Palpa Valley	Rio Palpa	*542.5384*	*256*	*1.2660*	
		Rio Vizcas	*836.2117*	*243*	*0.9508*	
		Σ Palpa Valley	1378.7501	248	2.2168	78.0
	Ingenio Valley	Q. Yapana	*356.4651*	*90*	*≈ 0.05*	
		Q. Ingenio	*1212.7181*	*292*	*3.4618*	
		Σ Ingenio Valley	1569.1832	246	3.4618	86.5
South	Nazca Valley	Q. Cinco Cruces	*190.0344*	*175*	*≈ 0.01*	
		Rio Socos	*153.3761*	*157*	*≈ 0.01*	
		Rio Aja	*483.6671*	*275*	*1.8415*	
		Rio Tierra Blanca	*461.8120*	*225*	*1.4581*	
		Σ Nazca Valley	1288.8896	228	3.2996	96.5
	Taruga Valley	Rio Taruga	314.1050	*258*	*≈ 0.14*	91.5
	Chauchilla Valley	Q. Chauchilla	292.5830	*218*	*≈ 0.01*	n.a.
	Las Trancas Valley	Rio Las Trancas	487.3760	279	1.7794	93.5
	Total		7556.5689	175	≈ 14.5	80.6

(1) calculation based on SRTM DEM (Jarvis *et al.*, 2006); (2) calculation based on SRTM DEM and regression of elevation and rainfall acc. to Hesse, 2004; (3) data source: ONERN, 1971; MINAG, 2007; (4) data source: ONERN, 1971.

Irrigation in the study area is conducted by simply diverting the sediment-laden water from the rivers to a system of permanent open and unlined channels distributing the water to the fields. The diversion structures conveying the water from the river bed to the intake points of the permanent channel system are of ephemeral character and adjusted to the actual water level in the rivers. The intake point is often equipped with a weir to limit water intake. Devices for lifting water from the river bed to the irrigation channels, like the ones documented for other regions of the world (e.g. Butzer, 1976), are not used and have not been documented archaeologically. Distribution of water on the fields takes place by a dense system of furrows established during seedbed preparation. In the southern part of the Rio Grande catchment (the Nazca Valley, Taruga Valley and Las Trancas Valley) so-called puquios, i.e. up to several-hundred-metres-long open trench or subterraneous filtration galleries, are used to tap additional water from the aquifers in the valleys. According to Schreiber & Lancho Rojas (1995), the use of puquios in the Nazca area dates back probably 1500 years. Since the last century, irrigation water supply is supplemented with groundwater pumped from wells. Based on data from the 1960s, approx. 10% of the present irrigated area is supplied with water from wells (ONERN, 1971). Diversion of river runoff for irrigation purposes is considerable. The average proportion of river runoff diverted for irrigation purposes was estimated to be 54–96%, assuming that the volume of water diverted from the rivers amounts to a maximum of 70% of the irrigation channel capacity (ONERN, 1971, cf. Table 1).

Naturally flooded areas are, at least today, not used for agriculture. This is probably due to the fact that higher floods are often accompanied by strong lateral erosion during the rising stage, and deposition of rather coarse material during the falling stage. However, previously flooded areas are eventually reclaimed by directing sediment-laden water via irrigation channels to the reclaimed area.

The vast majority of the irrigated area (17 963 ha, 78% of the total irrigated area) is located in several-hundred-metre-wide valley bottoms incised into the surrounding conglomerates of the Pampa de Nazca or the foothills of the Cordillera Occidental (Fig. 1). About 13% of the total irrigated area is located in the narrow valley bottoms of the headwaters and the rest (9%) is situated along the lower reaches of the Rio Nazca and the Rio Grande. The core area of the irrigated river oases is characterized by up to 3.5-m thick poorly sorted silty sands and sandy silts with variable clay content usually lacking evidence of stratification. However, charcoal, other artefacts and singular large clasts whose presence within the fine-grained matrix cannot be explained by fluvial processes are present (Hesse & Baade, 2007). In the late 1960s, the soils in the river oases were mapped as fluvisols (ONERN, 1971). Based on extensive investigations of the sediments in the valley bottom of the Palpa Valley, we conclude that the fine-grained sediments in the river oases actually represent irragric anthrosols (ATir). Irragric anthrosols "are formed as a result of prolonged sedimentation (predominantly silt) from irrigation water" (FAO, 1998; IUSS Working Group WRB, 2006). Extensive dating of soil profiles in the Palpa Valley revealed that the build-up of irragric anthrosols in this valley started at least 2960 ± 120 cal BP, perhaps even 4200 ± 700 years ago, and that irrigation agriculture was widely applied around 2500 years ago (Hesse & Baade, 2007; Hesse, 2008). These findings are in good agreement with the results of archaeological investigations of different settlement sites in the Palpa Valley and along the Rio Grande de Nazca (Reindel & Isla, 2004; Reindel, 2008). Comparison of several dated soil profiles showed that long-term average sedimentation rates are between 0.26 and 3.04 mm/year, and measurements of the amount of sediment currently transported to individual irrigated fields yielded present-day sedimentation rates of between 1.4 and 3.0 mm/year (Hesse & Baade, 2008).

METHODS

In order to quantify the amount of sediment trapped in the river oases of the Rio Grande de Nazca drainage basin due to the diversion of water and sediment for irrigation purposes, and thus to quantify the impact of irrigation agriculture on the long-term sediment yield from the western slopes of the Andes to the Pacific Ocean, we combined the results of our field studies in the Palpa Valley with remote sensing data, hydrological data, and soil survey data. The SRTM digital elevation model (DEM) with a grid resolution of 90 m (Jarvis *et al.*, 2006) provided the basis for calculating watershed properties using ArcHydro for ArcGIS 8.3 (Maidment, 2002). Hydrological characterization of the catchments is based on gauge station mean discharge data published in MINAG (2007) and additional data provided by Junta de Usuarios Palpa (2007). The length of the data sets used to calculate mean runoff is not documented in MINAG (2007), but, the data span probably over 30 years, with some missing years.

Present-day vegetated and irrigated areas were mapped at a scale of 1:30 000 by visual interpretation of a Landsat ETM+ (Nasa Landsat Program, 2004) near infrared composite from April 2000 (irrigation season in the study area) using the channels 4 (NIR), 3 (visible red) and 2 (visible green) in the red, green and blue video channels, respectively. Discrimination of vegetated areas is simple due to the stark contrast between moist and vegetated valley bottom areas and virtually bare desert surfaces. In the wide valley bottoms, agricultural fields are well discernible from other vegetated areas (riparian vegetation) based on their geometry and structure. Only in the upper reaches of the rivers and the lower reach of the Rio Grande is discrimination of irrigated fields and other vegetated areas not always possible.

The soil survey data used to extrapolate our findings in the Palpa Valley to the whole Rio Grande drainage basin were generated during an extensive land reconnaissance survey conducted in the late 1960s (ONERN, 1971). Based on detailed soil profile descriptions and the relation of soil groups to topographic positions, we used the data on spatial extent and mean soil depth to derive the volume of irragric anthrosols. In particular, we interpreted the soils of the Series Nazca, Series Santa Cruz, Series Pajonal, Series Jahuay and Series Puquial (Table 2) to represent irragric anthrosols dating back to pre-historic time. All these soils belong to a group of soils occurring on non-flooded terraces of different heights above the river beds in the Rio Grande system (ONERN, 1971). In addition to this, we interpreted the soils of the Series Ribereño, which are associated with flooded areas, to represent incipient irragric anthrosols. Using the soil survey data has the advantage of omitting late 20th century extensions of the irrigation system, which occurred locally. Unfortunately, neither present-day sediment yield data for the gauging stations, nor

Table 2 Spatial extent and thickness of irragric horizon of soils used to calculate the volume of irragric anthrosols in the Rio Grande drainage basin (data source: ONERN, 1971).

Soil series	Series Nazca	Series Santa Cruz	Series Pajonal	Series Jahuay	Series Puquial	Series Ribereño	other soils
Extent (ha)	10 353	808	1134	1543	83	2090	7868
Thickness of irragric horizon (m)	>1.3	0.5	1.15	1.20	1.0	0.2	–

independent erosion estimates for the upstream areas are available. Therefore, we are currently unable to relate the amount of sediment stored in the river oases to upstream sediment yield.

RESULTS AND DISCUSSION

The results of the quantification of the sediment trapped by irrigation agriculture in the river oases of the Rio Grande de Nazca drainage basin is summarized in Table 3. Comparison of the extent of the irrigated area in the river oases (irrigated area 2000 in Table 3) with the extent of the irragric anthrosols mapped in the late 1960s indicates that irrigated areas expanded by about 29% within the past 35 years. However, this expansion often took place in marginal parts of the valleys, where heavy machinery has been used to establish irrigation terraces.

Table 3 Irragric anthrosols (ATir) in the river oases of the Rio Grande de Nazca drainage basin.

	Valley	Irrigated area 2000	Extent of ATir(1)	Volume of ATir(1)	Mean depth of ATir	Duration settlement history	Mean ATir sediment-ation rate	Sediment stored per unit of catchment area
		(ha)	(ha)	(×10^3 m^3	(m)	(year cal. BP)	(mm/year)	(mm)
North	Santa Cruz Valley	1613	1142	14 486	1.27	?	0.508	34.95
	Rio Grande Valley	1287	1154	9302	0.81	≥3400(2)	0.324	5.14
	Palpa Valley	1924	1708	18 625	1.09	≥3000(3)	0.436	13.51
	Ingenio Valley	2557	2080	23 511	1.13	≥2000(4)	0.452	14.98
South	Nazca Valley	5305	4504	52 798	1.17	≥1900(4)	0.468	40.96
	Taruga Valley	2986	1687	14 954	0.89	≥1500(5)	0.356	47.61
	Chauchilla Valley	167	n.a.	n.a.	n.a.	≥1500(5)	n.a.	n.a.
	Las Trancas Valley	2126	1670	18 211	1.09	≥1500(5)	0.436	37.37
	Total	17 963	13 945	151 886	1.09		0.436	20.10

(1) ONERN, 1971; (2) Reindel, 2008; (3) Hesse & Baade, 2007; (4) Silverman & Proulx, 2002; (5) Schreiber & Lancho Rojas, 1995.

The total volume of irragric anthrosols stored in the river oases at the foot of the Cordillera Occidental amounts to 152×10^6 m^3. This volume most certainly represents a minimum value. For purposes of robustness and data consistency, we used 1.3 m for the irragric horizon thickness of the Series Nazca soils, despite the fact that this soil's upper fine grained layers are at least 1.3 m thick (ONERN 1971) and our observation that irragric anthrosols in the Palpa Valley are locally up to 3.5 m thick. Comparing the mean thickness of irragric anthrosols in the Palpa Valley derived from the soil survey data (1.09 m, Table 3) with the result of our mapping in the Palpa Valley (mapped area: 1243 ha, mean thickness of irragric horizon: 1.25 m, cf. Hesse & Baade, 2008) indicates that the total volume of irragric anthrosols might be underestimated by 15%. In addition, the data in Table 3 do not include the volume of irragric anthrosols in the narrow upstream sections of the headwaters (approx. 5.8×10^6 m^3) and the material stored in the lower reaches of the Rio Nazca and the Rio Grande (approx. 14.5×10^6 m^3). The main reason for not including these areas is the difficulty in discriminating irrigated fields and other vegetated areas (riparian vegetation) in the narrow valleys. Also, our observations indicate that arable land in the narrow valley stretches is often rather young as infrequent floods often erode considerable portions of the narrow valley bottom. Including these areas in the calculations would increase the initial figure by 13%. This rather low value clearly shows that the river oases at the foot of the Cordillera Occidental represent the most important sediment trap along the sediment transport route from the slopes of the Cordillera Occidental to the Pacific Ocean.

In the Palpa Valley the build-up of irragric anthrosols started locally around 3000 years ago and widespread formation of irragric anthrosols is ascertainable by 2500 years ago. For the other river oases of the Rio Grande system dating of anthrosols is not yet available. In the areas where archaeological investigations targeted time frames preceding the Nasca time (starting approx. 2000 years ago, Silverman & Proulx, 2002), archaeological findings indicate a settlement history of more than 3000 years (Reindel & Isla, 2004; Reindel, 2008). We assume that the anthrosols were deposited uniformly within the last 2500 years, despite the fact that the data on the minimum duration of settlement history compiled in Table 3 seemingly indicate a somewhat shorter duration for the southern part of the Rio Grande drainage system. This yields a mean long-term deposition rate of irragric anthrosols for all river oases of 0.436 mm/year, while the mean long-term deposition rate for individual sub-basins varies from 0.324 mm/year for the Rio Grande Valley to 0.508 mm/year for the Santa Cruz Valley.

Relating the amount of sediment stored in the river oases to the upstream catchment areas yields minimum values for the late Holocene (last 2500 years) gross denudation rate on the western slopes of the Cordillera Occidental. The results for the sub-basins reveal a high variation with a rather low value of 5.14 mm for the Rio Grande sub-basin and a maximum value of 47.6 mm for the Taruga sub-basin. Correlation analysis shows a significant ($P < 0.05$) positive relationship between the minimum gross denudation rate and the extent of the vegetated ($\rho = 0.857$) and irrigated ($\rho = 0.786$) area in the river oases. Significant negative relationships were found with the upstream catchment area ($\rho = -0.821$), the amount of water available per unit area of irrigated fields ($\rho = -0.857$) and the runoff downstream of the river oases ($\rho = -0.786$) calculated from mean gauging station runoff and the percentage of runoff used for irrigation (cf. Table 1). This indicates, that the calculated values of minimum gross denudation rate are affected by the sediment delivery ratio being a function of catchment size and catchment properties (Walling, 1983; Ferro & Minacapilli, 1995), and the human induced sediment trap efficiency (Heinemann, 1984) of the irrigation schemes. The strong positive relationship with the extent of the irrigated area as well as the strong negative relationship with the amount of water available for irrigation and the amount of runoff in the rivers downstream of the irrigated areas, are clear indicators of a significant human impact on the sediment transfer from the slopes of the Cordillera Occidental to the Pacific Ocean. Furthermore, the results of the statistical analysis suggests that quantification of the amount of sediment stored in irragric anthrosols in the river oases of the Rio Grande system offers the potential to estimate gross denudation rate on the western slopes of the Cordillera Occidental. However, as extreme hydrological events might remobilize parts of the fine sediment stored in the valley bottom, detailed sedimentological investigations are necessary to account for this process.

CONCLUSIONS

Based on investigations of irragric anthrosols, this paper provides evidence that irrigation agriculture can have an impact on the amount of sediment delivered from upland regions to the oceans in semi-arid to arid regions. This impact might reach back to the onset of irrigation agriculture in these regions (often several millennia BP). Therefore, it needs consideration when reconstructing Holocene landscape dynamics from sedimentary evidence in depositional environments. Volumetric assessments of sediment stored in the valley bottom combined with information on the onset of human settlement can yield a first estimate of the long term accumulation of sediment by irrigation agriculture. In the Rio Grande de Nazca drainage basin the volume of sediment stored in irragric anthrosols is estimated to be 152–202 × 10^6 m^3. Relating this volume to the upstream catchment area results in a mean minimum denudation rate of 8 mm per 1000 years for the western slopes of the Cordillera Occidental in southern Peru.

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