Hydro-BID case study N°3: Impact of El Niño events on sediment loading in the Chancay-Lambayeque Basin, Peru

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Water and Sanitation Division

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HYDRO-BID
CASE STUDY N°3:

IMPACT OF EL NIÑO EVENTS ON SEDIMENT LOADING IN THE CHANCAY- LAMBAYEQUE BASIN, PERU

Jorge Escurra
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FOREWORD

The Inter-American Development Bank (IDB) provides financial and technical support for infrastructure projects in water and sanitation, irrigation, flood control, transport, and energy, and for development projects in agriculture, urban systems, and natural resources. Many of these projects depend upon water resources and may be affected negatively by climate change and other developments that alter water availability, such as population growth and shifts in land use associated with urbanization, industrial growth, and agricultural practices. Assessing the potential for future changes in water availability is an important step toward ensuring that infrastructure and other development projects meet their operational, financial, and economic goals. It is also important to examine the implications of such projects for the future allocation of available water among competing users and uses to mitigate potential conflict and to ensure such projects are consistent with long-term regional development plans and preservation of essential ecosystem services.

As part of its commitment to help member countries adapt to climate change, the IDB is sponsoring work to develop and apply the Regional Water Resources Simulation Model for Latin America and the Caribbean, an integrated suite of watershed modeling tools known as Hydro-BID. Hydro-BID is a highly scalable modeling system that includes hydrology and climate analysis modules to estimate the availability of surface water (stream flows) at the regional, basin, and sub-basin scales. The system includes modules for incorporating the effects of groundwater and reservoirs on surface water flows and for estimating sediment loading. Data produced by Hydro-BID are useful for water balance analysis, water allocation decisions, and economic analysis and decision support tools to help decision-makers make informed choices among alternative designs for infrastructure projects and alternative policies for water resources management.

IDB sponsored the development of Hydro-BID and provides the software and basic training free of charge to authorized users; see hydrobidlac.org. The system was developed by RTI International (RTI) as an adaptation of RTI's proprietary WaterFALL® modeling software, based on over 30 years of experience developing and using the U.S. National Hydrography Dataset (NHDPlus) in support to the U.S. Geological Survey and the U.S. Environmental Protection Agency.

In Phase I of this effort, RTI prepared a working version of Hydro-BID that includes: (1) the Analytical Hydrography Dataset for Latin America and the Caribbean (LAC AHD), a digital representation of 229,300 catchments in Central America, South America and the Caribbean with their corresponding topography, river and stream segments; (2) a geographic information system (GIS)-based navigation tool to browse AHD catchments and streams with the capability of navigating upstream and downstream; (3) a user interface for specifying the area and period to be modeled and the period and location for which water availability will be simulated; (4) a climate data interface to obtain rainfall and temperature inputs for the area and period of interest; (5) a rainfall-runoff model based on the Generalized Watershed Loading Factor (GWLF) formulation; and (6) a routing scheme for quantifying time of travel and cumulative flow estimates across downstream catchments. Hydro-BID generates output in the form of daily time series of flow estimates for the selected location and period. The output can be summarized as a monthly time series at the user's discretion.

In Phase II of this effort, RTI has prepared an updated version of Hydro-BID that includes (7) improvements to the user interface; (8) a module to simulate the effect of reservoirs on downstream flows; (9) a module to link Hydro-BID and groundwater models developed with MODFLOW and incorporate water exchanges between groundwater and surface water compartments into the simulation of surface water availability; and (10) an application for modeling sediment loads using Modified Universal Soil Loss

Equations at specified locations in a surface water network, with pre-computed parameters including soil erodibility factor and topographic factor, with user inputs of cover management and support practice factors based on land use.

RTI has performed case study analyses using Hydro-BID in partnership with IDB water-sector client institutions in several countries. This Technical Note, prepared for the Autoridad Nacional del Agua (ANA, the National Water Authority) of Peru, is the ninth report in a series of publications describing the Hydro-BID system and case studies.

ACKNOWLEDGEMENTS

The authors wish to express thanks to individuals and organizations that made important contributions to the development of this study of the Chalpi Basin in Ecuador.

Sergio Campos, Chief of the IDB Water and Sanitation Division, provided senior leadership and strong support for developing case studies that apply Hydro-BID to a range of water supply and water resource management challenges in the LAC region. Dr. Fernando Miralles-Wilhelm, who was previously on staff at IDB and is now Professor of Earth System Sciences at the University of Maryland, provided technical guidance for the study. Raul Muñoz and Pedro Coli of IDB served as liaisons to the client organization, the Autoridad Nacional del Agua (ANA, National Water Authority) of Peru.

In addition, we are grateful for the excellent collaboration and constant support of staff at ANA who were engaged with the development and implementation of the study from its beginning. Special thanks to Pedro Guerrero for his guidance and to Ms. Delia Huanambal, who developed the Hydro-BID model for the Chancay-Lambayeque basin.

This work relied upon key technical inputs from our colleagues at RTI International, especially John Buckley and Mark Bruhn.

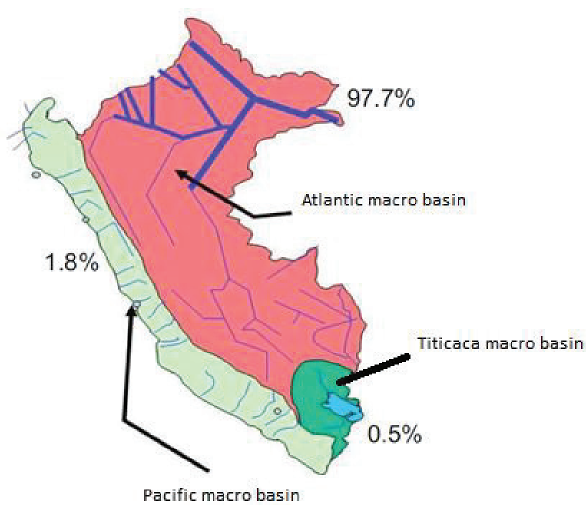
1. PURPOSE OF THE CASE STUDY

This case study was performed as part of an on-going effort to build the basin modeling skills of professional staff working for the Autoridad Nacional del Agua (ANA) and to demonstrate capabilities of the Hydro-BID system relevant to water resources management challenges in Peru. A member of ANA's regional staff developed the Hydro-BID model for the Chancay-Lambayeque basin, with technical support from RTI. RTI staff then used the model to demonstrate the use of a new Hydro-BID module for simulating sediment loading.

The coastal plain of Peru is home to 53% of Peru's population (Sevilla, 2014) and contains only 1.8% of the country's water resources, most of which drains to the Atlantic through the Amazon basin (**Figure 1**). Peru has a healthy, diversified economy with annual GDP growth at 6.4% (2004-2013) and population growth at 1.3% per annum (BCRP, 2014). Agriculture, most of which is located in the coastal plain, contributes 7% of national GDP. The combination of population increases, rising incomes and growth in irrigated agriculture are leading to a rapid increase in water demand throughout the coastal zone. With support from IDB, the government prepared its national water resources plan (Plan Nacional de Recursos Hidricos), approved by Decreto Supremo in 2015 (013-2015-MINAGRI). One of the plan's high priorities is to increase water storage capacity and improve reservoir management in the coastal plain.

The coastal plain of Peru is greatly affected by the El Niño Southern Oscillation (ENSO), with higher-than-average rainfall during El Niño events. During the planning stage of this project, most ENSO models were forecasting that a strong El Niño would occur in the first half of 2016 (NOAA Climate Prediction Team, 2016). The Government of Peru is investing around US$ 5,000 million to reduce the nation's vulnerability to natural disasters, including ENSO events (ReliefWeb, 2015).

The Tinajones reservoir in the Chiclayo province and inside the Chancay-Lambayeque basin is the fourth-largest reservoir in Peru, with a maximum usable capacity of 319 million cubic meters (hm^3). Given the importance of reservoir capacity, projected increases in water demand and the region's vulnerability to ENSO events, ANA requested that this case study demonstrate the use of Hydro-BID's new sediment loading module to model sediment loading to the Tinajones reservoir during ENSO events. This would help ANA to determine potential threats to the reservoir due to sediment load and preprare mitigation or adaptation actions.

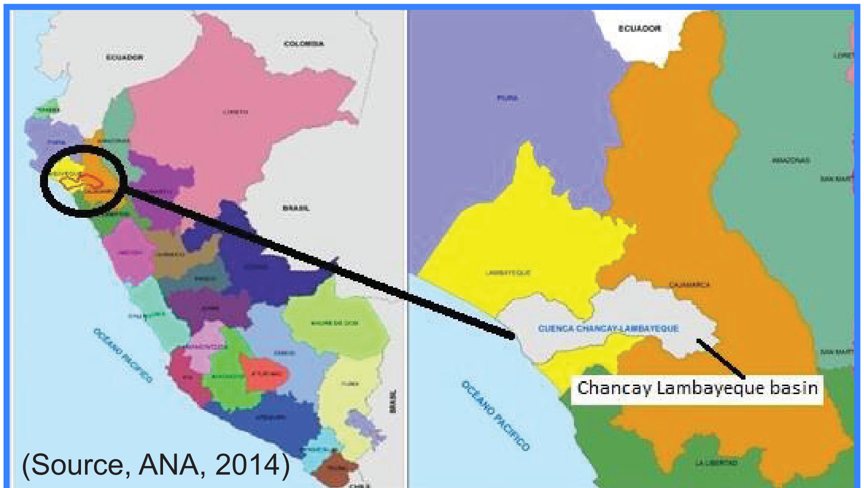


(Source: Sociedad de Urbanistas del Peru, 2011).

Figure 1. Water availability in the three macro basins in Peru

2. PROFILE OF THE CASE STUDY AREA

Peru is situated in the western part of South America. It borders Ecuador and Colombia to the north, the Pacific Ocean to the west, Brazil and Bolivia to the east, and Chile to the south. The Andes Mountains naturally divide Peru's mainland into three geographic regions: the Costa (coastal plain and Pacific basin), the Sierra (Andes Mountains and Titicaca Lake basin), and the Jungle (Amazon basin). This study focuses in the Chancay-Lambayeque basin in the northwestern area of Peru (**Figure 2**).

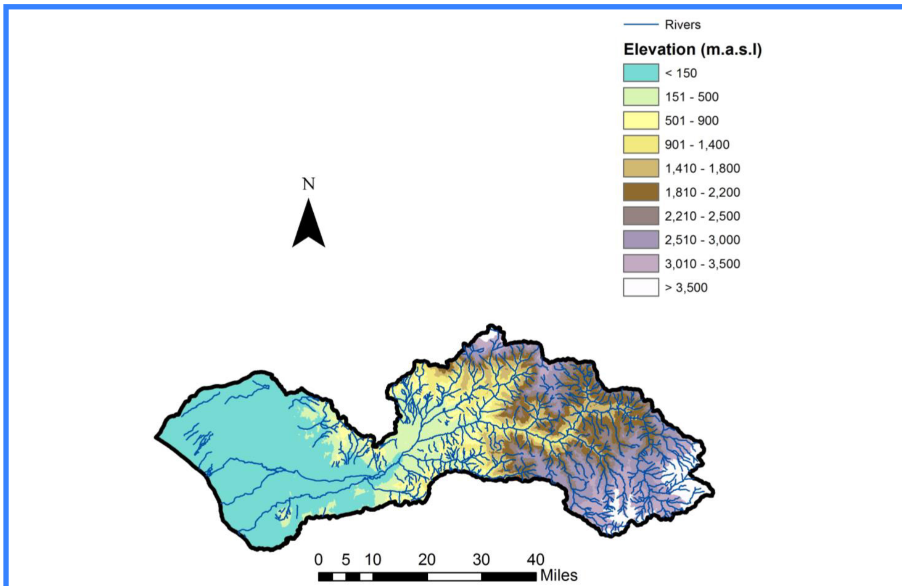


(Source, ANA, 2014)

Figure 2. Location of the Chancay-Lambayeque basin

The main cities in the basin are Chiclayo, Lambayeque, and Ferreñafe. Chiclayo is the capital of Lambayeque region and is the country's fourth-largest city, with an estimated population in 2015 of approximately 811,000 people in the greater metropolitan area (Instituto Nacional de Estadística del Peru, 2013).

Elevation in the Chancay-Lambayeque basin ranges from 3,500 meters above sea level at the headwaters to sea level at the coast; **Figure 3** shows an elevation map of the basin.

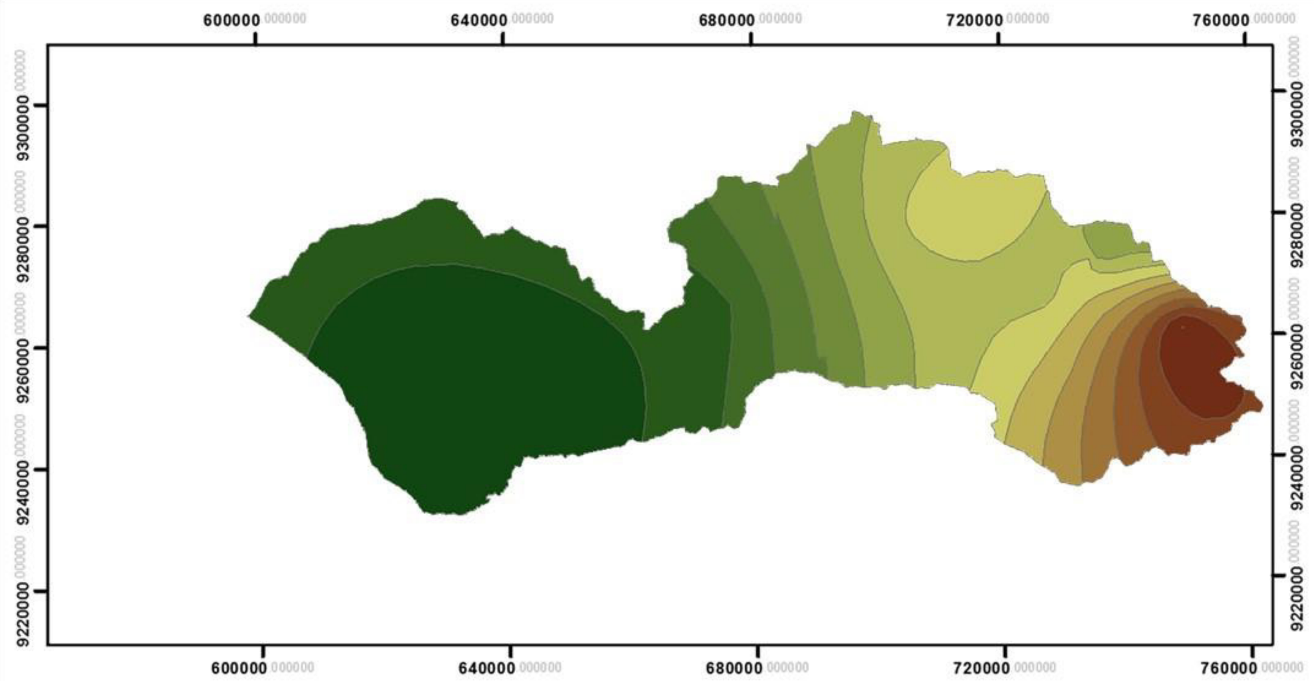


(Source: NASA Shuttle Radar Topography Mission)

Figure 3. Elevation map of the Chancay-Lambayeque basin

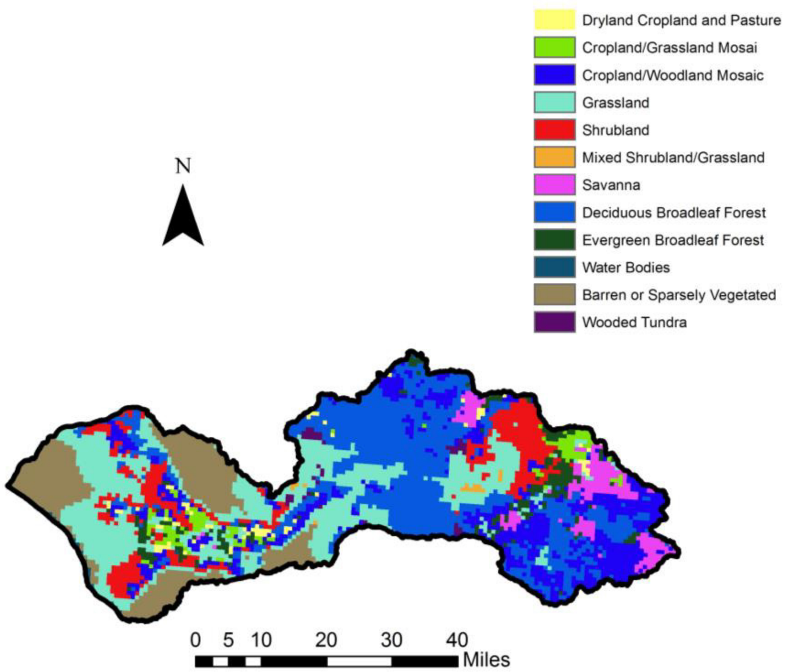
The climate in Chancay-Lambayeque basin is dry and subtropical. The average temperature is 23°C. Annual precipitation, depending on location, varies from 100mm to 1,400mm as shown in **Figure 4**. Because of low relative humidity, average evaporation of the Tinajones reservoir can be as high as 6.7 mm/day (ANA 2015).

Land use in the basin is shown in **Figure 5**; the characterization of cropland/woodland mosaic is the most predominant land use. **Figure 6** shows a map of the soil types in the basin; most of the soils are mainly silty with a regular amount of sand and clay. The level of runoff is low and water retention and infiltration characteristics of soils within the basin is moderate to high. Chancay-Lambayeque is one of the basins most vulnerable to ENSO events in Peru. The El Niños in 1982-83 and 1997-98 generated serious human and economic loss, and a previous event in 1925-26 was even more intense (SENAMHI, 2010).



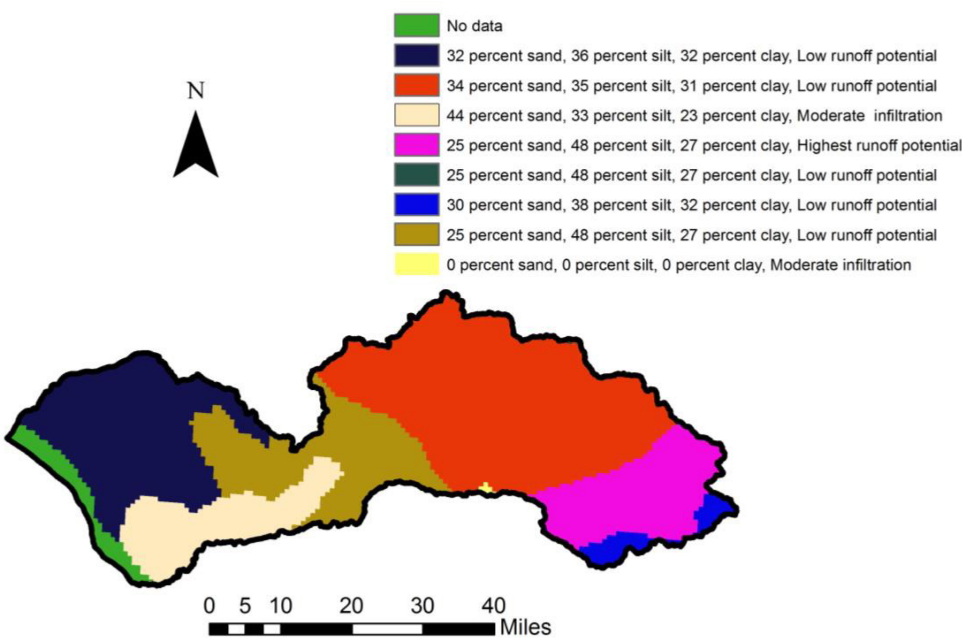
(Source, ANA, 2014)

Figure 4. Precipitation in Chancay-Lambayeque basin



(Source: USGS Land cover 2000, EROS Data Center 1998, resolution 1km x 1km)

Figure 5. Land use in the Chancay-Lambayeque basin



(Source: the FAO Harmonized World Soil Database, Fisher et al., 2008, resolution 1 km x 1 km)

Figure 6. Soil characteristics of the Chancay-Lambayeque basin

3. PREPARATION OF THE BASIN MODEL

The Hydro-BID model was developed by ANA staff member Ms. Delia Huañambal Vichez, with guidance and technical support from RTI. This section describes the methodology used in developing the basin model.

3.1 SETTING UP THE HYDRO-BID MODEL

ANA used the input data and the catchment and stream network topologies of the Analytical Hydrography Dataset for Latin America and the Caribbean (LAC AHD), as described in Hydro-BID Technical Note 1 (RTI International 2013). Hydro-BID uses the General Watershed Loading Factor rainfall-runoff model with input data on land uses, soil types, rainfall and temperature within the study area. Daily rainfall and temperature are interpolated for each catchment to generate catchment-specific values for daily flows. Flows are routed through stream networks defined by the AHD. Hydro-BID runs from a single database compiled at any scale from an individual watershed to a large regional basin. Flows are compared to observations from gage stations to calibrate and validate the model. The structure and operation of the model are described in Hydro-BID Technical Note 2, Second Edition (RTI International 2016).

3.2 AHD OF THE STUDY AREA

Figure 7 shows the LAC AHD map for the Chancay-Lambayeque basin. The basin has two main parts: (i) the highland, non-regulated portion to the east that receives water mainly from natural flows, with the addition of inflows from the Tunnel Chotano; and (ii) the lowland portion to the west that is regulated by the Tinajones water system, including the Tinajones reservoir, canals, intakes, and other structures. **Figure 8** shows the regulated and non-regulated zones. The point of change between the two areas is the outlet of the sub-basin Ramada which is just upstream of the Raca Rumi gage station. Below this point there are a series of water infrastructures that influence water distribution in the basin. The current modeling exercise focuses on natural flows from rainfall and runoff above Racarumi, in order to model flows and sediment above the Tinajones reservoir.

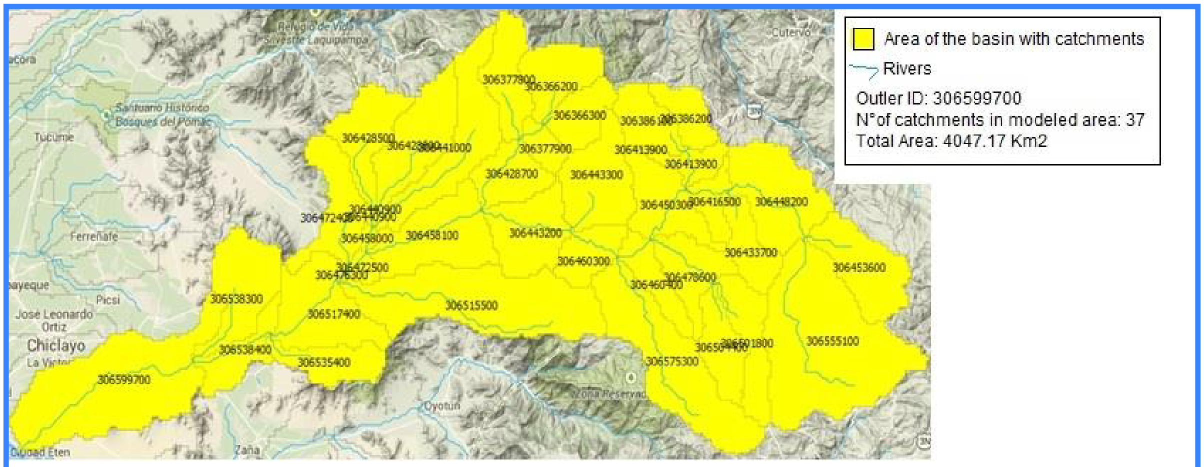
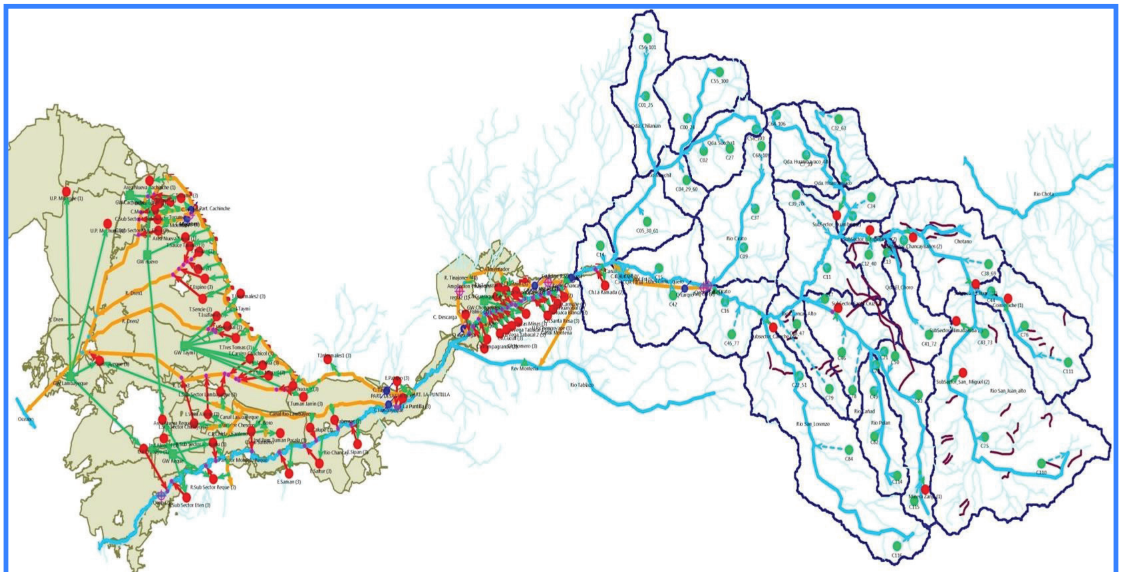


Figure 7. AHD map for the Chancay-Lambayeque basin



(Source, ANA, 2014)

Figure 8. Differentiation of the regulated and non-regulated zones in the Chancay-Lambayeque basin

3.3 PREPARING WEATHER AND FLOW DATA

Data from sixteen weather stations were used for the analysis. Ten of the stations generate daily precipitation and temperature values; the other six measure precipitation only. Data from the Racarumi flow gaging station was used for calibration and validation of the model. **Figure 9** shows the locations of the weather stations (precipitation in blue and temperature in red) and the flow station (green). In addition, it shows the modeled catchments and rivers from the AHD.

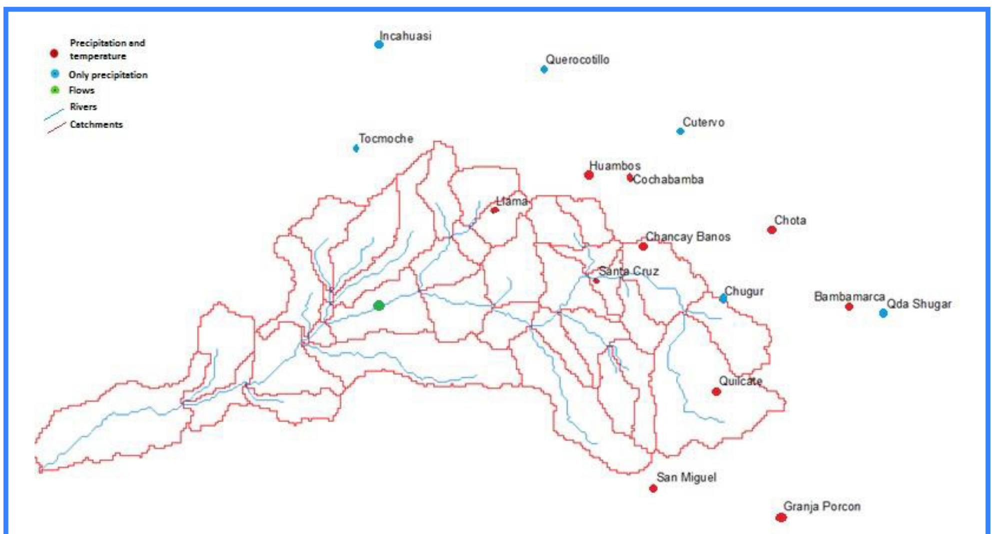


Figure 9. Location of weather and flow stations for the Chancay-Lambayeque basin

Table 1 shows the characteristics of the sixteen weather stations used for modeling the Chancay-Lambayeque basin. All weather data were provided by SENAMHI, the National Meteorological and Hydrological Office of Peru. The data sets for all stations have a timeline from January 2000 to April 2010. Missing values were replaced using an interpolation procedure based on a formula used by the US. National Weather Service, which calculates a daily weather value based on distance weighting factors applied to data from the closest weather stations. **Figure 10** shows the closest weather stations and their respective distances to the weather station "Chancay Baños" where the data filling process was applied.

Table 1. Characteristics of weather stations for the Chancay-Lambayeque basin

Name of station	Latitude (°)	Longitude (°)	Timeline	Number of days with data	Source
Bambamarca	6.676	78.518	January 2000 – April 2010	3773	SENAMHI
Chancay Banos	-6.575	-78.867	January 2000 – April 2010	3773	SENAMHI
Chota	-6.547	-78.648	January 2000 – April 2010	3773	SENAMHI
Chugur	-6.666	-78.733	January 2000 – April 2010	3773	SENAMHI
Cochabamba	-6.46	-78.8886	January 2000 – April 2010	3773	SENAMHI
Cutervo	-6.3792	-78.8045	January 2000 – April 2010	3773	SENAMHI
Granja Porcon	-7.0333	-78.6333	January 2000 – April 2010	3773	SENAMHI
Huambos	-6.4536	-78.9630	January 2000 – April 2010	3773	SENAMHI
Incahuasi	-6.2336	-79.3186	January 2000 – April 2010	3773	SENAMHI
Llama	-6.5144	-79.1225	January 2000 – April 2010	3773	SENAMHI
Qda Shugar	-6.6877	-78.4569	January 2000 – April 2010	3773	SENAMHI
Querocotillo	-6.2736	-79.0369	January 2000 – April 2010	3773	SENAMHI
Quilcate	-6.82	-78.7438	January 2000 – April 2010	3773	SENAMHI
San Miguel	-6.9833	-78.85	January 2000 – April 2010	3773	SENAMHI
Santa Cruz	-6.6330	-78.9475	January 2000 – April 2010	3773	SENAMHI
Tocmoche	-6.4080	-79.3558	January 2012 – March 2014	3773	SENAMHI

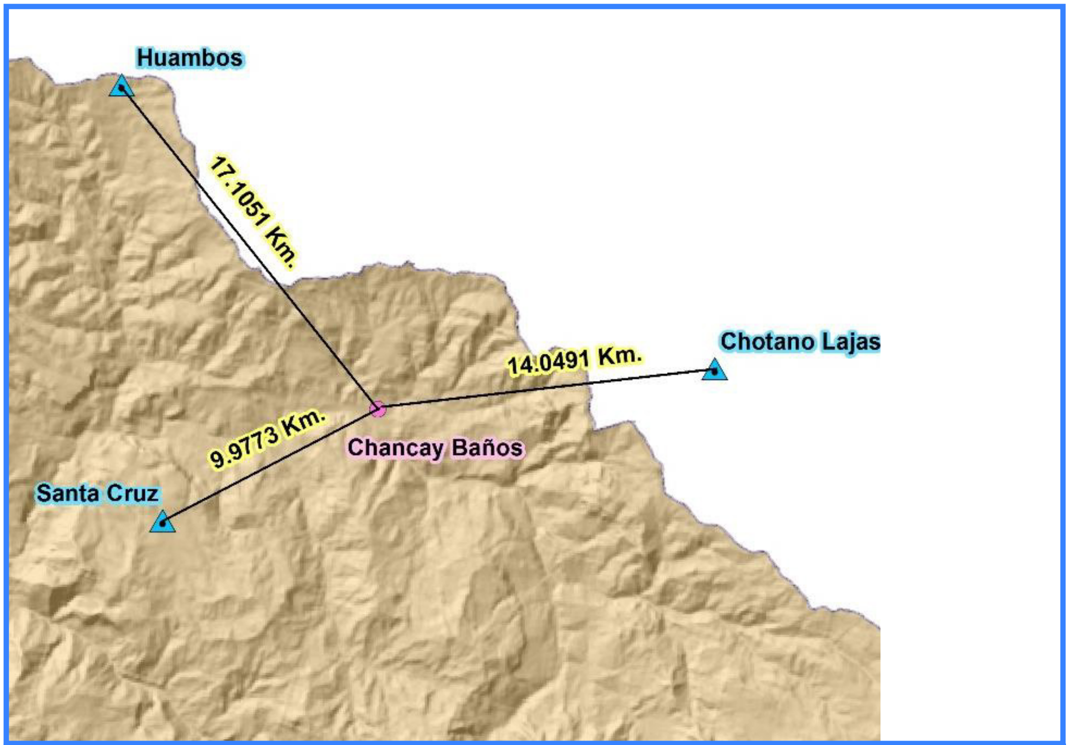


Figure 10. Closest weather stations and their respective distances to Chancay Baños

Equation 1 was used to fill missing values for daily precipitation at Chancay Baños.

$$Pp = ((Pp_1*(1/D_1^2))+(Pp_2*(1/D_2^2))+(Pp_3*(1/D_3^2)))/ Wi \quad (1)$$

where Pp is the daily precipitation (cm) at Chancay-Baños; Pp_1 is the daily precipitation (cm) at Santa Cruz; D_1 is the distance (km) between Chancay-Baños and Santa Cruz; Pp_2 is the daily precipitation (cm) at Huambos; D_2 is the distance (km) between Chancay-Baños and Huambos; Pp_3 is the daily precipitation (cm) at Chotano Lajas; and D_3 is the distance (km) between Chancay-Baños and Chotano Lajas.

Flow data collected at the Racarumi gage station were available for the period January 1970 to December 2014. **Figure 11** shows the daily flows as measured at Racarumi for five years from 1995 to 2000. The Chancay-Lambayeque is a perennial river with base flow of 1 to 2 cubic meters per second (cms). Daily flows increase from December to April and decrease from May to September in each year. Average daily flow is between 30 and 40 cms. Daily flows exceeding 150 cms have been recorded in most years and flows exceeding 300 cms were recorded during the ENSO event of 1997-98.

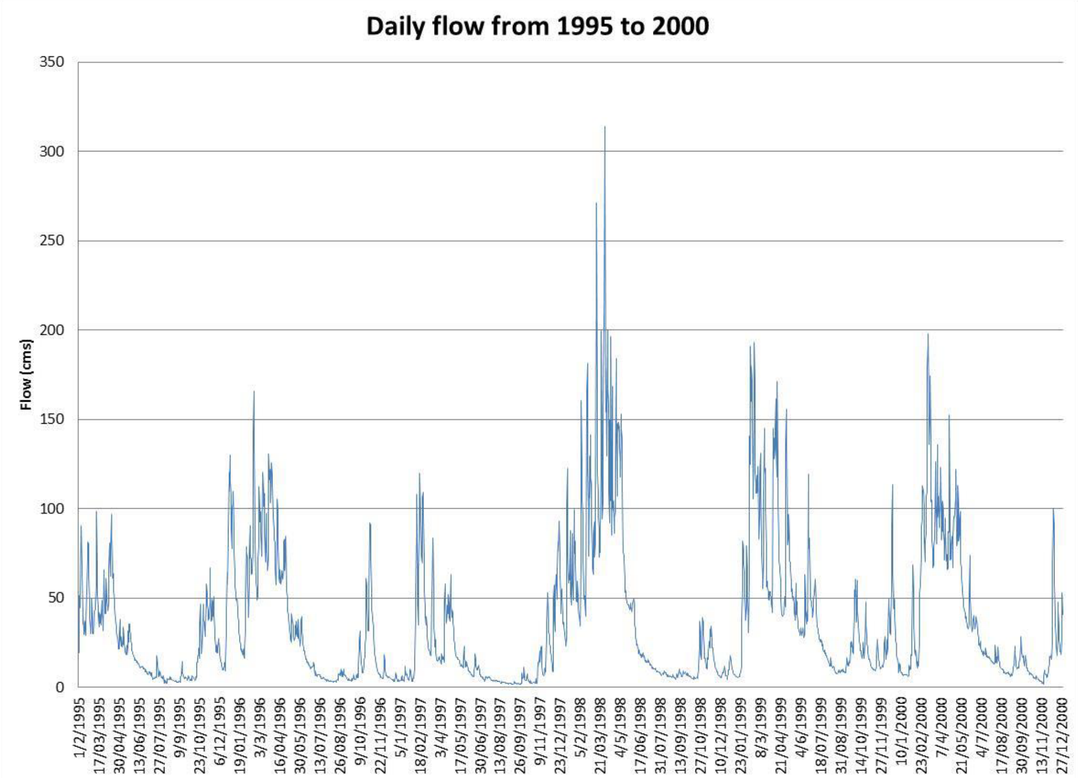


Figure 11. Daily flow data from 1995 to 2000 for Racarumi gaging station

3.4 CALIBRATING AND VALIDATING THE MODEL

The model was calibrated and validated using using data from the Racarumi flow station for the period from 2001 to 2009. **Figure 12** shows the hydrograph generated by Hydro-BID using the calibrated model. **Figure 13** presents validation statistics for the calibrated model. Simulated vs. observed flows revealed an Overall Volume Error of -41 %; an Overall Volume Error of less than ±40% is considered “satisfactory” (Debels at al., 2005). The correlation –r is 0.8, which is considered “strong” (Krause, 2005). The modified correlation coefficient is 0.7, also considered to reflect a good fit. The Nash-Sutcliffe Efficiency (NSE) is 0.48. An NSE value equal to 1 indicates perfect model performance, and an NSE value equal to 0 indicates the model is, on average, providing predictive value no greater than that provided by the mean simulated flow rate (Schaefli and Gupta, 2007). An NSE of 0.48 indicates the model has acceptable predictive value.

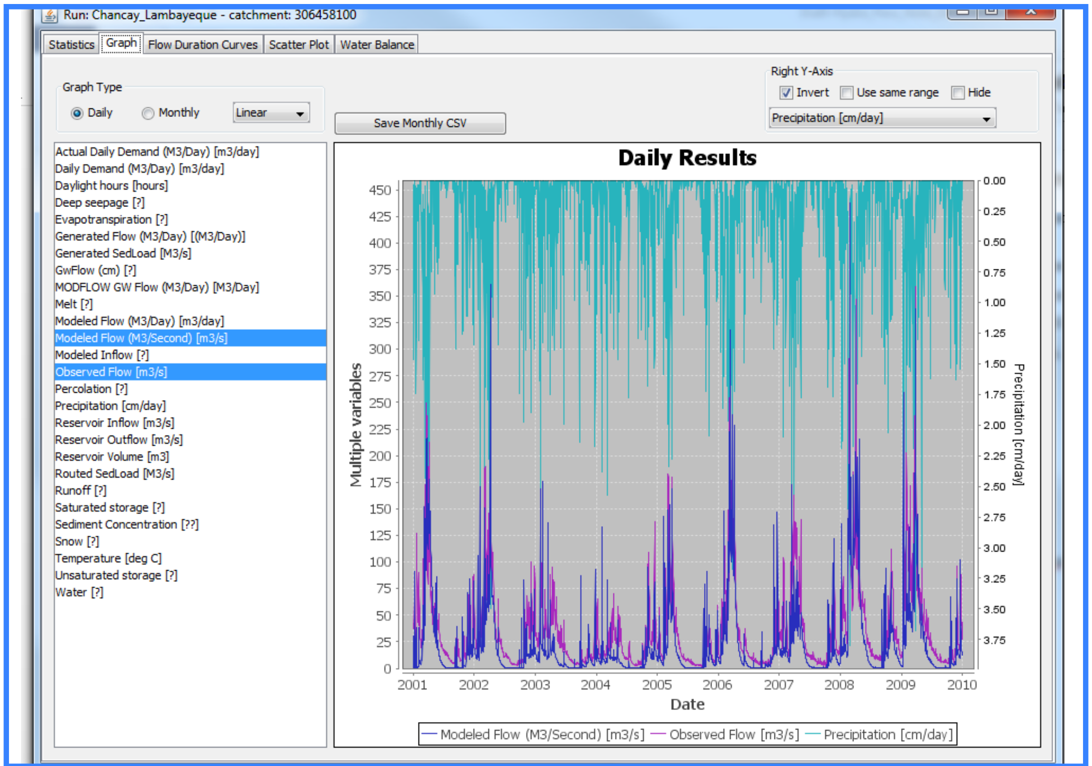
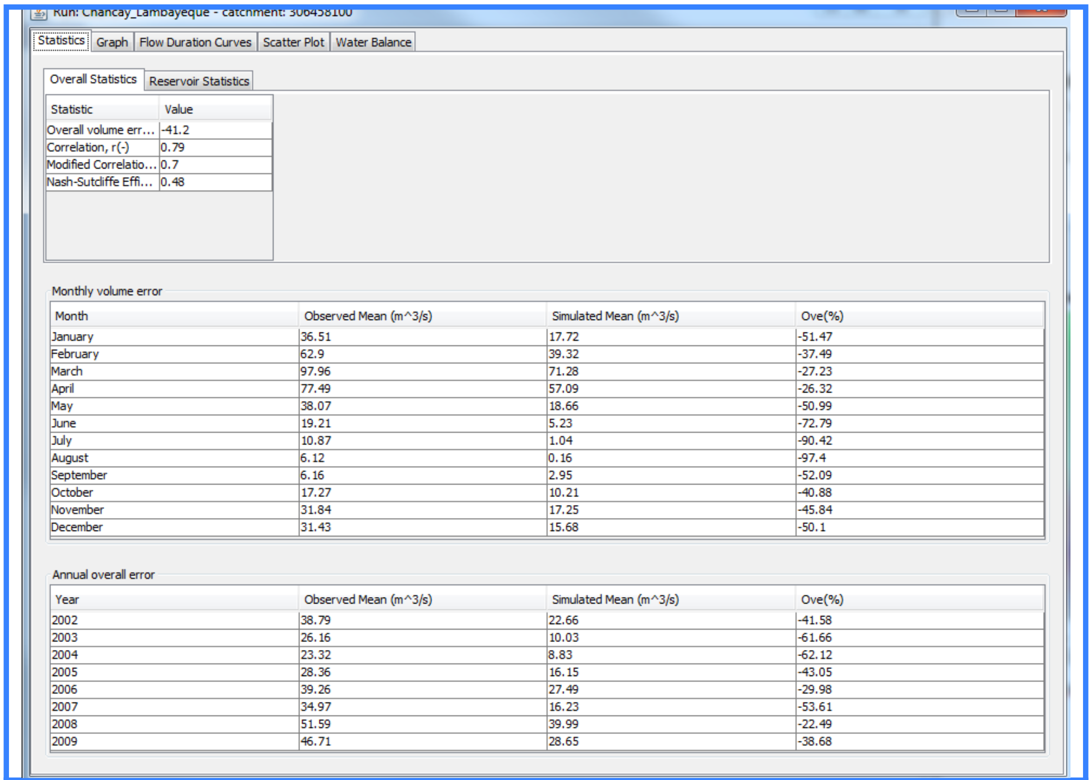


Figure 12. Observed and simulated daily flows at Racarumi 2001 to 2009



Statistic	Value
Overall volume err…	-41.2
Correlation, r(-)	0.79
Modified Correlatio…	0.7
Nash-Sutcliffe Effi…	0.48

Monthly volume error

Month	Observed Mean (m^3/s)	Simulated Mean (m^3/s)	Ove(%)
January	36.51	17.72	-51.47
February	62.9	39.32	-37.49
March	97.96	71.28	-27.23
April	77.49	57.09	-26.32
May	38.07	18.66	-50.99
June	19.21	5.23	-72.79
July	10.87	1.04	-90.42
August	6.12	0.16	-97.4
September	6.16	2.95	-52.09
October	17.27	10.21	-40.88
November	31.84	17.25	-45.84
December	31.43	15.68	-50.1

Annual overall error

Year	Observed Mean (m^3/s)	Simulated Mean (m^3/s)	Ove(%)
2002	38.79	22.66	-41.58
2003	26.16	10.03	-61.66
2004	23.32	8.83	-62.12
2005	28.36	16.15	-43.05
2006	39.26	27.49	-29.98
2007	34.97	16.23	-53.61
2008	51.59	39.99	-22.49
2009	46.71	28.65	-38.68

Figure 13. Validation statistics for the flow model

4. SEDIMENT LOADING EFFECT OF ENSO EVENTS

The objective of this analysis is to simulate sediment loadings that occurred at the Racarumi gage, near the feeder canal, during the El Niño events of 1982-83 and 1997-98. The analysis focuses on the non-regulated portion of the Chancay-Lambayeque basin above the Racarumi Intake.

Sediment loads reduce the lifespan of reservoirs due to siltation. In a 2011 report by the Proyecto Especial Olmos-Tinajones, engineers responsible for the Tinajones reservoir estimated that 9% of its storage capacity had been lost to sediment accumulation since its initial commissioning in 1969 (PEOT 2011). This is actually a modest loss of storage over the period; sediment transport into the Tinajones reservoir is limited because the reservoir is off of the main river channel and water is carried to the reservoir through a feeder canal.

The sediment loading module was developed by RTI International as a component of the Hydro-BID system. It is fully described in Technical Note 2, Second Edition (RTI 2016). This is the first application of the module and results should be considered preliminary until it has been fully validated through application in multiple locations with satisfactory results. This case study demonstrates its application for possible future use by ANA and is not, at this time, intended to provide results to support operational decisions.

The analysis is presented in four steps.

- In the first step, the sediment loading model is calibrated for the upper Chancay-Lambayeque basin using simulated flows generated for a selected calibration period as inputs to the sediment loading equation, and then comparing the resulting simulated sediment yields to observed yields for the same period. This step is performed using monthly data for the year 2001, based on the availability of sediment data for that year.

- In the second step, adjustment factors are calculated to reflect the additional precipitation observed during the two El Niño events in 1982-83 and 1997-98, compared to the average precipitation observed over the 2000-2009, used as baseline period. This step was also performed using monthly averages, to match the form in which precipitation data are available for the El Niño events.

- In the third step, a simulated record of daily precipitation during the El Niño events is developed by applying the precipitation adjustment factors to the average daily precipitation derived from the 2000-2009 baseline data set. The simulated daily record of precipitation is then used as input to the previously calibrated Hydro-BID model to generate a simulated record of daily flows at the Racarumi Intake.

- In the fourth step, the simulated record of daily flows at the Racarumi Intake is used as input to the calibrated sediment model to generate a simulated record of daily sediment loadings at Racarumi, for the baseline period 2000-09 and for El Niño years. Estimates of monthly sediment loads are then calculated for comparison.

4.1 SEDIMENT LOADING CALCULATION AND CALIBRATION

The sediment load transported from a basin is influenced by soil characteristics, intensity of precipitation, land use, slope, agricultural practices, and other factors. Hydro-BID uses the Modified Universal Soil Loss Equation (MUSLE) developed by Williams (1975). In the MUSLE equation (Equation 2), daily rates of erosion are a function of daily runoff and other factors:

$$Sed_t = 11.8(Q_t.Q_{peak})^{0.56}\ K_{USLE}.C_{USLE}.P_{USLE}.LS_{USLE}.CFRG \qquad (2)$$

where Sed_t is sediment yield on day t in (metric ton, i.e. tonnes); Q_t is surface runoff volume for that day (m3); Q_{peak} is peak daily flow (m3/s); LS_{USLE} is the topographic factor; K_{USLE} is the soil erodibility factor; C_{USLE} is the cover management factor; P_{USLE} is the support practice factor; and CFRG is the coarse fragment factor.

The sediment transport equation has five parameters that are adjusted during calibration. **Table 2** describes how each parameter is estimated using the Hydro-BID model.

Table 2. Sediment parameters used in the Hydro-BID model

Variables	Description	Sources
SEDIMENT [DAY]	Sediments (tons/day)	Calculated
AREA	Area of individual land use landuse (ha)	landUseArea = sl.getArea()
RUNOFF[DAY]	Runoff from the land use (cm)	landUseRunoff (calculated using GWLF)
KUSLE	Soil erodibility factor	Table=Catchmnet_soil values Name=KFACT
CUSLE	Cover Management factor	See lookup table : Cover and practice management factors for USLE
PUSLE	Support practice factor	See lookup table : Cover and practice management factors for USLE
LSUSLE	Topographic factor	Table=Catchmnet_soil_valuesName=LS_FACTOR
CFRG	Coarse and fragmentation factor	Default=1.0

ANA staff obtained data for observed levels of suspended solids and sediment loading at Racarumi for the year 2001, shown in **Table 3.** These data were recorded by the Empresa Tecnica de Conservación y Mantenimiento S.A. and Duke Energy Egenor in 2001 and were included in a project report prepared by Asesores de Tecnicos Asociados.

Table 3. Sediment loadings measured at Racarumi Intake in 2001

Month	Volume (MCM)	Suspended Solids (g/L)	Tons(mes)
Jan-01	158,743	0.089	14128.1
Feb-01	148,084	0.145	21472.2
Mar-01	168,884	0.74	124974.2
Apr-01	104261	0.054	5630.1
May-01	58609	0.035	2051.3
Jun-01	55842	0.013	725.9
Jul-01	44534	0.008	356.3
Aug-01	48152	0.01	481.5
Sep-01	34951	0.525	18349.3
Oct-01	32427	0.01	324.3
Nov01	52182	0.305	15915.5
Dec-01	80558	0.021	1691.7

The daily precipitation record for 2001 was used as input to the previously calibrated Hydro-BID model for the upper Chancay-Lambayeque basin to generate a record of simulated daily flows at Racarumi. The daily flow series was then input to the sediment model to simulate daily sediment loads at Racarumi, and the results were shown as monthly totals for comparison with the observed data shown in Table 3. The parameters shown in Table 2 were adjusted to achieve good model fit (simulated values should be similar to observated values). The simulated and observed data are presented in **Figure 14.** A screenshot of the HydroBID model parameters page including the final parameters for the sediment model generated by this analysis is shown in **Figure 15.** As can be seen, The sediment model achieves excellent fit during peak flow periods but is less accurate for simulating sediment loads during low flow periods.

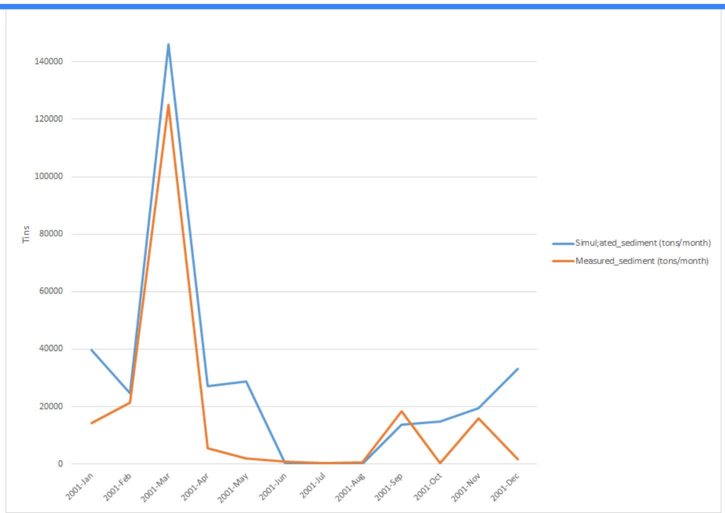


Figure 14. Comparison between simulated and observed sediment loadings at Racarumi Intake

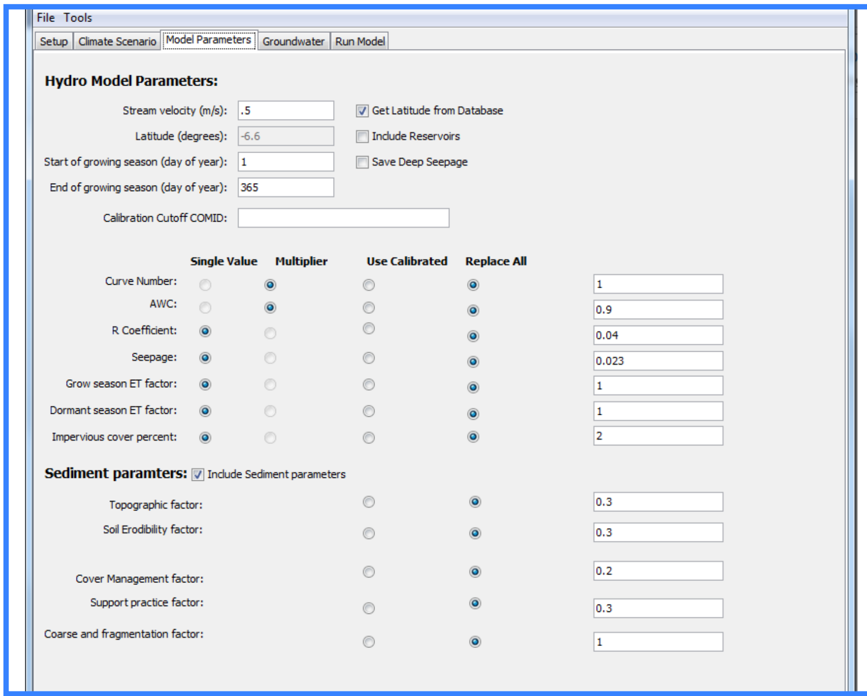


Figure 15. Parameters from the sediment model calibration

4.2 PRECIPITATION INCREASES DURING EL NIÑO EVENTS

Monthly precipitation recorded during the El Niño events of 1982-83 and 1997-98 were compared to average monthly precipitation recorded during the 2000–09 baseline period. Although El Niño events also affect temperature, this study considered only the differences in precipitation. The analysis was achieved with information of the Llamas weather station (see Figure 10). **Table 4** shows the comparison. Highlighted values in the Difference % columns will be used as precipitation adjustment factors in the next step of analysis.

Table 4. Comparison of monthly precipitation values during El Niño periods to baseline period 2000-2009 at Llama weather station

Month 2000-09	Avg. Monthly Precip. cm	Month 1982	Precip. cm	Difference vs.2009* %	Month 1998	Precip. cm	Difference. vs. 2009* %
Sep	2.1	Sep-82	1.4	-33	Sep-97	1.2	-42
Oct	3.8	Oct-82	3.8	0	Oct-97	1.0	-73
Nov	4.2	Nov-82	2.0	-52	Nov-97	4.7	12
Dec	5.4	Dec-82	17.9	231	Dec-97	17.6	226
Jan	9.5	Jan-83	17.8	87	Jan-98	23.9	152
Feb	19.6	Feb-83	11.6	-41	Feb-98	41.4	111
Mar	27.2	Mar-83	45.6	68	Mar-98	28.0	3
Apr	12.2	Apr-83	44.3	263	Apr-98	32.8	169
May	4.2	May-83	15.4	268	May-98	10.0	139
Jun	1.7	Jun-83	1.3	-28	Jun-98	2.5	42
Jul	0.5	Jul-83	0.1	-71	Jul-98	0.0	-100
Aug	0.5	Aug-83	0.2	-65	Aug-98	0.1	-80

*Difference calculated as percentage of baseline. E.g., for Sep-82, (1.4-2.1)/2.1 = -33%.

From **Table 4** it can be observed that the critical months of El Niño events are from December to May, during which the excess precipitation is often 150-250% of baseline precipitation. Precipitation is very low on average during the period from June to November; in El Niño years, precipitation is even lower than average during the months immediately before (Sep-Nov) and after (Jun-Aug) the high rainfall months. For sake of convenience, because the Hydro-BID model runs and accumulates results for yearly periods defined as January through December, subsequent analyses focus on the period January through August rather than defining years as starting in December, when El Niño events begin. Thus, the analysis reflects events in most, but not all of each “El Niño year.”

4.3 FLOW INCREASES DURING EL NIÑO EVENTS

The precipitation adjustment factors from Table 4 were used to generate simulated daily precipitation records for the El Niño periods. The simulated precipitation records were then used as input to the previously calibrated Hydro-BID basin model to generate simulated daily flow series at the Racarumi gage. **Table 5** shows the monthly changes for precipitation and flows from January to August, as a percentage of baseline, for El Niño years.

Month	%Precip ENSO 1983	%Precip ENSO 1998	%Flow 1983 $Q_{ENSO83}/Q_{2000-2009}$	%Flow 1998 $Q_{ENSO98}/Q_{2000-2009}$
January	87	152	155	307
February	-41	111	-18	295
March	68	3	87	54
April	263	169	308	178
May	268	139	498	269
June	-28	42	387	269
July	-71	-100	260	248
August	-65	-80	222	211

Table 5. Precipitation and flow increases during El Niño events

Figure 16 shows the average flow rates from the simulation, plotted by month for the baseline period (2000-09) and for El Niño years, from January to August. It is clear that ENSO 1982-83 produced higher peak flows than ENSO 1997-98 and that both events produced the highest flows in April, one month later than is the average case for baseline years. It is interesting that both ENSO events show a decrease in flows early in the season after the initial increase, in February 1983 for ENSO 1982-83 and in March 1998 for ENSO 1997-98. Flow rates return to baseline conditions in July.

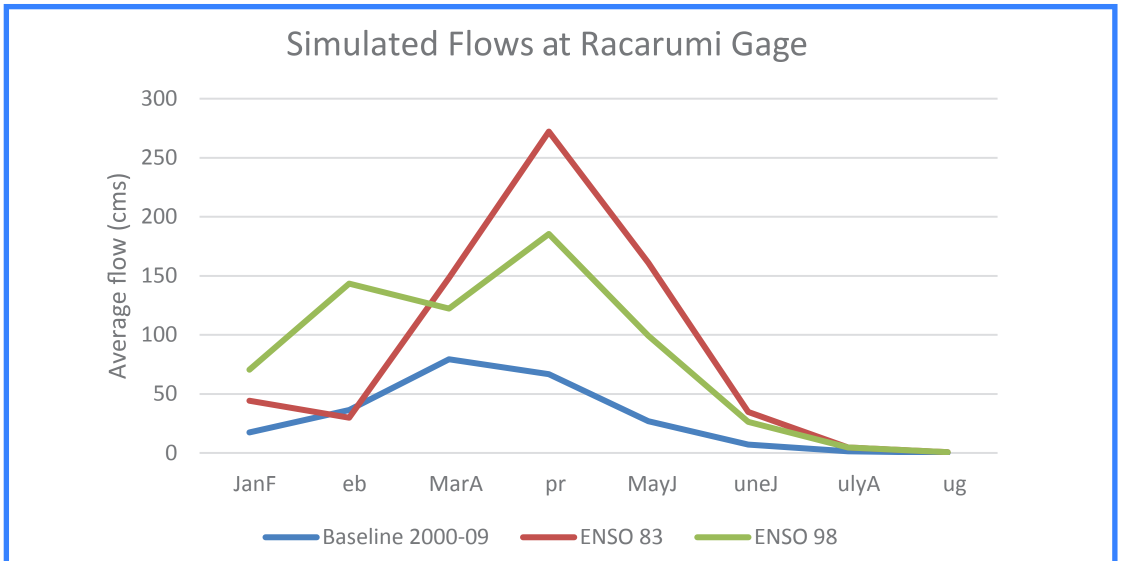


Figure 16. Average flows at Racarumi Gage in baseline and El Niño year3

4.4 SEDIMENT LOADING DURING EL NIÑO EVENTS

The simulated record of daily flows at the Racarumi Intake was used as input to the calibrated sediment model to generate a simulated record of daily sediment loadings at Racarumi, for the baseline period 2000-09 and for El Niño years. Results are shown in **Table 6** and **Figure 17.**

Table 6. Flow and sediment loading increases during El Niño Events				
Month	% Flow 1983 $Q_{ENSO83}/Q_{2000-2009}$	% Flow 1998 $Q_{ENSO98}/Q_{2000-2009}$	% Sediment ($SED_{ENSO83}/SED_{2000-2009}$)	% Sediment ($SED_{ENSO98}/SED_{2000-2009}$)
January	155	307	330	677
February	-18	295	-73	376
March	87	54	198	8
April	308	178	1617	860
May	498	269	2602	1021
June	387	269	-62	382
July	260	248	-100	-100
August	222	211	-100	-100

As expected per the structure of the model, the higher flows generated by El Niño events produce higher estimates of sediment loading for the simulated periods. The ENSO 1982-83 produced more sediment than ENSO 1997-98. The same patterns observed for flows are also observed for sediment loading, i.e. peak loading occurs in April, one month later than is generally the case in non-ENSO years; and there is a decline in loadings early in the season after the initial increase, manifested in February for ENSO 1982-83 and in March for ENSO 1997-98. The month with the peak for the variation of flow has the peak for the variation of sediment loading as well.

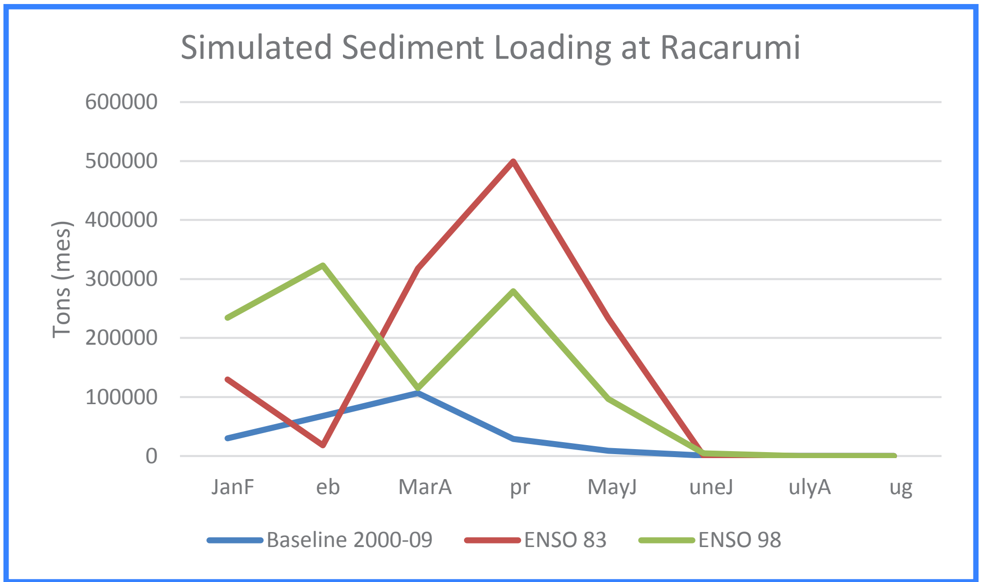


Figure 17. Simulated sediment loading at Racurami Intake for baseline and El Niño years

5. CONCLUSIONS

This case study had two objectives. First, as part of an on-going effort to build the basin modeling skills of professional staff working for the Autoridad Nacional del Agua (ANA), a member of ANA's professional staff developed a Hydro-BID model for the Chancay-Lambayeque basin. Second, to demonstrate capabilities of the Hydro-BID system that are relevant to water resources management challenges in Peru, RTI staff used the Hydro-BID model to generate a simulated river flow series and estimate the sediment loadings generated by the upper Chancay-Lambayeque basin as they might have been measured at the Racarumi gaging station during the El Niño events of 1982-83 and 1997-98.

ANA staff were successful in developing, calibrating, and validating a Hydro-BID model of the upper, uncontrolled portion of the Chancay-Lambayeque basin. The staff captured and processed precipitation and temperature data, including use of an interpolation procedure for filling missing data. Staff then set up and calibrated the model, achieving a sufficient fit for the model to be validated.

RTI applied the Hydro-BID model to generate simulated flow series for a baseline period defined as 2000 to 2009; used the flow series for 2001 to generate estimated sediment loadings and calibrate the sediment loading model against observed sediment data for 2001; and then used the calibrated sediment model to generate simulated sediment loadings for the baseline period and for both ENSO years. The results of this effort support two conclusions:

1. For the Chancay-Lambayeque basin, the ENSO event of 1982-83 produced higher flow rates and sediment loadings than the event in 1997-98. The peak monthly loading in 1983 is estimated to have been more than 499,000 tons, compared to the highest monthly loading of approximately 279,000 tons in 1998 and 107,000 tons during the baseline period.

2. ENSO events appear to cause an increase in flows and sediment loading early during the event (December-January), then show a decrease (February-March), followed by peak precipitation, river flows and sedimentation in April. Flows then fall-off steadily from May until the event expires in July. This ENSO flow pattern contrasts with the normal pattern observed for the baseline period, in which peak flow occurs in March and declines to very low levels by end of May.

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