# MINIMUM INSTREAM FLOW ESTIMATION AT UNGAGED STREAM SITES IN PUERTO RICO

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DRNA

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## 1. INTRODUCTION

### 1.1. Study Description

Minimum streamflow information is commonly used to determine the water available for extraction and to analyze instream environmental parameters. Minimum streamflow estimates are frequently desired at ungaged locations, either on a stream having gages at other locations, or a stream without any gages.

This study presents regional regression equations to estimate minimum streamflow using two parameters: watershed area and mean annual rainfall. These equations are based on a revised rainfall map which incorporates the available rainfall data from 127 raingage stations and also considers geographic parameters.

### 1.2. Scope and Purpose of Report

This study describes a methodology for minimum streamflow estimation and consists of two major elements.

- A new isoheytal map for Puerto Rico showing contour lines of mean annual rainfall has been prepared based on contour curve fitting within the GIS environment, and adjusted based on geographic criteria such as proximity to the coastline, elevation, and vegetation mapping (Holdrige life zone).
- Regional regression equations for mean discharge and for minimum streamflow exceedances ($Q_{90}$, $Q_{95}$, $Q_{98}$, $Q_{99}$, and $Q_m$) have been prepared based on the revised isoheytal map. The regression equations have been developed to simulate current "natural" runoff conditions, using streamflow data from gage stations with minimum influence by upstream reservoirs, diversions and loss to groundwater.

### 1.3. Limitations of the Analysis

The minimum streamflow equations do not account for the effects produced by the existence of reservoir operations, intakes and diversions, or infiltration into coastal alluvial or karst aquifers. For those cases it is necessary to make a more detailed study in order to obtain more representative results. The equations should not be used in watersheds smaller than one square mile.

### 1.4. Authorization

Preparation of this report has been authorized by the Department of Natural and Environmental Resources (DNER) by contract # 050-08-001302.

## 2. MEAN ANNUAL RAINFALL MAP

### 2.1. Current Rainfall Map

Several isoheytal maps have been prepared for Puerto Rico over the past four decades (Calversbert, 1970; Black and Veatch, 1971; DNER, 2003). The map published by Calversbert (1970) presented in Figure 1, was prepared using rainfall data from 1930 to 1960. The map published by DNER (2003) has significant discrepancies with station rainfall at several locations. Table 1 presents those stations with more than 10% of difference between values obtained from that map and those obtained from the rain gage station data. The location of these stations is presented in Figure 2. The current analysis stemmed from the desire to use the most recently available data to minimize discrepancies between maps and station data.

Table 1: Rain Gages with more than 10% of Difference from DNER (2003) Isoheytal Map.

| Rain Gage | Mean Annual Rainfall (in/yr) | | % Difference |
|---|---|---|---|
| | Gage Station Data | DNER Map | |
| San Juan City | 59.1 | 79.0 | 25.2 |
| Peñuelas 1 NE | 54.7 | 43.7 | -25.1 |
| Toro Negro Forest | 93.9 | 76.6 | -22.5 |
| Río Blanco Lower | 107.8 | 91.3 | -18.1 |
| Carite Dam | 74.4 | 90.2 | 17.6 |
| Peñuelas Salto Garzas | 75.6 | 90.7 | 16.7 |
| Lajas Substn | 45.1 | 53.1 | 14.9 |
| Caguas 1 W | 54.1 | 63.3 | 14.6 |
| Negro-Corozal | 70.8 | 82.7 | 14.4 |
| Yauco 1 NW | 45.5 | 39.8 | -14.4 |
| Aibonito 1 S | 57.7 | 50.8 | -13.7 |
| Jayuya | 75.5 | 67.0 | -12.7 |
| Melanía Dam | 39.0 | 44.3 | 12.0 |
| Potala | 30.0 | 34.1 | 11.9 |
| Río Piedras Exp Stn | 69.4 | 78.7 | 11.9 |
| San Lorenzo Espino | 119.0 | 106.8 | -11.4 |
| Sabana Grande 2 ENE | 62.4 | 56.1 | -11.3 |
| Toro Negro Plt 2 | 88.9 | 99.9 | 11.0 |
| Isabela Substn | 61.3 | 68.5 | 10.5 |
| Humacao 2 SSE | 83.2 | 92.4 | 9.9 |

## 2.2. Rainfall Data

Rainfall data were obtained from the US Department of Commerce National Climatic Data Center (NCDC). The NCDC database has 143 rain gages with record periods dating from 1900. A screening process was undertaken to eliminate from the analysis stations with less than 15 years of data. Other eliminated stations were those very close to other stations and with a notable difference in mean annual rainfall with other nearby gages having a longer period of record. Table 2 presents the omitted rain gages and the reasons. The rain gages used for the analysis are presented in Table 3 and Figure 3. Some stations with 14 years of record were included in the analysis because the area they are located lack of any surrounding station and the 14 years of data provides a better representation of the area.

Table 2: Rain Gages Omitted in the Analysis.

| Rain Gage | Record Begin Date | Record End Date | Record Years | Rainfall (in/yr) | Reason |
|---|---|---|---|---|---|
| Bayaney | Jun-1970 | Aug-1979 | 9 | 38.75 | Record < 15 Years |
| Boca | Jul-1996 | Dec-2006 | 10 | 37.21 | Record < 15 Years |
| Caguas 2 ENE | Aug-1960 | May-1967 | 7 | 50.33 | Record < 15 Years |
| Garrochales | Sep-1965 | Apr-1970 | 5 | 60.41 | Record < 15 Years |
| Guayanilla | Jan-1955 | Aug-1961 | 7 | 36.89 | Record < 15 Years |
| Guineo RSVR | Jan-1955 | Mar-1969 | 14 | 97.52 | Record < 15 Years |
| Indiera Baja | Nov-1952 | Sep-1962 | 10 | 74.62 | Record < 15 Years |
| Jayuya 1 SE | Mar-1960 | May-1981 | 21 | 60.51 | Inconsistent with nearby gage stations A/ |
| Josefa | Jan-1955 | Jan-1969 | 14 | 45.32 | Record < 15 Years |
| La Fe | Jan-1956 | Mar-1969 | 13 | 72.94 | Record < 15 Years |
| Maricao | Jan-1955 | Apr-1969 | 14 | 103.8 | Record < 15 Years |
| Naguabo 3 E | Apr-1972 | May-1983 | 11 | 79.93 | Record < 15 Years |
| Naguabo 6 W | Jan-1955 | May-1967 | 12 | 90.43 | Record < 15 Years |
| Palmarito | Mar-1963 | Apr-1975 | 12 | 84.55 | Record < 15 Years |
| Ponce Mercedita Ap | Jan-1957 | Nov-1968 | 12 | 34.19 | Record < 15 Years |
| Potala | Jan-1955 | Feb-1969 | 14 | 30.02 | Record < 15 Years |
| Rincón 2 NNW | Nov-1957 | May-1968 | 11 | 57.78 | Record < 15 Years |
| Río Piedras | Jan-1931 | Dec-1961 | 30 | 76.79 | Inconsistent with nearby gage stations B/ |
| St Just | Jan-1955 | Dec-1966 | 12 | 80.12 | Record < 15 Years |
| Saltillo 2 Adjuntas | May-1981 | Dec-1991 | 11 | 91.97 | Record < 15 Years |
| Toa Baja Levitown | Jan-2005 | Dec-2006 | 2 | 75.25 | Record < 15 Years |
| Vieques Island #2 | Mar-1983 | Jan-1994 | 11 | 49.92 | Record < 15 Years |
| Yauco 1 S | Jan-1955 | Jun-1969 | 11 | 29.55 | Record < 15 Years |
| Yaurel 3 NNE | Jan-1955 | Mar-1969 | 11 | 45.6 | Record < 15 Years |

A/ Inconsistent with gage station Jayuya (Period of Record 1909-2002, Rainfall of 75.5 in/yr).

B/ Inconsistent with gage station Río Piedras Exp Stn (Period of Record 1959 - 2006, Rainfall of 69.37 in/yr).

Table 3: Rain Gages Used to Generate Isoheytal Map.

| Rain Gage | Record Begin Date | Record End Date | Rainfall (in/yr) |
|---|---|---|---|
| Aceituna | Jan-1955 | Dec-2006 | 76.90 |
| Adjuntas 1 NW | Jan-1955 | Dec-2006 | 78.29 |
| Adjuntas Substn | Jan-1970 | Dec-2006 | 73.62 |
| Aguirre | Jan-1931 | Oct-1966 | 42.89 |
| Aguirre | Apr-1955 | Dec-2006 | 40.47 |
| Aibonito 1 S | Jan-1906 | Dec-2006 | 57.72 |
| Arecibo 3 Ese | Jul-1931 | Jan-1999 | 54.39 |
| Arecibo Obsy | Feb-1980 | Dec-2006 | 82.64 |
| Barceloneta 2 | Jan-1955 | May-1990 | 53.34 |
| Barceloneta 3 SW | Sep-1990 | Dec-2006 | 60.39 |
| Barranquitas | Jan-1955 | Dec-1991 | 57.38 |
| Benavente-Hormigueros | Aug-1973 | Aug-2002 | 59.95 |
| Borinquen AP | Feb-1974 | Dec-2006 | 53.66 |
| Cabo Rojo | Jan-1955 | Aug-1969 | 56.41 |
| Cacaos-Orocovis | May-1981 | Dec-2006 | 82.76 |
| Caguas | May-1899 | Aug-1960 | 61.25 |
| Caguas 1 W | Mar-1970 | Mar-1995 | 54.08 |
| Calero Camp | Jan-1955 | Dec-2006 | 56.29 |
| Cambalache Exp Forest | Jan-1932 | Feb-1966 | 51.00 |
| Candelaria Toa Baja | Jan-1955 | May-1973 | 78.14 |
| Candelaria Toa Baja | Oct-1973 | Aug-1995 | 74.74 |

| Rain Gage | Record Begin Date | Record End Date | Rainfall (in/yr) |
|---|---|---|---|
| Canóvanas | Jan-1955 | Dec-2006 | 74.37 |
| Caonillas Utuado | Jan-1955 | Nov-1987 | 73.32 |
| Caonillas Villalba | Jan-1955 | Sep-1969 | 55.12 |
| Carite Dam | Jan-1955 | Apr-1980 | 74.37 |
| Carite Plt 1 | Jan-1955 | Mar-1980 | 72.83 |
| Cataño | Jan-1955 | May-1976 | 69.17 |
| Cayey 1 E | Jan-1955 | Jun-2001 | 58.32 |
| Central San Francisco | Jan-1955 | Jun-1996 | 31.04 |
| Cerro Gordo Ciales | Oct-1969 | Sep-1997 | 82.26 |
| Cerro Maravilla | Apr-1969 | Dec-2006 | 94.46 |
| Cidra 1 E | Sep-1899 | Jun-1994 | 66.49 |
| Coamo 2 SW | Jan-1955 | Dec-2003 | 36.40 |
| Coloso | Oct-1899 | Dec-2006 | 80.29 |
| Comerío Falls Plt 2 | Feb-1959 | May-1974 | 65.74 |
| Corozal Substn | Jan-1931 | Dec-2006 | 75.06 |
| Corral Viejo | Apr-1970 | Dec-2006 | 59.18 |
| Culebra Island | Jan-1920 | Jul-1975 | 33.08 |
| Dorado 2 Wnw | Jan-1931 | May-2006 | 65.21 |
| Dos Bocas | Jan-1937 | Dec-2006 | 76.82 |
| Ensenada 1 W | Jan-1955 | Dec-2006 | 30.76 |
| Fajardo | Jan-1931 | Jan-1996 | 64.81 |

| Rain Gage | Record Begin Date | Record End Date | Rainfall (in/yr) |
|---|---|---|---|
| Garzas | Jan-1939 | Jan-1981 | 86.16 |
| Guajataca Dam | Jan-1955 | Dec-2006 | 71.13 |
| Guavate Camp | Dec-1969 | Jun-1994 | 99.56 |
| Guayabal | Jan-1955 | Dec-2006 | 49.85 |
| Guayama 2E | Jan-1911 | Dec-2006 | 52.61 |
| Gurabo | Apr-1946 | May-1967 | 63.75 |
| Gurabo Substn | Mar-1956 | Dec-2006 | 64.19 |
| Hacienda Constanza | Oct-1969 | Dec-2006 | 73.89 |
| Hato Arriba Arecibo | Feb-1974 | Aug-1994 | 55.08 |
| Humacao 2 SSE | Jan-1931 | Jan-1996 | 83.19 |
| Indiera Alta | Oct-1962 | Jun-1990 | 76.42 |
| Isabela Substn | Jan-1901 | Dec-2006 | 61.30 |
| Jájome Alto | Jan-1955 | Dec-2006 | 77.47 |
| Jayuya | Apr-1909 | Aug-2002 | 75.50 |
| Juana Díaz Camp | Jan-1931 | Dec-2006 | 42.21 |
| Juncos 1 SE | Jan-1931 | Dec-2006 | 66.87 |
| Lajas Substn | Jan-1900 | Dec-2006 | 45.14 |
| La Muda Caguas | Sep-1971 | Jun-1994 | 78.92 |
| Lares | Jun-1903 | Dec-1991 | 93.21 |
| Los Caños | Jan-1955 | Aug-1973 | 62.63 |
| Magüeyes Island | Jan-1959 | Nov-2006 | 28.68 |
| Manatí 2 E | Jan-1900 | Dec-2006 | 62.23 |
| Maricao 2 SSW | May-1969 | Dec-2006 | 95.33 |

| Rain Gage | Record Begin Date | Record End Date | Rainfall (in/yr) |
|---|---|---|---|
| Maricao Fish Hatchery | Jan-1955 | Dec-2006 | 98.6 |
| Matrullas Dam | Jan-1955 | Apr-1981 | 86.64 |
| Maunabo | May-1899 | Apr-2003 | 73.95 |
| Mayagüez City | Jan-1957 | Dec-2006 | 75.08 |
| Mayagüez AP | Jan-1900 | Dec-2006 | 76.16 |
| Melania Dam [A/] | Jan-1955 | Jan-1969 | 39.03 |
| Mona Island | Jan-1955 | Aug-1974 | 35.91 |
| Mona Island 2 | Feb-1980 | Dec-2006 | 39.09 |
| Monte Bello Manatí | Oct-1969 | Sep-2001 | 61.62 |
| Mora Camp | Jan-1955 | Dec-2006 | 58.9 |
| Morovis 1 N | Feb-1956 | Dec-2006 | 71.37 |
| Negro-Corozal | Jan-1976 | Dec-2006 | 70.75 |
| Paraíso | Jan-1956 | Dec-2006 | 98.21 |
| Patillas | Apr-1982 | Jun-2003 | 57.79 |
| Patillas Dam | Jan-1931 | Jan-1969 | 70.23 |
| Peñuelas Salto Garzas | Mar-1971 | Dec-2003 | 75.55 |
| Peñuelas 1 NE | Jan-1955 | Feb-1971 | 54.69 |
| Pico del Este | Oct-1969 | Jun-2005 | 174.38 |
| Ponce 4 E | Apr-1954 | Dec-2006 | 35.12 |
| Ponce City | Jul-1970 | Aug-1998 | 29.45 |
| Puerto Real | Jan-1955 | Aug-2001 | 48.04 |
| Quebradillas | Jan-1955 | Sep-2000 | 55.69 |
| Rincón | Jun-1968 | Nov-2006 | 55.41 |

| Rain Gage | Record Begin Date | Record End Date | Rainfall (in/yr) |
|---|---|---|---|
| Río Blanco Lower | Jan-1955 | Dec-2006 | 107.83 |
| Río Blanco Upper | Jan-1955 | Mar-1974 | 161.78 |
| Río Cañas | Jan-1955 | Dec-1969 | 36.66 |
| Río Grande el Verde | Feb-1956 | Dec-1987 | 96.36 |
| Río Jueyes [A/] | Jan-1955 | Jan-1969 | 31.13 |
| Río Piedras Exp Stn | Jan-1959 | Dec-2006 | 69.37 |
| Roosevelt Roads | Jul-1959 | Mar-2004 | 51.61 |
| Sabana Grande 2 ENE | May-1977 | Dec-2006 | 62.39 |
| Sabater [A/] | Jan-1955 | Jan-1969 | 37.78 |
| San Cristóbal | Jan-1956 | Mar-1972 | 76.33 |
| San Germán 4 W | Nov-1904 | Jul-1973 | 64.37 |
| San Juan City | Jan-1955 | May-1977 | 59.07 |
| San Juan Intl Ap | Jan-1956 | Dec-2006 | 54.36 |
| San Lorenzo 3S | Mar-1966 | Dec-2006 | 98.57 |
| San Lorenzo Espino [A/] | Jan-1945 | Jun-1959 | 118.96 |

| Rain Gage | Record Begin Date | Record End Date | Rainfall (in/yr) |
|---|---|---|---|
| San Lorenzo Farm 2 NW | Jan-1955 | Sep-1988 | 72.61 |
| San Sebastián 2 WNW | Apr-1955 | Oct-1997 | 91.25 |
| Santa Isabel 2 ENE | Jan-1955 | Dec-2006 | 34.50 |
| Santa Rita | Jan-1955 | Dec-2006 | 33.30 |
| Toa Baja 1 SSW | Jan-1955 | Aug-1994 | 68.01 |
| Toro Negro Forest | Aug-1982 | Dec-2006 | 93.85 |
| Toro Negro PLT 2 | Jan-1955 | Jul-1981 | 88.94 |
| Trujillo Alto 2 SSW | Feb-1957 | Dec-2006 | 71.96 |
| Utuado | Jan-1931 | Jul-1998 | 73.36 |
| Vieques Island | Jan-1955 | Sep-1976 | 42.68 |
| Villalba 1 SE | Jan-1955 | Dec-2006 | 64.19 |
| Yabucoa 1 NNE | Jan-1955 | Mar-1995 | 79.11 |
| Yauco 1 NW | Dec-1981 | Dec-2006 | 45.52 |

[A/] Station with 14 years of record included in the analysis.

## 2.3. Isoheytal Map

The NCDC rainfall gage station data were used to interpolate a surface within the Arc-GIS environment using *spline curves* to create the initial isoheytal countours. *Spline* algorithms can create very smooth surfaces from moderately detailed data and provide exact interpolation within smoothing limits. This method is best suitable for gently varying surfaces, such as rainfall.

The initial contour lines were then adjusted based on coastline proximity, elevation and vegetation mapping. The resulting contours were checked against USGS streamgage data, comparing rainfall and runoff per unit of watershed area to reveal any unusual discrepancies. The rainfall-runoff relationship resulting from the final isoheytal map is presented in Figure 4. The resulting rainfall surface and rainfall contour map are presented in Figure 5 and Figure 6 respectively.

The following physical parameters were used to realign rainfall contours in areas of sparse gage data:

- Contours adjacent to the ocean were adjusted to lie roughly parallel to the coastline, instead of locally curving around coastal rain gage stations;
- Contours along the Cordillera Central were adjusted to run generally parallel to the mountains peaks to better reflects orographic effects; and
- Contours were also checked against Holdridge Life Zone vegetation map, since this mapping system reflects long-term rainfall patterns (Ewel and Whitemore, 1973).

# 3. LOW FLOW ESTIMATION AT UNGAGED SITES

This section describes two methods to estimate low-flow at ungaged stream sites, regional regression analysis and station index method.

## 3.1. Regional Regression Analysis

### 3.1.1. Methodology

Multiple Linear Regression techniques were used to develop a series of equations to estimate average daily streamflow equaled or exceeded on 90%, 95%, 98%, and 99% of the time as well as mean streamflow, also referred as $Q_{90}$, $Q_{95}$, $Q_{98}$, $Q_{99}$, and $Q_m$ respectively. Equations used average daily streamflow as the dependent variable, and Watershesd Area and Mean Annual Rainfall as independent variable. These two independent parameters were selected because they have the highest predictive values and because these data are readily available.

The Multiple Linear Regression analysis relates two or more explanatory variables with a response variable by fitting a linear equation to the observed data (McCuen, 1993). The Multiple Linear Regression Model for the analysis is defined by:

$$Q = a + b{*}A + c{*}P \tag{3.1}$$

where,

Q = Streamflow (cfs)

A = Basin area ($mi^2$)

P = Mean annual rainfall (in/yr)

a, b, c = Regression coefficients

The matrix notation of the model has the following form:

$$\hat{Y} = X \cdot \beta + \epsilon \tag{3.2}$$

where:

$\hat{Y}$: Estimated discharge vector:

$$\hat{Y} = \begin{bmatrix} \hat{Q}_1 \\ \vdots \\ \hat{Q}_i \end{bmatrix} \tag{3.3}$$

$X$: Watershed parameters matrix:

$$X = \begin{bmatrix} 1 & A_1 & P_1 \\ 1 & \vdots & \vdots \\ 1 & A_i & P_i \end{bmatrix} \tag{3.4}$$

$\beta$: Regression coefficient vector:

$$\beta = \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{3.5}$$

$\epsilon$: Residual (error term):

$$\epsilon = Y_i - \hat{Y}_i \tag{3.6}$$

where,

Y = True streamflow vector

$\hat{Y}$ = Estimated streamflow vector

Logarithmic transformation was performed to linearize the hydrologic data. The resulting transformed equation was used for the analysis:

$$\log Q = a + b*\log A + c*\log R \tag{3.7}$$

Appling antilogarithm to both sides of the equations, the previous equation can be rewritten as:

$$Q = 10^{a} * A^{b} * P^{c} \tag{3.8}$$

Eq. (3.8) is the form used for the regional regression equations.

### 3.1.2. Streamflow Data

Daily streamflow data were obtained from the 22 USGS gage stations in Puerto Rico with more than ten years of daily data and where low flows were little affected by reservoir operation, water supply intakes and diversions, or infiltration into coastal alluvial or karst aquifers. The drainage area for these stations ranges from 1 to 100 square miles. Figure 7 shows the location of these stations and the watershed area tributary to each.

Minimum streamflow values were determined at each station for exceedance probabilities of 99, 98, 95 and 90% using a daily flow duration analysis (Table 4).

Table 4: USGS Streamflow Data Used in Regression Analysis.

| Station Number | Station Name | Drainage Area ($mi^2$) | Rainfall (in/yr) | $Q_m$ (cfs) | $Q_{99}$ (cfs) | $Q_{98}$ (cfs) | $Q_{95}$ (cfs) | $Q_{90}$ (cfs) |
|---|---|---|---|---|---|---|---|---|
| 50025155 | Río Saliente | 9.31 | 78.10 | 30.75 | 3.30 | 3.66 | 4.50 | 5.89 |
| 50034000 | Río Bauta | 16.75 | 80.12 | 39.33 | 3.40 | 3.80 | 4.70 | 6.10 |
| 50048770 | Río Piedras | 7.53 | 75.27 | 21.37 | 1.40 | 1.60 | 2.50 | 3.90 |
| 50049100 | Río Piedras | 15.47 | 73.40 | 54.68 | 4.61 | 6.60 | 8.80 | 11.00 |
| 50050900 | Río Grande de Loíza | 6.00 | 116.29 | 32.43 | 4.60 | 5.10 | 5.90 | 6.90 |
| 50053025 | Río Turabo | 7.16 | 100.61 | 22.26 | 4.00 | 4.40 | 5.30 | 6.20 |
| 50055225 | Río Cagüitas | 16.91 | 56.96 | 34.10 | 2.70 | 3.90 | 6.10 | 7.70 |
| 50058350 | Río Cañas | 7.57 | 69.72 | 14.96 | 1.60 | 1.82 | 2.60 | 3.20 |
| 50065500 | Río Mameyes | 6.80 | 143.46 | 55.72 | 10.96 | 11.00 | 14.00 | 16.00 |
| 50065700 | Río Mameyes | 11.87 | 107.09 | 73.4 | 8.70 | 10.00 | 13.00 | 17.00 |
| 50075000 | Río Icacos | 1.25 | 156.48 | 14.17 | 2.50 | 3.30 | 4.00 | 4.70 |
| 50081000 | Rio Humacao | 6.60 | 88.88 | 21.00 | 0.77 | 0.82 | 2.60 | 5.80 |
| 50092000 | Río Grande de Patillas | 18.38 | 89.23 | 59.31 | 7.50 | 8.80 | 11.00 | 13.00 |
| 50100200 | Río Lapa | 9.98 | 55.43 | 9.04 | 0.00 | 0.02 | 0.07 | 0.15 |
| 50100450 | Río Majada | 16.45 | 65.33 | 8.80 | 0.00 | 0.01 | 0.09 | 0.33 |
| 50108000 | Río Descalabrado | 12.87 | 43.53 | 19.95 | 0.04 | 0.08 | 0.15 | 0.34 |
| 50110900 | Río Toa Vaca | 14.25 | 63.63 | 16.75 | 0.86 | 1.00 | 1.30 | 1.80 |
| 50113800 | Río Cerrillos | 11.87 | 80.02 | 29.59 | 3.60 | 4.00 | 4.80 | 6.20 |
| 50136000 | Río Rosario | 17.64 | 93.22 | 52.81 | 5.50 | 6.90 | 9.00 | 11.00 |
| 50141000 | Río Blanco | 15.19 | 75.62 | 37.13 | 7.00 | 7.50 | 8.70 | 10.00 |
| 50144000 | Río Grande de Añasco | 92.30 | 87.55 | 425.53 | 47.00 | 54.00 | 64.00 | 75.00 |
| 50147800 | Río Culebrinas | 71.60 | 89.36 | 294.10 | 26.00 | 29.00 | 35.00 | 42.00 |

### 3.1.3. Regression Analysis

Three multiple linear regression models were analyzed for this study:

**1) <u>Ordinary Least Squares (OLS):</u>**

Hydrologists have commonly used OLS method to estimate the regression coefficient vector of the linear model for regression analyses. This method obtains parameter estimates that minimize the sum of squared residuals. The OLS regression coefficient vector ($\beta_{\mathrm{OLS}}$ ) can be solved using matrix analysis by solving Eq. (3.9:

$$\beta_{\mathrm{OLS}} = (X^T \cdot X)^{-1} \cdot X^T \cdot Y \tag{3.9}$$

where:

Y= Observed discharge vector

$X$= Matrix of the watershed parameters

The OLS method is the faster regression method for this type of analysis and is analyzed very quickly once the data in Table 4 is setup in a spreadsheet. However, it introduces a significant error because the regression is calculated on logged parameter values, which represent a non-linear transformation of the original dataset.

**2) <u>Manual Numerical Search for Least Square Error (MNS):</u>**

The MNS method consists of a numerical search of the least square error (MNS) using an iterative spreadsheet solver. This method used as initial values the results from the OLS, and by an iterative process the regression coefficients are varied until the minimum square error is found, as compared to original data (without the log transformation). This method required approximately twice the time required by the OLS analysis.

**3) <u>Generalized Least Squares (GLS):</u>**

Recent studies of minimum streamflow analysis have employed the Generalized Least Squares (GLS) regression technique. This method takes into account varying sampling error and cross correlation among concurrent flows. It was developed by Stedinger and Tasker (1985) and has become a standard for regression analysis of flood frequency data. Stedinger and Tasker (1985) and Stedinger and Tasker (1986) showed that the GLS procedures provide more accurate parameter estimators, relatively unbiased estimate of the model error variance and a better estimation of parameter sampling variance than those estimated with OLS. Moss and Tasker (1991) showed that GLS procedures describe model accuracy in regional regression analysis better than OLS.

A discussion and implementation of the GLS is presented in Stedinger and Tasker (1989) and Griffis and Stedinger (2007). The GLS estimate of $\beta_{\mathrm{GLS}}$ is given by Stedinger and Tasker (1985) as:

$$\beta_{GLS} = \left(X^T \Lambda^{-1} X\right)^{-1} X^T \Lambda^{-1} Y \tag{3.10}$$

where Λ is the covariance of the model. In the GLS model Λ is estimated by

$$\Lambda = \sigma_\delta^2 I_N + \hat{\Sigma} \tag{3.11}$$

where $\sigma_\delta^2$ is an estimate of the model error variance and $\hat{\Sigma}$ is an (i × i) matrix of sampling covariance with elements:

<u>Diagonal elements (i = j):</u>

$$\Sigma_{ij} = \mathrm{Var}[Y_i] \tag{3.12}$$

Chowdury and Stedinger (1991) provide the following first order approximation of the sampling error (Var[$Y_i$]),

$$\begin{aligned}\mathrm{Var}[Y_i] = \Bigg[1 + k_i\gamma_i + k_i^2\left(\frac{1}{2} + \frac{3}{8}\gamma_i^2\right) + k_i\gamma_i W_i \frac{\partial k_i}{\partial \gamma_i}\left(3\gamma_i + \frac{3}{4}\gamma_i^3\right) \\ + W_i^2\left(\frac{\partial k_i}{\partial \gamma_i}\right)^2\left(6 + 9\gamma_i^2 + \frac{15}{8}\gamma_i^4\right)\Bigg]\frac{\hat{\sigma}_i^2}{n_i} + (1 - W_i)^2\,\hat{\sigma}_i^2\,\mathrm{MSE}_{\gamma_i}\left(\frac{\partial k_i}{\partial \gamma_i}\right)^2\end{aligned} \tag{3.13}$$

<u>Off-diagonal elements (i≠j):</u>

$$\begin{aligned}\Sigma_{ij} = \hat{\rho}_{ij}\,\frac{m_{ij}\,\hat{\sigma}_i\,\hat{\sigma}_j}{n_i n_j}\Bigg[1 + \frac{k_i\gamma_i}{2} + \frac{k_j\gamma_j}{2} + \frac{k_i k_j}{2}\left(\hat{\rho}_{ij} + 0.75\gamma_i\gamma_j\right) \\ + k_j\gamma_i W_i \frac{\partial k_i}{\partial \gamma_i}\left(3\,\hat{\rho}_{ij} + 0.75\gamma_i\gamma_j\right) + k_i\gamma_j W_j \frac{\partial k_j}{\partial \gamma_j}\left(3\,\hat{\rho}_{ij} + 0.75\gamma_i\gamma_j\right) \\ + W_i W_j \hat{\sigma}_i\,\hat{\sigma}_j \frac{\partial k_i}{\partial \gamma_i}\frac{\partial k_j}{\partial \gamma_j}\mathrm{Cov}[\gamma_i, \gamma_j]\Bigg]\end{aligned} \tag{3.14}$$

where:

$\hat{\sigma}_i$ = estimate of the standard deviation of flows at site i

$K_i$ = T-year frequency factor for the distribution used

$n_i$ = record length at site i

$\gamma_i$ = station skew at site i

$m_{ij}$ = concurrent record length of sites i and j

$\hat{\rho}_{ij}$ = estimate of the lag zero correlation of flows between sites i and j

$\mathrm{Cov}[\gamma_i, \gamma_j]$ = covariance matrix estimator,

$$\text{Cov}[\gamma_i, \gamma_j] = \hat{\rho}_{\gamma_j\gamma_i}\sqrt{(\text{Var}[\gamma_i]\ \text{Var}[\gamma_i])} \tag{3.15}$$

Methodologies for estimating station skew are presented in IACWD (1982). The cross correlation $\left(\hat{\rho}_{\gamma_j\gamma_i}\right)$ is estimated using the approximation developed by Martins and Stedinger (2002),

$$\hat{\rho}_{\gamma_j\gamma_i} = \text{Sign}(\hat{\rho}_{ij})\left(m_{ij} \,/\sqrt{(m_{ij} + n_i)(m_{ij} + n_j)}\right)^{\delta} \tag{3.16}$$

and Griffis (2003) provides and approximation for ($\text{Var}[\gamma_i]$ and $\text{Var}[\gamma_i]$),

$$\text{Var}[\gamma_i] = \left[\frac{6}{n_i} + a(n_i)\right]\left[1 + \left(\frac{9}{6} + b(n_i)\right)\gamma_i^2 + \left(\frac{15}{48} + c(n_i)\right)\gamma_i^4\right] \tag{3.17}$$

The model error variance $\sigma_\delta^2$ and the vector of regression coefficients $\beta_{GLS}$ are estimated jointly by iteratively searching for a nonnegative solution to the equation (Stedinger and Tasker, 1985),

$$\left(\hat{Y} - X * \beta\right)^T\left(\sigma_\delta^2 * I_n + \hat{\Sigma}\right)^{-1}\left(\hat{Y} - X * \beta\right) = N - (k + 1) \tag{3.18}$$

where $\sigma_\delta^2$ is the estimator of the unknown model error variance and $\beta_{GLS}$ is given by Eq.(3.10). This method takes approximately eighty times the effort required to the OLS analysis because of the need to research and calculate many intermediate parameter values.

### 3.1.4. Regression Analysis Results

The mean square error was used as an indicator of the goodness of fit of the regression model. The mean square error is defined as average squared difference between the observed and estimated values as defined by:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\epsilon_i^2 = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2 \tag{3.19}$$

Table 5 shows the mean square error produced by the different models. These results are presented graphically in Figure 7.

Table 5: Mean Square Error Comparison.

| Equation | OLS | MNS | GLS |
|---|---|---|---|
| $Q_{99}$ | 118.31 | 8.44 | 4.31 |
| $Q_{98}$ | 55.35 | 10.05 | 5.07 |
| $Q_{95}$ | 44.96 | 11.60 | 6.72 |
| $Q_{90}$ | 37.32 | 16.49 | 10.09 |
| $Q_{mean}$ | 423.52 | 144.14 | 122.06 |

Results of Table 5 show that the best fit to the observed data is provided by the GLS method, and the worst fit is provided by the OLS method. Results of MNS method are close to the GLS results. Based on these results, the GLS model was selected as the model which provides the best approximation to the observed data. Table 6 presents the regression parameters obtained from the GLS analysis.

Table 6: Regression Equation Parameters for Estimating Runoff.

| Parameter | Regression Coefficients | | | | |
|---|---|---|---|---|---|
| | $Q_{mean}$ | $Q_{90}$ | $Q_{95}$ | $Q_{98}$ | $Q_{99}$ |
| $10^a$ | 9.869E-04 | 3.127E-06 | 8.985E-07 | 2.237E-07 | 1.237E-07 |
| b | 1.075 | 0.986 | 1.016 | 1.057 | 1.059 |
| c | 1.787 | 2.756 | 2.966 | 3.200 | 3.307 |

The following are the equations obtained from this analysis:

$$Q_m = 9.869 * 10^{-04} * A^{1.075} * P^{1.787} \tag{3.20}$$

$$Q_{90} = 3.127 * 10^{-06} * A^{0.986} * P^{2.756} \tag{3.21}$$

$$Q_{95} = 8.958 * 10^{-07} * A^{1.016} * P^{2.966} \tag{3.22}$$

$$Q_{98} = 2.237 * 10^{-07} * A^{1.057} * P^{3.200} \tag{3.23}$$

$$Q_{99} = 1.237 * 10^{-07} * A^{1.059} * P^{3.307} \tag{3.24}$$

Figure 9 to Figure 13 compare actual streamflows to the values estimated by the regression equations. The equations produce a good fit to the observed data when the estimated flow exceeds 2 cfs (Figure 14). When the estimated values were less than 2 cfs the equations are not reliable, as can be seen in Figure 14. Figure 15 shows how the percent error between the observed and estimated values increases as the estimated flow decreases. Stations with estimated low flow less than 2 cfs and large error correspond to small south coast watershed.

### 3.2. Station Index Method

The station index method determines streamflow at an ungaged site using as reference a streamflow data from a nearby gage station. The most common procedure is the Drainage-Area ratio method. This method computes the streamflow at the ungaged location based on the ratio of drainage areas between the gaged and ungaged location. This method is suitable when the mean annual rainfall is similar for both watersheds. This method is defined by the following equation:

$$Q_u = \frac{A_u}{A_g} Q_g \tag{3.25}$$

where:

$Q_u$ = minimum streamflow at the ungaged site

$Q_g$ = minimum streamflow at the gaged site

$A_u$ = drainage area at the ungaged site

$A_g$ = drainage area at the gaged site

However in Puerto Rico rainfall variations are frequently large over short distances due to orographic effects. Because of this a more appropriate method to use in Puerto Rico is to translate the data from the gaged site to the ungaged site by the ratio of mean flows computed by the regression equation (Eq. 3.20). The following equation defines this method:

$$Q_u = \frac{Q_{mean\_u}}{Q_{mean\_g}} Q_g = \frac{A_u^{1.075} * P_u^{1.787}}{A_g^{1.075} * P_g^{1.787}} \tag{3.26}$$

where:

$Q_u$ = minimum streamflow at the ungaged site

$Q_g$ = minimum streamflow at the gaged site

$Q_{mean\_u}$ = mean streamflow computed at ungaged site (Eq. 3.20)

$Q_{mean\_g}$ = mean streamflow computed at gaged site (Eq. 3.20)

$P_u$ = mean annual rainfall (in/yr) at ungaged site

$P_g$ = mean annual rainfall (in/yr) at gaged site

# 4. CONCLUSIONS AND RECOMMENDATIONS

This report presents a new mean annual rainfall map for Puerto Rico (Figure 5 and Figure 6).

- Regional regression equations (Eq. 3.20 to 3.24) for mean discharge and for minimum streamflow ($Q_m$, $Q_{90}$, $Q_{95}$, $Q_{98}$, and $Q_{99}$) are presented in section 3.1.4 of this report.
- The regression equations are not reliable for estimated discharges less than 2.0 cfs (Figure 14 and Figure 15). The regional regression equations are not suitable for watersheds with less than 1 square mile of drainage area. In these small watersheds factors such as vegetative cover, soils and local groundwater interactions and the possibility of unknown private withdrawals, have a much larger role in determining low flow.

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FIGURES

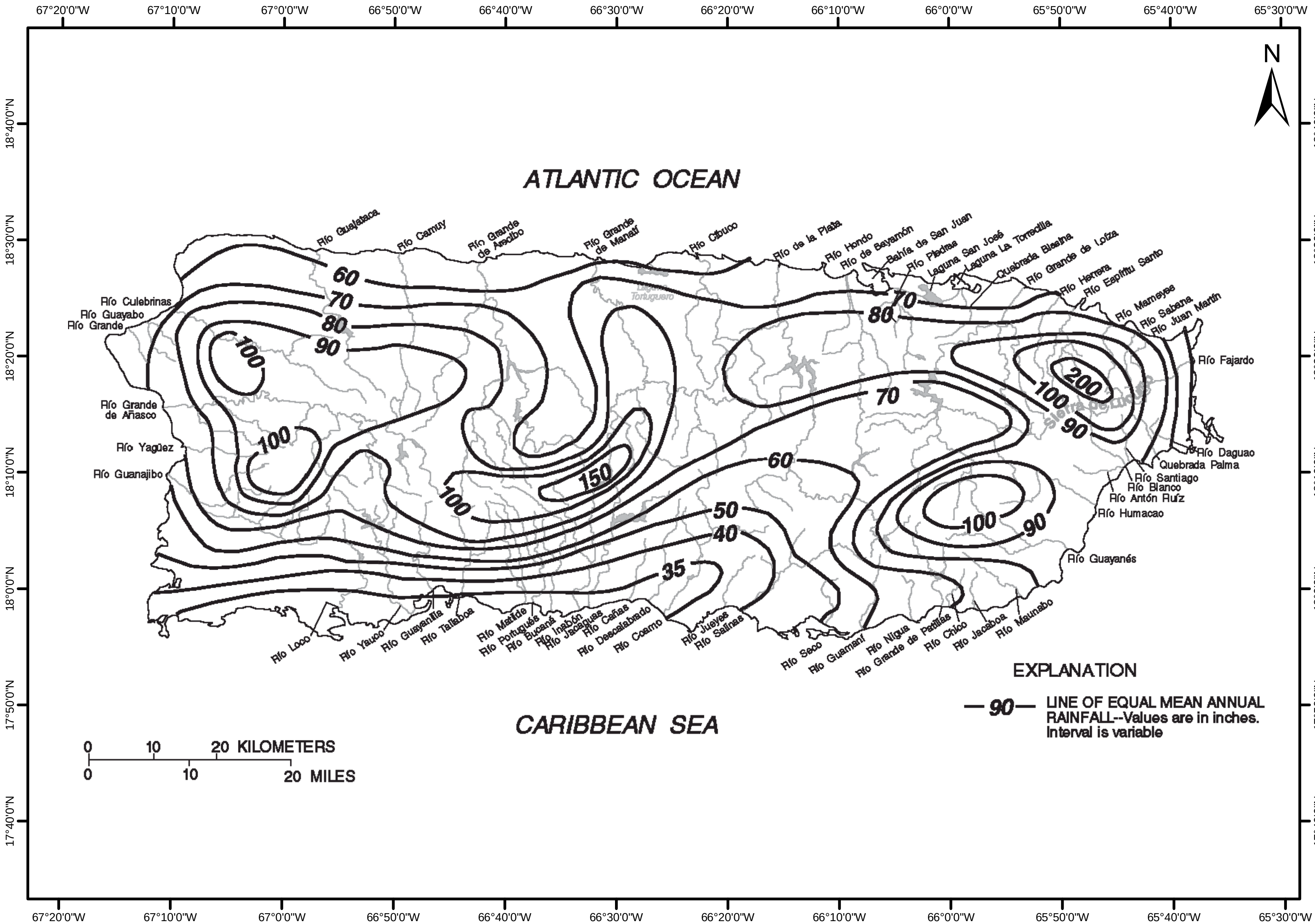



Figure 1: Mean annual rainfall, prepared using rainfall data from 1931 to 1960 (Calversbert, 1970).

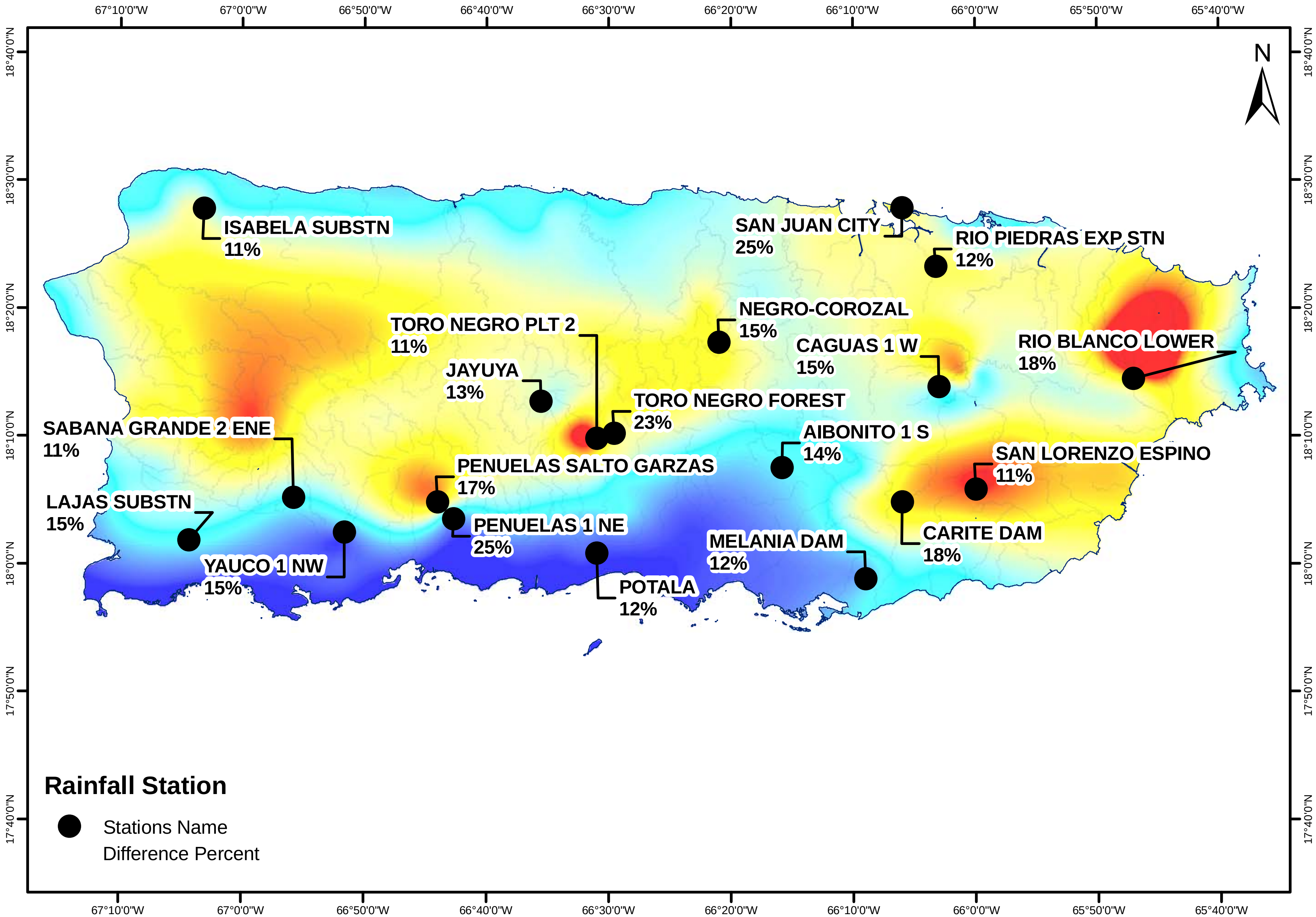
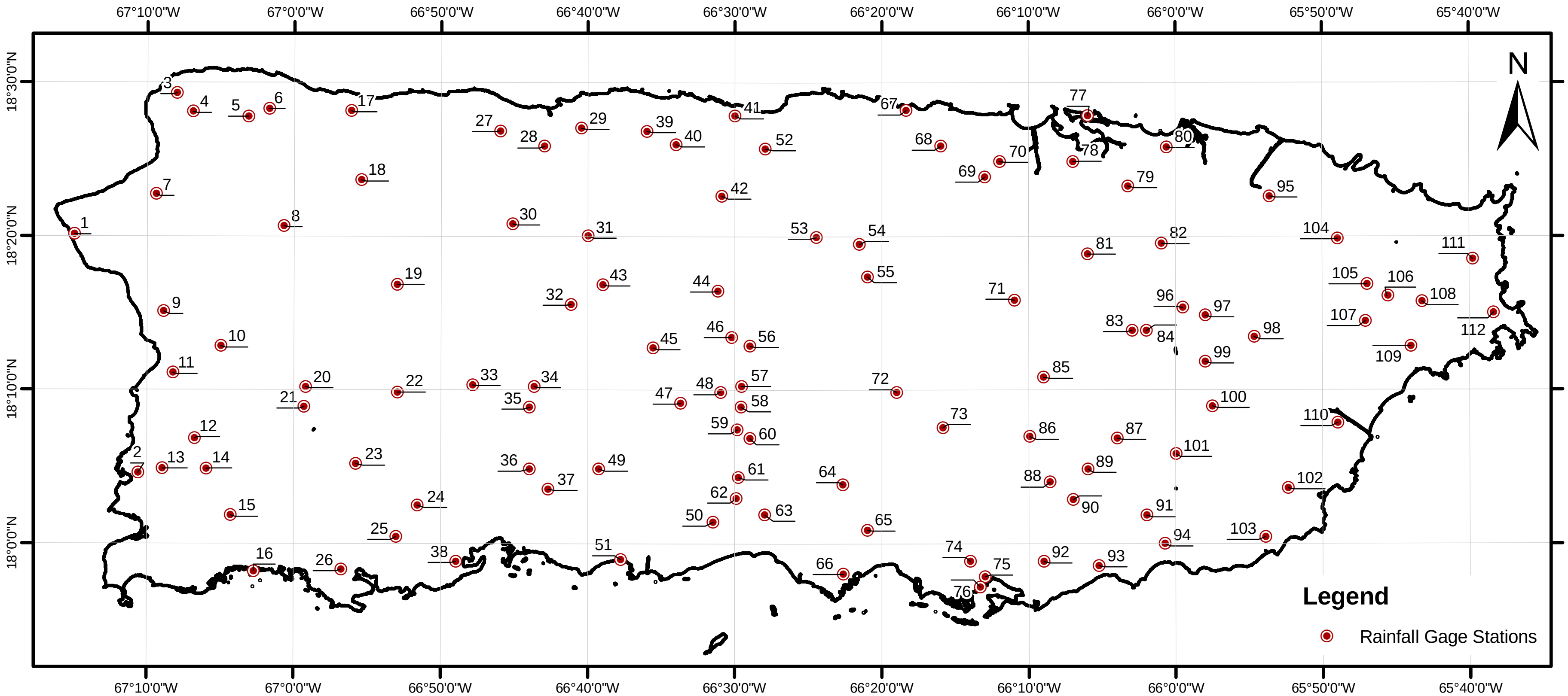



Figure 2: Rain gages with more than 10% difference in mean annual rainfall between station data and DNER (2003) rainfall map.




| Station Name | ID | Station Name | ID | Station Name | ID | Station Name | ID | Station Name | ID | Station Name | ID | Station Name | ID |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rincón | 1 | Guajataca Dam | 18 | Garzas | 35 | Manatí 2 E | 52 | Candelaria Toa Baja | 69 | Cayey 1 E | 86 | Maunabo | 103 |
| Puerto Real | 2 | Lares | 19 | Peñuelas 1 NE | 36 | Morovis 1 N | 53 | Candelaria Toa Baja | 70 | Guavate Camp | 87 | Río Grande el Verde | 104 |
| Borinquen AP | 3 | Maricao Fish Hatchery | 20 | Peñuelas Salto Garzas | 37 | Corozal Substn | 54 | Comerío Falls Plt 2 | 71 | Jajome Alto | 88 | Río Blanco Upper | 105 |
| Calero Camp | 4 | Maricao 2 SSW | 21 | Central San Francisco | 38 | Negro-Corozal | 55 | Barranquitas | 72 | Carite Dam | 89 | Pico del Este | 106 |
| Isabela Substn | 5 | Indiera Alta | 22 | Cambalache Exp Forest | 39 | Matrullas Dam | 56 | Aibonito 1 S | 73 | Carite Plt 1 | 90 | Río Blanco Lower | 107 |
| Mora Camp | 6 | Sabana Grande 2 ENE | 23 | Barceloneta 3 SW | 40 | Toro Negro Forest | 57 | Sabater | 74 | Patillas Dam | 91 | Paraíso | 108 |
| Coloso | 7 | Yauco 1 NW | 24 | Barceloneta 2 | 41 | Aceituna | 58 | Aguirre | 75 | Melania Dam | 92 | San Cristóbal | 109 |
| San Sebastián 2 WNW | 8 | Santa Rita | 25 | Monte Bello Manatí | 42 | Villalba 1 SE | 59 | Aguirre | 76 | Guayama 2E | 93 | Humacao 2 SSE | 110 |
| Mayagüez City | 9 | Ensenada 1 W | 26 | Caonillas Utuado | 43 | Caonillas Villalba | 60 | San Juan City | 77 | Patillas | 94 | Fajardo | 111 |
| Hacienda Constanza | 10 | Hato Arriba Arecibo | 27 | Cerro Gordo Ciales | 44 | Guayabal | 61 | Cataño | 78 | Canóvanas | 95 | Roosevelt Roads | 112 |
| Mayagüez AP | 11 | Los Caños | 28 | Jayuya | 45 | Juana Díaz Camp | 62 | Río Piedras Exp Stn | 79 | Gurabo Substn | 96 | Vieques Island | 113 |
| Benavente-Hormigueros | 12 | Arecibo 3 Ese | 29 | Cacaos-Orocovis | 46 | Río Cañas | 63 | San Juan Intl Ap | 80 | Gurabo | 97 | Culebra Island | 114 |
| Cabo Rojo | 13 | Arecibo Obsy | 30 | Cerro Maravilla | 47 | Coamo 2 SW | 64 | La Muda Caguas | 81 | Juncos 1 SE | 98 | | |
| San Germán 4 W | 14 | Dos Bocas | 31 | Toro Negro PLT 2 | 48 | Río Jueyes | 65 | Trujillo Alto 2 SSW | 82 | San Lorenzo Farm 2 NW | 99 | | |
| Lajas Substn | 15 | Utuado | 32 | Corral Viejo | 49 | Santa Isabel 2 ENE | 66 | Caguas 1 W | 83 | San Lorenzo 3S | 100 | | |
| Magüeyes Island | 16 | Adjuntas Substn | 33 | Ponce 4 E | 50 | Dorado 2 Wnw | 67 | Caguas | 84 | San Lorenzo Espino | 101 | | |
| Quebradillas | 17 | Adjuntas 1 NW | 34 | Ponce City | 51 | Toa Baja 1 SSW | 68 | Cidra 1 E | 85 | Yabucoa 1 NNE | 102 | | |

Figure 3: National Climatic Data Center rainfall gage stations used to generate mean annual rainfall map.

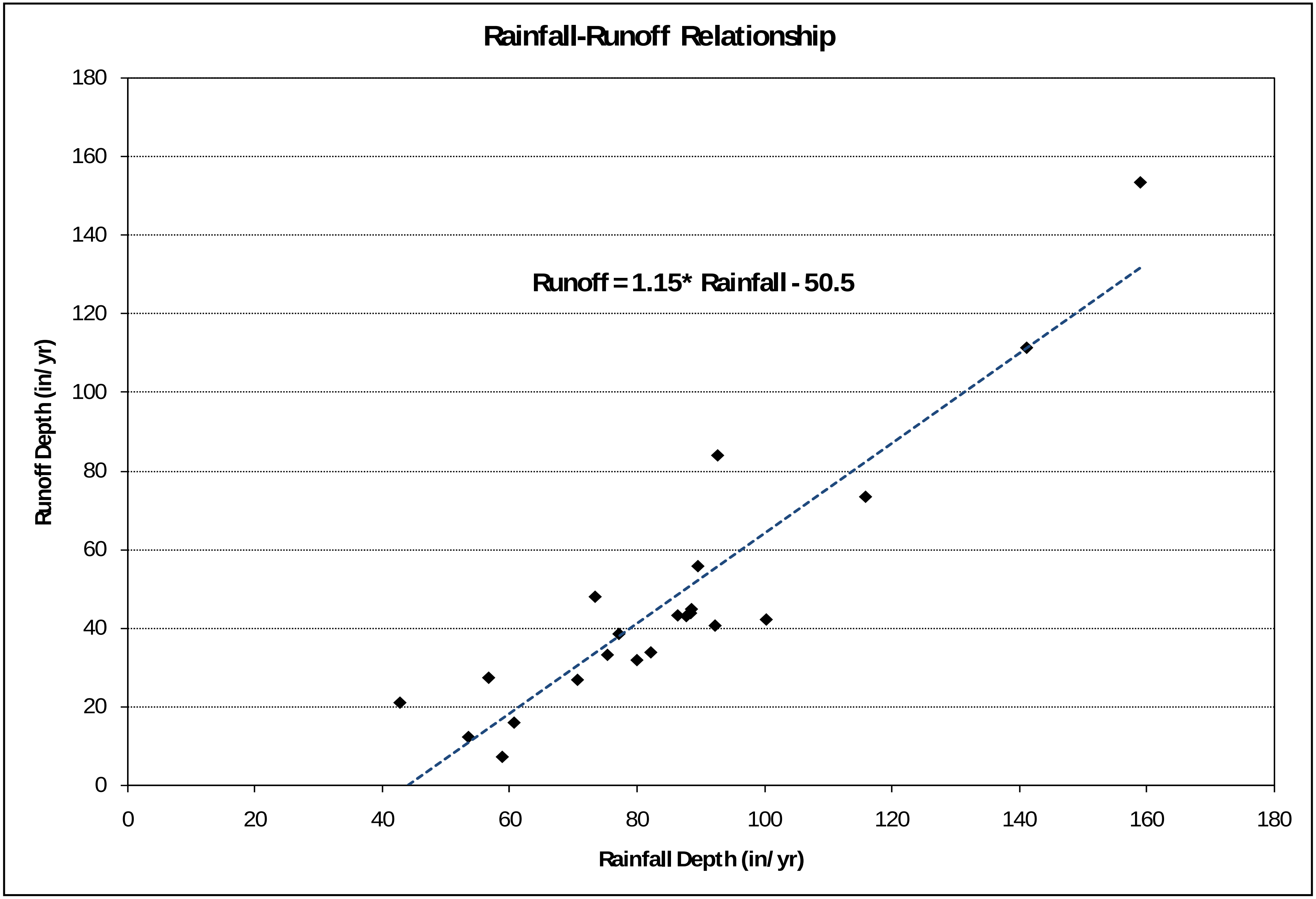
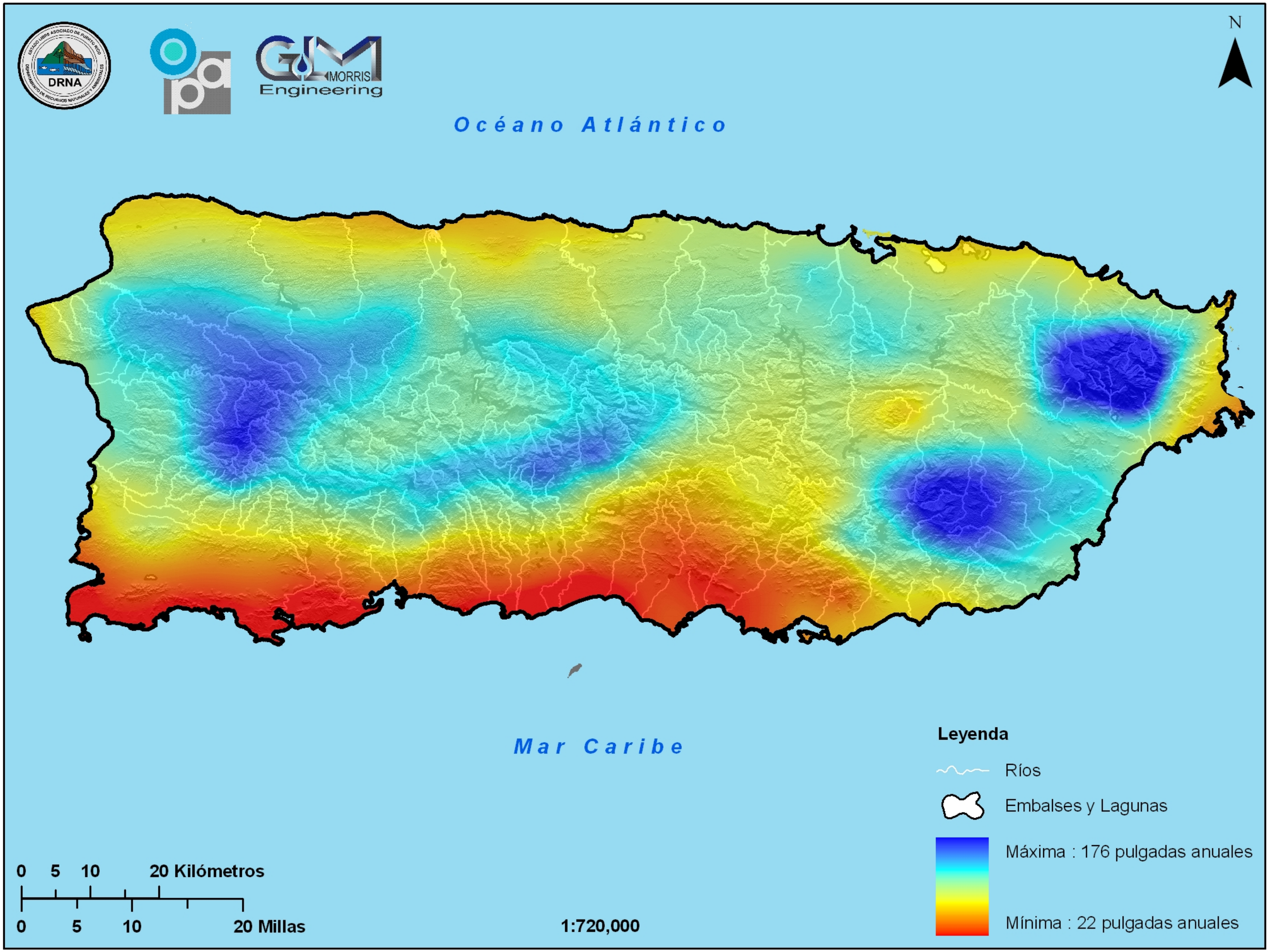



Figure 4: Rainfall-runoff relationship resulting from the final mean annual rainfall map.




Preparado por GLMorris Engineering para DRNA, 2009

Figure 5: Mean annual rainfall surface map for Puerto Rico.

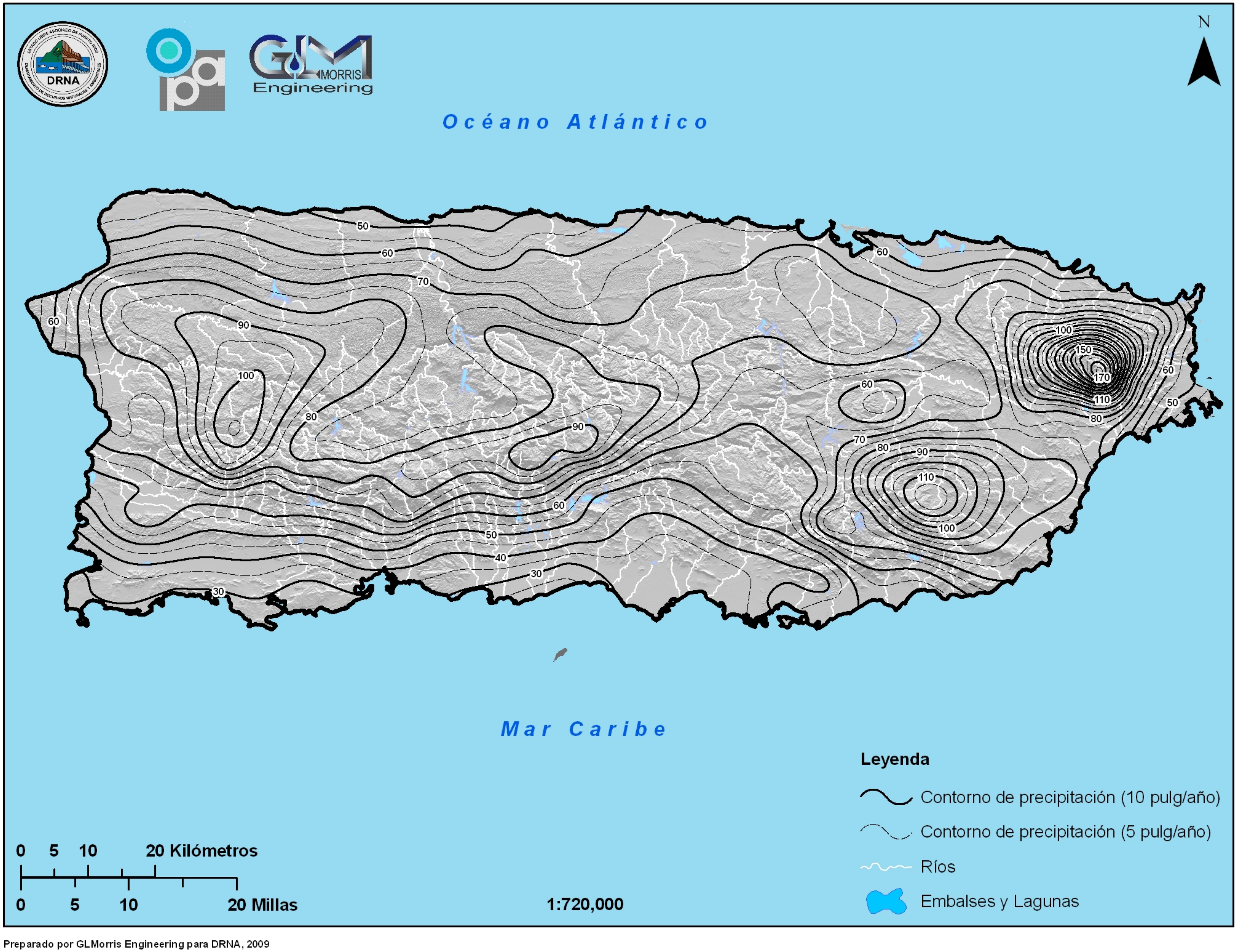



Figure 6: Mean annual rainfall contours map for Puerto Rico.

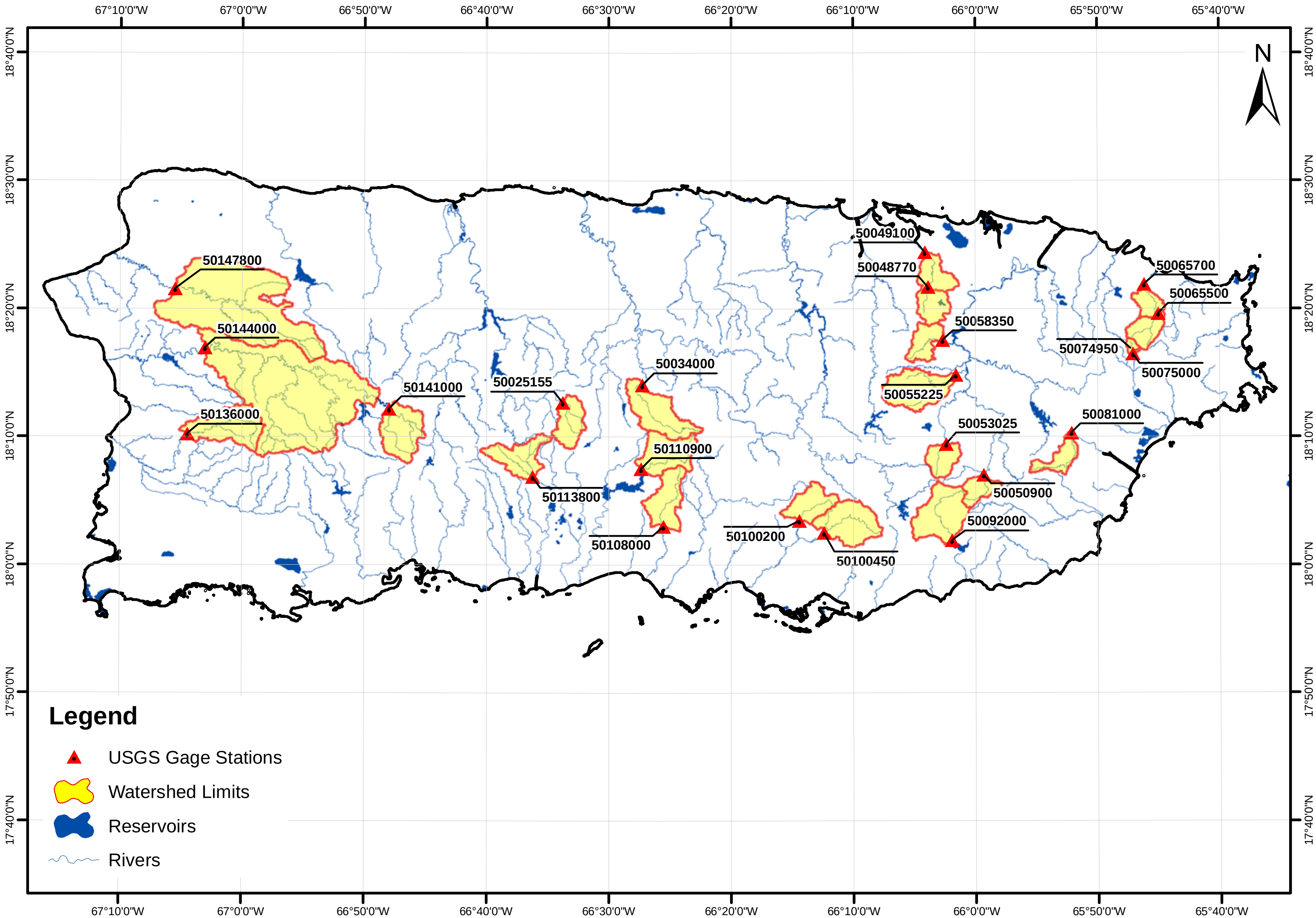



Figure 7: USGS streamflow gage stations location used in regression analysis.

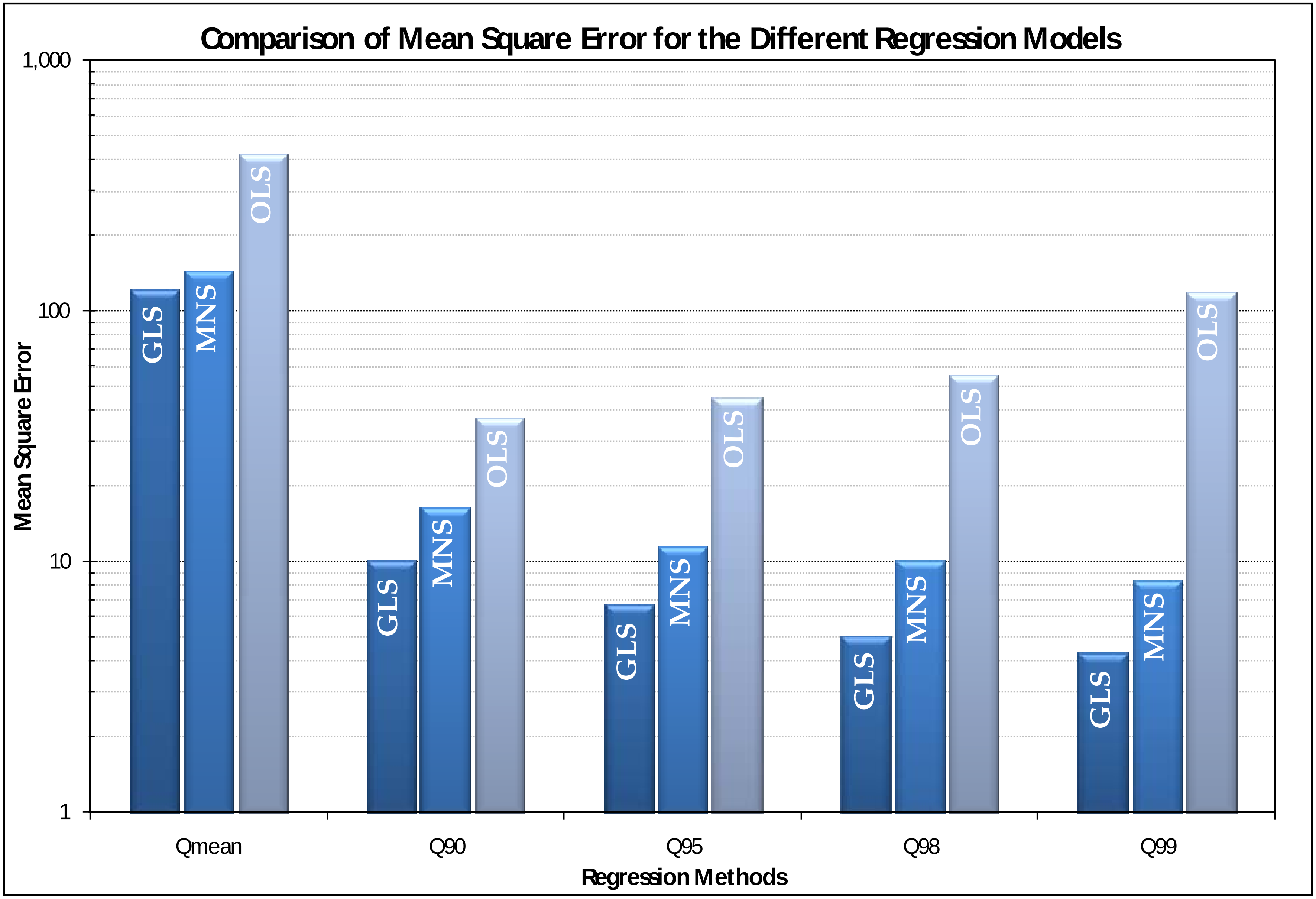



Figure 8: Comparison of Mean Square Error for the different regression models.

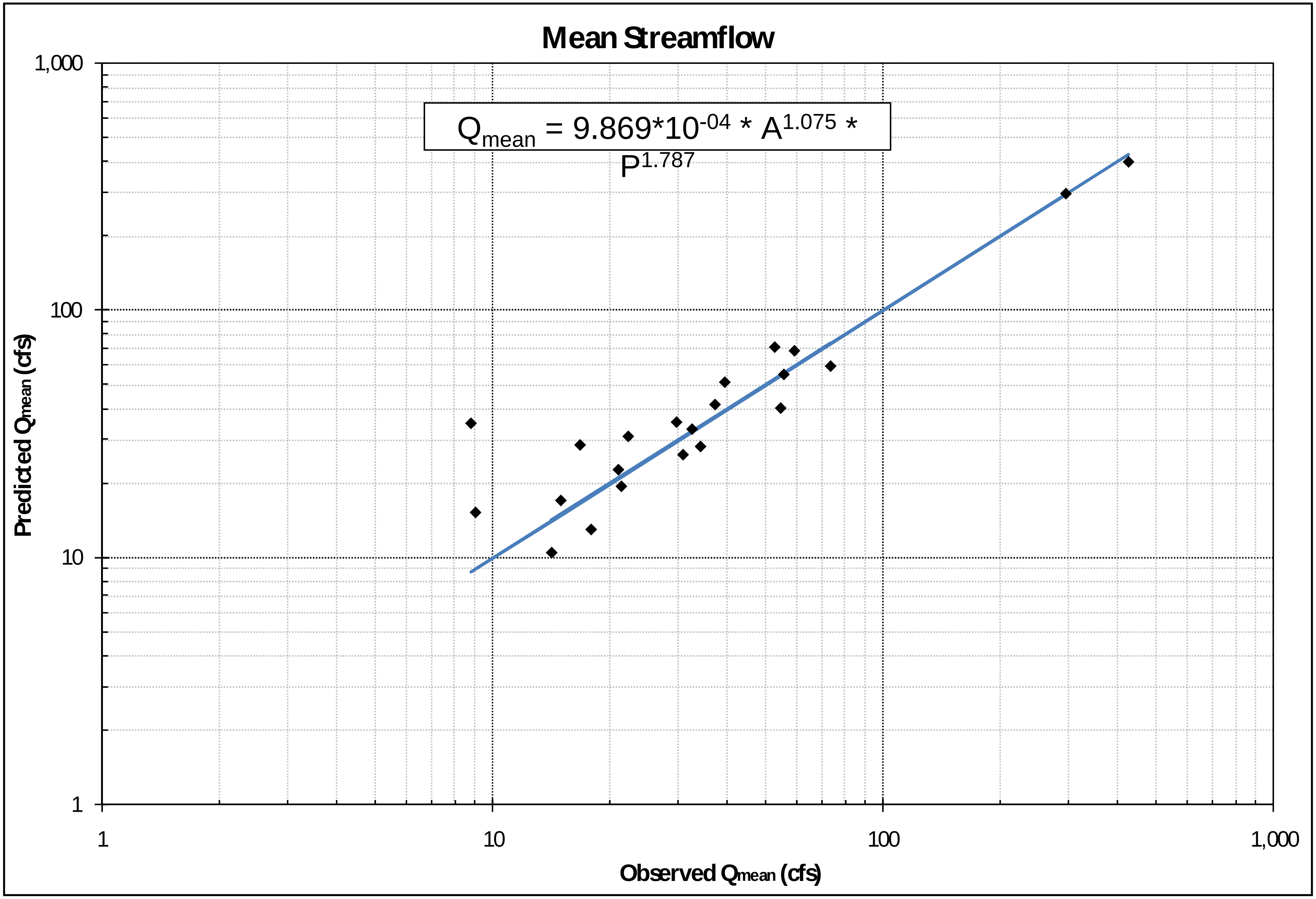



Figure 9: Relation between observed and predicted $Q_{mean}$ flow.

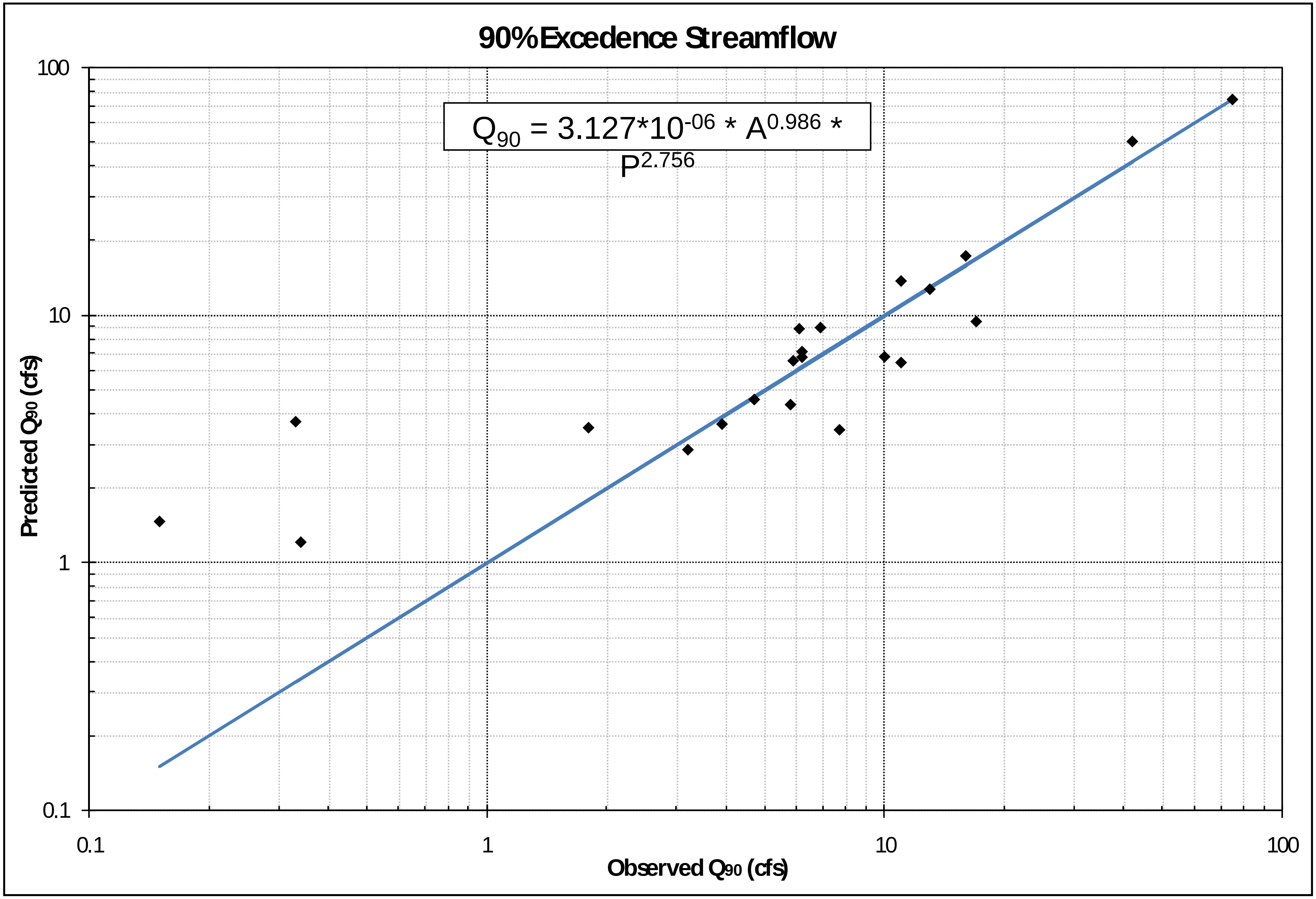



Figure 10: Relation between observed and predicted $Q_{90}$ flow.

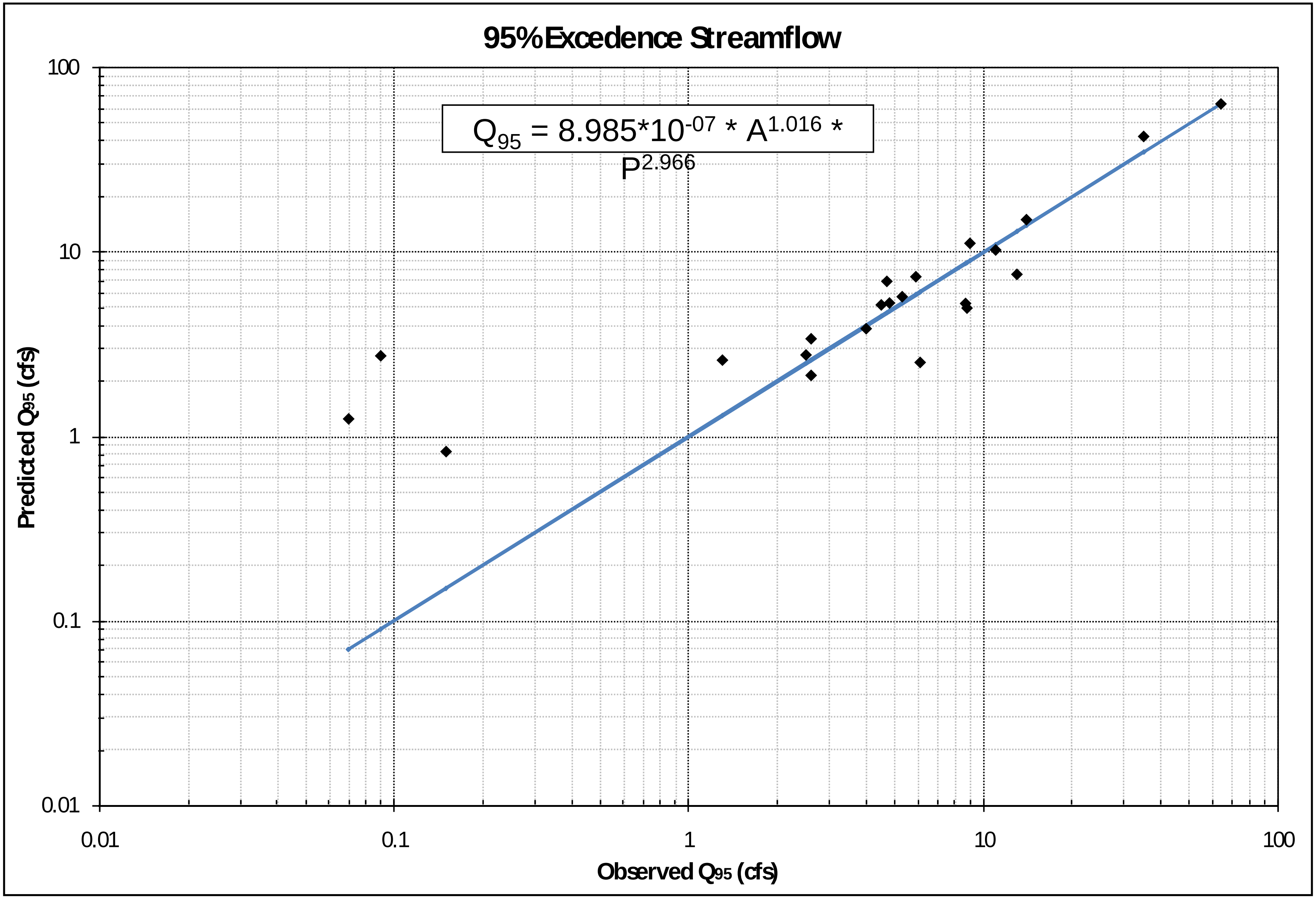



Figure 11: Relation between observed and predicted $Q_{95}$ flow.

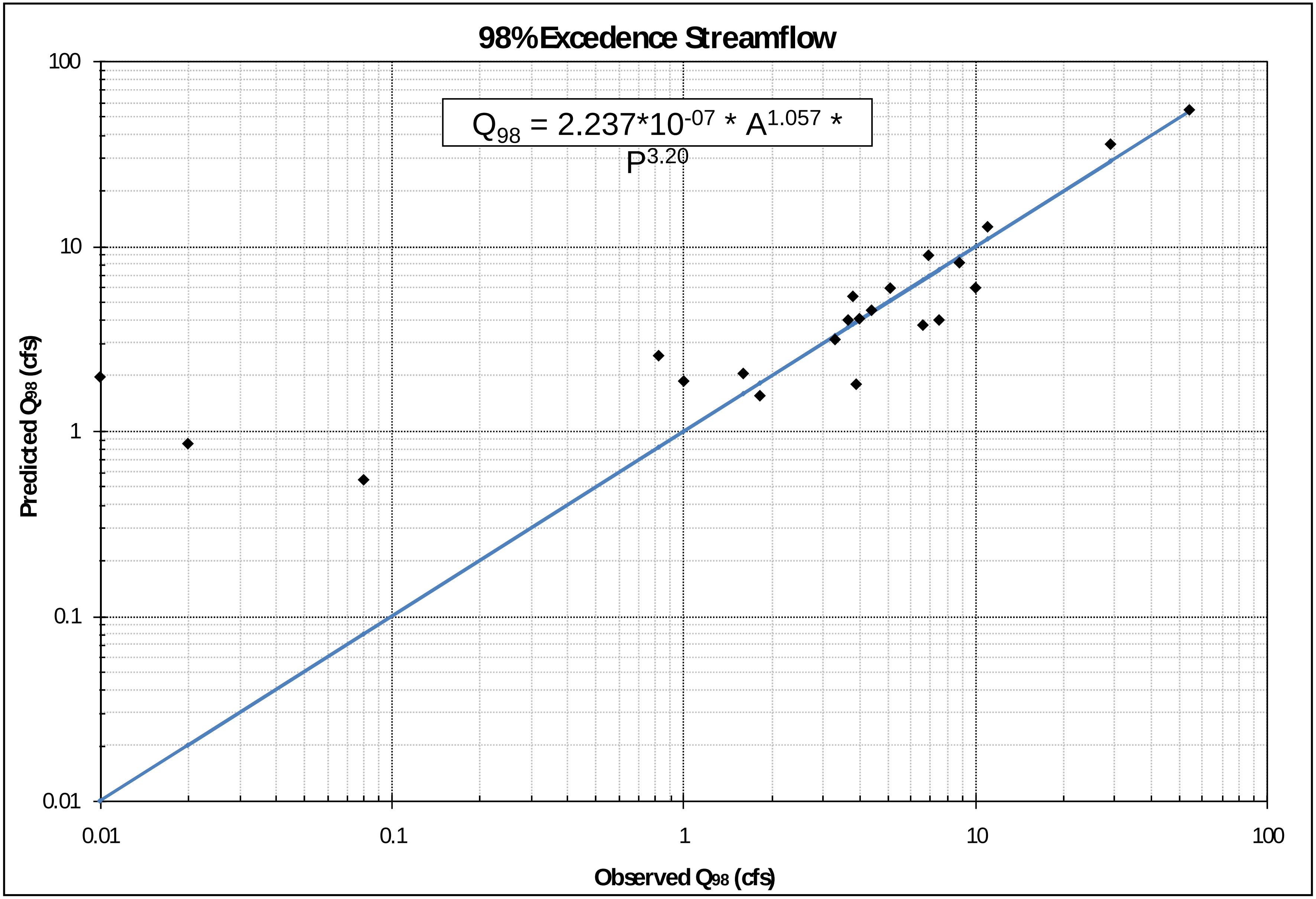



Figure 12: Relation between observed and predicted $Q_{98}$ flow.

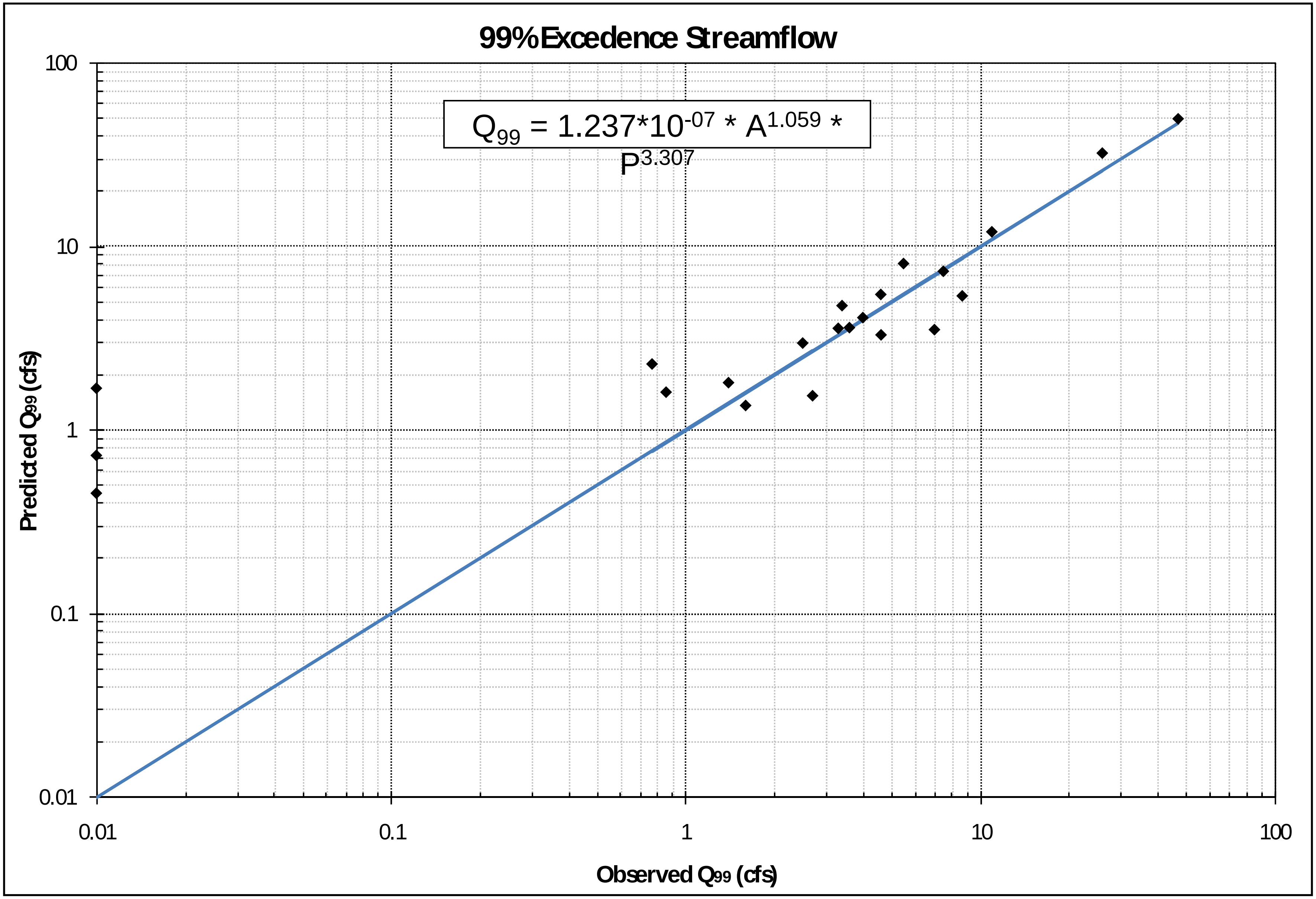



Figure 13: Relation between observed and predicted $Q_{99}$ flow.

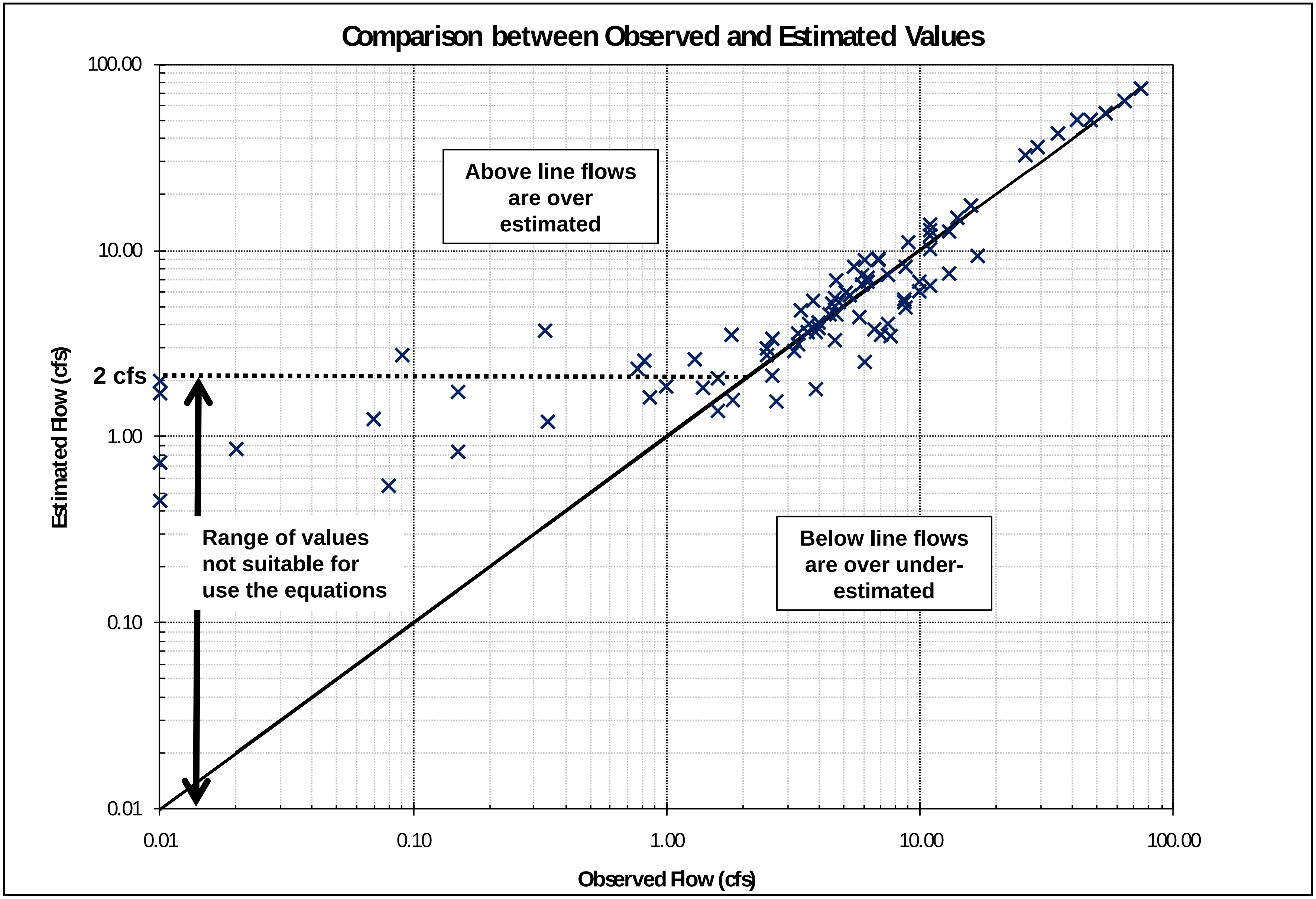



Figure 14: Relation between observed and predicted flow for all recurrence intervals compared to line of perfect correlation to gage station data.

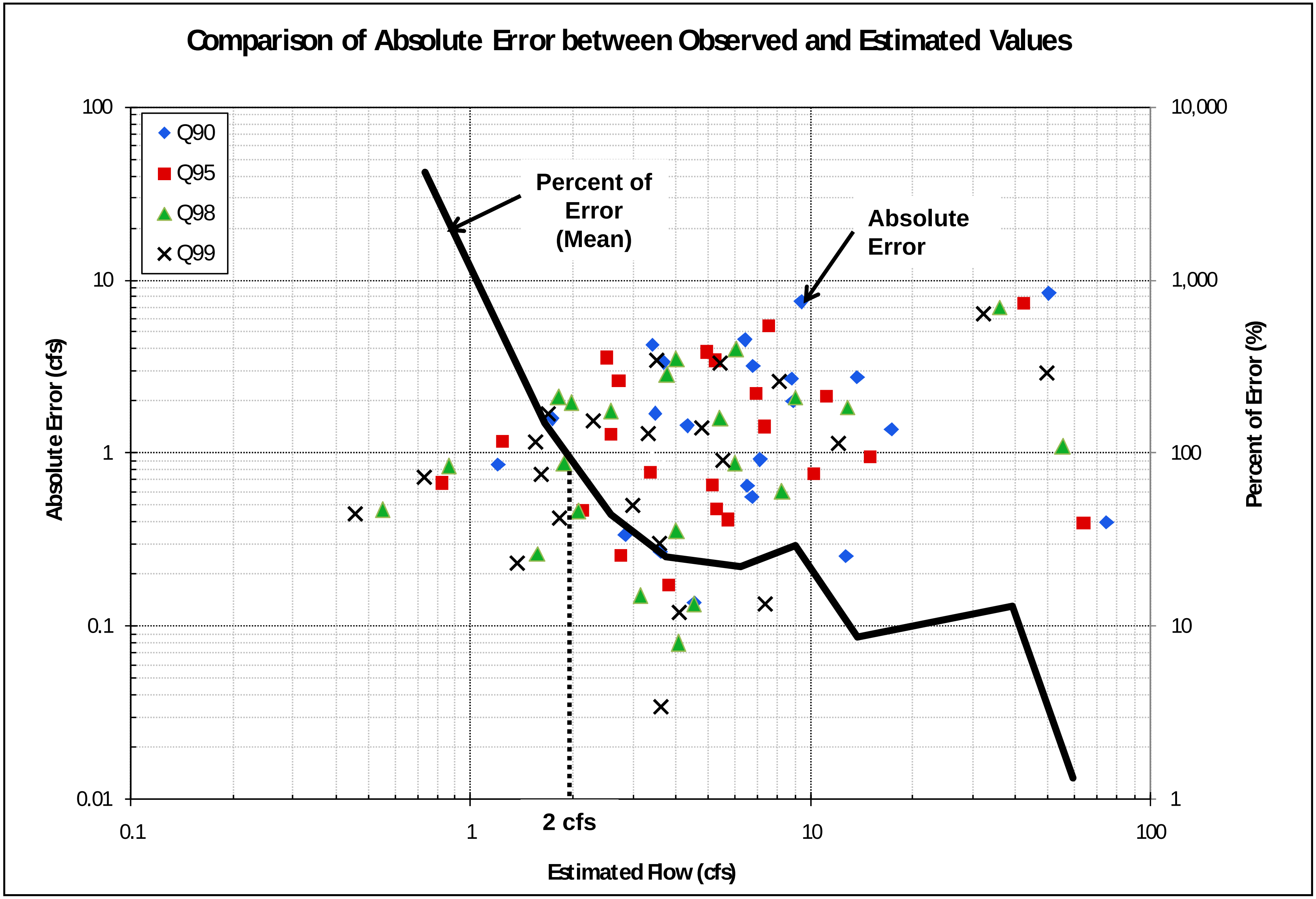



Figure 15: Error between observed and predicted values for the different return intervals.

# APPENDIXES

# APPENDIX A: SAMPLE CALCULATIONS

**Example 1: Determination of $Q_{99}$ at Río Bauta using the Station Index Method.**

The station index method can be used if there is a gage station near the interest point watershed with enough data to perform an exceedance analysis (>10 years). The data from the gaged site is translated to the ungaged site by the ratio of mean flows computed by the regression equation (Eq. 3.20).

In this example, the $Q_{99}$ of a point at Río Bauta is desired. The interest point is located downstream the USGS gage station Río Bauta Station (50034000) as presented in Figure A-1.

**Information of the interest point:**

Watershed area (A) = 28.29 mi$^2$
Mean annual rainfall (P) = 80.54 in

**Information of the gage site:**

Watershed area (A) = 16.74 mi$^2$
Mean annual rainfall (P) = 80.12 in
$Q_{99g}$ obtained from the USGS Streamflow Data = 3.4 cfs

Calculate $Q_{mean}$ for both sites using Equation (3.20):

$$Q_m = 9.869 * 10^{-04} * A^{1.075} * P^{1.787}$$

Ungaged site:

$$Q_m = 9.869 * 10^{-04} * 28.29^{1.075} * 80.54^{1.787}$$

$$Q_m = 91.38\ cfs$$

Gaged site:

$$Q_m = 9.869 * 10^{-04} * 16.74^{1.075} * 80.12^{1.787}$$

$$Q_m = 51.52\ cfs$$

Determine $Q_{99}$ for the ungaged site with the Equation (3.26):

$$Q_{99u} = \frac{Q_{mean\_u}}{Q_{mean\_g}} Q_{99g}$$

$$Q_{99u} = \left(\frac{91.38}{51.52}\right) 3.4$$

$$\boldsymbol{Q_{99u} = 6.03\ cfs}$$

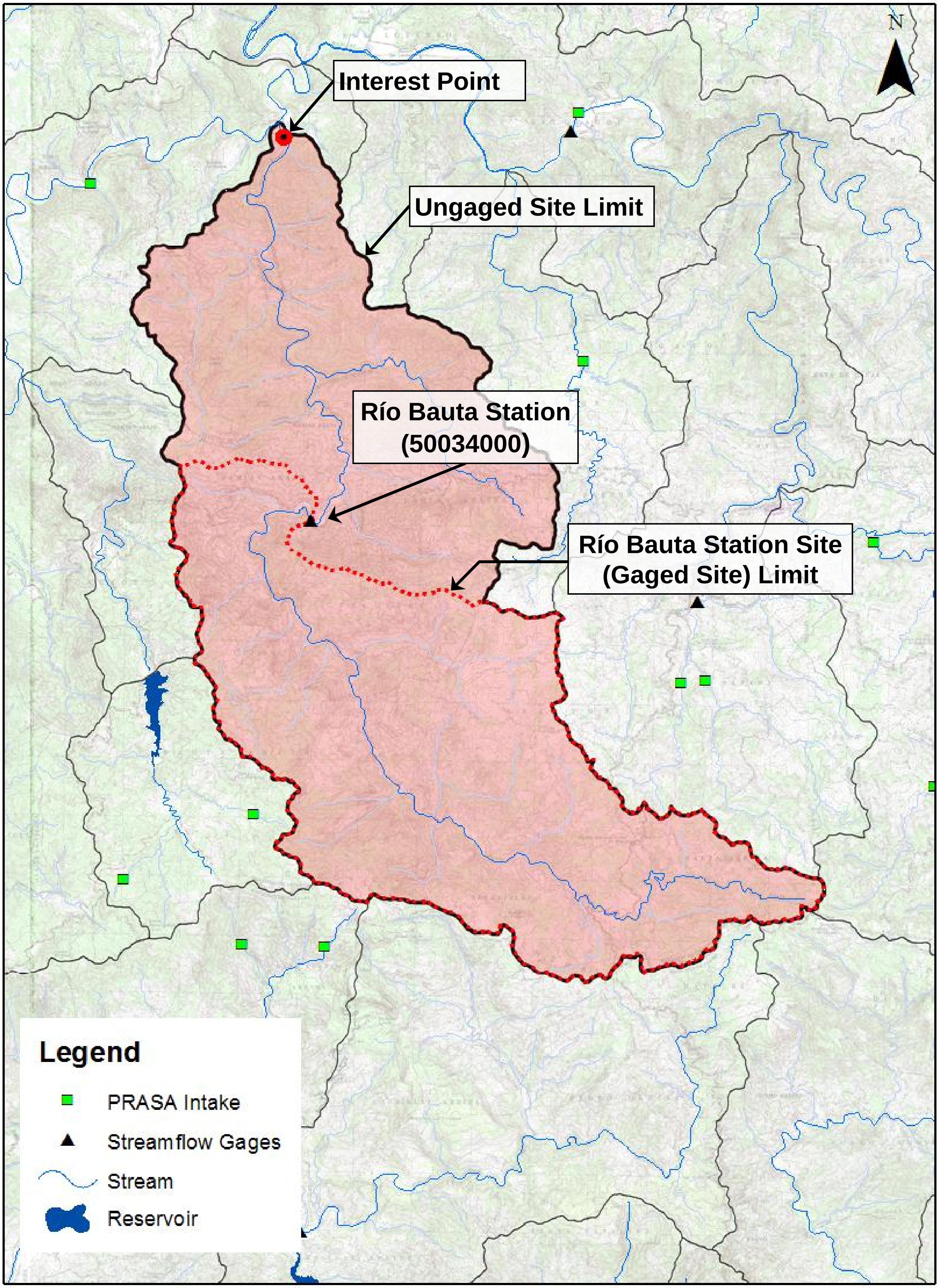



Figure A-1: Example 1. $Q_{99}$ of an ungaged site at Río Bauta is determined using USGS Río Bauta Stations (50034000) as reference.

**Example 2: Determination of $Q_{99}$ at Río Cialitos using the Station Index Method.**

As in Example 1, the interest point is near a gage station thus the Station Index method can be applied (Figure A-2). The interest point is located in Río Cialitos (Figure A-2) and the $Q_{99}$ this point will be estimated using the streamflow data of the Río Bauta Station (50034000).

**Information of the interest point:**

Watershed area (A) = 15.48 $mi^2$
Mean annual rainfall (P) = 80.16 in

**Information of the gage site:**

Watershed area (A) = 16.74 $mi^2$
Mean annual rainfall (P) = 80.12 in
$Q_{99}$ obtained from the USGS Streamflow Data = 3.4 cfs

Calculate $Q_{mean}$ for both sites with Equation (3.20):

$$Q_m = 9.869 * 10^{-04} * A^{1.075} * P^{1.787}$$

**Ungaged site**:

$$Q_m = 9.869 * 10^{-04} * 15.48^{1.075} * 80.16^{1.787}$$

$$Q_m = 47.42\ cfs$$

**Gaged site:**

$$Q_m = 9.869 * 10^{-04} * 16.74^{1.075} * 80.12^{1.787}$$

$$Q_m = 51.52\ cfs$$

Determine $Q_{99}$ for the ungaged site with the Equation (3.26):

$$Q_{99u} = \frac{Q_{mean\_u}}{Q_{mean\_g}} Q_{99g}$$

$$Q_{99u} = \left(\frac{47.42}{51.52}\right) 3.4$$

$$\boldsymbol{Q_{99u} = 3.13\ cfs}$$

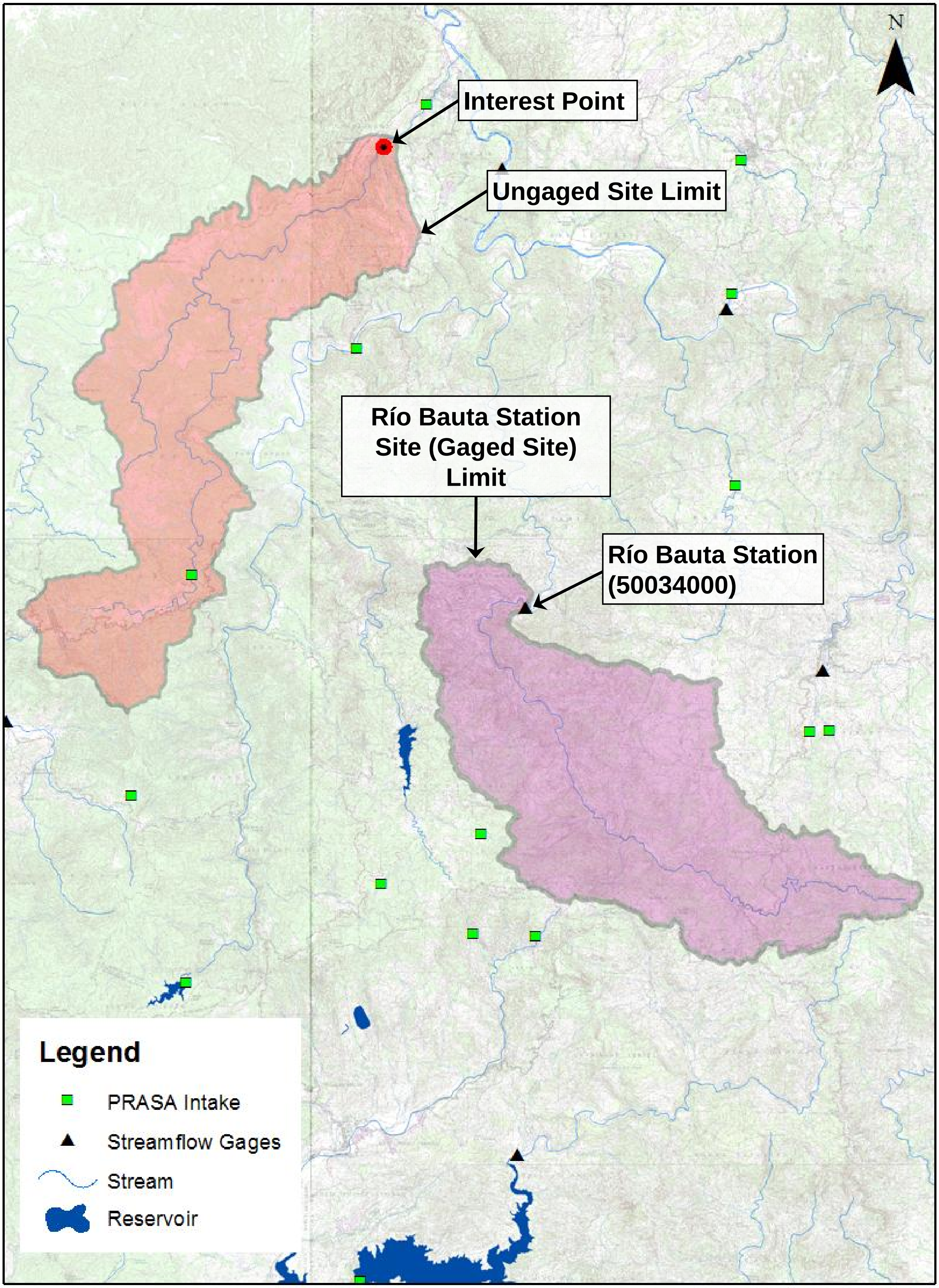



Figure A-2: Example 2. $Q_{99}$ of an ungaged site with an intake at Río Cialitos is determined using USGS Río Bauta Stations (50034000) as reference.

**Example 3: Determination of $Q_{99}$ at Río Bauta using the Regression Equation.**

If there is no streamflow station near the interest point, the minimum flows can be estimated using Equation (3.24. For this example, data from Example 1 will be used for comparison purposes.

**Example 1 information of the site:**

Watershed area (A) = 28.29 $mi^2$
Mean annual rainfall (P) = 80.54 in

Determine $Q_{99}$ using Equation (3.24:

$$Q_{99} = 1.237 * 10^{-07} * A^{1.059} * P^{3.307}$$

$$Q_{99} = 1.237 * 10^{-07} * 28.29^{1.059} * 80.54^{3.307}$$

$$\boldsymbol{Q_{99} = 8.57\ cfs}$$