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Low-Head Hydropower Assessment of the Brazilian State of São Paulo

Open-File Report 2014–1206

Tietê River near Ibitinga, São Paulo, Brazil

U.S. Department of the Interior
U.S. Geological Survey

Cover. Portion of a Landsat 8 image showing Tietê River near Ibitinga, São Paulo, Brazil. Image acquired September 2, 2014.

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U.S. Department of the Interior
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U.S. Department of the Interior
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U.S. Geological Survey
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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second per square kilometer [(m^3/s)/km^2]	91.49	cubic foot per second per square mile [(ft^3/s)/mi^2]

Elevation, as used in this report, refers to distance above the vertical datum.

Vertical and horizontal coordinate information is referenced to the World Geodetic System 1984 (WGS 84).

NOTE TO USGS USERS: Use of hectare (ha) as an alternative name for square hectometer (hm^2) is restricted to the measurement of small land or water areas. Use of liter (L) as a special name for cubic decimeter (dm^3) is restricted to the measurement of liquids and gases. No prefix other than milli should be used with liter. Metric ton (t) as a name for megagram (Mg) should be restricted to commercial usage, and no prefixes should be used with it.

Low-Head Hydropower Assessment of the Brazilian State of São Paulo

By Guleid A. Artan,[1] William M. Cushing,[2] Melissa L. Mathis,[3] and Larry L. Tieszen[2]

Abstract

This study produced a comprehensive estimate of the magnitude of hydropower potential available in the streams that drain watersheds entirely within the State of São Paulo, Brazil. Because a large part of the contributing area is outside of São Paulo, the main stem of the Paraná River was excluded from the assessment. Potential head drops were calculated from the Digital Terrain Elevation Data,which has a 1-arc-second resolution (approximately 30-meter resolution at the equator). For the conditioning and validation of synthetic stream channels derived from the Digital Elevation Model datasets, hydrography data (in digital format) supplied by the São Paulo State Department of Energy and the Agência Nacional de Águas were used. Within the study area there were 1,424 rain gages and 123 streamgages with long-term data records. To estimate average yearly streamflow, a hydrologic regionalization system that divides the State into 21 homogeneous basins was used. Stream segments, upstream areas, and mean annual rainfall were estimated using geographic information systems techniques. The accuracy of the flows estimated with the regionalization models was validated. Overall, simulated streamflows were significantly correlated with the observed flows but with a consistent underestimation bias. When the annual mean flows from the regionalization models were adjusted upward by 10 percent, average streamflow estimation bias was reduced from -13 percent to -4 percent. The sum of all the validated stream reach mean annual hydropower potentials in the 21 basins is 7,000 megawatts (MW). Hydropower potential is mainly concentrated near the Serra do Mar mountain range and along the Tietê River. The power potential along the Tietê River is mainly at sites with medium and high potentials, sites where hydropower has already been harnessed. In addition to the annual mean hydropower estimates, potential hydropower estimates with flow rates with exceedance probabilities of 40 percent, 60 percent, and 90 percent were made.

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[3]SGT, Inc., Contractor to the U.S. Geological Survey; work performed under contract G10PC00044.

Introduction

This report describes methods and processes used to produce a hydropower assessment for the Brazilian State of São Paulo by the U.S. Geological Survey (USGS). The work was done on behalf of the Corporación Andina de Fomento (CAF) – Development Bank of Latin America. The assessment emphasizes low-head hydropower potential. Typically turbines that operate on streams with drops in elevation that are less than 20 meters (m) are classified as low-head hydropower. Low-head hydropower plants usually do not require damming of the streams; therefore, they have fewer negative environmental impacts than high-head hydropower plants and they offer the opportunity to provide off-grid power in remote areas where the installation of power grids often is prohibitively expensive. Assessment of hydropower potential requires calculating the drops in elevation and estimating the potentially available streamflow with associated exceedance probability levels for all stream segments that are within the study area.

In the subsequent sections of this report, we introduce the data and methods used to produce a hydropower potential assessment for the Brazilian State of São Paulo. The objective of the work was to build datasets that can be used for detailed feasibility studies on the development of small hydropower plants; these studies will be done by a Brazilian consulting firm.

Assessment Area

The hydropower assessment was completed for all the streams located entirely within the State of São Paulo (fig. 1). We excluded streams that the State of São Paulo shares with other Brazilian states; for example, no assessment was carried out for the main stem of the Paraná River.

Figure 1. The extent of the study area (shaded black) is the State of São Paulo, shown with the map of Brazil.

Digital Elevation Model

Potential head drops and stream connectivity were calculated using a Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) Digital Terrain Elevation Data (DTED2), which has a 1-arc-second resolution (approximately 30-m at the equator) (Farr and others, 2007). The data are from the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA), and are archived by the USGS Earth Resources Observation and Science (EROS) Center. The USGS and NGA have an agreement to improve the accuracy of the DEM and to archive the data. Even though the SRTM DEM is restricted from public access, this agreement allows the USGS to process the full resolution 1-arc-second DEM data and to create derivative products for most of South and Central Americas.

River Network Datasets

The São Paulo State Department of Energy and the Agência Nacional de Águas (ANA) supplied the USGS with hydrography data (in digital format). This data layer was used for the conditioning and validation of synthetic stream channels derived from the DEM datasets. The ANA hydrography data layer was digitized from 411 topographic sheets at a 1:50,000 scale in a horizontal datum South American Datum 1969 (SAD-69) and Lambert Conformal Conic projection. To have more confidence the synthetic streams derived from the DEM, which is the basis for the hydropower assessment, the ANA hydrography layer was used to validate the drainage network of the synthetic streams and to eliminate erroneous streams.

Regionalized Stream Discharge Characteristics

Streamflow data used to assess hydropower potential were produced using the hydrologic regionalization method of São Paulo State (Liazi and others, 1988). The hydrologic regionalization divides the State into 21 homogeneous regions (fig. 2). Estimating flow rates using the São Paulo State regionalization method on the synthetic streams required two inputs: the spatial extent and the mean annual rainfall of the upstream contributing area to the location of interest. The hydrologic regionalization models for estimating the mean annual flow rate (Liazi and others, 1988) are of the form

$$Q=(a+b*P)*Area/1{,}000 \qquad (1)$$

where

Q is the mean annual flow (m^3/sec),
a and b are model parameters that are basin specific,
P is the mean annual precipitation of the contributing watershed area above the segment end in millimeters (mm), and
Area is the contributing area to the stream segment where the computation is done (km^2).

Streamflow and Rainfall Data

Stream and rain gage data used for this study are from the ANA hydrological information system Website Sistema de Informações Hidrológicas-HidroWeb (*http://hidroweb.ana.gov.br*). Data used were from 1,424 rain gages with at least 10 years of data records and 123 streamgages with at least 28 years of data records. The rain gage stations were well distributed throughout the study area and sufficient to characterize annual rainfall (fig. 3*A*). The streamgages were more densely distributed in the southeastern section and had minimal coverage in western portions of São Paulo (see fig. 3*B*).

The spatial mean annual rainfall for the study area was estimated from the ANA rainfall database using an inverse distance weighted interpolation method. The most recent streamgage data are from the early 1990s.

DEM Data Conditioning

Potential head drops and stream connectivity were calculated from the DTED2 DEM dataset. For some areas, especially areas with low relief, synthetic streams derived from DEM data could diverge from the real conditions hydrographically present on the ground. Hydrological conditioning is the process of modifying elevation pixels from the DEM to improve stream channel modeling that more closely represents ground conditions.

Stream Conditioning

For areas having moderate to high relief and a well-developed drainage network, the watershed data derived from the DEM generally worked well. In areas with low relief, the synthetic hydrography derived from the first DEM processing deviated from the ANA-supplied hydrographic network. In cases where the synthetic streams deviated substantially from the ANA hydrography layer, a conditioning process was applied to better align synthetic streams to the topographic hydrographic data. Figure 4 shows an overlay of synthetic streams from the DEM and the hydrography dataset from ANA in part of the study area. In general, there is good spatial agreement between the two datasets, excluding the fact that the synthetic stream reaches were shorter than the ANA hydrography reaches in the upstream areas. The shortness of the synthetic streams was a result of setting the stream cells' generation threshold higher to avoid the inclusion of "false" synthetic stream reaches. False synthetic stream reaches would have inflated the power potential estimates.

Five DEM conditioning steps were made: (1) areas in the DEM that needed modifications were identified by comparing synthetic streams with the ANA-supplied hydrography data, (2) the stream segments that intersect those areas were selected, (3) DEM pixels underlying areas of the selected stream segments were set to zero, (4) synthetic stream networks were created from the DEM with the modified pixels, and (5) using the synthetic stream networks from the modified DEM and the original DEM, all elevation pixels underlying the network were reduced by 20 m and then hydrologic fill processing was applied. This relative depth conditioning technique allows the enforcement of natural stream channels with minimal alteration of relative elevation measurements. Because all pixels intersecting the stream network

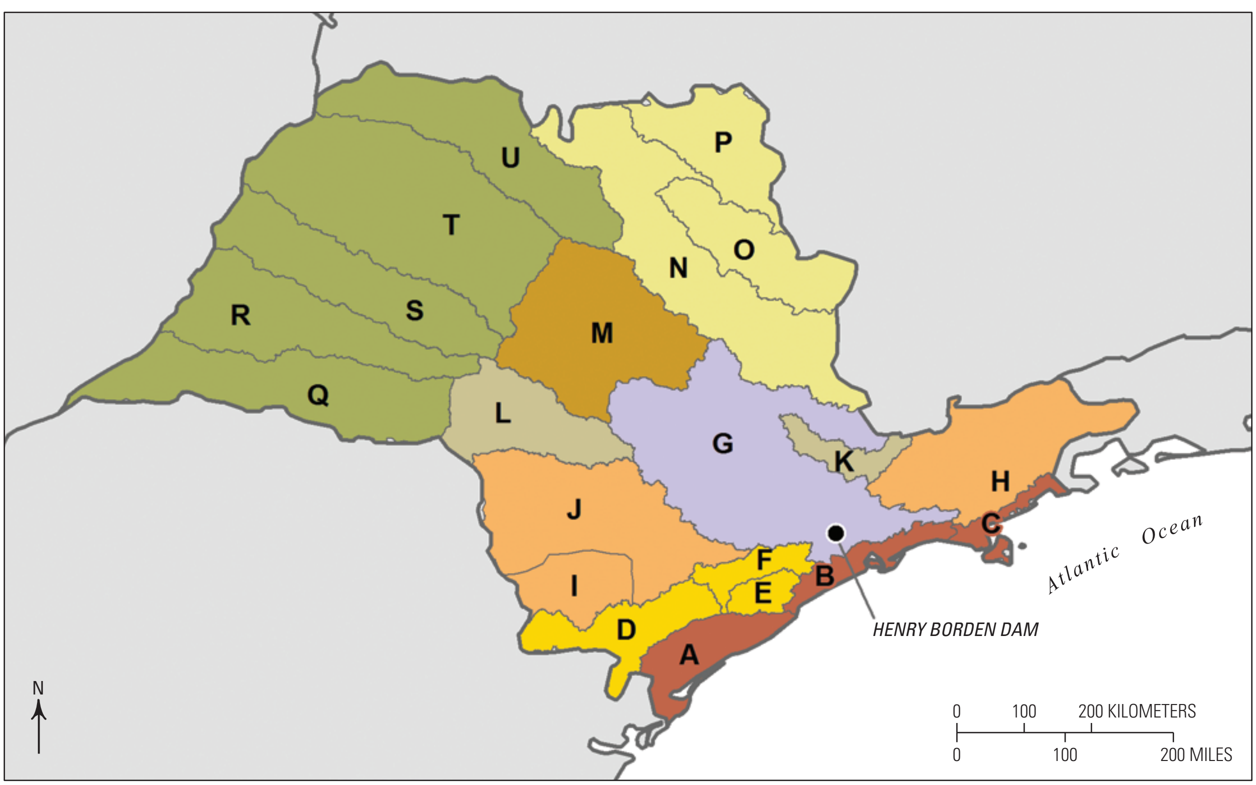

Figure 2. The hydrologic units within the State of São Paulo.

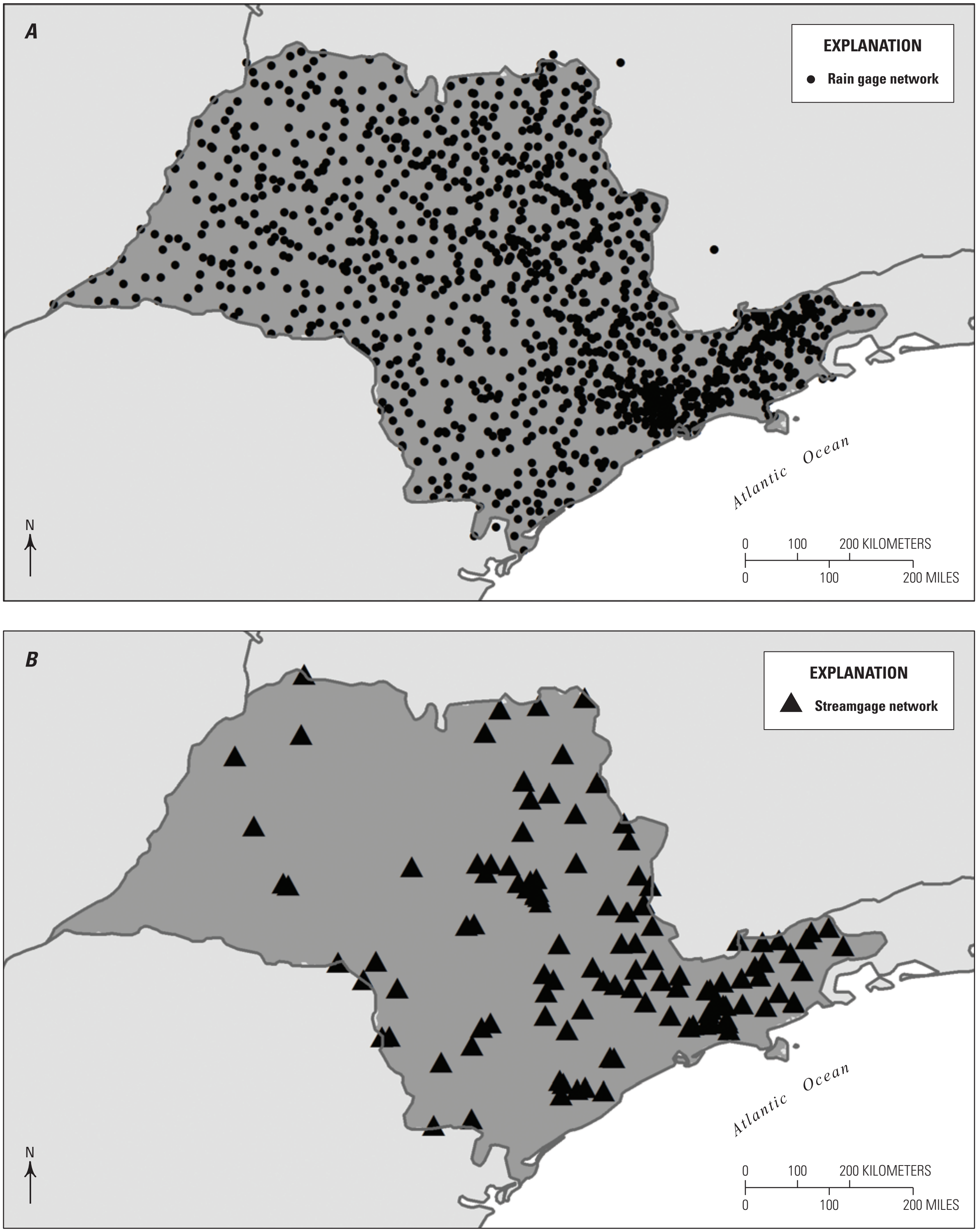

Figure 3. Locations of the Agência Nacional de Águas gages that were used to estimate the distribution of rainfall and to validate estimated streamflow: *A*, rain gages, and *B*, streamgages.

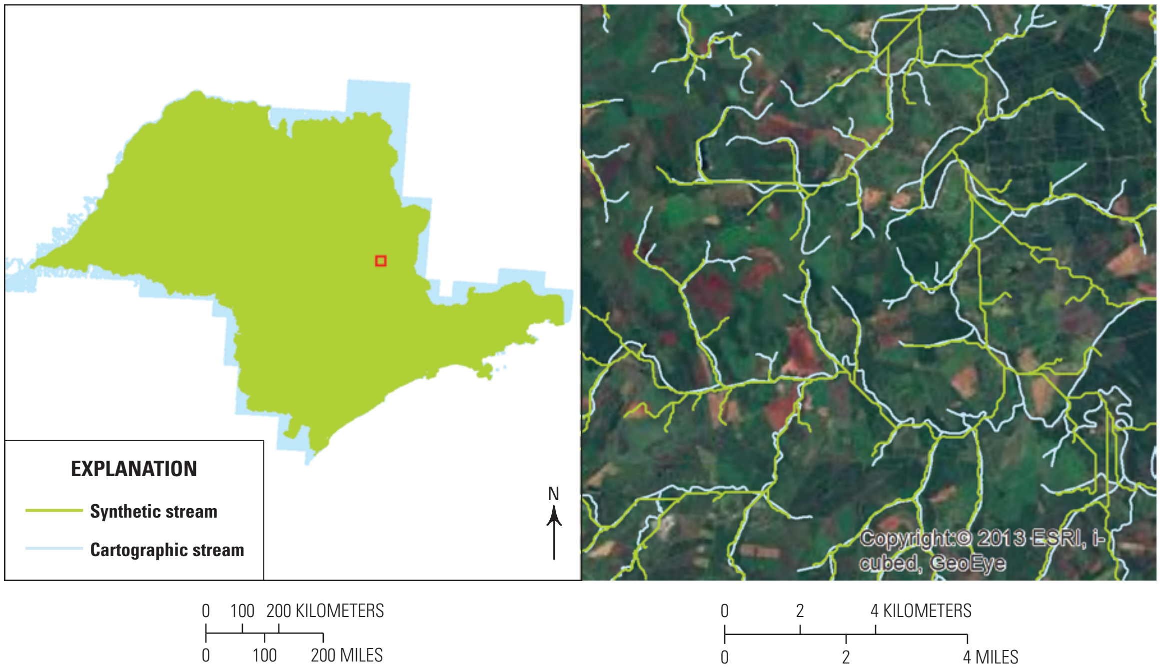

Figure 4. Stream networks from the Agência Nacional de Águas dataset overlaid on synthetic streams created from the SRTMDEM.

were modified, their elevation relative to one another does not change, which allows for consistent elevation drop calculations on the stream network.

Stream Segmentation and Drop Estimations

Elevation drop is a fundamental component in estimating low-head hydropower potential. The drop is calculated at intervals of 1-km segments along the synthetic streams presented in the Stream Conditioning section. Stream segmenting starts at the mouth or at a confluence of other streams with the stream of interest; some segments can be less than 1 km, but this only happens at the end of a stream or downstream from a confluence. This process continues upstream in every synthetic stream until the points have been equally distributed along the stream. During this segmentation process, a unique identification is given to every stream segment, which is used as a key for all the attributes of the segments. The upstream and downstream points of the stream segments created in the first step are used to extract the upstream and downstream elevation values from the DEM. Elevation drops were calculated by taking the difference between the upstream and downstream elevation measurements of the segments. Calculated elevation drops assigned to the stream segments are part of the hydropower assessment database attribute table.

Synthetic Streams Contributing Area Compared to Agência Nacional de Águas Streamgages Contributing Area

The synthetic stream network created from the DEM was visually compared with ANA-generated hydrographic data and quantitatively compared with watershed areas in the ANA streamgage database. There was good spatial agreement between upstream areas recorded in the ANA database and those estimated from the DEM data. The comparison indicated that there were no large discrepancies in drainage area from the two sources (fig. 5*A*); however, although the agreement was within 2 percent on average, there were a few small basins where the discrepancy between the two area estimates was greater than 20 percent (fig. 5*B*).

Assessment of the Streamflow Estimates

Streamflows were estimated with hydrologic regionalization models. Estimated streamflow was validated by comparisom with average flows calculated from gages with long-term data records. The flow validation was extended to the streamflows estimated from the developed Flow Duration Curves.

Mean Annual Flow

The equations for the hydrologic regionalization of Liazi and others (1988), described in the "Streamflow and Rainfall Data" section, were applied at every stream segment. Stream segments, upstream areas, and mean annual rainfall were estimated using geographic information systems (GIS) techniques. Pixel-to-pixel flow direction and flow accumulation calculated from the 30-m DEM provided the framework for the calculation of the upstream mean rainfall for every pixel on the stream segments.

The continuous parameterization technique described by Harvey and Eash (1996) was applied to calculate the upstream area-weighted mean annual rainfall of every pixel on the streams. This parameterization technique uses the same rationale as the flow accumulation algorithm, but instead of treating every pixel as one unit, each pixel is weighted by the rainfall value calculated for the pixel with inverse distance weighted interpolation. Figures 6*A*–*B* show the differences between the local mean annual rainfall and area-weighted mean annual rainfall values for a neighborhood of several pixels in the study area.

The accuracy of the flows estimated with the regionalization method for São Paulo was validated by comparing the estimated flows to the ANA streamgage-observed flows from sites with long-term data records (more than 28 years). The ANA streamgage database contains 119 gages, of which 34 gages had long-term data records. Average annual flows and flows with exceedance probabilities of 40 percent, 60 percent, and 90 percent estimated with the regionalization method were compared to observed streamflow with corresponding exceedance probabilities. Figure 7*A* shows the comparison of the mean streamflow estimates from the regionalization equations with the flows from the ANA database. Overall, simulated streamflows were significantly correlated with the observed flows but with a consistent underestimation bias (fig. 7*A*). When the annual mean flows from the regionalization models (Liazi and others, 1988) were adjusted upward by 10 percent, average streamflow estimation bias reduced from -13 percent to -4 percent (fig. 7*B*).

Flow Duration Curves

In addition to the average yearly streamflows used to estimate annual potential hydropower, several values of the streamflow Flow Duration Curves (FDCs) were calculated. The FDCs are usually shown as a plot of a percentage of time that streamflow is likely to equal or exceed a specified value of interest. With the given FDC dataset, users should be able to calculate reliability levels for various hydropower potential levels. For example, the FDC can be used to show the percentage of time river flows can be expected to exceed a design flow of some specified value, or to show the discharge of the stream that occurs or is exceeded some percentage of the time (for example, 90 percent of the time).

The FDCs of the segments were predicted using equations from the São Paulo regionalization method (Liazi and others, 1988). Predicted FDCs were validated by comparing those estimated with a log-Pearson Type III distribution fit to ANA streamgage datasets. The log-Pearson distribution was fit to only those streamgages with at least 28-year records. For the hydropower assessment, the shapes of the FDCs in low-flow regions are of most interest. The shapes of the curves in the high-flow regions indicate the type of likely flood regime, whereas the shapes of the low-flow regions characterize the ability of the basin to sustain low-flow regimes during dry seasons. The median flow is the discharge that is exceeded 50 percent of the time. The basic time unit of flow used in

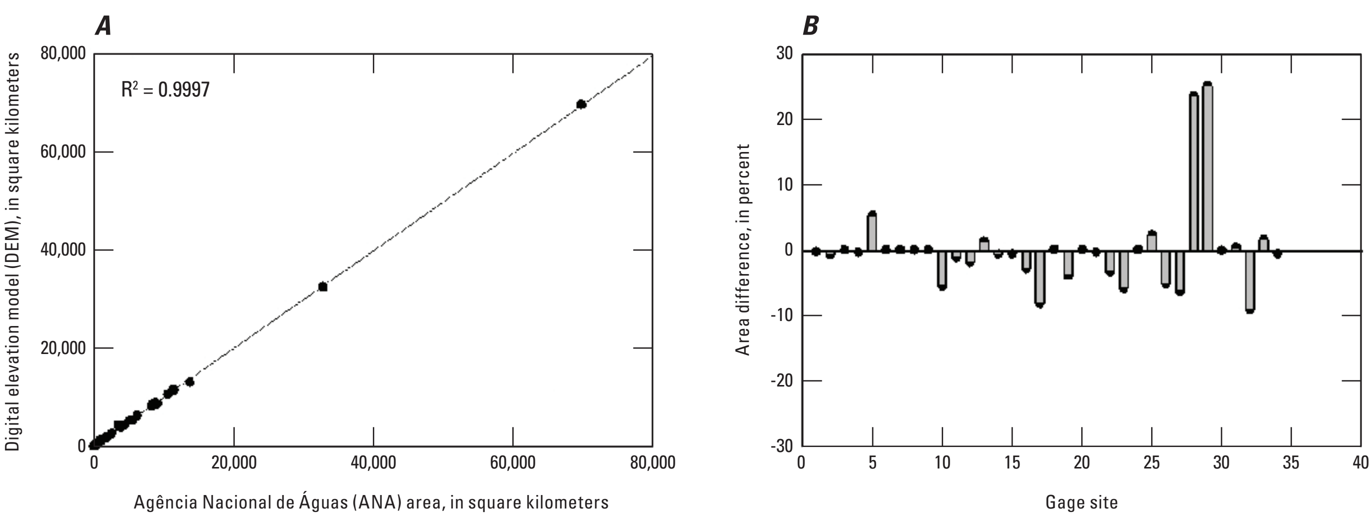

Figure 5. Scatterplot with the 1:1 line of upstream area recorded in the Agência Nacional de Águas database and contributing area calculated from the digital elevation model for the same locations; and *B*, bar chart of percent disagreement between the two areas.

preparing the FDC affects the appearance of the FDC. When mean flows for a 1-year period are used instead of daily values, as in this case, the averaging flattens the resulting FDC.

Figures 8*A–O* depict the FDC estimates from the regionalization method at 15 selected sites from the ANA streamflow database. The FDCs from the observed streamflow data were from the annual average flows fitted to a log-Pearson distribution. Overall, the two FDC estimates agree for most parts of the curves, but there is constant underestimated bias in the FDCs estimated from the regionalization method for the parts of the FDC that represent the low-flow regime conditions. The regionalized hydrologic equations underestimation bias of the low-flow regimes is more apparent in figures 9*A–F*.

Included in the estimated flows database delivered with the final product is the value of the 7-day minimum flow expected in the stream segments. The estimates of 7-day minimum flows could be used to estimate flows that should be left in the streams for ecological protection and subtracted from the discharge that goes into the calculation of the hydropower. We did not validate the 7-day minimum flow estimates because of a lack of observed minimum flow data, but from a literature review (Rezende and others, 2010) we concluded that the minimum flow estimates seem to have poor predictive skills. The most recent studies of the observed streamflow in the ANA database were from the early 1990s; hence, there could be new water abstraction developments that are not reflected in either of the observed or estimated flow data.

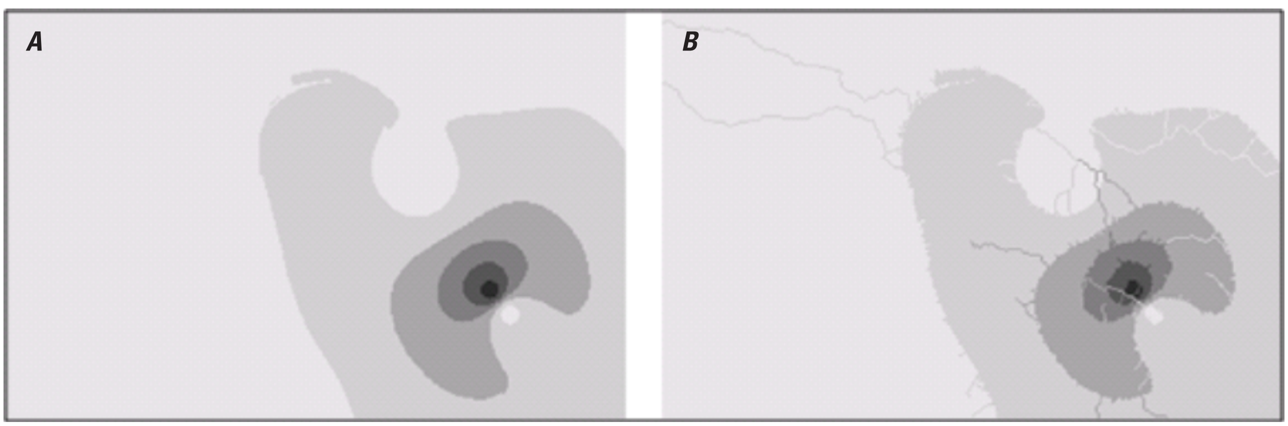

Figure 6. Part of the study area showing *A*, mean annual precipitation fields, and *B*, mean annual precipitation for the same areas when weighted by upstream area.

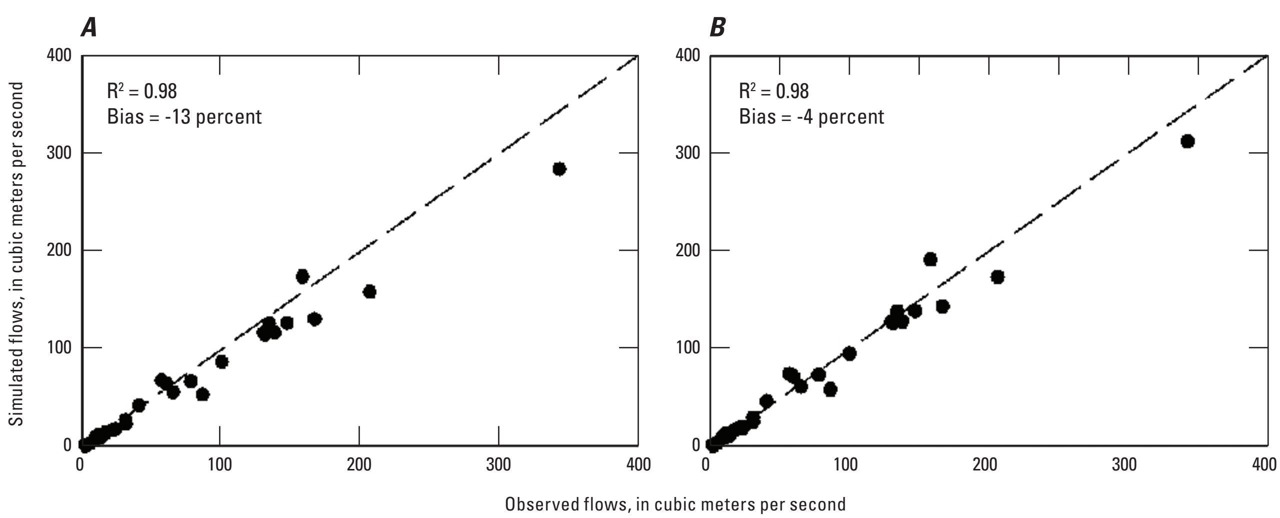

Figure 7. Evaluation of the annual average streamflows estimated with the hydrologic regionalization model compared to observed long-term annual mean streamflows: *A*, streamflows estimated with original equations, and *B*, streamflows estimated with improved regression equations derived from available stream and rain gage data of the study area.

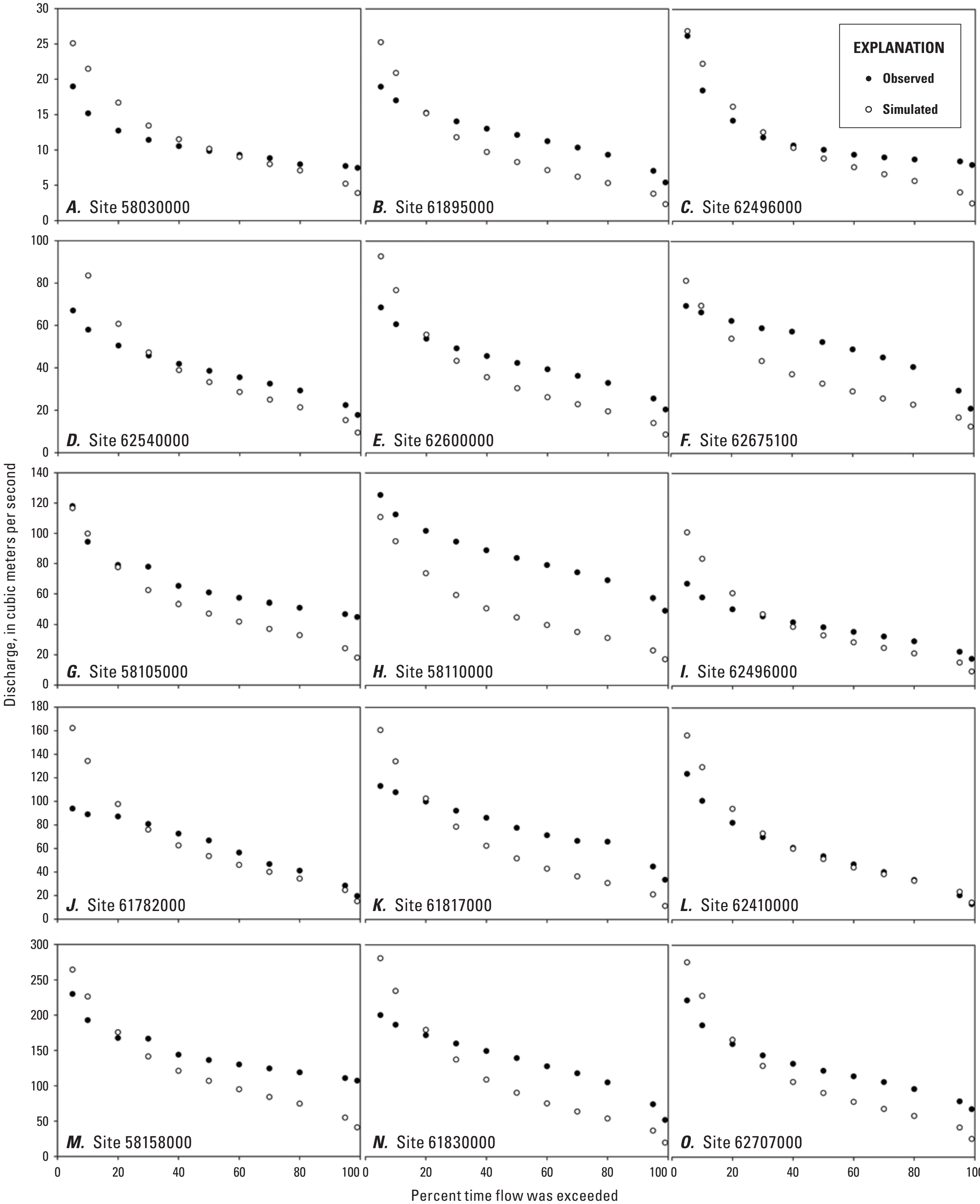

Figure 8. Comparison of Flow Duration Curves (FDCs) calculated from log-Pearson distribution fit of observed annual mean flows with FDCs estimated from the regionalized hydrologic equation of watersheds in the State of São Paulo (Liazi and others, 1988).

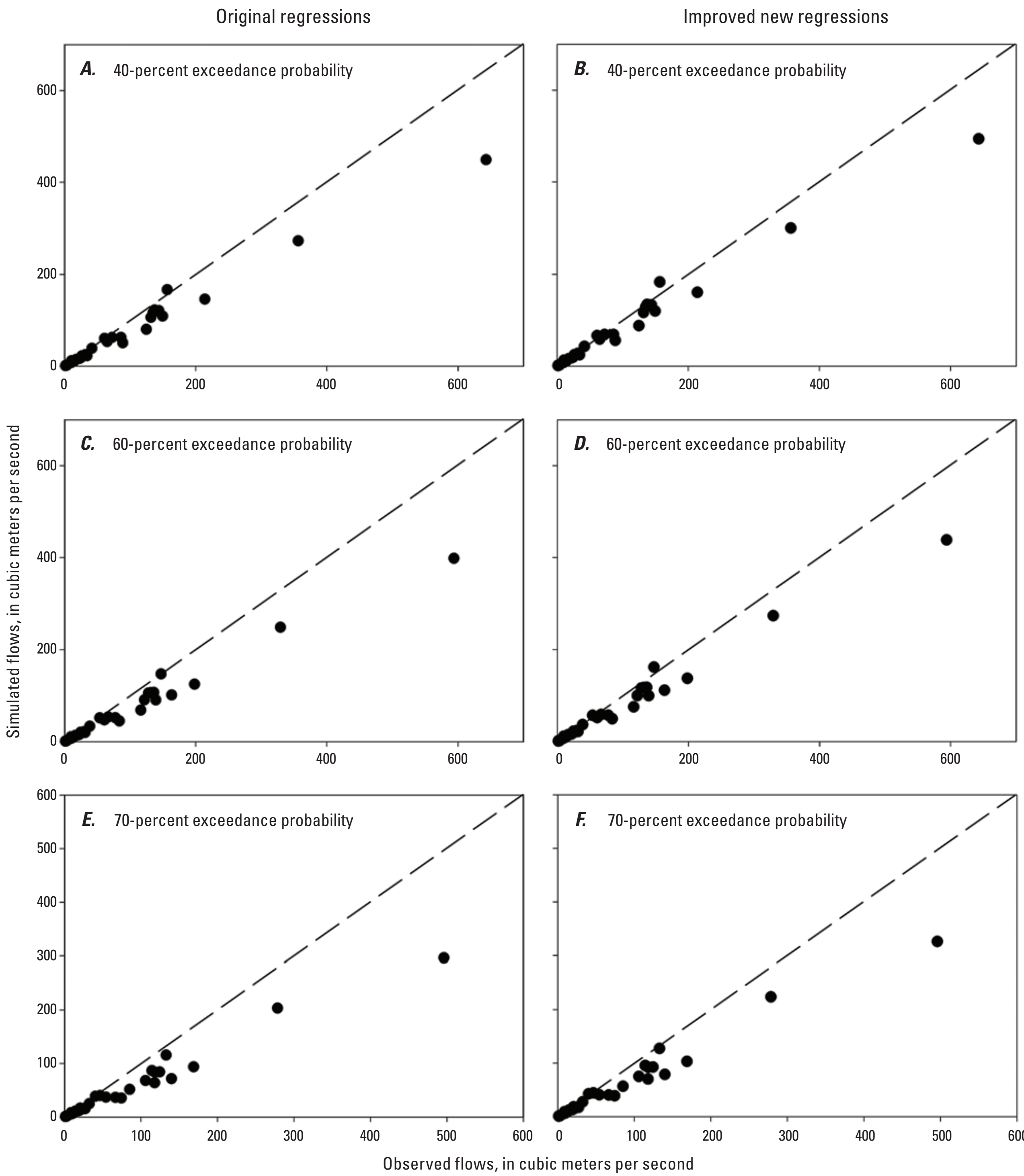

Figure 9. Observed flows at gages with long-term data at 40 percent, 60 percent, and 70 percent exceedance probability plotted with flows estimated with the regionalized hydrologic equations on the right (*A*, *C*, *E*), and estimated with the modified regionalized equations on the left (*B*, *D*, *F*).

Hydropower Assessment Results

The study produced a comprehensive estimate of the magnitude of hydropower potential available in the streams that drain watersheds entirely in the State of São Paulo. Watershed assessment locations are shown in figure 10. Streams in São Paulo but with sizeable contributing areas outside of the borders of the State of São Paulo were excluded from the analysis and are shown in light blue in figure 10. The hydropower potential of each stream reach was calculated using the hydraulic head and annual mean flow rates at the inlet of the reach estimated using the regionalization model (Liazi and others, 1988). The hydraulic head associated with each stream reach was obtained using the elevation data in the DEM dataset. The hydropower for the river segments was then estimated as

$$P=g*H*Q*10-3 \qquad (2)$$

where

- P is hydropower potential [megawatt],
- H is hydraulic head [m] of the stream segment,
- Q is the flow rate of the water in the segment [m^3/s], and
- g is gravitational acceleration of 9.81 m/s^2.

For potential hydropower, turbine efficiency was assumed to be 100 percent and no hydraulic head loss was considered in the calculation; therefore, the resulting hydropower estimates are for gross potential.

In addition to the annual mean hydropower estimates, potential hydropower estimates with mean annual flows estimated using an improved set of regression equations, and with flow rates with exceedance probabilities of 40 percent, 60 percent, and 90 percent, are given with the hydropower assessment datasets delivered to CAF.

The results of the hydropower assessment are presented with an emphasis on five power classes shown in table 1. The sum of the first four classes is equal to the total power and represents classification by power class, and the low head/low power class is a classification by power technology (see fig. 11). The final product of the hydropower assessment is a GIS streams vector layer segmented every 1 km with attributes containing estimated flows (m^3/s), head drop (m), and power potentials (Megawatts (MW)) at the four above-described levels of the probability. Figure 12 presents a summary of results for average power potential of the four power categories for the streams considered in the analysis.

The accuracy of the power potential estimates is dependent on the accuracy of the individual stream reach power potentials that were summed to produce total values. The

Figure 10. Major streams in São Paulo where the hydropower assessment was completed (shown in dark blue).

calculated reach flow rates had a standard error of 13 percent. The DEM data, for a random discrete location in South America, had an absolute height error of 6.2 m (Farr, 2007; Rodríguez, 2006), but the analyses indicate that the uncertainty in the difference between two elevations in near proximity (hydraulic head drop) is much better than the elevation uncertainty for an individual location. Because of the direct relation between power potential and flow rate, the standard error of the reach power potential would be at least 13 percent. The uncertainty of the calculated hydraulic head values further increases the uncertainty of the power potential values. However, if the errors are uniformly distributed, the accuracy of a total value produced by summing a large number of reach power potentials will be better than the accuracy associated with the individual values that were summed.

Table 1. Hydropower classes.

[<, less than; >, greater than]

Hydropower class	Power class
Micro	< 100 Kilowatt.
Mini	100 to 1,000 Kilowatt.
Small	1 to 50 Megawatt.
Medium and large	> 50 Megawatt.
Low head/low power	< 1 Megawatt and < 9.1 meter drop.

Hydropower Potential by Basin

Potential hydropower was aggregated by basin for the State of São Paulo (fig. 2). The total power potential for each of the four basic power classes was calculated by adding power potential totals for each power category within each basin. A GIS layer containing the basin boundaries was intersected with a hydropower assessment dataset of stream reaches. Figure 13 shows total annual mean power potentials of the 21 hydrologic regions stacked by power categories. The sum of all the validated stream reach mean annual hydropower potentials in the 21 basins is 7,000 MW. Hydropower potential is mainly concentrated near the Serra do Mar mountain range and along the Tietê River (fig. 10). The power potential along the Tietê River is mainly at sites with medium and high potentials, sites where hydropower has already been harnessed.

Segment Hydropower Potential

Stream segments with power potentials less than 1 MW and more than 100 kilowatts (kW) with hydraulic heads less than 9 m were summed to provide an estimate of total low head/low power potential at watersheds and regional levels (Hall and others, 2004). Low head/low power potential is presented as separate categories in figure 14 because to exploit low head/low power potential requires the deployment of unconventional systems or microhydro technology that could increase the cost of developing hydropower potential. Basins G and P (fig. 2) had the highest potential for low head/low power potential among the 21 basins (fig. 14).

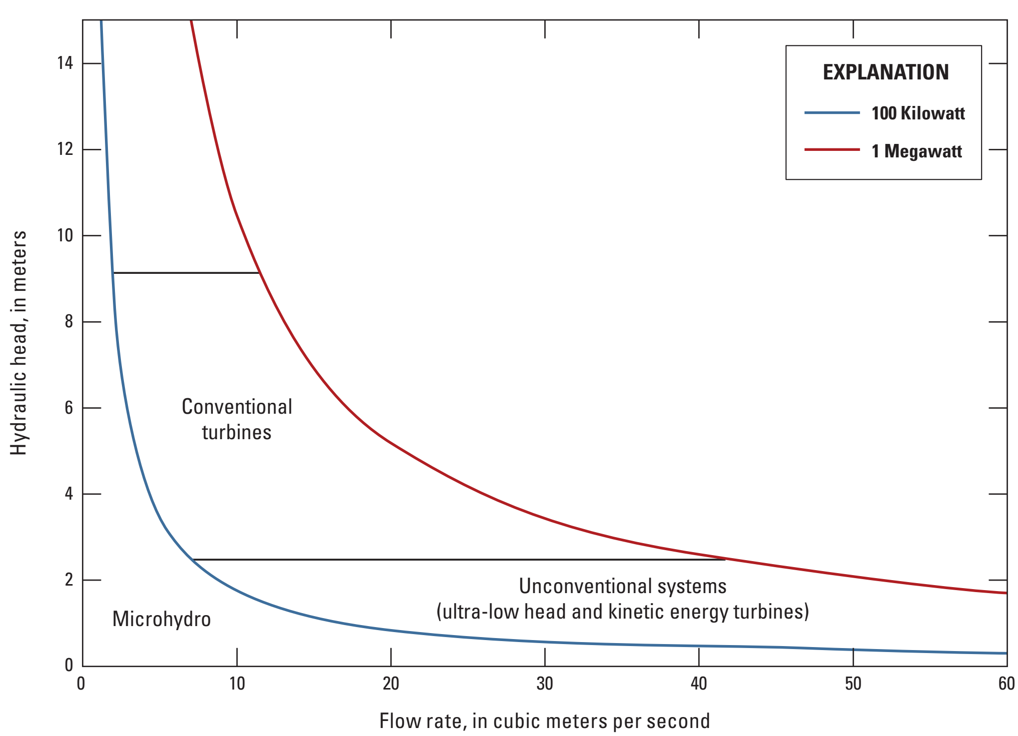

Figure 11. Three classes of low head/low power technologies (from Hall and others, 2004).

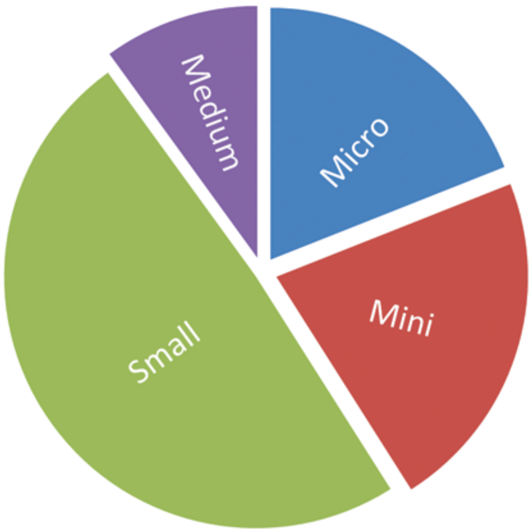

Figure 12. Power category distribution for the potential annual mean hydropower of all the streams that are entirely in the State of São Paulo.

Available Hydropower Potential

The amount of potential available hydropower is equal to the potential hydropower minus the hydropower already developed. For every stream, we calculated developed hydropower from the ANA hydroelectric database coverage. Figure 15 summarizes the undeveloped hydropower potential within the watersheds in the State of São Paulo, subdivided into three categories. In the undeveloped streams, there is no site within the medium and large power category. A few sites along the major rivers (Tietê and do Peixe) have small elevation drops and large enough flows to possibly achieve low-head hydropower within the medium power categories.

We determined that the hydropower capacity within the study area as provided by the ANA hydroelectric database overestimated the amount of developed potential power for some sites. Some of the developed plant capacities in the ANA hydroelectric database could not be justified on the natural average annual streamflow rates alone. Power capacities of some plants were greater than the average power that could be warranted using average flow rates and the hydraulic head of the plant's location (for example, Henry Borden Dam, fig. 2).

To produce an estimate of developed power potential that is comparable to the potential power estimates, which are based on annual mean flow rates, it will be necessary to estimate the average energy generated by each hydroelectric plant, a task that is beyond the scope of this study. A drawback of using actual power generated is that efficiency of power generation is not included in the numbers estimated with such a method.

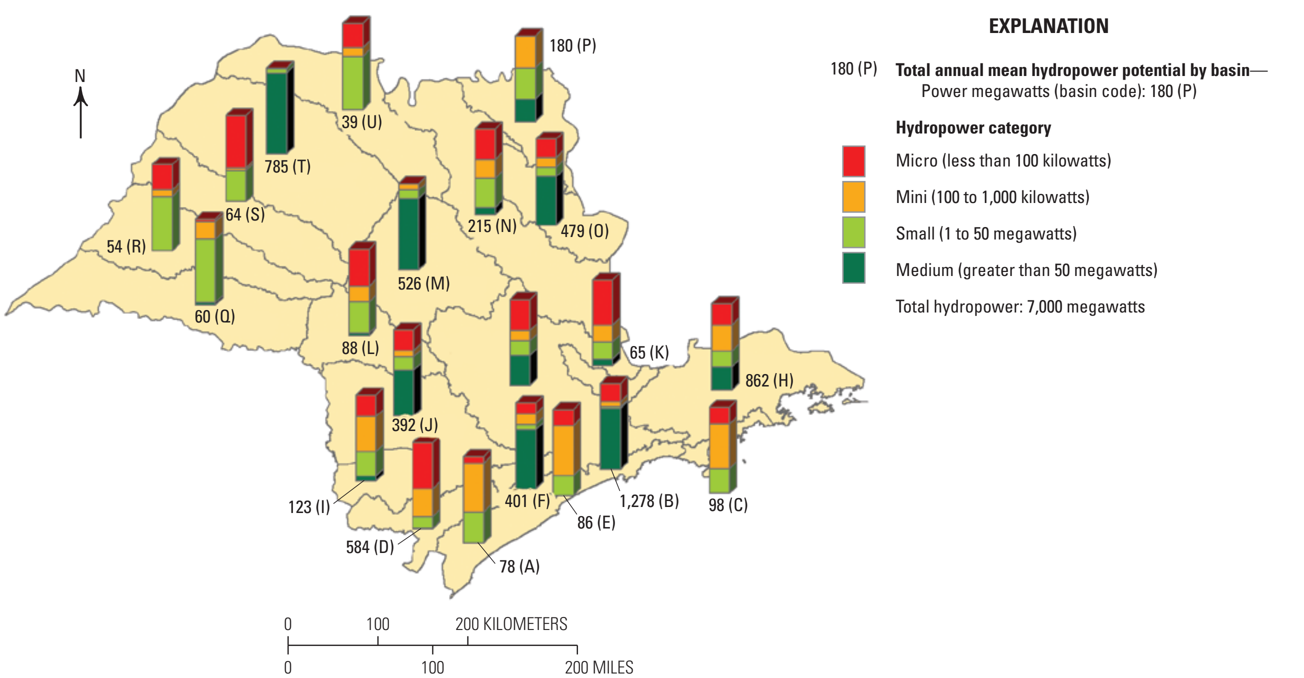

Figure 13. Total annual mean hydropower potential of the 21 basins within the State of São Paulo.

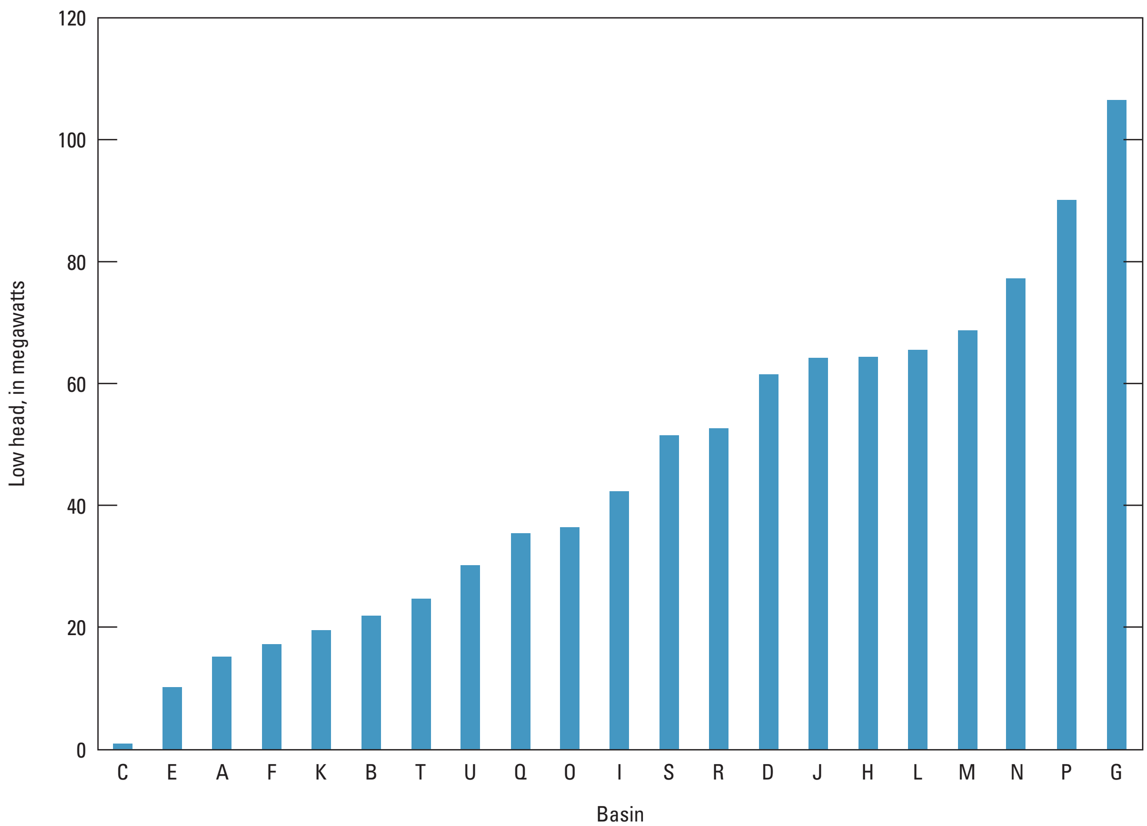

Figure 14. Total low head/low power potential summarized by basin (see fig. 2 for basin locations).

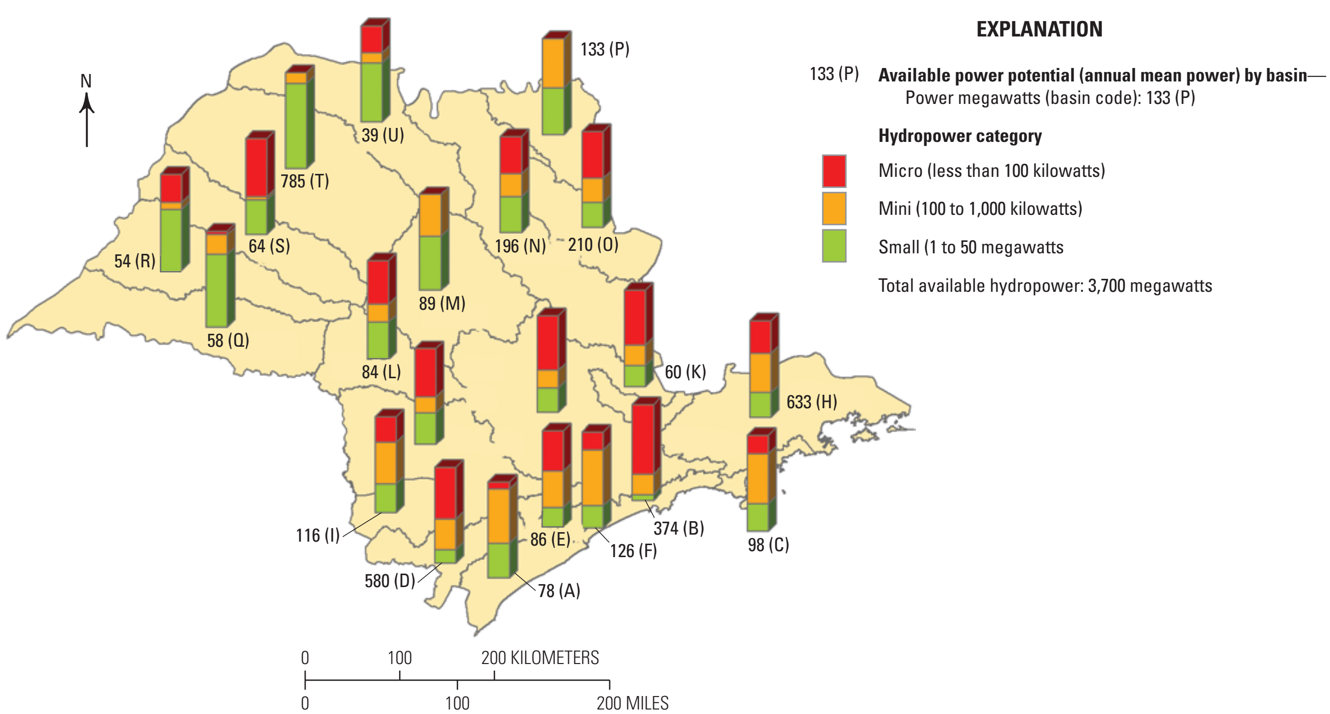

Figure 15. Distribution of available power potential (annual mean power) of São Paulo energy resources among three hydropower classes.

Developed and Reaming Hydropower

To determine the final potential hydropower that can be developed, areas where hydropower cannot be developed (for example, parks, wildlife refuges) need to be identified and excluded. At the time of this report, maps of areas excluded from hydropower development in São Paulo were not available. If available, an excluded area data layer could be intersected with the potential hydropower data layer to identify stream reaches that should be excluded from consideration as potential sources of hydropower. In the final product, stream reaches would be coded as either excluded or not excluded from hydropower development.

Web Mapping Service And Contour Level Extraction

In addition to the GIS streams layer, the data are available in a Web mapping service for collaborating agencies to view and extract information. This service provides access to an interactive map of São Paulo that allows users to select a stream segment and identify its estimated power potential and related attributes (fig. 16). In addition to presenting the information as a Web map, the data also are distributed as an Esri Map Service (*http://www.geosur.info/map-viewer/hydropower*).

CAF and the consulting firm IX Estudos e Projetos needed access to the 1-arc-second (30-m) resolution DEM of the region for a follow-up detailed hydropower assessment for the high potential areas identified in this study. The restricted nature of the SRTM data presented a unique challenge to the feasibility phase of the project. With permission from NGA, the USGS developed a Web geoprocessing service that provides a method for collaborating agencies to extract contours from the DEM. The extraction is done through a Web mapping site on the Esri Geoprocessing Server (*http://tps.geosur.info/arcgis/rest/services/Models/GeoSUR_HydroDerivatives/GPServer*). The contour extraction is limited to a 20-km^2 area surrounding the selected stream. The contour intervals are set to 2 m and range between the minimum elevations at the prospective dam location and a height specified by the user. After running the Web mapping tool, the contour lines are delivered as a downloadable Esri shapefile product (fig. 16).

A ***B***

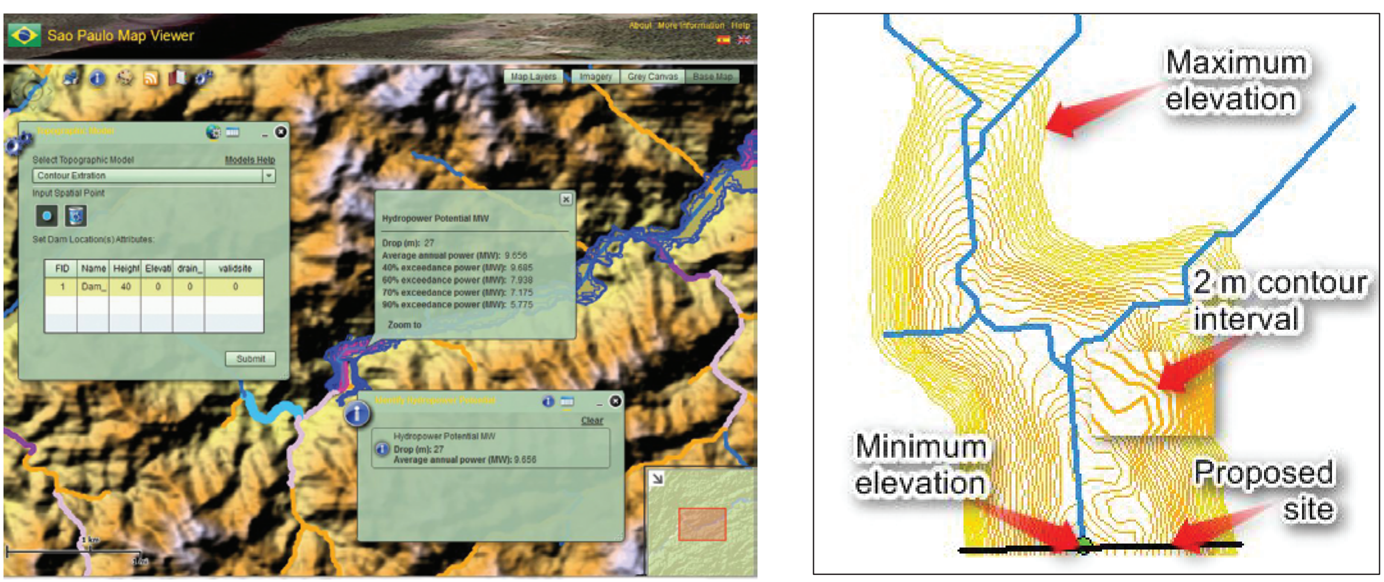

Figure 16. The user interface of the Web mapping site (*A*) that was developed for extraction of contour lines from the DEM, and an example of an extracted contour line product (*B*).

Summary

A comprehensive assessment of the hydropower potential available in all the watersheds in the Brazilian State of São Paulo was completed. Potential head drops were calculated from a digital elevation model with a 1-arc-second resolution (approximately 30-meter resolution at equator). The hydrometeorological data (rainfall and discharge) used come from a dense network of gages. Streamflow was estimated using 21 hydrologic regionalization functions. The potential hydropower of all streams was estimated as 7,000 megawatts. The potential hydropower is mostly concentrated near the Serra do Mar mountain range and along the Tietê River, areas where most hydropower has already been harnessed. To estimate the potential for low head/low power, stream segments with power potentials less than 1 megawatt and more than 100 kilowatts with hydraulic heads less than 9 meters were aggregated. Basins G and P showed the highest potential for low head/low power.

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