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Hydro-BID case study N°4: Application of Hydro-BID in Bermejo River Basin to quantify sediment loads, Argentina

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HYDRO-BID CASE STUDY N°4:

APPLICATION OF HYDRO-BID IN BERMEJO RIVER BASIN TO QUANTIFY SEDIMENT LOADS, ARGENTINA

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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 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, for COREBE, is the fourth report in a series of publications describing the Hydro-BID system and case studies. Other recent Technical Notes include for case studies completed recently in Ecuador, Peru, and Brazil.

ACKNOWLEDGEMENTS

The authors wish to express thanks to individuals and organizations that made important contributions to the development of this study of the Bermejo.

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 Latin American and Caribbean 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 served as IDB liaisons with COREBE in Argentina, to arrange for and support the study.

We are grateful for the excellent collaboration and constant support from the staff of COREBE, who were very engaged with the study from its beginning to its conclusion. We are especially thankful to Edgardo and Marcelo for their prompt responses to our requests for data and information.

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 REPORT

In 2013, COREBE conducted a comprehensive water resource assessment of Bermejo Region II (COREBE, 2013), that is located in the northern part of Argentina, known as the Chaco and covers part of the Provinces of Jujuy, Salta, Santiago del Estero, Chaco and Formosa. This study analyzed water resource availability for hydropower generation using small dams in the watershed. The main inputs to the analyses were based on long-term climate and hydrological conditions. The approach used in this study is based on empirical relationship between climate, land use, and land cover with flows on an annual basis. In addition to water resource availability, the study also computed sediment loads from watersheds at 1,000 ha resolution.

This study provided an initial assessment of water availability in high resolution; however, COREBE has realized some significant limitations. The first limitation of the study is that because of the mean annual time -scale analyses, the variability of water resources both seasonally and inter-annually have not been accounted for in the study and could have consequences on the availability of water. Secondly, the study lacks a method to study the sensitivity of water availability as impacted by future climate change. In addition, the study has similar limitations in regard to sediment evaluation.

To overcome the above limitations, COREBE requested IDB to develop a hydrological model for Bermejo Region II. The model development, which is the main objective of this project, is the first step towards enhancing the water resource assessment of the region. COREBE also emphasized an initial comparison of hydrological and sediment model results to the previous study results.

The objectives of the current study are:

1. To create a high- resolution Analytical Hydrography Dataset (AHD) equivalent to the 1,000 ha catchments for Region II.

2. Seamlessly integrate the high-resolution AHD into the national and South America AHD of coarser resolution, which is about 100 km^2.

3. Parametrize Hydro-BID using publicly available land cover and soil data at the high-resolution AHD.

4. Set-up and calibrate Hydro-BID for Region II. Validate the hydrology model.

5. Develop sediment load tools using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) and the Gavrilovic and Zemljic methods.

6. Compare the performance of both sediment tools and provide recommendation on their use and implementation.

7. Provide sensitivity of flow and sediment to climate changes.

8. Provide the calibrated models to COREBE’s hydrologists and train them to use the model.

2. THE STUDY AREA

The Río Bermejo is located in the extreme northwestern region of Argentina and drains portions of the provinces of Jujuy and Salta, with additional flow from southern Bolivia. The basin includes a wide range of ecosystems, ranging from high mountain ranges receiving little rainfall to subtropical valleys receiving more than 1,200 mm of annual rainfall each year. As the river descends in elevation, it eventually joins the Rio Plata and drains to the Atlantic Ocean. Figures 2-1 show the ranges in precipitation in the basin.

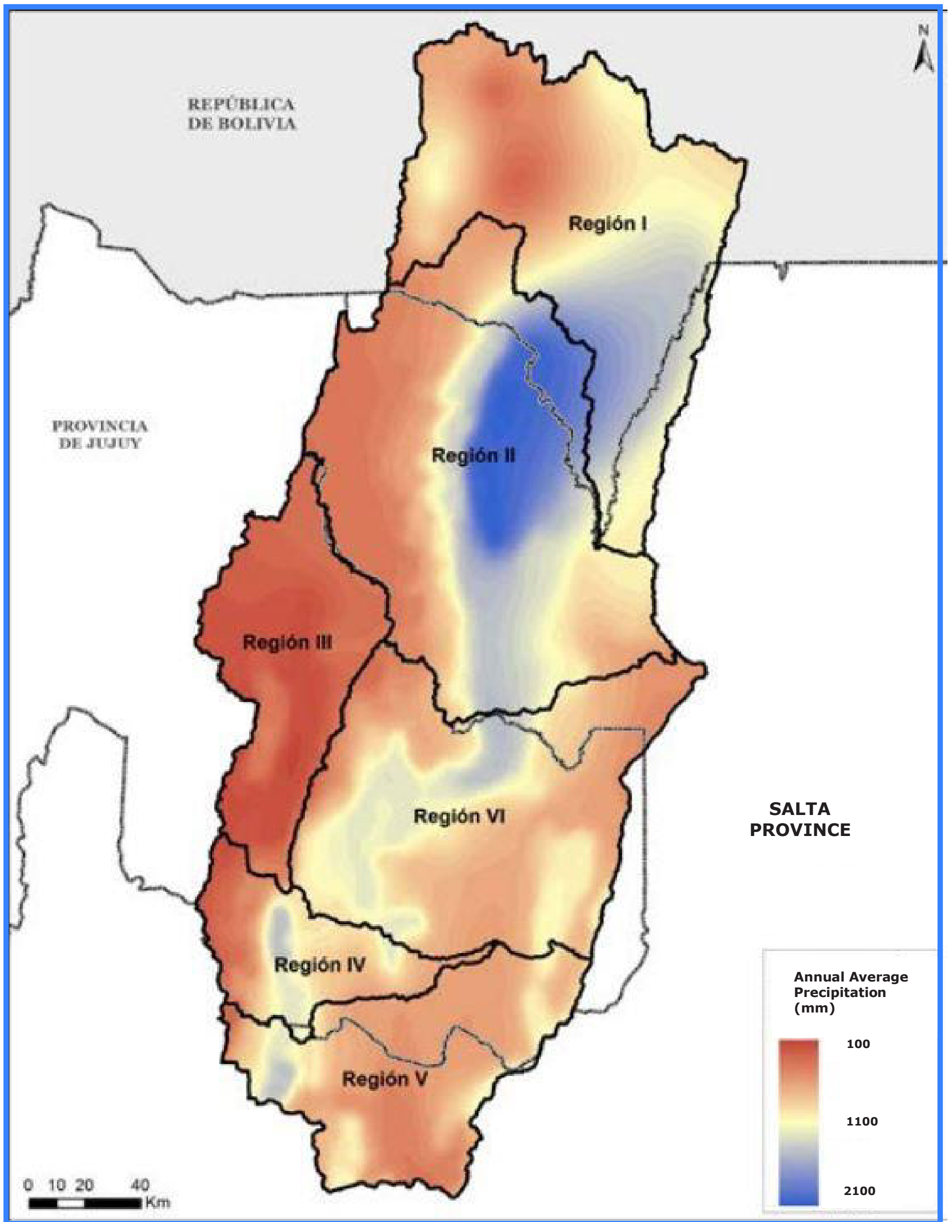

Figure 2–1. Precipitation distribution in the Rio Bermejo Basin (in millimeters per year). Source: COREBE (2013)

3. APPROACH OF THE MODELING WORK

The Analytical Hydrography Dataset (AHD) (Rineer and Bruhn, 2013) is an integral part of the Hydro-BID modelling package. AHD is a comprehensive watershed dataset encompassing all of Latin America that allows rapid spatial characterization of a watershed and serves as the core mechanism for flow routing in the hydrology model. However, the original AHD dataset for Region II of the Bermejo was in a relatively coarse resolution, with an average sub-catchment size of 90.09 km^2. After being provided with a more spatially detailed catchment shapefile by COREBE, AHD was modified to incorporate these high-resolution catchments.

Region II of the Bermejo River Basin was delineated into 1,709 high-resolution catchments of approximately 15 km^2 in size. These high- resolution catchments are slightly smaller than the delineated subcatchments layer provided by COREBE, this layer has an average catchment size of 18.5 km^2. This permanent modification to the AHD will continue to allow high-resolution watershed calculations in future model versions. **Figure 3–1** provides an overview of the high-resolution catchments used to model this basin, with details provided in **Table 3–1.**

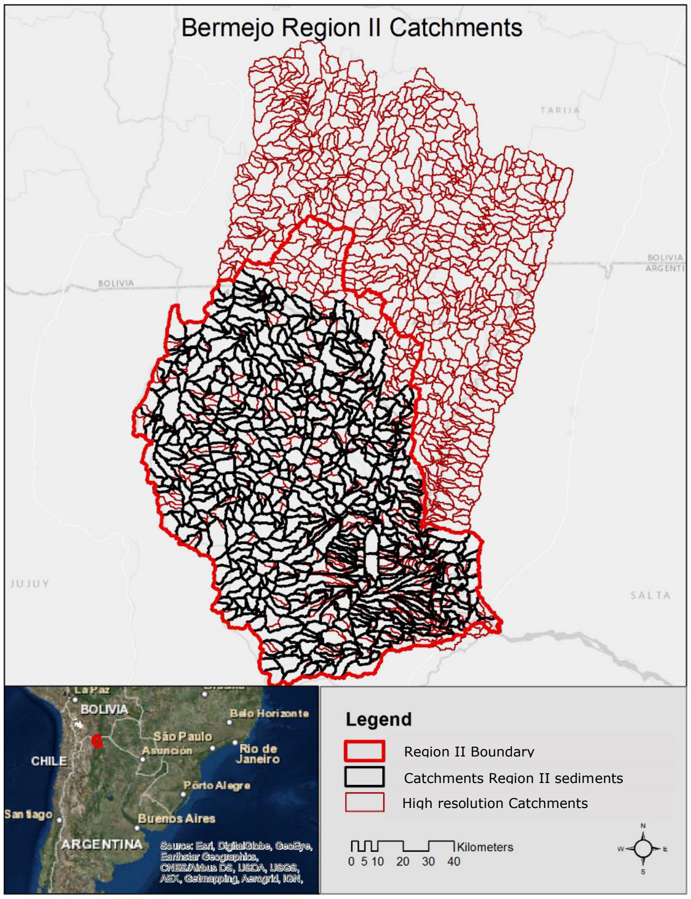

Figure 3–1. Overview of the high-resolution AHD catchments used in the Hydro-BID model for Bermejo Region II.

Table 3–1. Summary of AHD datasets.

	Unmodified AHD	Modified AHD	COREBE Sub-catchments
Count	581	2,012	2,187
Average catchment size (km2)	90.09	15.6	18.3

The total drainage area of the basin is 25,431 km^2. Climate data from 21 stations within the basin were used to create an interpolated climate dataset covering the entire basin for a 30-year period of record. Three gages were selected for model calibration within the basin and two gages were used to validate the model. Once the flow modeling was complete, two sediment load calculation methods were used to determine the modeled sediment load at five gages in the watershed. **Table 3–2** outlines the data sources used by the Hydro-BID model.

Table 3–2. Data sources for the Hydro-BID model.

Dataset	Source
Daily Average Temperature	COREBE
Daily Average Precipitation	COREBE
Daily Average Flow	COREBE
Annual Observed Sediment Loads	COREBE
Calculated Sediment Loads	COREBE
Land Use Classifications	USGS
Soil Classifications	FAO

3.1 PREPARING CLIMATE DATA.

Precipitation data from 21 climate stations and temperature data from 8 climate stations in the basin were used to create an interpolated climate dataset to cover the Bermejo Region II study area (**Table 3–3**). Due to large differences in annual average precipitation (source: http://www.portaldesalta.gov.ar/clima.htm), the basin was divided into two regions: "dry" and "wet." The dry region covers the western mountainous portion of the basin, and the wet region is everything east of the mountains (**Figure 3-2)**. The wet region receives roughly six times more precipitation than the dry region annually (http://www.portaldesalta.gov.ar/clima.htm).

To account for these differences, the interpolated precipitation dataset was prepared separately for catchments in the dry region and catchments in the wet region. **Table 3-3** includes a breakdown of the regional location for each gage used in the interpolation. Climate data were interpolated with the inverse distance weighting method to spatially average data from the three nearest climate stations at each AHD catchment. Due to the smaller number of temperature stations, gaps in the temperature dataset were filled by linear interpolation to ensure that data were available for at least three stations for every day in the period of record. The interpolated climate dataset was created for a 30-year time frame: 1984–2014. **Figure 3-2** provides an overview of the climate stations used in creating the interpolated climate dataset for Region II of the Bermejo River Basin.

Table 3–3. Climate stations used to create the interpolated climate dataset.

Station	Data	Region
Santa Victoria Oeste	Precipitation	Dry
Paltorco	Precipitation	Dry
Tuc Tuca	Precipitation	Dry
El Pabellon	Precipitation	Dry
San Isidro	Precipitation	Dry
Las Higueras	Precipitation	Dry
Iruya	Precipitation	Dry
Colanzuli	Precipitation, Temperature	Dry
Trigo Huaico	Precipitation	Dry
Poscaya	Precipitation	Dry
Nazareno	Precipitation	Dry
El Molino	Precipitation	Dry
San Antonio	Precipitation	Dry
Alarache	Precipitation, Temperature, Flow	Wet
Balapuca	Precipitation, Temperature, Flow	Wet
Aguas Blancas	Precipitation, Temperature, Flow	Wet
Cuadro Cedros	Precipitation, Temperature, Flow	Wet
Arrasayal	Precipitation, Temperature	Wet
Las Bateas	Precipitation	Wet
San Jose	Precipitation, Temperature, Flow	Wet
Pozo Sarmiento	Precipitation, Temperature, Flow	Wet

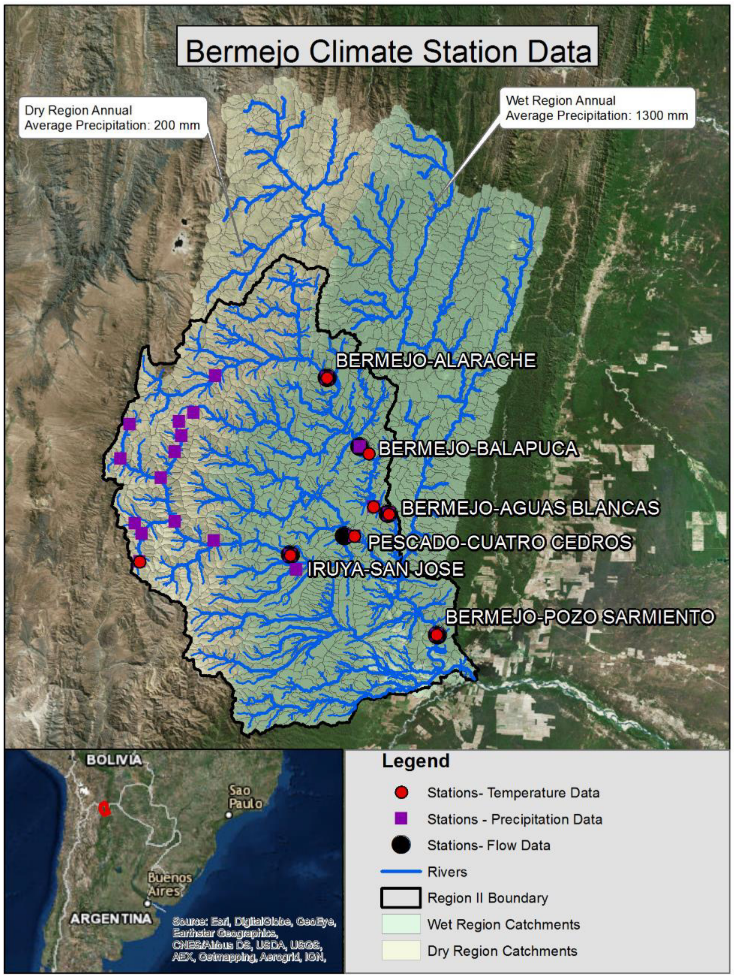

Figure 3–2. Overview of the climate stations used to create the interpolated climate dataset for Bermejo Region II.

3.2 OVERVIEW OF SEDIMENT DATA

RTI was provided with two datasets by COREBE characterizing sediment measurements and modeling efforts. These datasets are summarized below:

- Slides containing observed sediment loads at 15 gages in the watershed and details of a study using the Gavrilovic and Zemljic method to model sediment loads (method is explained in chapter 5.2), including the calculated values at each gage. **Table 3–4** summarizes the data available from the presentation. The presentation was titled: "Planning for multipurpose use of Water Resources on the High Basin of the Bermejo River in the Republic of Argentina – Development of a Planning and Management Tool"

- Shapefiles containing intermediate calculation steps for the Gavrilovic and Zemljic method at the sub-catchment level. The calculated sediment yield from each catchment in the shapefile is displayed in Figure 3-3. Note that these values are for locally generated sediment and do not include upstream contributions.

Table 3–4. Sediment data from COREBE presentation.

Station	Period	Median (10^3 tonnes/yr)	Maximum (10^3 tonnes/yr)	Minimum (10^3 tonnes/yr)	Calculated (10^3 tonnes/yr)	Ratio (Median/ Calc)
Alarecehe	1972–1989	5,023	9,701	929	5,130	0.98
Balapuca	1972–1989	7,956	16,034	2,407	8,618	0.92
Arrazayal	1971–1985	10,980	24,735	2,372	9,274	1.18
Aguas Blancas	1946–1989	8,345	22,748	1,607	9,299	0.90
Astilleros	1970–1984	11,938	23,587	2,979	13,313	0.90
San Telmo	1968–1989	14,247	49,732	4,024	14,321	0.99
Pozo Sarmiento	1946–1989	705,821	176,796	15,169	50,466	13.99
San Jose	1983–1986	13,127	19,519	3,963	10,741	1.22
El Angosto (Astilleros)	1983–1986	889	2,033	163	1,329	0.67
Cuatro Cedros	1968–1989	5,313	13,453	346	4,913	1.08
Pena Alta	1968–1989	3,630	12,981	395	3,799	0.96
Arrayanal	1968–1989	1,346	6,468	101	1,270	1.06
San Juancito	1968–1971	4,954	9,945	1,975	7,315	0.68
Bajada de Pinto	1943–1949, 1956–1980	1,995	6,375	126	2,563	0.78
Caimancity	1959–1989	18,447	107,558	1,510	18,650	0.99

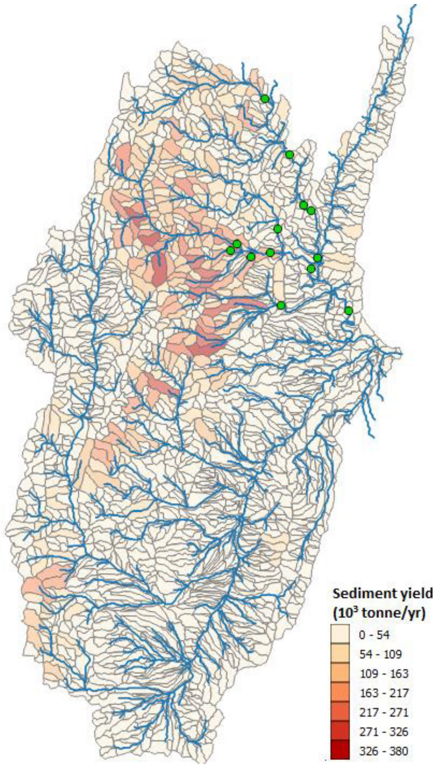

Figure 3–3. Annual sediment yield from the sub-catchment shapefile. Stations with observed sediment values from the presentation are mapped in green.

Upstream sediment contributions were summed at five gages to estimate the total sediment load from the shapefile. These values are displayed and compared against values from the presentation in **Table 3–5.**

The variations in estimated sediment load most likely are caused by errors during summation of upstream contributions in the shapefile. The file only includes catchments in Argentina, and thus the aggregation failed to include properly the sediment contributions from the Rio Bermejo watershed in Bolivia.

Table 3–5. Comparison of provided sediment load data. All values in 10^6 tonnes/yr

	COREBE - Gavrilovic method	
Location	From Table 3-4	From Figure 3-3
San Jose	10.74	14.34
Pozo Sarmiento	50.47	35.59
Cuatro Cedros	4.91	7.48
Aguas Blancas	9.30	7.88
Balapuca	8.62	7.32

4. CALIBRATING THE MODEL

Region II of the Bermejo River Basin contains six gages with flow data. Three gages were selected for model calibration and two others were used to validate model results. The Pozo Sarmiento validation gage (see **Figure 4-1**) has a drainage area that extends beyond the calibrated rivers in Region II. Adjustments to the calibration parameters were made at this site to account for the additional flows and to provide a better estimate of flow from the outlet of the basin. The gages were calibrated from 1990 through 1998, that time frame contained the most high quality data, with roughly 90% of the daily flows available on average.

The calibration procedure is achieved first by using gages that represent the most upstream or headwater basins. After a satisfactory calibration has been achieved, calibrated values will be fixed in the database. Then the next downstream gage will be selected and parameters of the catchments immediately downstream of the head water up until the next gage will be calibrated. This procedure will continue until the outlet of the basin. At the end of the calibration, one complete set of calibration parameters are fixed and saved in the database for each individual sub-basin. For this application in Region II, each of the sub-basins in Figure 4-1 was assigned a unique set of parameters during calibration at the sub-basin's outlet stream gauge. Because no stream gauge was available downstream of Pozo Sarmiento, values from the immediate upstream calibration were applied to catchments in the lower basin. For a detailed description of the calibration procedure in Hydro-BID, refer to Chapter 4 of Technical note 2 second edition.

Table 4-1 presents the calibrated parameters of subbasins. The stations are mapped in **Figure 4-1.** **Table 4-2** presents the calibrated parameters of subbasins.

Table 4–1. Model parameters for sites in the Bermejo River Basin.

Gage	Type	Curve Number	Available Water Capacity	Recession Coefficient	Seepage
Balapuca	Calibration	0.9	0.6	0.014	0.00005
Cuadro Cedros	Calibration	1.1	0.2	0.014	0
San Jose	Calibration	1.2	0.2	0.0018	0.00005
Aguas Blancas	Validation	0.9	0.6	0.014	0.00005
Pozo Sarmiento	Validation	0.8	1.4	0.017	0.00005

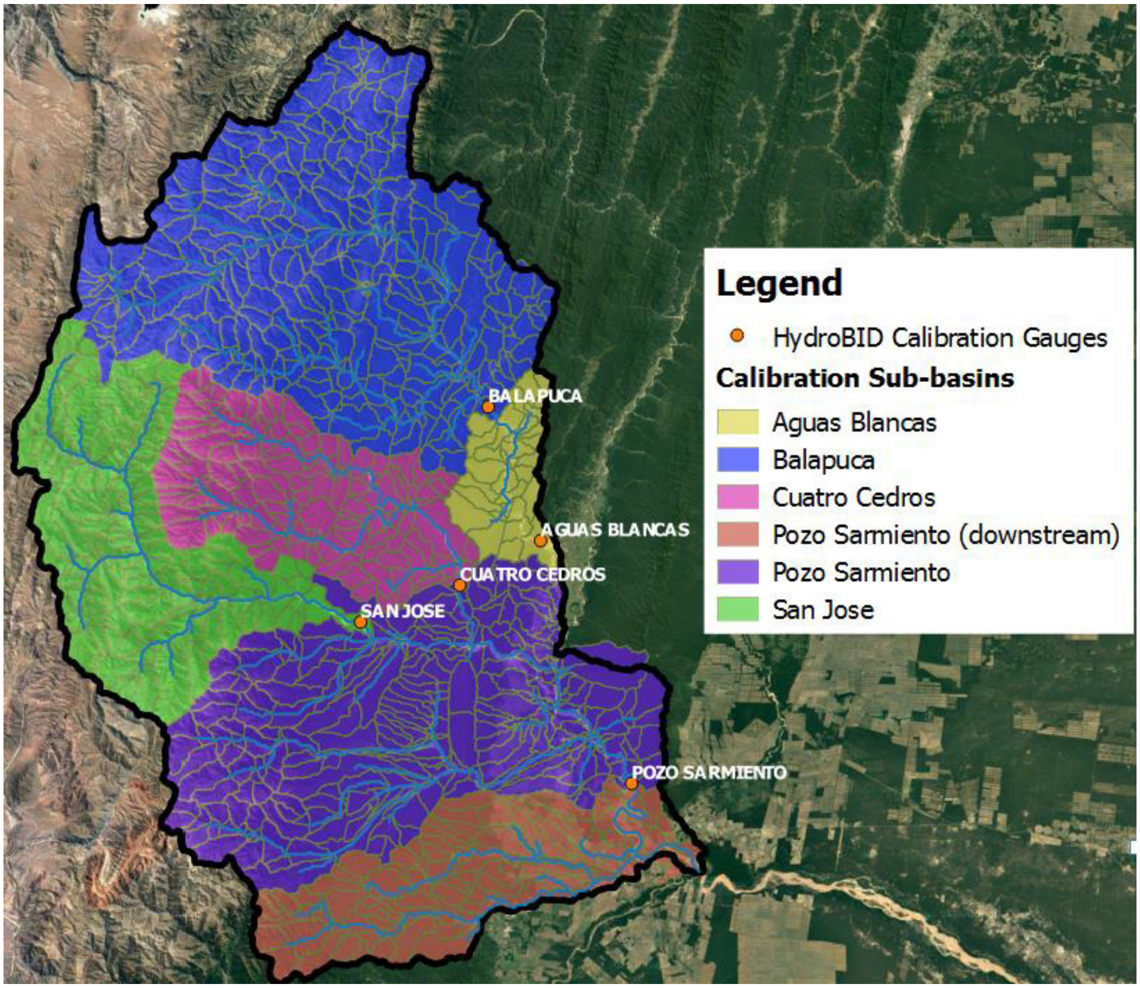

Figure 4–1. Flow stations and sub-basins used for Hydro-BID calibration and validation

In addition to summary statistics, quantitative metrics such as flow duration curves and hydrographs were used to evaluate model performance. The model was calibrated to best match the overall flow regime, including low, median, and high flows with less consideration for matching the magnitude of extreme events. **Figure 4–2a** is an example of a calibration flow duration curve for the calibration gage Balapuca. In this calibration, modeled flows match the overall flow regime of observed data but high and low flows are slightly underestimated and median flows are slightly overestimated. **Figure 4–2b** is the calibration hydrograph at Balapuca, the trends in daily flows are similar between modeled results and observed flows during the calibration period of 1990–1998.

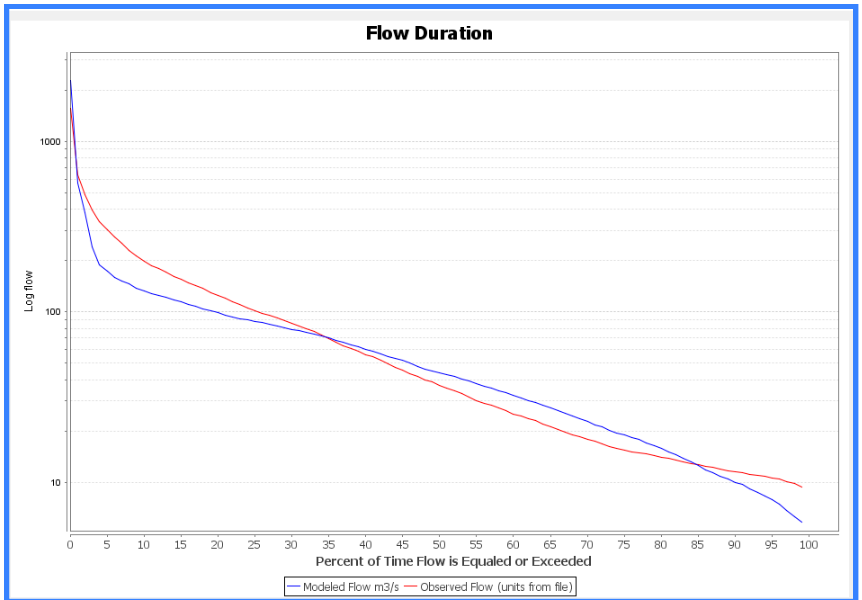

Figure 4–2a. Flow duration curve for the Balapuca gage from 1990 through 1998.

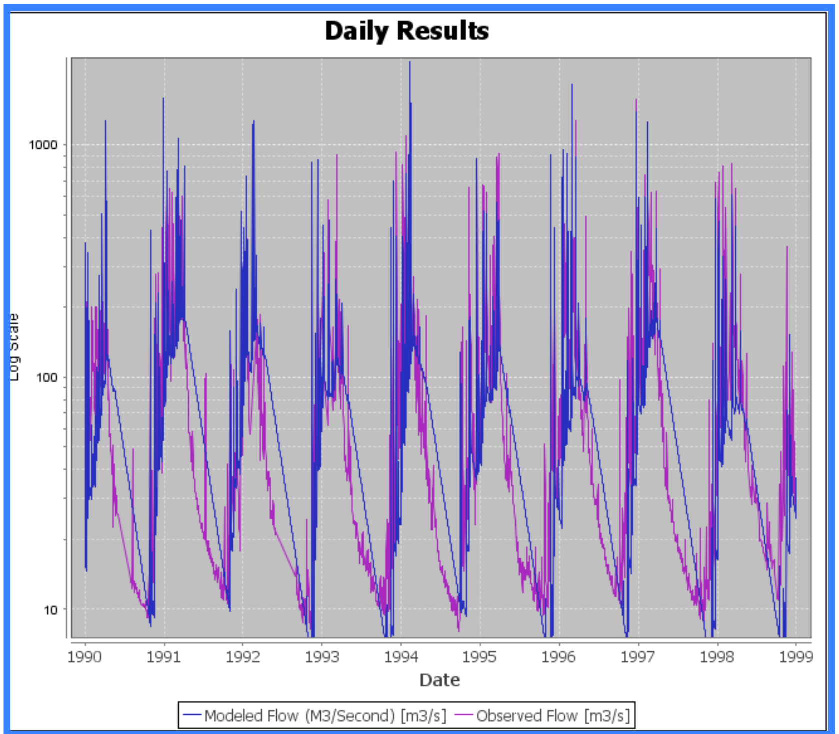

Figure 4–2b. Daily hydrograph for the Balapuca gage from 1990 through 1998.

Hydrographs and flow duration curves for the gages in the basin indicate that flows vary widely depending on the season, with base flows dropping by at least one order of magnitude during dry periods and surging by around one order of magnitude during precipitation events. These large swings in flow can be expected given the diversity in annual precipitation throughout the watershed. The San Jose gage displays lower flows and slightly less variability than the other gages due to its location near the western dry region of the basin (**Figure 4–3**).

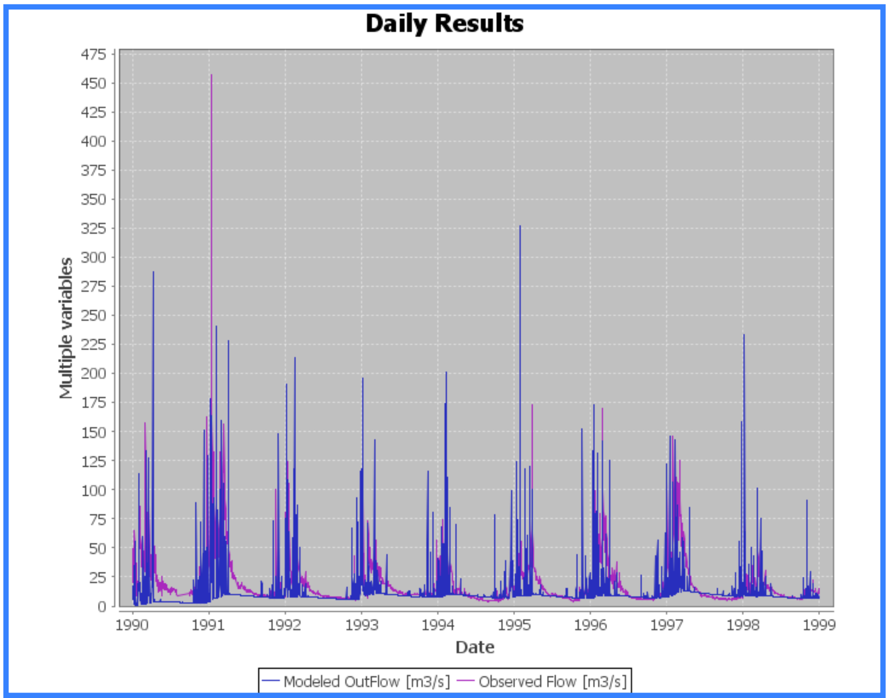

Figure 4–3. Daily hydrograph for the San Jose gage from 1990 through 1998.

Validation gages were used to evaluate model performance outside of calibration locations. Calibrated parameters were applied and then minor adjustments were sometimes made to account for larger differences in drainage area. The flow duration curve (Figure 4–4a) and monthly hydrograph (Figure 4–4b) for the Aguas Blancas validation gage display similar results to the calibration gage for Balapuca.

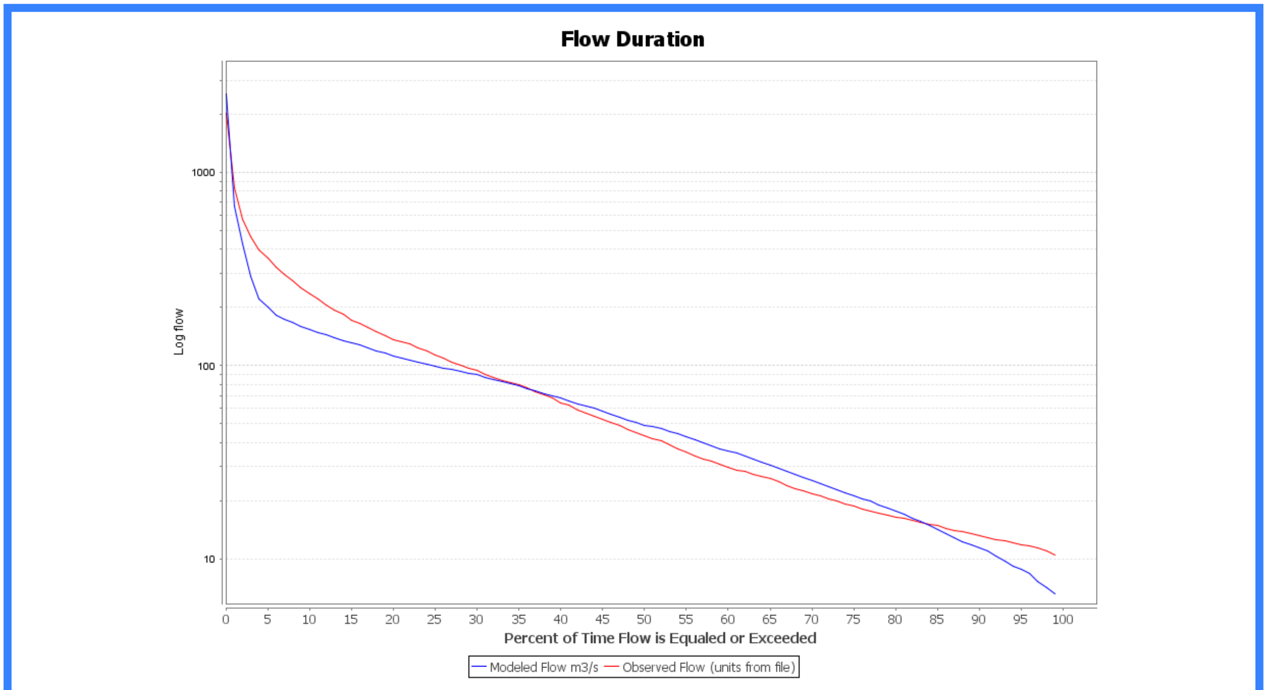

Figure 4–4a. Flow duration curve for the Aguas Blancas gage from 1990 through 1998.

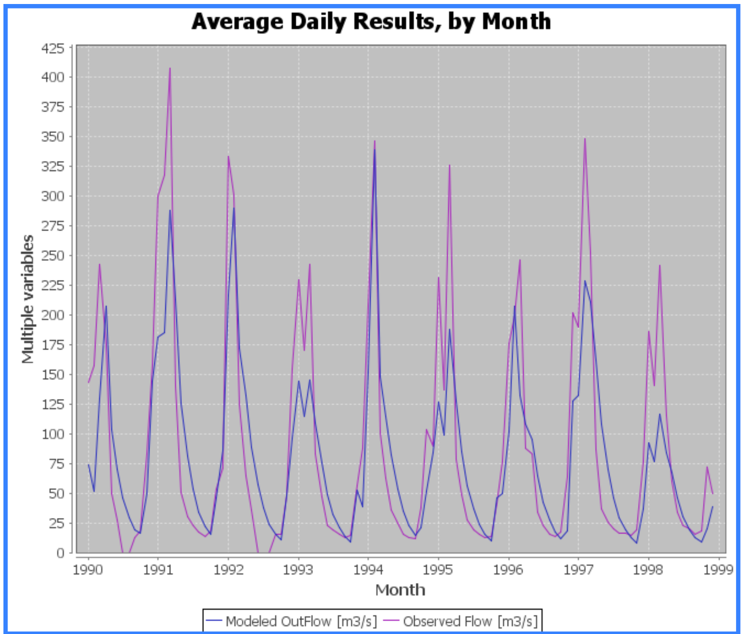

Figure 4–4b. Average monthly hydrograph for the Aguas Blancas gage from 1990 through 1998.

The Pozo Sarmiento gage was also used for model validation but due to its location near the outlet of the basin, the drainage area is much larger than the calibrated watershed in Region II. Adjustments were made to the calibration parameters at this site to account for the larger drainage area to provide a better estimate of modeled flow at the outlet of the river basin. The flow duration curve (Figure 4–5a) and monthly hydrograph (**Figure 4–5b**) demonstrate that modeled flows are a good match for observed flows across the entire flow regime at this site.

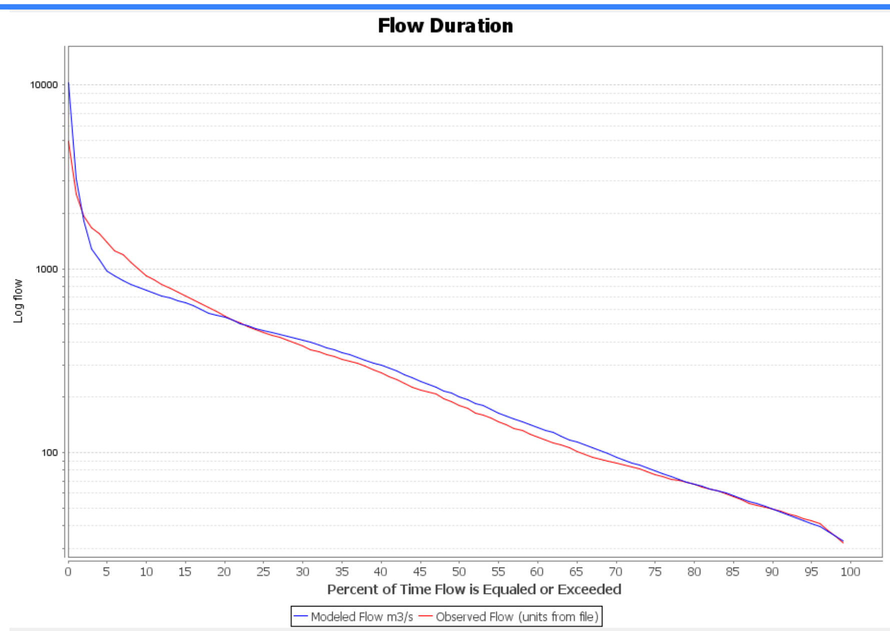

Figure 4–5a. Flow duration curve for the Pozo Sarmiento gage from 1990 through 1998.

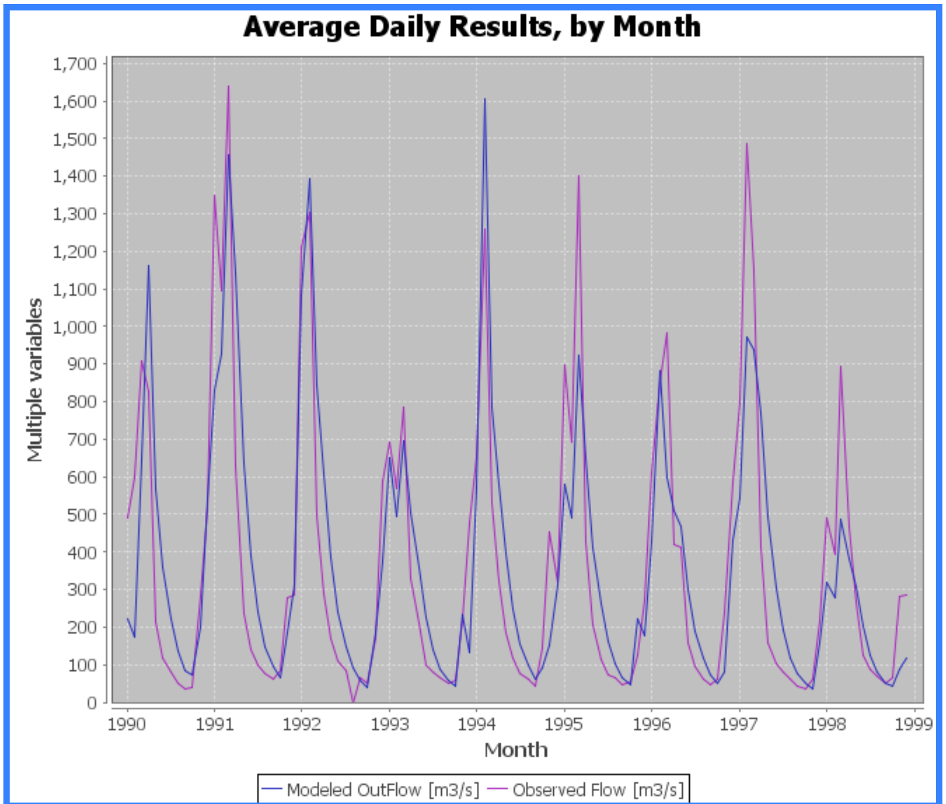

Figure 4–5b. Average monthly hydrograph for the Pozo Sarmiento gage from 1990 through 1998.

Table 4—2 contains information about each calibration and validation gage as well as model summary statistics for the sites in Region II.

Table 4–2. Overview of the calibration and validation gages in Region II of the Bermejo River Basin.

Gage	Type	Drainage Area (km^2)	Calibration Period	Overall Volume Error	Monthly Nash-Sutcliffe Efficiency
Balapuca	Calibration	4,459	1990–1998	-5.1%	0.55
Cuadro Cedros	Calibration	1,775	1990–1998	-18.4%	0.40
San Jose	Calibration	2,191	1990–1998	-30.7%	0.40
Aguas Blancas	Validation	5,048	1990–1998	-8.0%	0.70
Pozo Sarmiento	Validation	23,831	1990–1998	5.1%	0.71

5. SEDIMENT LOAD COMPARISON

Two sediment loading methods, the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) and the Gavrilovic and Zemljic method were applied to four gages in Region II of the Bermejo River Basin, with results compared to observed and independently calculated values from the COREBE presentation values.

5.1 MUSLE SEDIMENT CALCULATIONS

The modified universal soil loss (MUSLE) method (Williams, 1975) has been adapted to run with the Hydro-BID model. The MUSLE equation is as follows:

$$Equation\ 1{:}\ Sed_t = 11.8\,(Q_t\, Q_{peak})^{.56}\, K_{USLE}\, C_{USLE}\, P_{USLE} LS_{USLE}\, CFRG$$

Where

Sed_t = sediment load in tonnes

Q_t = runoff volume

Q_{peak} = peak flow rate

k = soil erodibility factor

LS = length slope factor

C = crop management factor

P = erosion control practice factor

CFRG = coarse fragment factor

Using the MUSLE method, sediment loads are generated and routed for each catchment in the flow network as a function of runoff from the peak flow rate. The other factors are based on characteristics of the soil and land use and management practices. Table 5-–1 provides the preliminary calculated annual sediment loads at four sites in Region II of the Bermejo River Basin from 1990 through 1998 using the MUSLE method.

Table 5–1. Summary of sediment loads using the MUSLE method for gages in Region II of Bermejo (preliminary data).

Location	Observed Average (10^6 tonnes/yr)	COREBE Calculated Value (10^6 tonnes/yr)	Hydro-BID Modelled Average (10^6 tonnes/yr)	Ratio (Hydro-BID/COREBE value)
San Jose	13.1	10.7	10.4	97%
Pozo Sarmiento	705.8	50.5	51.3	102%
Cuatro Cedros	5.3	4.9	4.8	98%
Aguas Blancas	8.3	9.3	9.5	102%
Balapuca	8.0	8.6	8.8	103%

The MUSLE method performed quite well after calibration in Hydro-BID. The modelled sediment loads closely matched COREBE calculated values. Hydro-BID modeled values also closely matched observed sediment loads. Both modeled values (COREBE and Hydro-BID) showed an important difference at the Pozo Sarmiento station which leads to the conclusion that probably this difference may have been produced by measuring errors at the station or a punctual anthropic or natural event (e.g. quarries, landslides) inside the action area of the station that is not being taken in account by the simulations.

5.2 GAVRILOVIC SEDIMENT CALCULATIONS

A second sediment loading calculation based on equations from Gavrilovic (1959) and modified by Zemljic (1971). Gavrilovic method has been widely used for the prediction of soil erosion and sediment yield on the basin scale and that was developed for management practices in erosion protection. This method was used to evaluate sediment loads at the same four sites in the basin. The Gavrilovic and Zemljic equations are as follows:

$$\text{Equation 2 : } G = W\,R$$

Where:

G = sediment load (m^3/year)

W = potential annual average sediment yield by surface erosion (m^3/year) (given by Equation 3)

R = redeposition or sediment retention coefficient (given by Equation 4)

$$\text{Equation 3: } W = T \times H \times \pi \times Z^{1.5} \times F$$

Where:

W = annual average erosion (m3/year)

T = coefficient of temperature (given by Equation 3.1)

$$\text{Equation 3.1: } T = (t/10+0.1)^{0.5}$$

Where:

t = annual average temperature (°C)

H = average annual precipitation (mm/year)

F = basin area (km^2)

Z = coefficient of erosion (given by Equation 3.2)

$$\textit{Equation 3.2: } Z = X\,Y\,[\,\varphi + J^{0.5}\,]$$

Where:

X = coefficient of land use

Y = coefficient of soil resistance

φ = coefficient of observed erosion

$$\textit{Equation } 4: R = \frac{(O \times D)^{0.5}\,(L + L_i)}{(L + 10) \times F}$$

O = perimeter of the basin (km)

D = elevation difference between mean and minimum elevation (km)

L = length of the main stream channel (km)

Li = length of secondary waterways (km)

F = basin area (km^2)

The sediment volume is multiplied by the density of wet-packed sand (2.7 tonnes/m^3) to yield the sediment load. These equations differ from MUSLE by calculating loads on an annual basis, and are not based on daily runoff data. The inputs include climate data as well as soil and land use and land management characteristics. These equations also differ from the MUSLE method by accounting for the portion of the load that is redeposited within the basin through a sediment retention function.

The presentation from COREBE included map images (Figures 5–1, 5–2, and 5–3) illustrating parameter distribution throughout the watershed. However, shapefiles for these values were not made available, so RTI used visual estimation to match the values during calibration.

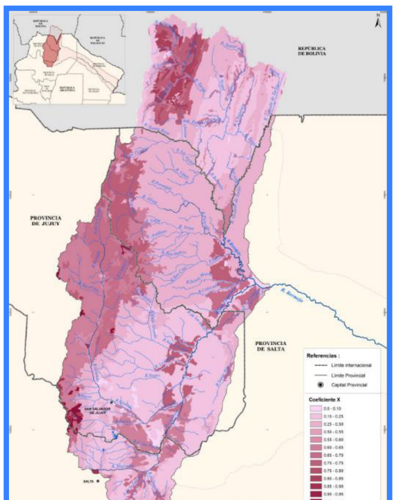

Figure 5–1. X parameter

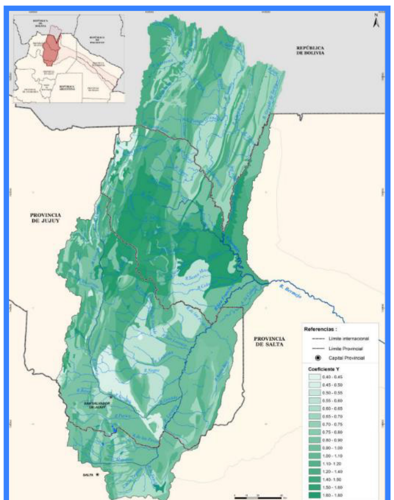

Figure 5-2. Y parameter

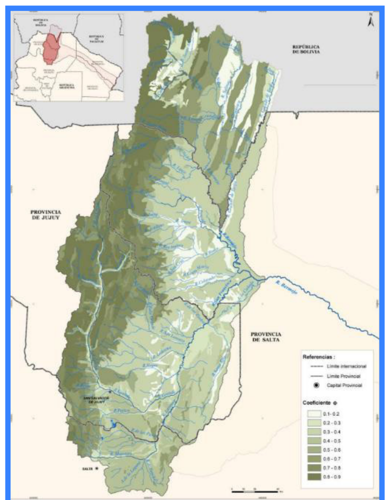

Figure 5–3. φ parameter

Sources COREBE 2013

Table 5–2 provides preliminary calculated annual sediment loads at four sites in Region II of the Bermejo River Basin from 1990 through 1998 using the Gavrilovic method and parameters estimations from COREBE maps.

Table 5–2. Summary of sediment loads using the Gavrilovic method for gages in Region II of the Bermejo River Basin (preliminary data).

Location	Observed Average (10^6 tonnes/yr)	COREBE Calculated Value (10^6 tonnes/yr)	Hydro-BID Modelled Average (10^6 tonnes/yr)	Ratio (Hydro-BID/ COREBE value)
San Jose	13.1	10.7	11.0	102%
Pozo Sarmiento	705.8	50.5	50.2	99%
Cuatro Cedros	5.3	4.9	5.4	109%
Aguas Blancas	8.3	9.3	8.8	94%
Balapuca	8.0	8.6	8.8	102%

Hydro-BID was successful in accurately replicating COREBE calculated values. The slight differences in values could be caused by approximation errors from visually attempting to match the sediment parameters and slight differences in spatial aggregation methods.

Table 5-3 below compares the calculated COREBE values against calculated Hydro-BID values. Section 3.2, Overview of Sediment Data, provides more detail on the data sources.

Table 5-3. Comparison of COREBE and Hydro-BID calculated sediment loads (values in 10^6 tonnes/year).

Location	COREBE		Hydro-BID Calculated Values	
	Observed Value	Gavrilovic Calculated Value	MUSLE Method	Gavrilovic Method
San Jose	13.1	10.7	10.4	11.0
Pozo Sarmiento	705.8	50.5	51.3	50.2
Cuatro Cedros	5.3	4.9	4.8	5.4
Aguas Blancas	8.3	9.3	9.5	8.8
Balapuca	8.0	8.6	8.8	8.8

Hydro-BID accurately recreated COREBE calculated values using both the MUSLE and Gavrilovic methods for all stations. However, both COREBE and Hydro-BID values differ substantially from observed values at the Pozo Sarmiento gage, located near the outlet of the study region. This may be caused by errors in routing, compounded by the large drainage area.

The spatial distribution of generated sediment load varies between HydroBID and COREBE values as show in **Figure 5-4.**

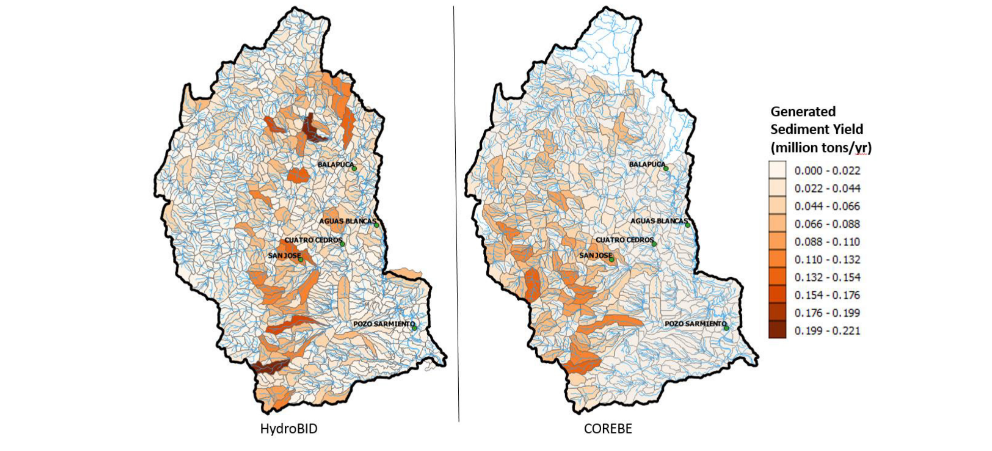

Figure 5-4. Comparison of average annual generated sediment values. Hydro-BID values are on the left, COREBE values on the right

In the Hydro-BID results, a small number of catchments in the wet portion of the basin dominate the generation of sediment. By contrast, the COREBE results show a more even distribution of magnitudes and a concentration of sediment-generating catchments in the western, drier portion of the basin.

These differences are most likely due to the coarser resolution of input data used by Hydro-BID. COREBE used high-resolution maps of X, Y and ϕ parameters as shown in **figures 5-1, 5-2, and 5-3**, respective. These values were visually approximated in Hydro-BID and implemented with unique values for each calibration sub-catchment as shown in **figure 4-1**. Similarly, COREBE used a high-resolution map for precipitation for calculating sediment yields, as shown in Figure 2-2. The climate data in Hydro-

BID, implementing by splitting the basin in to dry and wet regions as described in Section 3.1, generally estimates lower precipitation values in the dry region than COREBE, as shown in **Figure 5-5**. Sediment yield in the Gavrilovic method scales proportionately with precipitation (Equation 3), so this would have led to a lower estimation of sediment yield in the dry region.

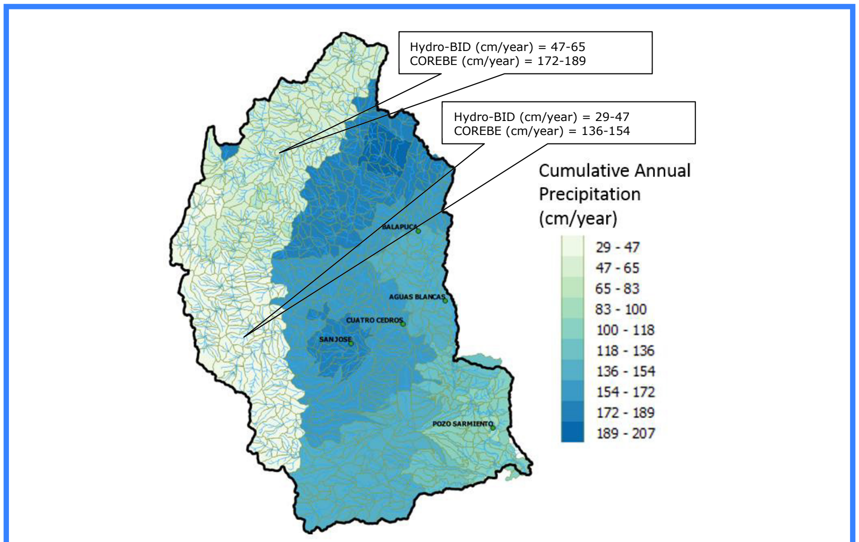

Figure 5-5. Cumulative annual precipitation as represented in Hydro-BID

6. CLIMATE CHANGE ANAYLISIS

6.1 INTRODUCTION

Climate change modeling is an inexact science, and the various methods are evolving continuously. Therefore, the estimation of future temperature and precipitation is usually addressed by considering various approaches, including (1) different emission scenarios, (2) different Global Circulation Models (GCMs), (3) the use of global models with grid resolution of 100–200 km, and (4) regional/downscaled models with grid resolution of 50 km. In addition, most climate modeling is currently done using Intergovernmental Panel on Climate Change 4 (IPCC4) methodologies. However, in this study we were also able to obtain the services of Centro de Investigaciones del Mar y la Atmósfera (CIMA) to conduct climate predictions using the new generation of climate models, known as Coupled Model Inter-comparison Project Phase 5 (CMIP5) that will be part of the IPCC5 convention.

Before considering the CIMA results, we summarize various earlier studies of climate change in Argentina and the complex Andean region. As an example, **Figure 6-1** shows expected changes in temperature and rainfall as evaluated by the Servicio Meteorológico Nacional and CIMA using an ensemble of 14 GCMs for the decade of 2020 to 2029. These data express as absolute rise in temperature in degrees Celsius, and as a percentage change in precipitation, over a base period of 1961 through 1990.

Overall, the expected changes are quite modest, for this not-too-distant decade. However, the highest temperature rise is expected to be in northwest Argentina, with an expected increase of annual temperature of about 1.1–1.2°C in the case study area.

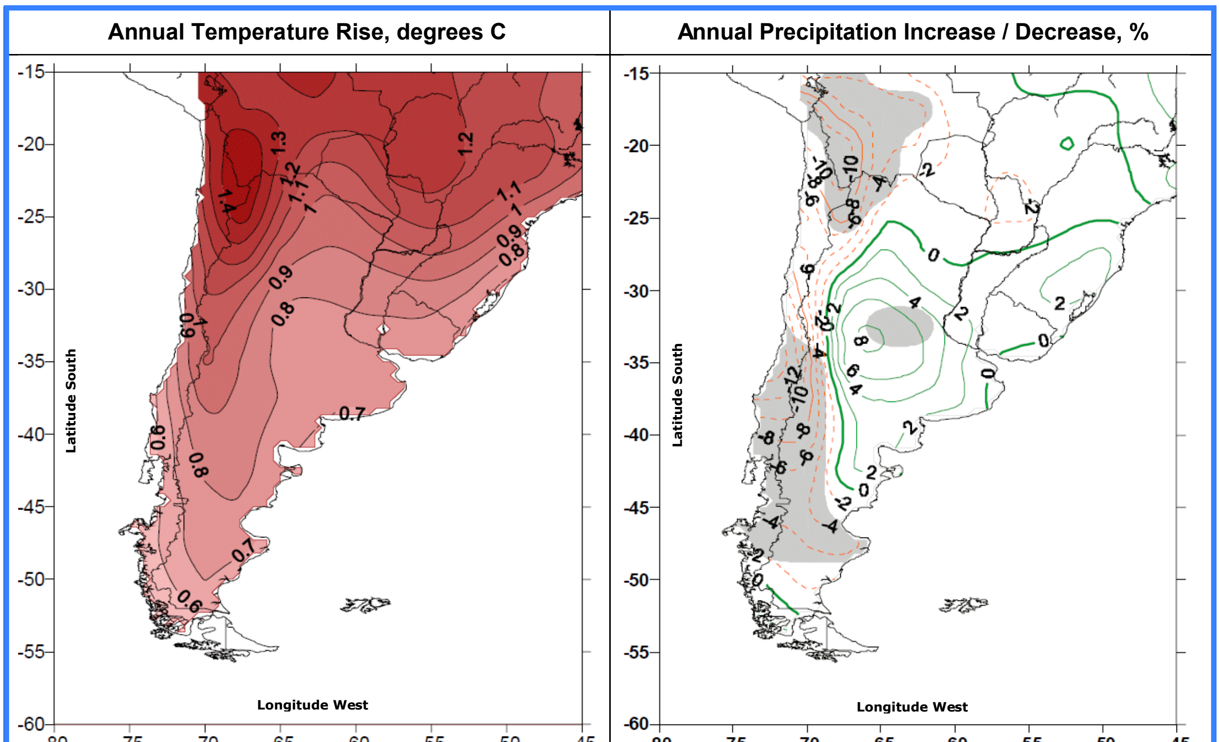

Figure 6–1. Estimated climate change in Argentina, 2020–2029.

Much lower temperature increases are expected in central Argentina. The northwest is predicted to experience some decline in annual precipitation, around 2% in the case study area. Central Argentina could experience noticeable increases in annual precipitation.

6.2 USE OF CLIMATE WIZARD

The next step was to use the online climate projection tool known as Climate Wizard (www.climatewizard.org) to project changes in temperature and rainfall out to the year 2060. This tool, developed by three U.S. universities and two international nongovernmental organizations (with endorsement from the World Bank), has many useful features that allow the user to:

- Select a time period for analysis, whether historical (using the Climate Research Unit database from the University of East Anglia in the UK) or future, for any given range of years to 2100;
- Select a single GCM or an ensemble of GCMs and one or more emission scenarios;
- Upload geographic shape-files and receive results in a gridded map format; and
- Obtain graphical information on annual values of output data over a multiyear scale.

We used Climate Wizard to generate future climate data for the Río Grande sub-basin and the upper Río San Francisco, using the A1B moderate emissions scenario (The A1B scenario describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies (IPCC Working Group III, 2000). The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system inside those the B scenario reflects a balance across the use of fossil intensive and non-fossil energy sources), and 2 GCMs:

- UK Met Office (UKMO) Hadley CM3.1—used frequently in Argentina in the past; and
- Commonwealth Scientific and Industrial Research Organization (CSIRO) MK3.

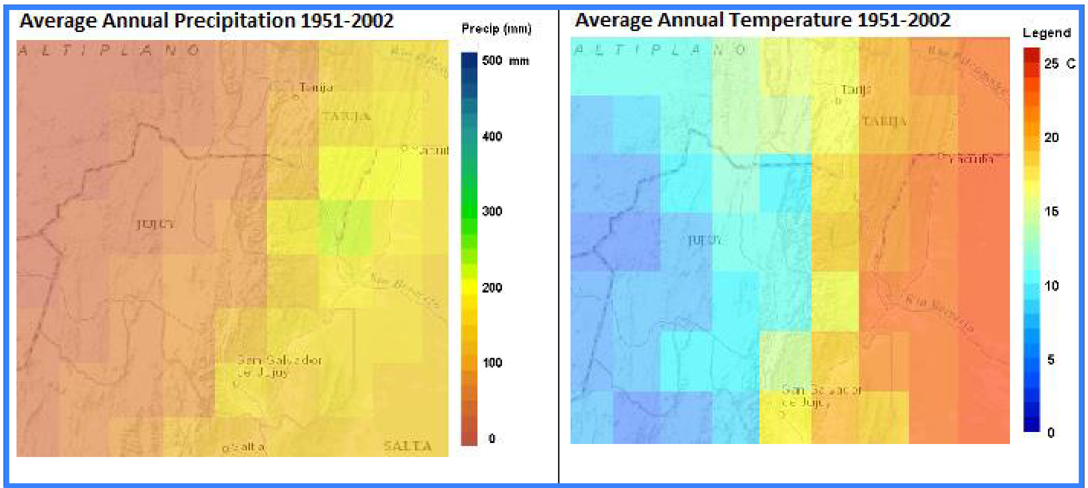

Figure 6–2. September mean temperature and precipitation.

Figure 6–2 shows a typical gridded output from Climate Wizard for the Río Grande and upper Río San Francisco basin for the month of September for the World Meteorological Organization (WMO) reference period of 1951–2002. There is a clear variation of temperature within the basin, while there is low variation on precipitation over the area.

In a previous study, monthly temperature and precipitation projections were compiled for each decade for 2001–2010 to 2051–2060 in the nearby Río Grande basin (Wyatt et al, 2014). From these temperature projections, climate scale factors were developed for use in the hydrologic modelling. The original factors from the previous study are relative to a baseline of 2001-2010 and were adjusted in order to implement a baseline using the period 1991-2000. The final precipitation multipliers and temperature adjustments for each decade are shown in **Tables 6–1a** and **6–1b**, respectively.

Table 6–1a. Precipitation scale factors from Climate Wizard.

	2021–2030	2041–2050
Jan	2.024	1.581
Feb	1.512	1.406
Mar	1.108	1.229
Apr	1.060	0.831
May	0.903	0.895
Jun	1.201	1.001
Jul	0.860	0.819
Aug	1.452	1.111
Sep	1.431	1.037
Oct	1.560	1.519
Nov	1.980	1.828
Dec	1.096	1.136

Table 6–1b. Temperature adjustment factors from Climate Wizard (ºC).

	2021–2030	2041–2050
Jan	0.948	1.444
Feb	0.501	0.789
Mar	0.703	0.983
Apr	0.941	1.279
May	0.943	1.162
Jun	0.435	1.180
Jul	1.807	2.255
Aug	1.043	1.217
Sep	0.398	1.302
Oct	1.202	1.701
Nov	-0.100	0.380
Dec	0.559	1.018

6.3 NEXT GENERATION CLIMATE MODELING

6.3.1 Climate Projections Used

CIMA, the leading climate modeling group in Argentina, prepared two types of climate projections:

1. CMIP5, the next-generation global climate models—using the middle-level Representation Concentration Pathway (RCP)—RCP4.5. These projections can be carried out through 2060. The data grid spacing varies depending on the GCM used, but grid spacings are on the order of 100–200 km. The CMIP5 with RCP 4.5 is roughly comparable to earlier GCM models using the A1B Special Report on Emissions Scenario (SRES), as shown in **Figure 6–3.**

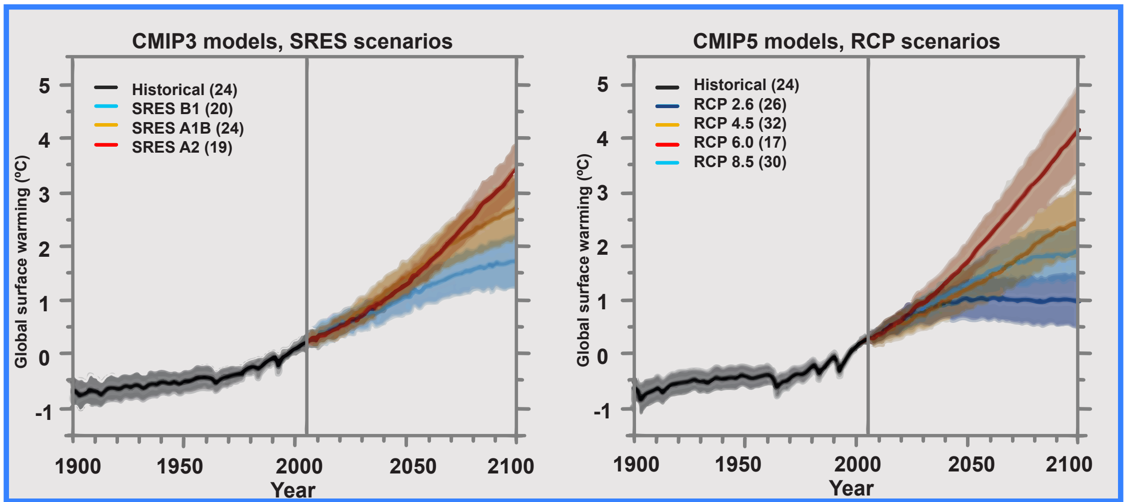

Figure 6–3. Comparison of earlier generation and new generation climate models.

2. A regional model that uses Fifth-Generation Penn State/National Center for Atmospheric Research Mesoscale Model (MM5) to downscale the UKMO HadAM3H Global Circulation Model with the A1B SRES Scenario. This model has greater resolution—with a grid spacing of 50 km, creating 20 grid points—but has only been carried out to 2040.

6.3.2 CMIP5 Climate Model Calibration

Similarly to Climate Wizard, the CIMA Climate Model was developed in a previous study for the Río Grande basin (Wyatt et al, 2014). During calibration of this model, the project team compared predictions of temperature and precipitation in the 20th century by each of the six GCMs to long-term historical records at three sites in or near the project area:

1. Oran: 1960–2010 for temperature and 1959–2010 for precipitation

2. Jujuy Airport: 1968–2010 for temperature and 1968–2010 for precipitation

3. Salta Airport: 1926–2010 for temperature and 1901–2010 for precipitation

They then used a root-mean—square method to adjust the predictions to minimize the difference between the observations and predictions. Having made the corrections, they compared the results of the six GCMs and found only very small differences between them. These factors are relative to a baseline of 2001-2010 and were adjusted to instead use a baseline of 1991-2000.The aggregated scale factors for future decades, developed from the six GCMs, are shown in **Tables 6–2a** and **6–2b.**

The changes in precipitation show no consistent inter-decadal or seasonal change. Future rainfall prediction shows no clear trend, but temperature shows a steady increase, especially in the dry winter months.

Table 6–2a. Precipitation scale factors for CIMA ensemble climate projections.

Precipitacion Multiplication Factor		
	2021–2030	**2041–2050**
Jan	1.564	1.551
Feb	1.464	1.357
Mar	1.097	1.256
Apr	1.075	1.084
May	0.832	0.807
Jun	1.217	1.357
Jul	1.192	1.130
Aug	2.009	2.118
Sep	1.709	1.578
Oct	1.515	1.557
Nov	1.756	1.788
Dec	1.275	1.263

Table 6–2b. Temperature adjustment factors for CIMA ensemble climate projections.

	2021–2030	**2041–2050**
Jan	1.33	2.27
Feb	0.44	1.41
Mar	0.90	1.82
Apr	0.50	1.40
May	0.85	1.70
Jun	0.62	1.69
Jul	0.99	2.05
Aug	0.88	1.73
Sep	1.19	1.75
Oct	1.19	2.19
Nov	0.03	0.91
Dec	0.56	1.47

We also compared the results of the CMIP5 modeling to the results from Climate Wizard. **Table 6–3** shows a comparison of the CIMA and Climate Wizard precipitation adjustments for 2021–2030 and 2041–2050. The CIMA ensembles show a significantly higher summer rainfall, and slightly lower winter rainfall.

Table 6–3. Comparison of climate model precipitation adjustments.

Month	2021–2030		2041–2050	
	Climate Wizard	CIMA	Climate Wizard	CIMA
Winter (December-February)	1.438	1.434	1.571	1.391
Spring (March-May)	0.830	1.001	0.880	1.049
Summer (June-August)	0.970	1.473	1.386	1.535
Autumn (September - November)	1.994	1.660	1.542	1.641

6.4 ESTIMATING HYDROLOGIC IMPACTS FROM CLIMATE CHANGE

The two decades presented above, 2021–2030 and 2041–2050 were selected for further analysis under CIMA and Climate Wizard projections. The projected temperature and precipitation modifiers were used to modify the climate for each of the calibrated gages described in Section 4. Hydro-BID was used to estimate impacts of mean annual flow (the average total yearly discharge from a river basin across the simulation period) and sediment yields for each gage, as well as changes in flow regime due to climate change. Results were compared against “baseline” calibrated values presented in Sections 4 and 5.

6.4.1 Climate Change Impacts on Mean Annual Yield and Flow Regime

Tables 6–4a and **6–4b** show the average changes in mean annual yield for each climate projection for 2021–2030 and 2041–2050.

Table 6-4a. Percent change in mean annual flow from baseline, 2021–2030

Location	Climate Wizard	CIMA	Average
San Jose	8.5%	-8.0%	0.2%
Pozo Sarmiento	-3.6%	-16.5%	-10.0%
Cuatro Cedros	3.5%	-7.9%	-2.2%
Aguas Blancas	4.7%	-8.7%	-2.0%
Balapuca	4.9%	-8.6%	-1.8%

Table 6–4b. Percent change in mean annual flow from baseline, 2041–2050			
Location	**Climate Wizard**	**CIMA**	**Average**
San Jose	-10.6%	-10.2%	-10.4%
Pozo Sarmiento	-20.1%	-18.6%	-19.3%
Cuatro Cedros	-11.0%	-9.1%	-10.1%
Aguas Blancas	-12.2%	-11.1%	-11.6%
Balapuca	-12.0%	-10.9%	-11.5%

Overall, the climate change projections resulted in a lower annual yield from the Río Bermejo. Disagreement existed between the projections for 2021–2030, with the Climate Wizard adjustments resulting in a net increase in flow for almost all gages, whereas the CIMA adjustments showed a net decrease. Instead, the scenarios for 2041–2050 for both projections showed large decreases for all gages shown. The average change in mean annual flow for the river is shown below in **Figure 6–4.**

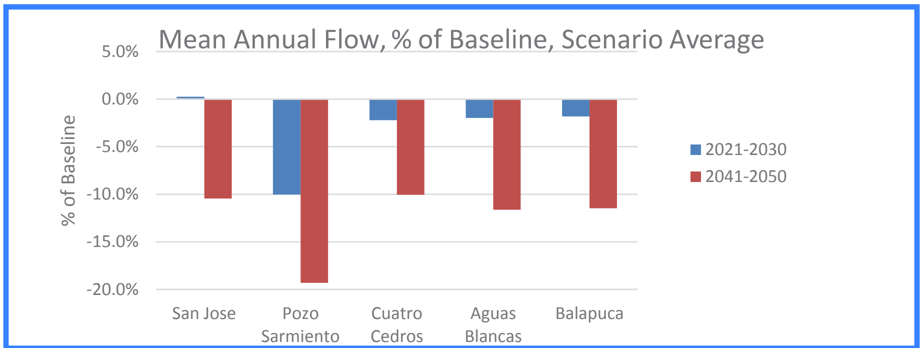

Figure 6–4. Average Percent Change in Mean Annual Flow

The greatest decrease in mean annual yield occurs at the most-downstream flow station, Pozo Sarmiento. To examine the changes in flow regime, the hydrograph and flow duration curve for Pozo Sarmiento from 2041–2050 are shown in **Figures 6–5a** and **6–5b**. Baseline flow is labeled as "Observed Flow."

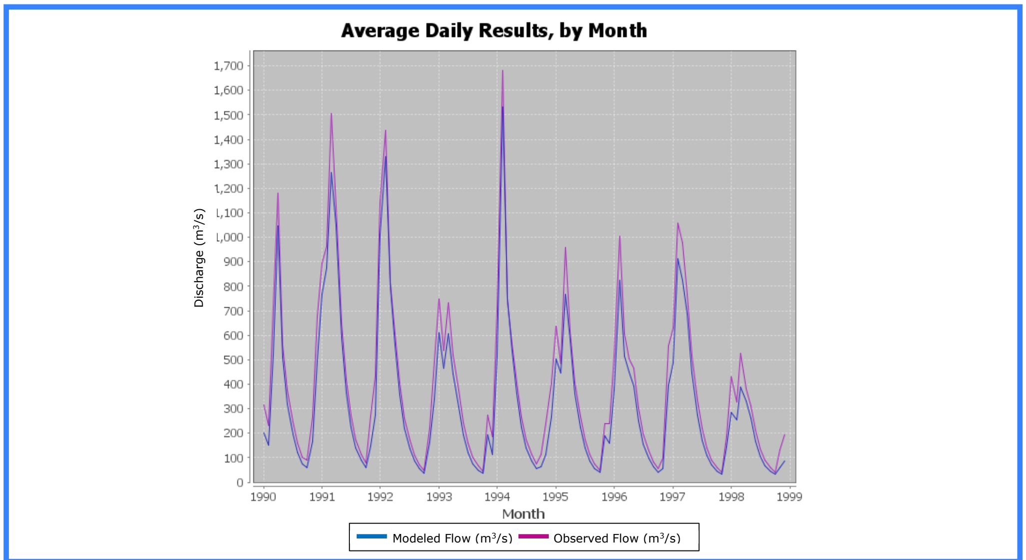

Figure 6–5a. Monthly hydrograph for Pozo Sarmiento from 2041-2050. Baseline flow is shown in pink and labeled as "Observed Flow."

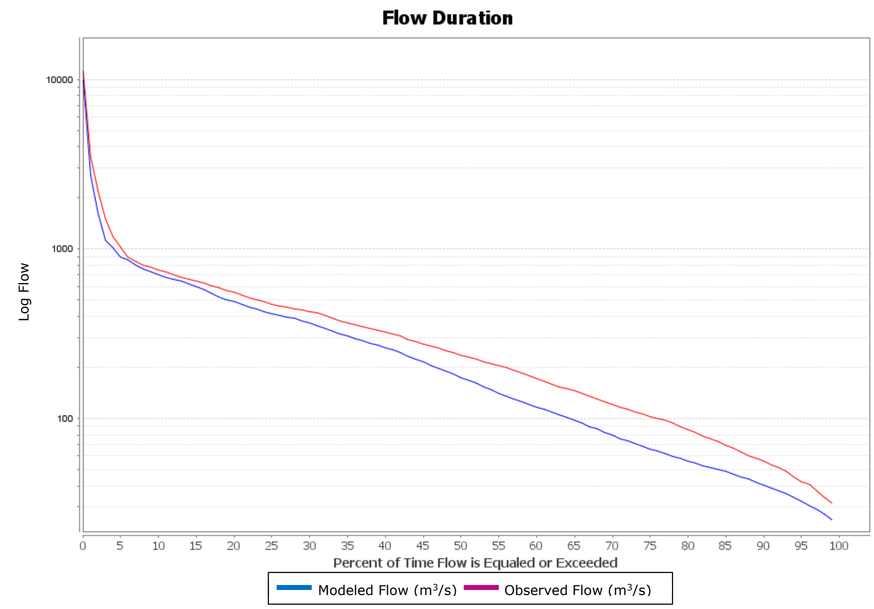

Figure 6–5b. Flow duration curve for Pozo Sarmiento from 2041-2050. Baseline flow is shown in red and labeled as "Observed Flow"

The hydrograph shows a consistent decrease in magnitude for nearly all flow events. The flow duration curve confirms this behavior, with further insight into where changes occur. The greatest difference occurs in low-flow conditions, with flows exceeding the 50th percentile dropping in value substantially more than high flow events, in average, low-flow conditions will reduce their probability of occurrence by more than 10% while peak-flows will reduce their probability of occurrence by less than 5%.

6.4.2 Climate Change Impacts on Sediment Yield

Sediment loading under climate change conditions was modeled under each set of climate adjustment parameters using both MUSLE and the Gavrilovic method as defined in Sections 5.1 and 5.2. The results for each method and climate projection are shown below in **tables 6–5a** (MUSLE) and **6–5b** (Gavrilovic).

Table 6–5a. Percent change in mean annual sediment load, MUSLE method.

Location	Climate Wizard		CIMA	
	2021-2030	2041-2050	2021-2030	2041-2050
San Jose	30.2%	11.9%	14.3%	15.4%
Pozo Sarmiento	32.8%	6.3%	9.9%	10.7%
Cuatro Cedros	70.7%	35.6%	40.4%	42.0%
Aguas Blancas	41.6%	12.3%	16.2%	16.9%
Balapuca	41.8%	12.3%	16.3%	17.0%

Table 6–5b. Percent change in mean annual sediment load, Gavrilovic method.				
	Climate Wizard		CIMA	
Location	2021-2030	2041-2050	2021-2030	2041-2050
San Jose	-9.5%	-19.5%	-7.2%	-6.3%
Pozo Sarmiento	-9.5%	-19.5%	-7.2%	-6.3%
Cuatro Cedros	-9.5%	-19.5%	-7.2%	-6.3%
Aguas Blancas	-9.5%	-19.5%	-7.2%	-6.3%
Balapuca	-9.5%	-19.5%	-7.2%	-6.3%

The two sediment transport prediction methods resulted in significantly different results. Under the MUSLE method, sediment loads increase in all scenarios, whereas loads decrease for all Gavrilovic scenarios. This is fundamentally a result of the calculations used by each method. MUSLE calculations (Equation 1 in Section 4) occur on a daily basis with consideration of both average and peak flow, and thus are more sensitive to changes in the flow regime. Note that in Figure 6–5b, the flow duration curve for Pozo Sarmiento, the difference between low and high flow events (between the 25^{th} and 75^{th} percentile), increased with climate change. With the MUSLE method, the greatest increase (by percentage) occurs at the Cuatro Cedros gage. However, the magnitude of change in mean annual sediment load varies between decades substantially. Using Climate Wizard the percentage of change increase greatly for the 2021–2030 period, and decrease in magnitude (but still remain above baseline) for 2041–2050. Under the CIMA projection, values increase moderately during the 2021–2030 period and basically maintain the same rate for the 2041–2050 period.

The Gavrilovic method (Equations 2 through 4 in Section 4) aggregates annual precipitation and temperature trends to produce annual yield. This coarser calculation does not include consideration of sub-annual peak flows, but instead changes with broader climate behavior. Changes in precipitation are directly proportional to changes in sediment in Equation 2. Due to a single climate modifier in each month being used for all catchments, estimated sediment yields decreased proportionality across all basins in each scenario, resulting in identical values for each column in Table 6–5b. Under the Climate Wizard projection, sediment loads decrease by larger margins when comparing the period from 2041 to 2050 with the period from 2021 to 2030 . By contrast, values decrease by approximately the same amount (~7%) under the CIMA projection for both periods.

7. CONCLUSIONS

Hydrologic modelling for Region II of the Río Bermejo was undertaken with Hydro-BID using climate and sediment data provided by COREBE in order to test model capabilities for climate change scenarios and also to test the sediment transport methodologies that where implemented (MUSLE and Gavrilovic). The Analytical Hydrography Dataset (AHD) was modified to incorporate more fine-resolution catchments, enabling precise calculations. A composite interpolated climate dataset was generated to represent the distinctly arid regions of the modelling area. The hydrologic model was calibrated and validated against five stations in Region II of the Bermejo River Basin, with low volumes of error.

Two sediment calculation methods were implemented in Hydro-BID: the Modified Universal Soil Loss Equation (MUSLE) and Gavrilovic. Sediment loads were calculated with each method and compared to observed values and internally calculated values provided by COREBE. RTI was able to closely replicate the calculated and observed results for almost every gage, with a deviance occurring between observed and COREBE calculated values at Pozo Sarmiento. Each method proved effective for estimating sediment yields.

Hydro-BID was calibrated for both methodologies with the purpose of analyzing their behavior and applicability for water resources management purposes. Along the process it was observed that Hydro-BID was able to reproduce with a good fit the values estimated by COREBE's analysis. However, important differences were found at the Pozo Sarmiento gage, these differences may be caused by gage problems or unidentified anthropic elements that escape from the characterization of the model. It is suggested that a study must be carried out in order to validate the characterization of the soil in the basin as well as the presence of any kind of process that may artificially increment the production or transport of sediments in the basin.

A climate change analysis was conducted using two sets of projections: Climate Wizard A1B and the next generation Centro de Investigaciones del Mar y la Atmosfera (CIMA) scenario. Water and sediment yields were evaluated for each scenario for the decades 2021–2030 and 2041–2050. Under the Climate Wizard scenario, flows increased initially in 2021–2030, but decreased slightly from baseline conditions for 2041–2050. Under the CIMA projection, flows increasingly lessened in value from 2021 to 2050.

These important variations that may happen when comparing climatic ensemble models are more common in complex topographic and climatic regions due to the fact that these regional models have a coarse grid (cells > 50 km) that sometimes does not take into account local climate particularities that may affect regional patterns such as wind circulation and evapotranspiration patterns specially within the mountains. In these cases, local based models like CIMA should be used for the analysis, design and planning purposes. For the analyzed scenarios in the Bermejo River, even if for the period 2041-2050 both models tend to predict the same behavior, it is advisable to use only values from the CIMA model for further analysis.

Overall, the hydrologic predictions indicate that flows would consistently decrease in the next 50 years (Figure 6-5b). Therefore, a detailed analysis of water demand/offer is recommended in order to study the possible effects of such decrease on available water volume on the sustainability of the service for distribution (urban and industrial) and irrigation.

Sediment yields under climate change were evaluated under both projections (Climate Wizard and CIMA) using each method (MUSLE and Gavrilovic). When evaluated with MUSLE, each decade and projection showed a net increase in sediment yield, despite an expected decrease in total flow. By comparison, the Gavrilovic method showed a decrease in sediment yield across all scenarios. The difference in sediment yields fundamentally rises from differences in formulation, with Gavrilovic yields using annual aggregations compared to the daily calculations of MUSLE.

Analyzing the results from the CIMA model scenario and for the MUSLE methodology, it can be observed that even if flows tend to decrease for both periods (2021-2030 and 2041-2050) there is an important effect of the peak discharges during high flows that would potentially lead to an increment of the overall sediment transport load (Table 6-5A). This effect is not noticeable using the Gavrilovic methodology, which only reflects annual values and does not take into account seasonal events (Table 6-5b). Nevertheless, the results indicate that the sediment transport depends more on high flow peaks that are only noticeable when using the MUSLE method.

In conclusion, although further studies are recommended in order to analyze in detail the range of validity of the Gavrilovic methodology, the results of this study suggest that the MUSLE method and the CIMA climate projections are more suitable for watershed management practices.

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