Waldökologie, Landschaftsforschung und Naturschutz | Heft 10 (2010) | S. 77–84 | 11 Fig., 3 Tab. | urn:nbn:de:0041-afsv-01091

Morphological development of the Ucayali River, Peru without human impacts

Morphologische Entwicklung des Ucayali in Peru ohne menschliche Einflüsse

Bernd Ettmer and Cesar Adolfo Alvarado-Ancieta

Abstract

The Ucayali River originates in the high Andean Mountains near the city of Cusco in Peru. After about 1,600 km, it joins with the Marañón River. Both the Ucayali River and the Marañón River are sources of the Amazon. From 2001 to 2005, the Ministry of Transport and Communication of Peru funded a study to determine the navigability of the Ucayali River. In the process, an extensive data set was acquired including hydrological and sedimentological data as well as a comprehensive topographical survey of the riverbed. Since the Ucayali River has experienced no stream channel modification in the past, the available data provide information about the flow pattern for a natural stream and insight into a reference ecosystem. This paper offers the first analysis of the available data and a sediment transport calculation for the Ucayali River.

Keywords: *Natural flow, sharp bends, scour, sediment transport*

Zusammenfassung

Der Ucayali entspringt in den Anden nahe der Stadt Cusco in Peru. Er fließt über eine Strecke von rd. 1.600 km durch Peru bis zum Zusammenfluss mit dem Marañón. Beide Flüsse bilden die Quellflüsse für den Amazonas. Im Rahmen einer Studie über die Schiffbarkeit des Ucayali wurden vom peruanischen Ministerium für Verkehr und Kommunikation von 2001 bis 2005 umfangreiche Datenerhebungen durchgeführt. Die Datenerhebungen umfassen u. a. hydrologische und sedimentologische Daten sowie umfangreiche Vermessungen des Flusslaufs. Da der Ucayali bislang keinerlei Regulierungs- oder Ausbaumaßnahmen unterlegen ist, geben die Daten einen Einblick in die natürlichen Fließverhältnisse eines großen Flusses und damit einen Einblick in ein Referenz-Ökosystem. Erste Ergebnisse der Datensichtung und Sedimenttransportberechnungen zum Ucayali werden vorgestellt.

Schlüsselwörter: Natürliches Fließgewässer, Mäander, Sedimenttransport

1 Introduction

The Ucayali River begins in the south of Peru near the city of Cusco in the Andes Mountains. The catchment area of the Ucayali River covers 337,519 km^2. The total length of the river stretches 1,600 km. The junction between the Marañón River and the Ucayali River constitutes the source of the Amazon. Figure 1 gives an overview of the Amazon system and the location of Ucayali River.

At the present time, the Ucayali River represents a natural river. No stream channel modifications such as straightening of the river, riverbed armoring, or bank protection have been undertaken. As presented in Figure 2 the Ucayali River has a meandering flow with numerous tributary streams and backwaters and shows natural sediment transport mechanisms (Alvarado-Ancieta & Ettmer 2008).

2 Basic results of topographical survey

The topographical survey of the river bed and floodplain was carried out between the city of Pucallpa and the confluence with the Amazon, a section of about 1,035 km. Pucallpa was defined as river station km 0 and the junction with the Marañón River as river station km 1,035. The riverbed was surveyed by boat with an echo-sounding system, and the banks were surveyed with a tachymetry system. In most cases that work was carried out by a team of nine persons as presented in Figure 3. They produced more than 2,000 detailed cross-sections of the Ucayali River.

As an example, Figure 4 shows cross-sections near river section km 235. The cross-sections were prepared with the Hydrologic Engineering Center River Analysis System (HEC RAS), from the U.S. Army Corps of Engineers. The average width, *w*, of the riverbed is approximately 600 m, and the water depth, *d*, is approximately 10 m during mean water conditions. Thus, the ratio of *w/d* is 60. Generally, the width of the riverbed ranged from 400 to 1,500 m, and the water depth from 8 to 15 m.

Figure 5 gives a plan view of the measured river section between Pucallpa and the junction with the Marañón River. The plan view illustrates the sinuous system of the Ucayali River. The sinuosity, *si*, defined as the ratio between the river length including curves and the direct distance without any curves, ranges from 1.2 to 1.5. That means the Ucayali River induces heavy bank erosion and shows a tendency toward bifurcation and tributary streams (Ahnert 1996).

The Ucayali River can be separated into three reaches. The first reach is located between the city of Pucallpa at km 0 and the entrance to a bifurcation at km 570. The average slope of that reach is 0.054 ‰. Then the Ucayali River divides into two arms called the Madre Channel and the Puinahua Channel. The Madre Channel is defined as the main stream with a longitudinal section of 270 km and an average slope of 0.055 ‰. At km 840, the Madre Channel and the Puinahua Channel unify again to a single flow section. Up to the junction with the Marañón River at km 1,035, the average slope is 0.028 ‰. The main values are presented in Table 1.

Figure 6 presents the thalweg (the lowest points along the entire length of the streambed) of the Ucayali River between the city of Pucallpa at km 0 and the confluence with the Marañón River at km 1,035. The average slope of the whole river section is approximately 0.05 ‰. Furthermore the variation in the riverbed elevation is remarkable, and deep bed elevations were frequently observed. This is due to the fact that the thalweg is defined as the deepest point in each cross-section, and at points where the river bends, the outer scour hole can be significantly deeper than the rest of the bed. In places, the scour holes can be more than 10 m deeper than the average bed depth.

In addition, more than 50 sinuous sections were identified between Pucallpa and the confluence of the Amazon. Some of these meanders were identified as sharp bends. Different experiments for sharp bend hydraulics have been done to identify the main characteristic parameters (i. e., Sutmuller & Glerum 1980, Odgaard 1982, Struiksma et al. 1985, Olesen

Fig. 1: Map of the Amazon system and Ucayali River stream course (Alvarado-Ancieta & Ettmer 2008).

Abb. 1: *Übersicht über das Amazonas Einzugsgebiet und den Verlauf des Ucayali (Alvarado-Ancieta & Ettmer 2008).*

Fig. 2: View of the Ucayali River a few kilometers above the city of Pucallpa, showing the meandering riverbed tributary streams and backwater (Consorcio H&O – ECSA 2005).

Abb. 2: *Blick aus dem Flugzeug auf den Ucayali mit Mäander, Nebenarm und Altarm, wenige Kilometer vor der Stadt Pucallpa (Consorcio H&O – ECSA 2005).*

Fig. 3: Survey team with speed boats and tachymetry equipment (Consorcio H&O – ECSA 2005).

Abb. 3: *Vermessungsteam mit Schnellboot und Ausrüstung (Consorcio H&O – ECSA 2005).*

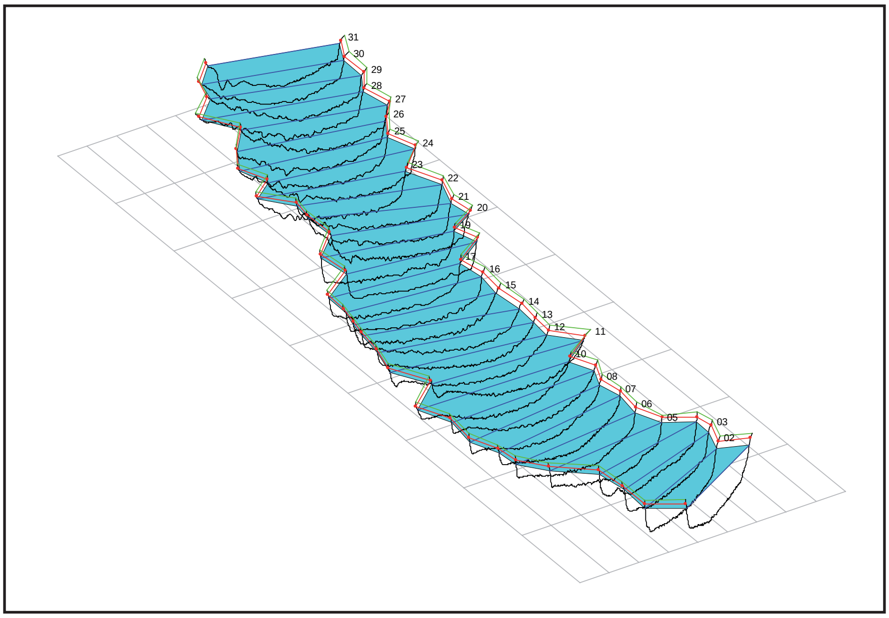

Fig. 4: Cross-sections near river station km 235, prepared with HEC RAS from the US Army Corps of Engineers (Alvarado-Ancieta & Ettmer 2008).

Abb. 4: *Querprofile in der Nähe des Fluss-km 235, aufgearbeitet mit der Software HEC RAS vom US Army Corps of Engineers (Alvarado-Ancieta & Ettmer 2008).*

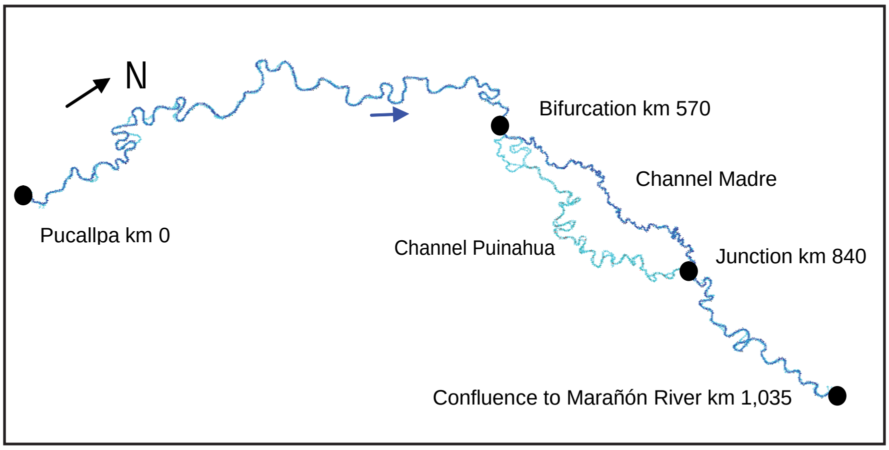

Fig. 5: Plan view of the Ucayali River with bifurcation into the Madre Channel and the Puinahua Channel.

Abb. 5: *Lageplan des Ucayali mit Verzweigung des Flusslaufes in den Kanal Madre und den Kanal Puinahua.*

Tab. 1: Three reaches of Ucayali River.

Tab. 1: *Die drei Fließabschnitte des Ucayali.*

Reach	Station (km)	Slope (‰)	Description
1	0–570	0.054	Pucallpa to the start of the bifurcation
2	570–840	0.055	Bifurcation
3	840–1,035	0.028	End of the bifurcation to the junction with the Marañón River

1987, Talmon 1992, Blanckaert & Graf 1999, Blanckaert 2002 and Alvarado-Ancieta 2004). Sharp bends have been defined according to the empirical equation (1):

$$R/B < 3 \qquad (1)$$

where R = radius of bend and B = width of river. It should be noted that sharp bends often have an angle of aperture (angle measured from the beginning to the end of the bend) of more than 180°. That means a strong morphological development of the river bed and river banks of the Ucayali River could be expected.

3 Basics of hydrology and sediment transport

Hydrological data were collected over 20 years at the hydrometric station of Pucallpa as shown in Table 2. Low water discharge was measured on 19.08.1985 as 2,200 m^3/s, whereas the maximum discharge was 20,440 m^3/s measured on 05.03.1984. The mean water discharge is approximately 4,000 m^3/s.

Between 2001 and 2004, more than 100 sediment samples were collected from the Ucayali River both as bed samples and as suspension samples (Fig. 7).

The sample probes corresponded to the gauging stations along the Ucayali River as shown in Table 3.

Figure 8 presents some representative sieve curves, used to assess the proportional contribution of sediment particles of different sizes, taken along the reach from Pucallpa km 0 to Libertad km 1,011. The sieve curves do not show any significant differences. Thus, the characteristic diameter of the sediment D_{50} (the sieve size at which 50 % of sediment weight pass through the sieve) only ranges from 0.15 to 0.40 mm with an average value of D_{50} = 0.25 mm.

The uniformity of the sediment can be calculated with equation (2) (Little & Mayer 1976).

Tab. 2: Discharges at the hydrometric station of Pucallpa.

Tab. 2: *Abflüsse an der Pegelstation Pucallpa.*

Description	Discharge (m^3/s)
Low water	2,200 on 19.08.1985
Mean low water	2,830
Mean water	ca. 4,000
Mean high water	16,370
Maximum flood	20,440 on 05.03.1984

Tab. 3: Gauging stations at Ucayali River.

Tab. 3: *Pegelstationen entlang des Ucayali.*

Name of gauging station	Station (km)
Pucallpa	0
Tiruntán	133.52
Contamana	261.26
Orellana	355.95
Juancito	562.32
Requena	897.83
Libertad	1,011.33

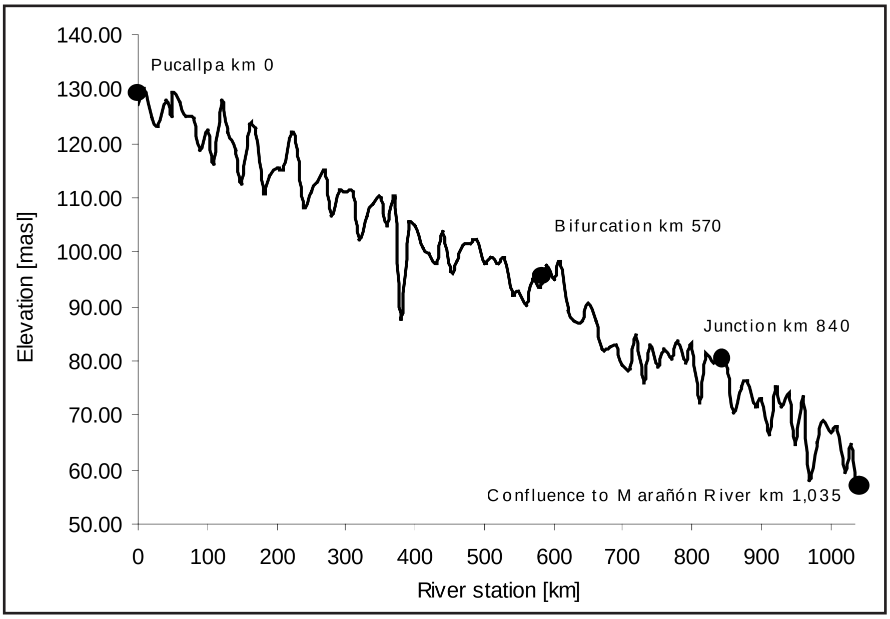

Fig. 6: Longitudinal section showing the thalweg of the Ucayali River between the city of Pucallpa and the junction with the Marañón River.

Abb. 6: *Längsschnitt des Talwegs zwischen der Stadt Pucallpa und dem Zusammenfluss mit dem Marañón.*

$$\sigma = (D_{84}/D_{16})^{0.5} \quad (2)$$

The grain diameter D_{84} was 0.30 mm and D_{16} was 0.15 mm. The calculated uniformity amounts to 1.41, indicating that the sediment of the Ucayali River could be described as nearly uniform.

Figure 9 shows the changes in D_{50} along a longitudinal section. The mean diameter D_{50} is 0.25 mm along the whole reach from Pucallpa to the confluence with the Amazon at km 1,035. Generally, only a small variation in D_{50}, with the lower bound at 0.15 mm and the upper bound at 0.40 mm, was observed. At km 250, however the D_{50} increased to 0.65 mm. The reason for that local coarsening of the sediment is the inflow of the Amacayacu River carrying coarser sediment into the Ucayali River. However, these effects were diminished after ca. 90 km at river station km 340, as shown in the diagram.

Hjulström (1935) gives a relation between the average velocity and the characteristic grain diameter, Figure 10. Thus, the begin of transportation of the grain size D_{50} = 0.25 mm. ranges between 0.15 and 0.30 m/s. It is in this range that the bed load transport of the Ucayali River begins and prevails up to an average velocity of approximately 0.94 m/s. Then, as the velocity increases, the sediment is suspended as described by the empirical approach of Kresser (1964),

Fig. 7: Sediment samples from river bed (a) and suspension samples (b) (Consorcio H&O – ECSA 2005).

Abb. 7: *Sedimententnahmen vom Flussbett (a) und Schwebstoffbeprobung (b) (Consorcio H&O – ECSA 2005).*

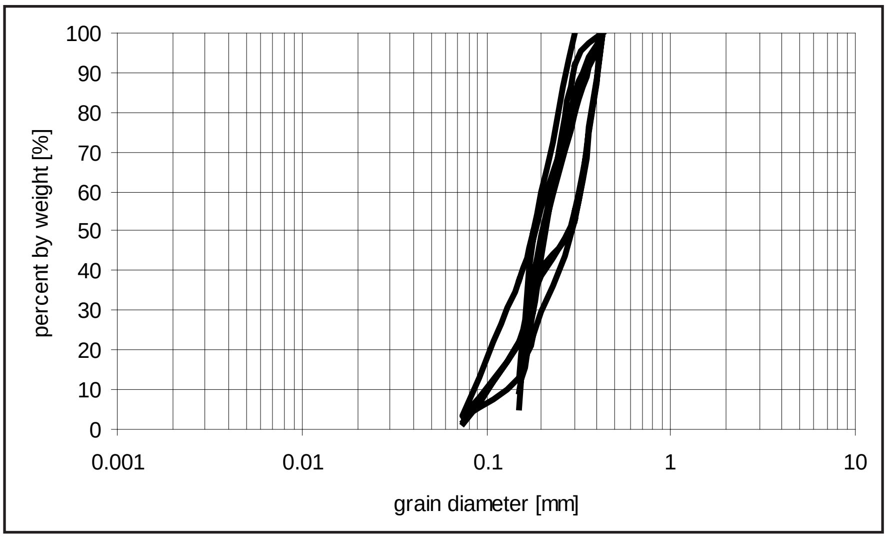

Fig. 8: Sieve curves from different probes between Pucallpa (km 0) and Libertad (km 1,011).

Abb. 8: *Sieblinien für verschiedene Probenahmestellen zwischen Pucallpa (km 0) und Libertad (km 1,011).*

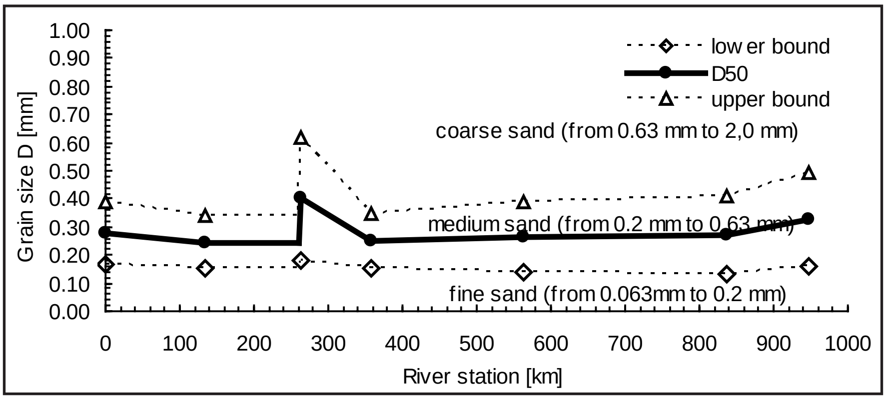

Fig. 9: Longitudinal profile of characteristic sediment diameter between Pucallpa (km 0) and Libertad (km 1,011).

Abb. 9: *Längsprofil der characteristischen Korndurchmesser zwischen Pucallpa (km 0) und Libertad (km 1,011).*

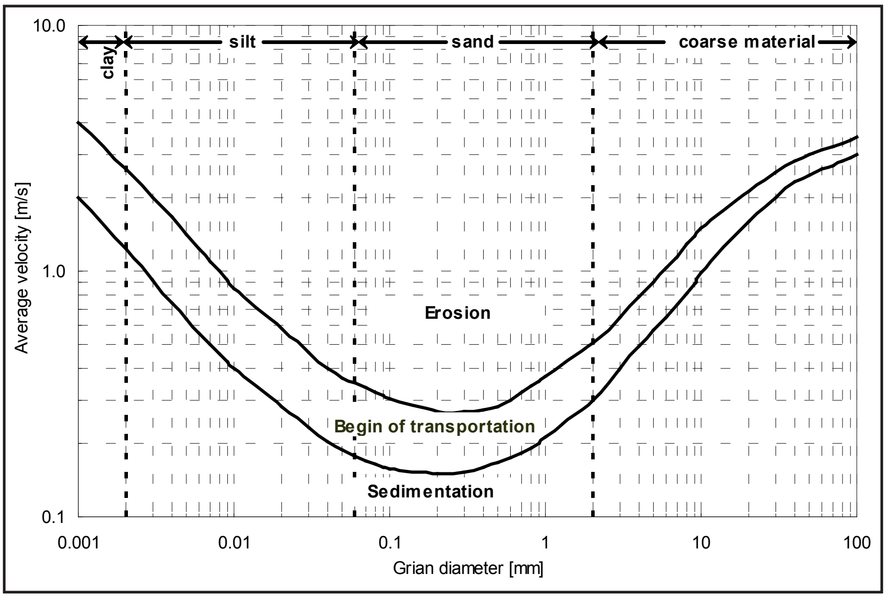

Fig. 10: Longitudinal profile of characteristic sediment diameter between Pucallpa (km 0) and Libertad (km 1,011).

Abb. 10: *Längsprofil der characteristischen Korndurchmesser zwischen Pucallpa (km 0) und Libertad (km 1,011).*

equation (3), with suspension load becoming the main type of sediment transport:

$$D = u_m^{\,2} / 360g \qquad (3)$$

where D = grain diameter for transition between bed load and suspension load; u_m = average velocity; g = acceleration of gravity.

Hydraulic conditions of the Ucayali River were calculated with the one-dimensional hydro-numerical model HEC-RAS from the U.S. Army Corps of Engineers (Consorcio H&O – ECSA 2005). The calculation showed that the average velocity of the Ucayali River exceeds 0.94 m/s for discharges of more than 2,200 m^3/s, a level defined as low water conditions in Table 2. Thus, suspension load transport occurs as soon as the river discharge exceeds low water conditions. Accordingly, suspension load can be defined as the main mode of sediment transport in the Ucayali River.

The average sediment transport rate was calculated based on suspension measurements from 2004 and 2005[1] at the gauging stations shown in Table 3. As shown in Figure 11, a functional dependency between discharge and suspension load can be described roughly as a linear trend. It should be noted that the maximum discharge during the measurement period was approximately 10,000 m^3/s. Equation (4) represents the linear regression:

$$S = 51.204Q - 27{,}797 \qquad (4)$$

where S = sediment transport due to suspension load [t/day]; Q = discharge.

As an example, the suspension load was calculated as 187,000 t/day at a discharge of 4,200 m^3/s. As calculated with values from Table 2, the sediment transport rate amounts to 177,000 t/day for the mean discharge (4,000 m^3/s) and approximately 1 million t/day for the flood discharge (20,440 m^3/s).

A further approximation of the annual sediment transport rate was calculated with equation (5) and mean water discharge of 4,000 m^3/s. The result was an annual sediment transport rate of ca. 65 million t/year.

$$S_{annual} = (51.204Q - 27{,}797)\,\Delta t \qquad (5)$$

where S_{annual} = suspension load per year; Δt = 365.25 days/year. A first evaluation of equation (5) delivers acceptable results by using values from Guyot et al. (1996 and 1999), Guyot & Filizola (2007).

4 Conclusions

Between 2001 and 2005 several basic investigations of the Ucayali River in Peru were carried out. Amongst others, a

1 Note: The sediment concentration was measured in [kg/m^3] and was calculated as [t/day].

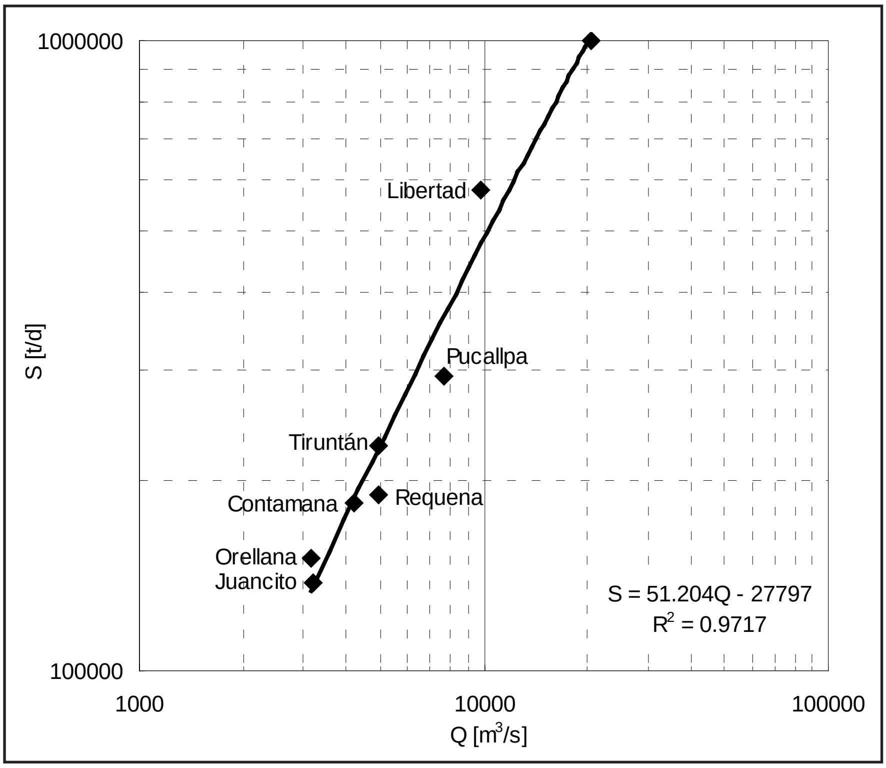

Fig. 11: Mean measured sediment concentration at gauging stations for different discharges.

Abb. 11: *Mittlere gemessene Sedimentkonzentration für verschiedene Abflüsse und Pegelstellen.*

longitudinal section of 1,035 km between the city of Pucallpa and the confluence of the Amazon was surveyed and more than 2,000 cross-sections were developed. A typical cross-section shows an average width of about 600 m and a water depth of 10 m during mean water conditions (4,000 m^3/s). The average slope on that reach is 0.05 ‰, and more than 50 sharp bends could be identified. Thus, the Ucayali River can be described as a sinuous system with a tendency toward bank erosion, bifurcation, and tributary streams. Further investigations showed that the bed material of the Ucayali River can be characterized as uniform sand with a characteristic diameter of D_{50} = 0.25 mm along the entire reach. The estimated sediment transport rate is approximately 65 million t/year, and the main type of sediment transport is suspension load.

References

Ahnert, F. (1996): Einführung in die Geomorphologie. UTB für Wissenschaft. Verlag Eugen Ulmer, Stuttgart: 440 pp.

Alvarado-Ancieta, C.A. (2004): Bed topography and scour in sharp river bends, and influence of bank protection works. M.Sc. Thesis HE 179, Vol. 1 & 2. International Institute for Infrastructure, Hydraulic and Environmental Engineering - IHE-Delft, The Netherlands.

Alvarado-Ancieta, C.A., Ettmer, B. (2008): Morfología Fluvial y Erosión en Curvas abruptas del Río Ucayali, Perú, Revista de interdisciplinaria de cienca y tecnología del agua, Ingeniería hidráulica en méxico, Vol. **XXIII**, núm. 4: 69-90. octubre-diciembre de 2008, ISSN-0186-4076 (published in Spanish)

Blanckaert, K., Graf, W.H. (1999): Experiments on flow in open channel-bends. Proc. 28th IAHR Congr., Techn. Univ. Graz, Graz, Austria.

Blanckaert, K. (2002): Analysis of coherent flow structures in a bend based on instantaneous-velocity profiling. 3rd International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering, EPFL, Lausanne, Switzerland.

Consorcio H&O – ECSA (2005): Estudio de Navegabilidad del Río Ucayali en el tramo comprendido entre Pucallpa y la confluencia con el río Maranon. Dirección General de Transporte Acuático del Ministerio de Transportes y Comunicaciones del Perú, Informe final, Volumen III, Estudio de la hídraulica fluvial, junio 2005. (published in Spanish)

Guyot, J.L., Filizola, N., Quintanilla, J., Cortez, J. (1996): Dissolved solids and suspended sediment yields in the Rio Madeira basin, from the Bolivian Andes to the Amazon. Erosion and Sediment Yield: Global and Regional Perspectives (proceedings of the Exeter Symposium), IAHS Publ. No **236**: 55-63.

Guyot, J.L., Jouanneau, J.M., Wasson, J.G. (1999): Characterization of river bed and suspended sediments in the Rio Madeira drainage basin (Bolivia Amazonia). Journal of South American Earth Sciences: 401-410.

Guyot, J.L., Filizola, N. (2007): Suspended sediment yield in the Amazon basin. An assessment using the Brazilian national data set. Hydrological Processes **23** (22): 3207-3215.

Hjulström, F. (1935): Studies of the morphological activity of rivers as illustrated by the river Fyris. Bulletin of the Geological Institute of the University of Upsala.

Kresser, W. (1964): Gedanken zur Geschiebe- und Schwebstoffführung der Gewässer. Österreichische Wasserwirtschaft **16** (1/2): 6-11.

Little, W.C., Mayer, P.G. (1976): Stability of channel beds by armouring. Journal of Hydraulics Division, ASCE, **102** (HY11): 1647-1661.

Odgaard, A.J. (1984): Flow and bed topography in alluvial channel bend. J. Hydr. Eng., ASCE **110** (4): 521-536.

Olesen, K.W. (1987): Bed topography in shallow river bends. Communications on Hydraulic and Geotechnical Engineering, Delft University of Technology, Faculty of Civil Engineering, The Netherlands.

Struiksma, N., Olesen, K.W., Flokstra, C., De Vriend, H.J. (1985): Bed deformation in curved alluvial channels. J. Hydr. Res., IAHR **23** (1): 57-79.

Sutmuller, A.M., Glerum H.L. (1980): Description and evaluation of measurements carried out in a bend flume with sand bed. Report. No. 14710101. Department of Civil Engineering, Delft Technical University, Delft.

Talmon, A.M. (1992): Bed topography of river bends with suspended sediment transport. Doctoral thesis. Faculty of Civil Engineering, Hydraulic and Geotechnical Engineering Division, Delft University of Technology, The Netherlands.

Ven Te Chow (1973): Open Channel Hydraulics. New York: McGraw-Hill International Editions, Civil Engineering Series, 1973.

Zanke, U. (1982): Grundlagen der Sedimentbewegung. Springer Verlag, Berlin.

submitted: 20.09.2009
reviewed: 12.04.2010
accepted: 15.04.2010

Adresses of authors:

Prof. Dr.-Ing. Bernd Ettmer (Germany)
University of Applied Sciences Magdeburg-Stendal
Department of Water and Waste Management
Breitscheidstr. 2, 39114 Magdeburg, Germany
Phone: + (49) (0) (391) 886 4429
Fax: + (49) (0) (391) 886 4430
Email: bernd.ettmer@hs-magdeburg.de

Dipl.-Ing., M.Sc., Cesar Adolfo Alvarado-Ancieta (Peru)
Civil Engineer, Director of Projects
GAUFF GmbH & Co. Engineering KG
Department of River Engineering, Hydropower and Dams
Passauer Straße 7, 90480 Nuremberg, Germany
Phone: + (49) (911) 9409208
Fax: + (49) (911) 9409201
Email: calvarado@gauff.com