



Hydro-BID: An Integrated System for Modeling Impacts of Climate Change on Water Resources. Part 2

Fekadu Moreda, Ph.D.

Fernando Miralles-Wilhelm
Raúl Muñoz Castillo

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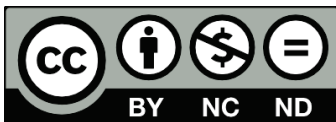


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Foreword

The Inter-American Development Bank (IDB) provides financial and technical support for infrastructure projects in water and sanitation, irrigation, flood control, transport, and energy. 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 agriculture. Assessing the potential for future changes in water availability is an important step toward ensuring that infrastructure 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 an integrated suite of watershed modeling tools known as Hydro-BID. The Hydro-BID modeling system includes hydrology and climate analysis modules to estimate the availability (volumes and fluxes) of fresh water at the regional, basin, and sub-basin scales. It will also include economic analysis and decision support tools to estimate the costs and benefits of adaptive measures and help decision makers make informed choices among alternative designs for infrastructure projects and alternative policies for water resources management.

Phase I of this effort produced a working version of Hydro-BID. As of this writing, Hydro-BID includes the following components:

- an Analytical Hydrography Dataset (AHD) for the Latin America and Caribbean region, representing over 229,000 catchments and their corresponding river and stream segments;
- a geographic information systems–based navigation tool to browse AHD catchments and streams with the capability of navigating upstream and downstream;
- a user interface for specifying the area and time period to be modeled and the location at which water availability will be modeled;
- a climate data interface to generate and apply rainfall and temperature inputs for the area and period of interest;
- a rainfall-runoff model based on the Generalized Watershed Loading Factor (GWLF) model; and
- a routing scheme for quantifying time of travel and accumulating 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.

As an illustration of the Hydro-BID system's inputs, operation, and outputs, the development team prepared a case study addressing water allocation issues in the Rio Grande basin in Argentina. The initial version of Hydro-BID has received enthusiastic response in presentations to potential users and constituents in the IDB and to outside technical audiences via conferences and workshops.

The work performed during Phase 1 is described in three Technical Notes. This document is Technical Note 2.

Overview of Technical Notes in this Series		
No.	Title	Summary
TN 1	An Analytical Hydrography Dataset for Latin America and the Caribbean (LAC)	TN1 provides an overview of the Analytical Hydrography Dataset (AHD), which is an analytical surface water geospatial dataset that is patterned after the U.S. National Hydrography Dataset Plus (NHDPlus). The AHD for the LAC region serves as the “base layer” for the Hydro-BID integrative model.
TN 2	Hydro-BID: An Integrated System for Modeling Impacts of Climate Change on Water Resources	TN2 provides an overview of the Hydro-BID integrative model, which combines the AHD; data on climate, land cover, and soils; and the GWLF run-off model to form a water resource simulation tool for use at the basin or sub-basin level. The model provides projected stream flows based on selected climate scenarios.
TN 3	Hydro-BID Case Study: A Water Resource Model of the Rio Grande Basin in Argentina	TN3 provides results from an application of the Hydro-BID integrated modeling system to the Rio Grande Basin, part of the greater Bermejo River Basin in Argentina. The case study provides options for addressing seasonal water shortages through improvements in the efficiency of agricultural and urban water uses.

1 Overview

Countries in Latin America and the Caribbean (LAC) have experienced an increase in the number and intensity of El Niño Southern Oscillation events over the past 30 years, causing record precipitation events in Venezuela (1999 and 2005), flooding in the Argentinean Pampas (2000 and 2002), droughts in the Amazon basin (2005), and a record hurricane season in the South Atlantic (2004). It is forecasted that within the next 20 years, from 12 to 81 million people in the LAC region will experience increased water stress, with the number increasing to between 79 and 178 million people by the 2050s. The impacts of climate change will vary across the region, as summarized by the Intergovernmental Panel on Climate Change (IPCC) (Magrin et al., 2007).

Across the LAC region, changing rainfall patterns will produce more intense rainfall in some areas and drought in others. More frequent and violent storms will damage infrastructure and strain drainage systems at some locations, while reduced rainfall increases water stress at other locations and rising sea levels threaten coastal aquifers with saline contamination. In mountainous regions, the loss of water storage in glaciers could cause long-term reductions in river flows and groundwater recharge, resulting in stress on water supplies for people, crops, and ecosystems, as well as reduced hydroelectric generating capacity. Hydropower is the main source of electricity for most Latin American countries and is at great risk from changes in water flows and water availability.

- The key factors affecting people's vulnerability to expected changes in water resources are known. On a macro scale, the main drivers are population growth and migration, uncontrolled urban growth, and inadequate infrastructure and services. At a finer level of resolution, the vulnerability of specific areas and populations is a function of several key factors, including: local geologic and hydrologic characteristics;
- local geography, land use, and vegetative cover;
- the presence or absence of suitable and sufficient water storage facilities;
- current levels of consumptive water demand relative to available supplies; and
- institutional frameworks governing water allocation and inter-basin transfers.

Prior work by RTI International has shown that the vulnerability of water supplies to climate change and other threats can vary widely within a river basin. Some areas will be highly vulnerable to small changes in precipitation or temperature, while other areas are "buffered" and will be relatively immune to even large changes in precipitation or temperature. These differences are most highly correlated with the level of development within the sub-basin, the drainage area and position within the larger watershed, the degree of groundwater flux to and from surface waters, and the reliability of existing storage systems. Measures designed to help adapt to climate change (for example, induced disruptions of water supplies) will be more effective, in both performance and cost, if they are planned using an integrative process that takes full advantage of available knowledge.

2 Introduction

Figure 1 presents a schematic representation of the integrated Hydro-BID system for quantitative simulation of hydrology and climate change. The system is built on an Analytical Hydrographic Dataset (AHD) for the Latin American and Caribbean region. The AHD is described in detail in Technical Note 1 of this series.

Hydro-BID utilizes the data structure and the catchment and stream network topologies of the AHD. It incorporates data on land uses, soil types, rainfall and temperature within the study area, as well as observed stream flows for use in calibration. Hydro-BID includes a pre-processor interface to disaggregate monthly climate data into a daily time series of temperature and rainfall, which is the required form of climate data input. The system applies a standard Generalized Watershed Loading Function (GWLF) model, coupled with a novel lag-routing methodology developed by RTI. Model output is generated as a time series of projected water flows, at either a daily or monthly scale. The system has a graphical user interface to accept model input, as well as to display graphical and tabular summary outputs.

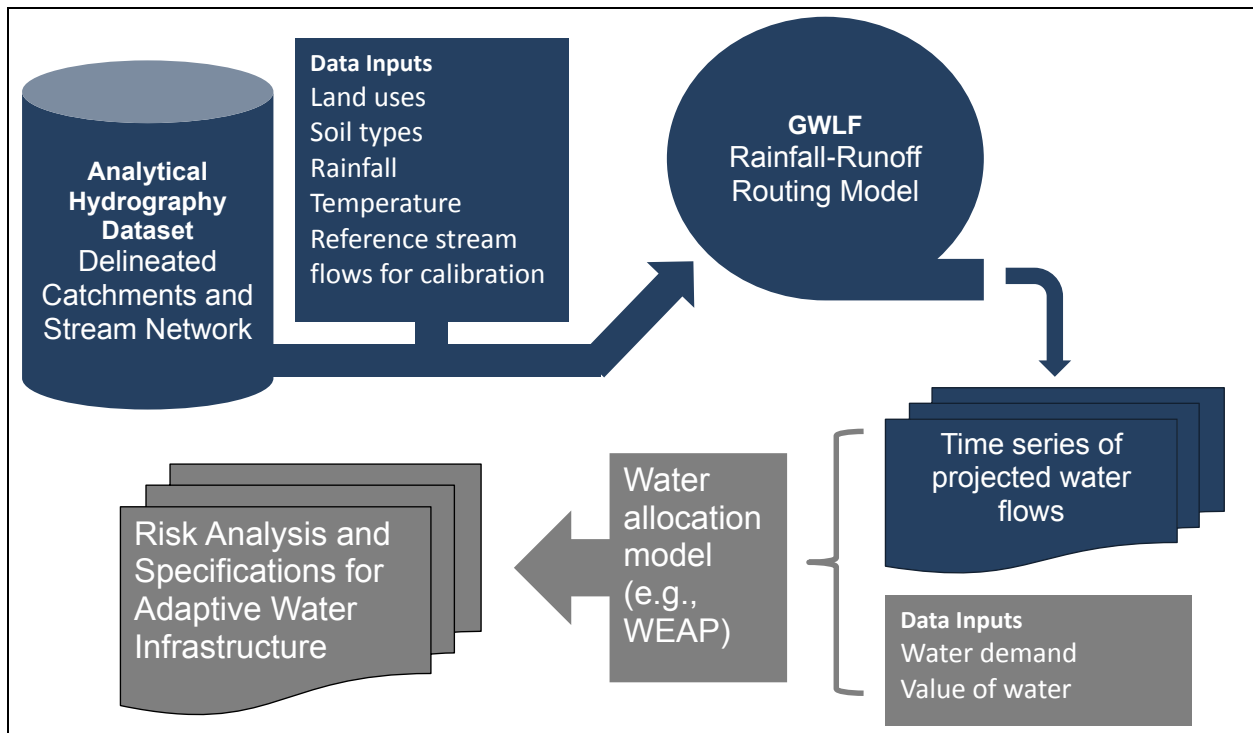


Figure 1. Hydro-BID flow chart

Output from the Hydro-BID system should be analyzed further in conjunction with additional data and projections for water demand, cost, the economic value generated by water uses, and the expected performance of the infrastructure in question, to develop water allocation schemes, risk analyses, and adaptive designs. Hydro-BID can be used with historical climate data or future climate projections to model basin-wide surface water flows, assess the potential impacts of climate change on water flows and infrastructure, and support the design of adaptive projects and strategies. The adaptation options include response to long-run declines in stream flows; an increase in flows; an increase in seasonal and inter-annual variation in flows; and extreme events such as drought and floods. Hydro-BID has been developed to serve as a key planning tool for

- water resources planning and management agencies;
- drainage/flood control authorities;
- irrigation authorities;
- hydroelectric power generators;
- water supply and sanitation utilities; and
- industrial water users.

3 Hydro-BID System Functionality

This section describes the basic equations governing the GWLF and RTI lag-routing methodology; the data and parameter requirements and the data flows of the modeling system; and the Hydro-BID system's Graphical User Interface (GUI).

3.1 *Generalized Watershed Loading Function and Lag-Routing*

Hydro-BID is based on the well-known GWLF (Haith, 1985; Haith et al., 1996) and enhanced by the RTI lag-routing methodology. GWLF has been tested and used in watersheds around the world (Schneiderman et al., 2007; Sha et al., 2013). The rainfall runoff model component of GWLF is applied on small catchment units by taking into account the land uses and soil conditions within the catchment. The response of each land use in a given catchment is treated separately to generate an estimate of runoff volume. The flow generated from each catchment, including shallow groundwater contributions or base flow, is routed through stream networks defined by the AHD. The distributed model architecture provides a high level of scalability. Impacts of climate change on water resources can be simulated at scales as small as an individual AHD catchment or across all of the catchments within an entire watershed. This architecture also makes the system very portable across the LAC region.

Figure 2 is a conceptual representation of a catchment with unsaturated and saturated soil layers as used in GWLF. The model computes runoff and base flows by catchment: runoff is generated in the form of excess infiltration and base flow is a gradual release from the saturated layer. After accounting for runoff from precipitation events, any water in excess of a calculated evaporation volume is infiltrated to the unsaturated layer. Over time, the infiltrated water percolates from the unsaturated layer downward to replenish the saturated storage. Water within the saturated layer enters the stream channel as base flow where it combines with runoff from the catchment and any inflows from the upstream catchments to provide the stream flow volume for the day. Note that the saturated layer, or water available as base flow, can be depleted by seepage to a deeper groundwater aquifer.

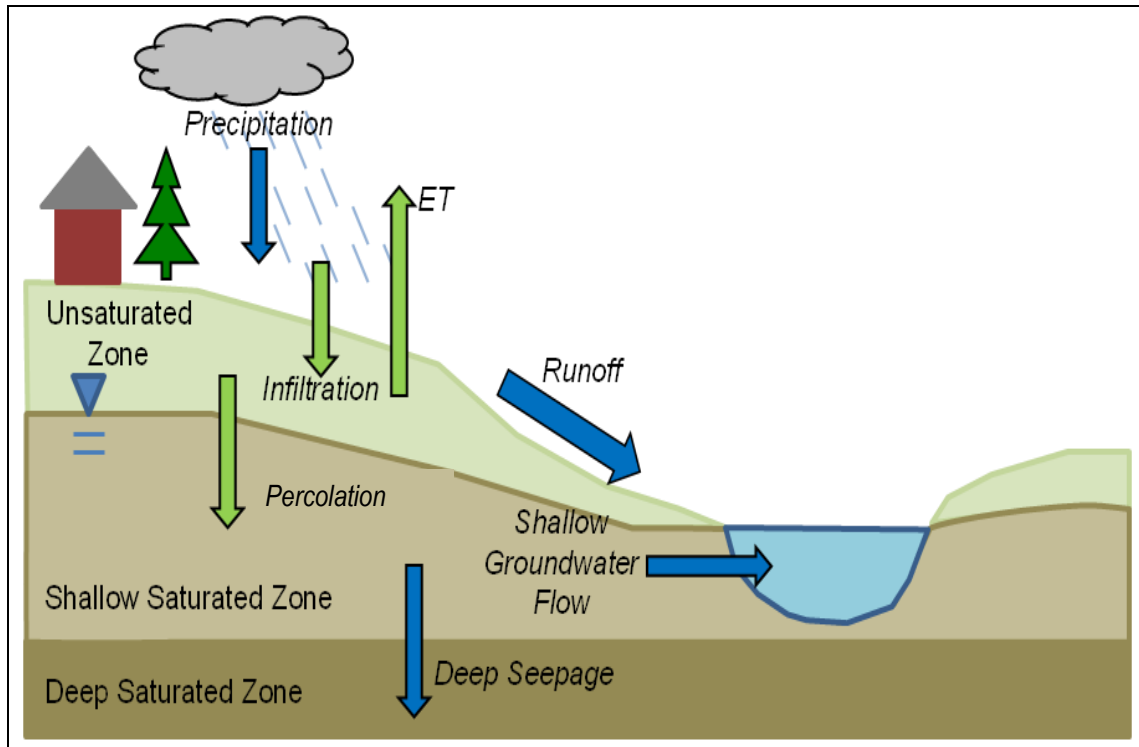


Figure 2. Schematic representation of the GWLF model (modified from Haith et al., 1996).

GWLF Model Computations

This section describes the equations used to compute each of the model components—snow melt, potential evapotranspiration, runoff, percolation, flow, and routing as provided by Haith et al (1996).

Snow Melt

The initial step in the snow accumulation ablation process is to classify precipitation as either liquid rain or freezing rain/snow. The classification is achieved by comparing the mean daily temperature, T_t , against a threshold, usually taken as 0°C . The snow cover balance of the study area is given as

$$SNO_t = SNO_{t-1} + R_t - SNO_{mt} \quad (\text{E. 1})$$

where SNO_t is the water content of the snow pack on a given day

R_t is the amount of precipitation in a day

SNO_{mt} is the amount of snow melt estimated as

$$SNO_{mt} = 0.45T_t \quad (\text{E. 2})$$

The melted snow is treated as rainfall to generate infiltration and also percolation to the subsurface. For large watershed-based model, the snow melt computation is implemented in areas subdivided by elevation bounds to account for non-uniform coverage of snow due to elevation difference. However, for the application of the model in a small area, such as AHD catchments, uniform coverage is expected.

Potential Evapotranspiration

GWLF relies on the potential evapotranspiration (PET) estimation method developed by Hamon (1962), which uses mean daily temperature and number of daylight hours to compute PET:

$$PET_t = \frac{0.021H_t^2 e_t}{T_t + 273} \quad (E. 3)$$

In this equation, H_t is the number of daylight hours per day during the month containing day t ; e_t is the saturated water vapor pressure in millibars on day t and T_t is the temperature on day t ($^{\circ}$ C). When $T_t \leq 0$, PET_t is set to zero. The saturated vapor pressure can be approximated as in Bosen (1960):

$$e_t = 33.8639 \left[(0.00738T_t + 0.8072)^2 - 0.000019(1.8T_t + 48) + 0.001316 \right] \text{ for } T_t > 0 \quad (E. 4)$$

The number of total daylight hours is computed as Forsythe et, al., 1995):

$$H_t = \frac{2 \cos^{-1} [-\tan \delta \tan \phi]}{\omega} \quad (E. 5)$$

where H_t = daylight hours

δ is the solar declination in radians

Φ is geographic latitude in radians

ω is the angular rotation of the earth.

The PET is then adjusted based on the underlying land use and cover condition using a cover factor

$$PET_{Adj(t)} = CV * PET_t \quad (E. 6)$$

where $PET_{Adj(t)}$ is the cover adjusted PET, and CV is the cover factor.

CV values depend on the vegetation and crop cover. The actual evapotranspiration is computed from the cover adjusted PET but is limited by the availability of water in the soil moisture.

Runoff

Surface runoff generated from both rainfall and snow melt is calculated using the U.S. Soil Conservation Service's curve number equation:

$$RO_t = \left(\frac{R_t - 0.2D_t}{R_t + 0.8D_t} \right)^2 \quad (E. 7)$$

where RO_t is runoff (cm)
 R_t is the sum of rain and melt
 D_t is the detention parameter, calculated as follows

$$D_t = \frac{2540}{CN_t} - 25.4 \quad (E. 8)$$

where CN_t is curve number assigned by land use and adjusted each day.

Curve numbers are assigned to each individual land use category and underlying soil hydrologic group considered in the model. For instance, a forest land use overlying well drained soils will have a different curve number than the same land use overlying poorly drained soils. Although the curve numbers are set within the model prior to a model run, each day the curve number for a land use/soils group is modified based on the antecedent soil moisture condition, as shown in **Figure 3**, below.

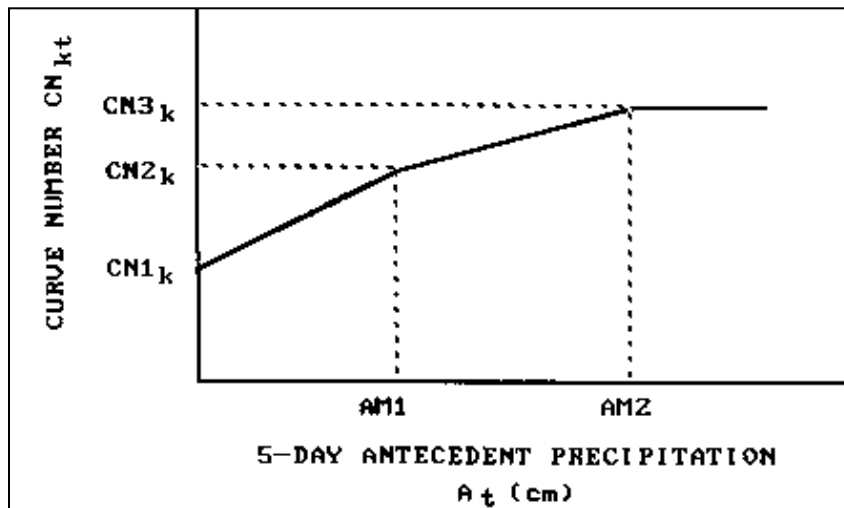


Figure 3. Curve numbers are selected as functions of antecedent moisture, as described in Haith (1985).

To compute the curve number for a given day, the antecedent soil moisture is computed by accumulating the past 5 days of rainfall and snow melt:

$$Amc5_t = \sum_{x=1}^5 R_{(t-x)} \quad (E. 9)$$

where $Amc5_t$ is antecedent precipitation of the past 5 days.

Curve numbers for dry, average, and wet antecedent moisture conditions are $CN1_k$, $CN2_k$, and $CN3_k$, respectively. The actual curve number for day t , $CN2_k$, is selected based on Figure 3 as a linear function of 5-day antecedent precipitation $Amc5_t$ given in Equation 9.

The model requires specification of $CN2_k$. Values for $CN1_k$ and $CN3_k$ are computed from Hawkins (1978) approximations:

$$CN1_k = \frac{CN2_k}{2.334 - 0.01334CN2_k} \quad (E.10)$$

$$CN3_k = \frac{CN2_k}{0.4036 - 0.0059CN2_k} \quad (E.11)$$

Percolation

The daily water balances within both soil storage compartments are calculated. The equation for the unsaturated layer is as follows:

$$U_{t+1} = U_t + R_t + M_t - Q_t - E_t - P_t \quad (E.12)$$

Similarly, for the saturated zone, the water balance is computed as follows:

$$S_{t+1} = S_t + P_t - G_t - D_t \quad (E.13)$$

In the above equations, U_t and S_t are the unsaturated and shallow saturated zone soil moistures at the beginning of day t , and Q_t , E_t , P_t , G_t and D_t are watershed runoff, actual evapotranspiration, percolation into the shallow saturated zone, groundwater discharge to the stream (i.e., base flow), and seepage flow to the deep saturated zone, respectively, on day t (cm).

Percolation occurs when unsaturated zone water exceeds available soil water capacity U^* (cm):

$$P_t = \text{Max} (0, (U_t + R_t + M_t - Q_t - E_t - U^*)) \quad (E.14)$$

The soil water capacity U^* has to be defined as a characteristic of the unsaturated soil layer. This parameter can be estimated from the soil property.

Evapotranspiration is limited by available moisture in the unsaturated zone:

$$E_t = \text{Min} ((CV_t * PET_t), (U_t + R_t + M_t - Q_t)) \quad (E.15)$$

As in Haan (1972), the shallow saturated zone is modeled as a simple linear reservoir. Groundwater discharge and deep seepage are as follows:

$$G_t = rS_t \quad (E.16)$$

$$D_t = sS_t \quad (E.17)$$

where r and s are groundwater recession and seepage constants, respectively (day^{-1}).

These two parameters tend to have high correlation.

Flow

The total flow generated from the catchment, F_t , is the sum of the runoff (RO_t) and the ground flow (G_t):

$$F_t = RO_t + G_t \quad (\text{E.18})$$

Routing

Consider the catchment network shown in **Figure 4**. The flows generated from each of the catchments are routed along each stream reach to the outlet catchment or to any downstream catchment based on a pre-calculated lag time. The lag time is defined as the time taken by the flow generated at a given catchment to reach a downstream catchment and computed as the product of the stream length divided by the average velocity. While the stream length is obtained directly from the stream network (AHD), the average velocity is a parameter in the model that can be specified. In the United States, an empirical equation is used to derive average velocities based on flow and slope (Jobson, 1996). In the LAC case, a default value of (0.5 m/s) is set, and the user may change the average velocity as a calibration parameter.

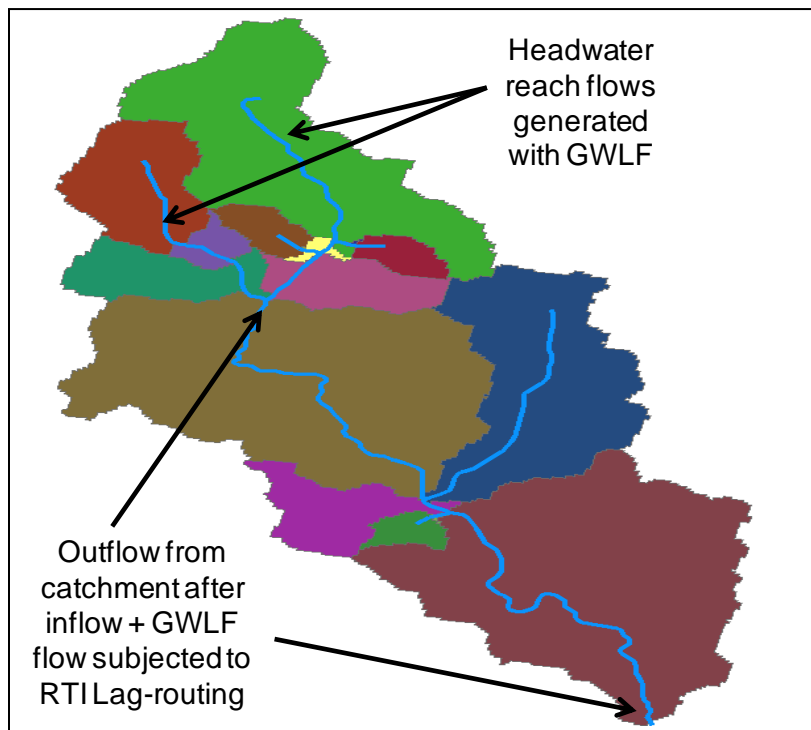


Figure 4. Routing flows through the AHD stream network

3.2 Parameterization and Data

Parameters of GWLF

Most of GWLF's required parameters are assembled in a database for each of the AHD catchments, including catchment area and stream length. The main parameters of GWLF are described in **Table 1**.

Table 1. Major GWLF parameters that are related to flow generation

Parameters	Description	Estimation Method
Available Soil water capacity (U*)	This parameter triggers the start of percolation	Can be estimated from soil characteristics
Curve number (CN)	Controls the initial amount of abstraction and used to compute detention	Chosen using land use and soil type classification
Evaporation curve coefficient (CV)	Represents seasonal variation of evaporation due to vegetation growth	Estimated monthly
Groundwater recession coefficient (r)	Controls the rate of ground water flow from the saturated storage	For gauged catchment, the recession parameter can be estimated using hydrograph separation techniques
Seepage parameter (s)	Controls the rate of seepage to the deep groundwater aquifer	Depending on the geological formation, seepage values can be highly variable

Curve Number

Table 2 is the curve number look-up table. Two sets of data are required to establish a curve number look-up table: the land use data and the soil data. To determine the curve number for a catchment from the look-up table (**Table 2**), the land use and dominant hydrologic soil group are identified, as shown in **Figure 5**.

Table 2. Curve number look up table (adapted from U.S. Department of Agriculture [USDA], 1986)

Land Use Type	Soil Hydrologic Group			
	A	B	C	D
Urban and Built-Up Land	82	88	92	93
Dryland Cropland and Pasture	64	75	82	85
Irrigated Cropland and Pasture	64	75	82	85
Mixed Dryland/Irrigated Cropland and Pasture	40	64	75	81
Cropland/Grassland Mosaic	40	64	75	81
Cropland/Woodland Mosaic	40	64	75	81
Grassland	49	70	80	87
Shrubland	45	57	68	74
Mixed Shrubland/Grassland	45	57	68	74
Savanna	49	70	80	87
Deciduous Broadleaf Forest	36	60	73	79
Deciduous Needleleaf Forest	36	60	73	79
Evergreen Broadleaf Forest	36	60	73	79
Evergreen Needleleaf Forest	36	60	73	79
Mixed Forest	36	60	73	79
Water Bodies	100	100	100	100
Herbaceous Wetland	49	70	80	87
Wooded Wetland	49	70	80	87
Barren or Sparsely Vegetated	77	86	91	94
Herbaceous Tundra	45	57	68	74
Wooded Tundra	45	57	68	74
Mixed Tundra	45	57	68	74
Bare Ground Tundra	77	86	91	94
Snow or Ice	100	100	100	100

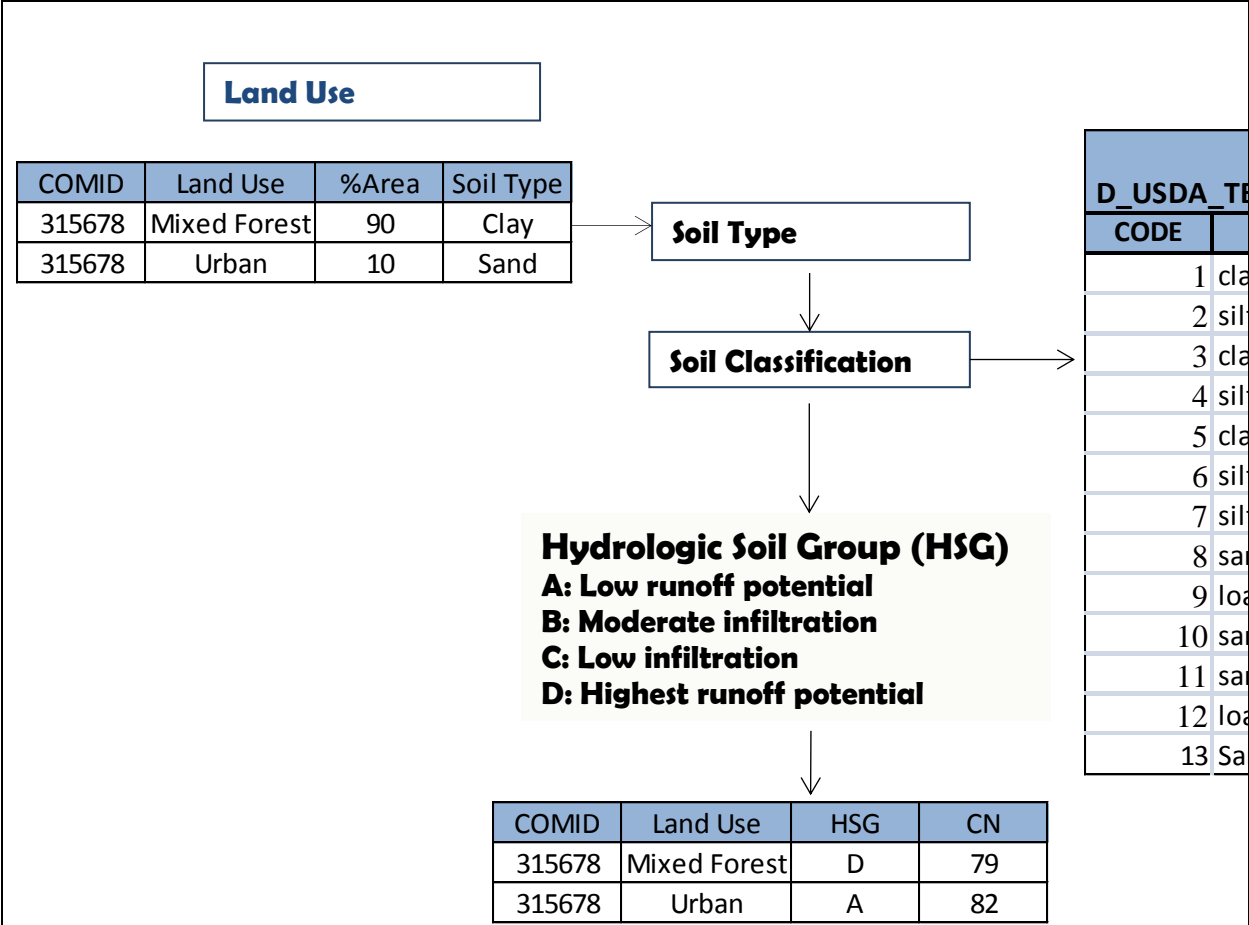


Figure 5. Schematic representation of curve number estimation. The example given here is for a hypothetical single AHD Catchment COMID=315678 which has two types of land uses (Mixed forest and Urban) and each land use has single dominant soil type.

Land Cover Data

The land cover data divides the land surface into different land cover types, including croplands, wetlands, and forests; artificial surfaces; water bodies; and permanent snow and ice (**Figure 6**). The gridded coverage is indexed to the AHD catchments to provide the area of each of the 24 land cover types within each catchment. The land cover grid cells within each catchment are indexed to the soil types they overlay. The land cover data used for this study were obtained from United State Geological Survey (USGS) Global land characterization http://edc2.usgs.gov/glcc/glcc_version1.php#SouthAmerica. The land use classification is described in <http://landcover.usgs.gov/pdf/anderson.pdf>.

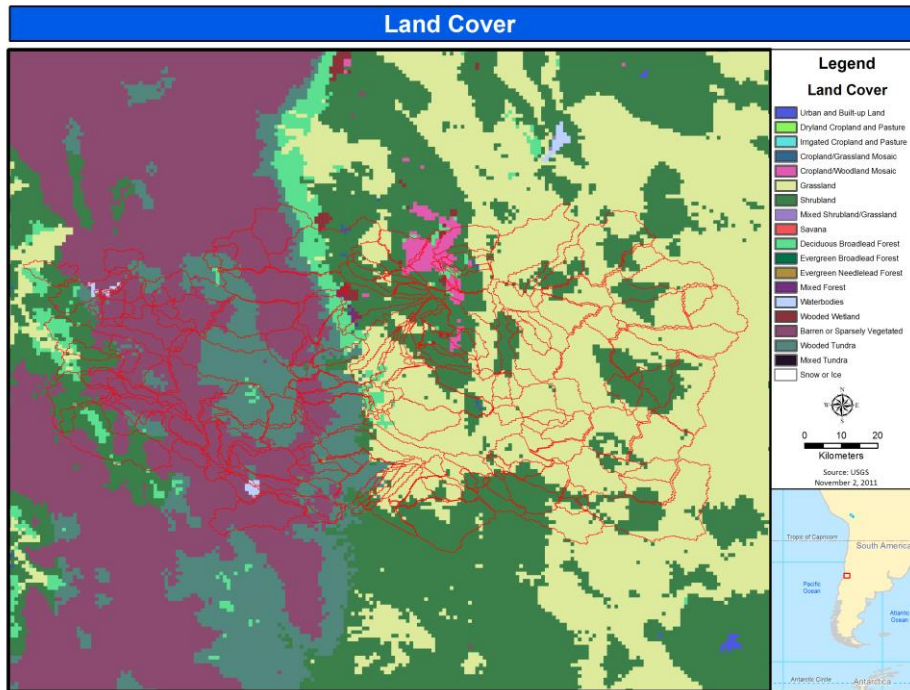


Figure 6. Land cover indexed to catchments

Soils Data

The Harmonized World Soil Database (HWSD) (<http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML>) can be used to parameterize curve numbers for the LAC region. The HWSD has the necessary soil parameters for the GWLF model for each land use within each AHD catchment. The HWSD combines vast volumes of regional and national updates of soil information with the 1:5,000,000-scale FAO-UNESCO Digital Soil Map of the World. As shown in **Figure 7**, the soil data layer is overlain on the AHD catchments to determine the dominant soil type in the catchment. Then, the dominant soil type is classified with a hydrological soil group based on the U.S. Department of Agriculture (USDA) classification (see **Table 3**). The hydrologic soil group determines the drainage property of the soil, as shown in **Table 4**. The hydrologic soil group has four types: A, B, C, and D. Type A corresponds to soil with high infiltration, and Type D corresponds to soils with poor drainage and thus low infiltration rates. Types B and C are intermediate classes.

The required soil parameters for the corresponding soil type are indexed to the catchment and land use.

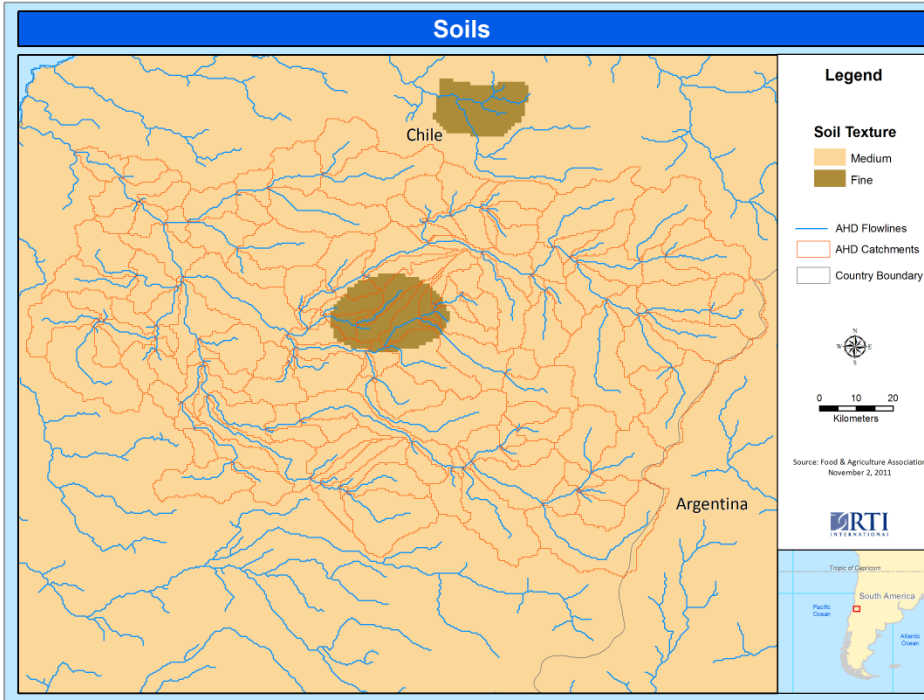


Figure 7. Overlay of soil data over AHD catchments

Table 3. USDA soil texture class (USDA, 1986)

CODE	VALUE
1	Clay(heavy)
2	Silty clay
3	Clay (light)
4	Silty clay loam
5	Clay loam
6	Silt
7	Silt loam
8	Sandy clay
9	Loam
10	Sandy clay loam
11	Sand
12	Loamy sand
13	Sandy loam

Table 4. Hydrological soil groups (HSG derived from soil property)

HSG	USDA Soil Texture Class	Soil Contents	Property
A	11, 12, 13	Sand, loamy sand, or sandy loam	Low runoff potential and high infiltration rates, even when thoroughly wetted; consists chiefly of deep, well to excessively drained sands or gravels
B	6, 7, 9	Silt loam, loam, or silt	Moderate infiltration rate and consists chiefly of soil with moderately fine to moderately coarse texture
C	10	Sandy clay loam	Low infiltration rates when thoroughly wetted and consists chiefly of soils with moderately fine to fine textures
D	1, 2, 3, 4, 5, 8	Clay loam, silty clay loam, sandy clay, silty clay, or clay	Highest runoff potential, very low infiltration rates when thoroughly wetted and consists chiefly of clay soils
0		Water	
-1		Ice/snow	

Source: (Hong, 2007)

Precipitation

The model requires a daily total precipitation time series for each catchment. Gridded precipitation from national and international databases for a historical record, as well as future climate change scenarios, can be indexed to each catchment (**Figure 8**). For small watersheds, gauge data can be assigned to the entire watershed.

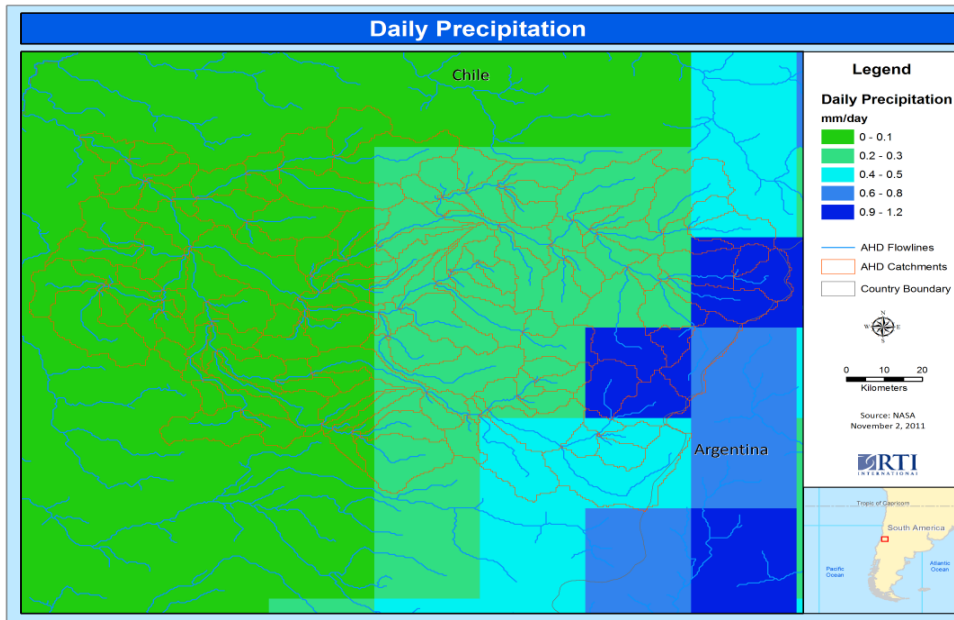


Figure 8. Precipitation indexed to AHD catchments

Temperature

The model requires a daily mean temperature time series for each catchment. Gridded temperature data from national and international databases for historical record, as well as future climate change scenarios, can be indexed to each catchment (**Figure 9**). For small watersheds, gauge data can be assigned to the entire watershed.

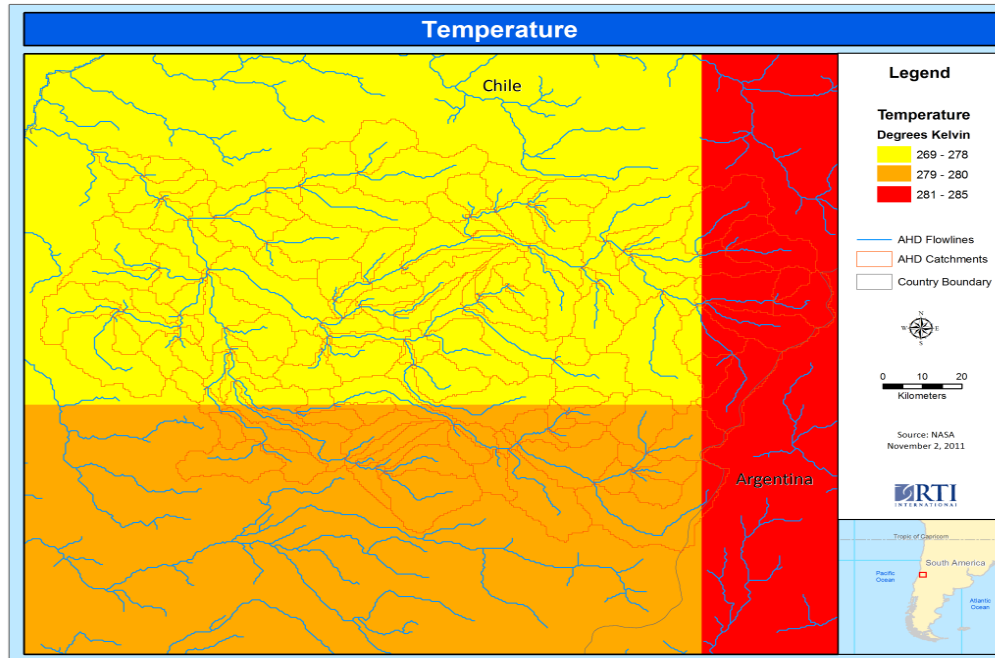


Figure 9. Temperature data indexed to AHD catchments

3.3 Data Assembly and Database Structure

Hydro-BID runs from a single database compiled for a watershed or for a region up to the extent of continental South America. In the current application, we use a freeware database called SQLITE (<http://www.sqlite.org/>). As shown in **Figure 10**, for a given region, a database is assembled using AHD, land use and land cover data, soils data, and meteorological data.

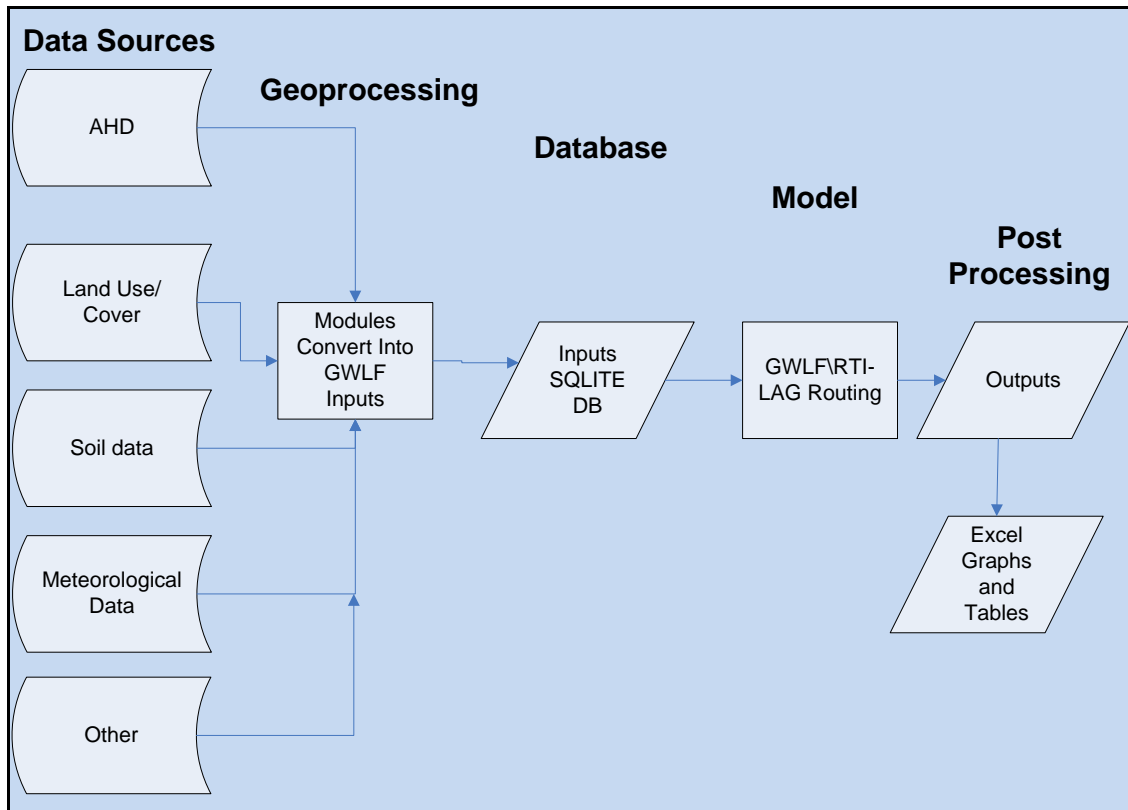


Figure 10. Data flow

A working SQLITE database contains the following tables:

1. Catchment
2. Catchment_navigation
3. Catchment_nlcd_soils
4. Met_observation

The naming convention for each of the four tables is shown in the screen capture in **Figure 11** and the tables are discussed below.

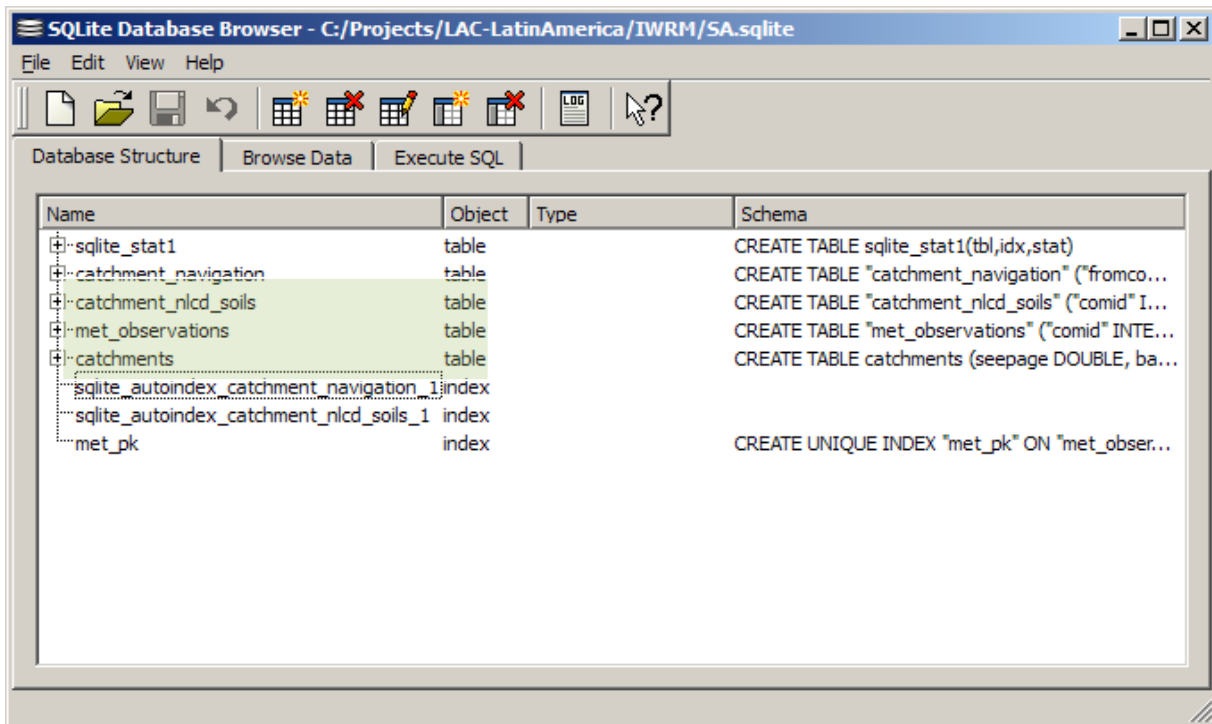


Figure 11. All model data are contained in one database: Example SA.sqlite for the entire South America

Catchment Table

Table 5 contains the core data that are derived from the AHD. The catchment table has a unique identifier column (COMID) and other properties that GWLF and RTI lag-routing methods use to simulate flows.

Table 5. Fields and data source for the catchment table

Field Name	Data Source
COMID	AHD
Total_area	AHD
Slope	AHD
Channel_length	AHD
Latitude	AHD
Longitude	AHD
awc_cm (available water content)	User defined
rcfs (Recession Coefficient)	User defined
Seepage	User defined
grow_season_start_date	User defined
grow_season_end_date	User defined
dormant_season_et_cover	User defined
grow_season_et_cover	User defined
impervious_cover_pct	User defined
mannings_n_number	Not used
bankfull_x_section_area_ft2	Not used
bankfull_width_ft	Not used
bankfull_depth_ft	Not used
bankfull_discharge_ft3	Not used

Catchment Navigation Table

The catchment navigation table is a key data source that creates a set of catchments that belong to a given watershed (**Table 6**). This table indicates the flow direction of a catchment, which is obtained from the AHD.

Table 6. Fields and data source for the Catchment_navigation table

Field Name	Data Source
Fromcomid	AHD
Tocomid	AHD

Catchment_nlcd_soils Table

The Catchment_nlcd_soils table contains essential data for hydrological models (**Table 7**). The land use and land cover data, as well as their associated area within a given catchment, allow calculation of runoff related to the land use type. Soil type is also used to determine the individual curve number for a given land cover.

Table 7. Fields and data source for the Catchment_nlcd_soils

Field Name	Data Source
COMID	AHD
Nlcd_id (land cover code)	Land Use/cover Data
Area	Land Use/cover Data
Curve Number	Processed using Land Cover and soil data

Met_observation Table

The Met_observation table contains climate input parameters (**Table 8**). The daily observed total precipitation (cm) and mean temperature (°C) are provided for each catchment in this table.

Table 8 Fields and data source for the Met_observation table

Field Name	Data Source
COMID	AHD
Measured data	User supplied
Avg_precip (Precipitation CM)	User supplied
Avg_temp (mean daily Temperature °C)	User supplied

4 Hydro-BID System Functionality and Usage

Hydro-BID includes the AHD data set, the combined GWLF/RTI lag-routing model, and the GUI, provided as executable files. The AHD is described in **Appendix A** and, in greater detail, in Technical Note 1 of this series.

In this section, we describe how to install the model, use the GUI, execute the model, and visualize results. We also describe the steps and options that are available to conduct hydrological simulations under multiple scenarios.

4.1 Getting Started

Hydro-BID is a standalone, Java-based tool that can be run on any PC with Java Runtime Environment (JRE) version 1.6 or newer installed. The JRE can be downloaded at no cost from Oracle's Java website.

The Hydro-BID program (IWRM.NBProj) can be installed by simply copying it to a hard drive and running the included batch file. At least 512 MB of RAM is required to run the program, while 1 GB of available RAM is recommended for optimal use.

The system contains the following files:

- IWRM.NBProj.jar -- the Java program
- launchIWRM.bat -- a batch file that executes the system
- lib -- a set of libraries
- Setting.txt -- a default setting file
- sa.sqlite -- the AHD database for South America. The database contains basic catchment delineation and stream segment data for all basins in the LAC region. The database includes additional data for the San Francisco basin in Argentina, for which this project developed a case study (see Technical Note 3).

4.2 Installing and Running Hydro-BID

To install Hydro-BID, copy the files described above into a folder.

Create a subfolder "Out," which will be used to save output of the model runs.

To run the Hydro-BID in Windows Explorer, double click (i.e., run) the file launchIWRM.bat. The GUI shown in **Figure 12** will appear. The GUI will be populated with the default values in the setting file, and all required data for a model run will be obtained from the current folder.

To run the existing setup, click "Go." The interface will display the status of the model run, as shown in **Figure 13**. When the run is completed, the interface will display "Done" on the status bar, as shown in **Figure 14**.

IWRM Interface

Setup And File Options:

Run Name:

Catchment:

Start date (dd/mm/yyyy):

End date (dd/mm/yyyy):

DB Location:

Output Dir:

Climate Data:

Climate Scenario:

Flows to compare:

Cutoff Files Folder:

Output: Outlet catchment All catchments

Climate Scenario:

Temperature Adjustment (+/-):

Precipitation Multiplier: Use Precipitation Multiplier(s)

Precipitation Adjustment (+/-): Use Precipitation Adjustment(s)

Hydro Model Parameters:

Stream velocity (m/s):

Latitude (degrees):

Start of growing season (day of year):

End of growing season (day of year):

	Single Value	Multiplier	
Curve Number:	<input type="radio"/>	<input checked="" type="radio"/>	<input type="text" value="0.9"/>
AWC:	<input type="radio"/>	<input checked="" type="radio"/>	<input type="text" value="0.9"/>
R Coefficient:	<input checked="" type="radio"/>	<input type="radio"/>	<input type="text" value=".005"/>
Seepage:	<input checked="" type="radio"/>	<input type="radio"/>	<input type="text" value="0.02"/>
Grow season ET factor:	<input checked="" type="radio"/>	<input type="radio"/>	<input type="text" value="1"/>
Dormant season ET factor:	<input checked="" type="radio"/>	<input type="radio"/>	<input type="text" value="1"/>
Impervious cover percent:	<input checked="" type="radio"/>	<input type="radio"/>	<input type="text" value="2"/>

Figure 12. Hydro-BID interface. Example run for Rio San Francisco basin (the case study described in Technical Note 3)

IWRM Interface

Setup And File Options:

Run Name: Sanfrancisco
 Catchment: 314090000
 Start date (dd/mm/yyyy): 1/1/2000
 End date (dd/mm/yyyy): 31/12/2010
 DB Location: SA.sqlite
 Output Dir: out
 Climate Data:
 Climate Scenario:
 Flows to compare: San_francisco_flow_monthly.csv
 Cutoff Files Folder: controls

Output: Outlet catchment All catchments

Climate Scenario:

Temperature Adjustment (+/-): 0
 Precipitation Multiplier: 0.8 Use Precipitation Multiplier(s)
 Precipitation Adjustment (+/-): 0 Use Precipitation Adjustment(s)

Hydro Model Parameters:

Stream velocity (m/s): 5
 Latitude (degrees): -30
 Start of growing season (day of year): 115
 End of growing season (day of year): 210

Single Value	Multiplier	
Curve Number: <input type="radio"/>	<input checked="" type="radio"/>	0.9
AWC: <input type="radio"/>	<input checked="" type="radio"/>	0.9
R Coefficient: <input checked="" type="radio"/>	<input type="radio"/>	0.005
Seepage: <input checked="" type="radio"/>	<input type="radio"/>	0.02
Grow season ET factor: <input checked="" type="radio"/>	<input type="radio"/>	1
Dormant season ET factor: <input checked="" type="radio"/>	<input type="radio"/>	1
Impervious cover percent: <input checked="" type="radio"/>	<input type="radio"/>	2

Working on COMID 314404100

Figure 13. Model running

IWRM Interface

Setup And File Options:

Run Name: TestRun_new
 Catchment: 314090000
 Start date (dd/mm/yyyy): 1/1/2000
 End date (dd/mm/yyyy): 31/12/2010
 DB Location: C:\Projects\LAC-LatinAmerica\IWRM\sa.sqlite
 Output Dir: out
 Climate Data:
 Climate Scenario:
 Flows to compare: C:\Projects\LAC-LatinAmerica\IWRM\sa_francisco_flow_monthly.csv

Output: Outlet catchment All catchments

Climate Scenario:

Temperature Multiplier: 0
 Precipitation Multiplier: 0.8

Hydro Model Parameters:

Stream velocity (m/s): 5
 Latitude (degrees): -30.0
 Start of growing season (day of year): 115
 End of growing season (day of year): 210

Single Value	Multiplier	
Curve Number: <input type="radio"/>	<input checked="" type="radio"/>	0.78
AWC: <input type="radio"/>	<input checked="" type="radio"/>	1
R Coefficient: <input checked="" type="radio"/>	<input type="radio"/>	0.005
Seepage: <input checked="" type="radio"/>	<input type="radio"/>	0.02
Grow season ET factor: <input checked="" type="radio"/>	<input type="radio"/>	1
Dormant season ET factor: <input checked="" type="radio"/>	<input type="radio"/>	1
Impervious cover percent: <input checked="" type="radio"/>	<input type="radio"/>	2

Done!

Figure 14. Model completes

4.3 Model Outputs

Hydro-BID can simulate stream flows in unimpaired watersheds for historic, current, and future conditions based on land use, precipitation, and temperature inputs. To simulate future conditions, precipitation and temperature inputs should be generated, either from downscaling from Global Circulation Models or by applying the expected percent increase or decrease to current precipitation and temperature data.

The typical model outputs for each catchment include the following time series:

- Daily surface runoff
- Daily base flow
- Daily total flow
- Daily soil moisture storage (surrogate, not real soil moisture)
- Daily actual evaporation.

The model outputs are saved in readily usable, comma-separated value (.csv) format in the defined output directory. The format of the file is shown in **Table 9**.

Table 9. Model output

COMID	Run Day	Date	Rain	Temp	Runoff	GwFlow (c	snow	melt	water	satstor	evapotrar	daylight h	percolatic	unsatstor	inflow_ra	RTWR (M
3.14E+08	1	1/1/2000	0.003223	12.59461	0	0	0	0	0.003223	0	2.78E-04	13.45341	0	0.002945	0	0
3.14E+08	2	2/1/2000	0.018891	12.5369	0	0	0	0	0.018891	0	3.19E-04	13.44763	0	0.021518	0	0
3.14E+08	3	3/1/2000	0.02636	12.11898	4.89E-05	0	0	0	0.02636	0	7.17E-04	13.44137	0	0.047111	0	0
3.14E+08	4	4/1/2000	0.181224	11.36769	0.001389	0	0	0	0.181224	0	0.003119	13.43464	0	0.224057	0	0
3.14E+08	5	5/1/2000	0.036084	11.83656	6.99E-05	0	0	0	0.036084	0	0.00438	13.42744	0	0.255691	0	0
3.14E+08	6	6/1/2000	0.229352	12.1813	0.001005	0	0	0	0.229352	0	0.005463	13.41978	0	0.478582	0	0
3.14E+08	7	7/1/2000	0.03638	13.09177	5.59E-05	0	0	0	0.03638	0	0.00575	13.41166	0	0.509156	0	0
3.14E+08	8	8/1/2000	0.25124	13.24356	4.70E-05	0	0	0	0.25124	0	0.005979	13.40308	0	0.754378	3028.464	0.350517
3.14E+08	9	9/1/2000	1.05574	13.75619	4.101157	0	0	0	1.05574	0	0.006329	13.39406	0	1.304128	94.89147	0.010983
3.14E+08	10	#####	0.021607	14.63483	1.12E-05	0	0	0	0.021607	0	0.006605	13.38459	0	1.319119	20404.26	2.361604
3.14E+08	11	#####	0.108201	14.77231	6.97E-04	0	0	0	0.108201	0	0.006666	13.37469	0	1.420073	3124360	361.6158

Based on the above output and observed flow time series, Hydro-BID produces graphical comparisons both on daily and monthly time steps, as shown in **Figure 15** and **Figure 16**, respectively. In addition to evaluating model performances, Hydro-BID computes statistics that assess seasonal and overall performance of the model (**Figure 17**). The formulas used to calculate these statistics are provided in **Appendix B**.

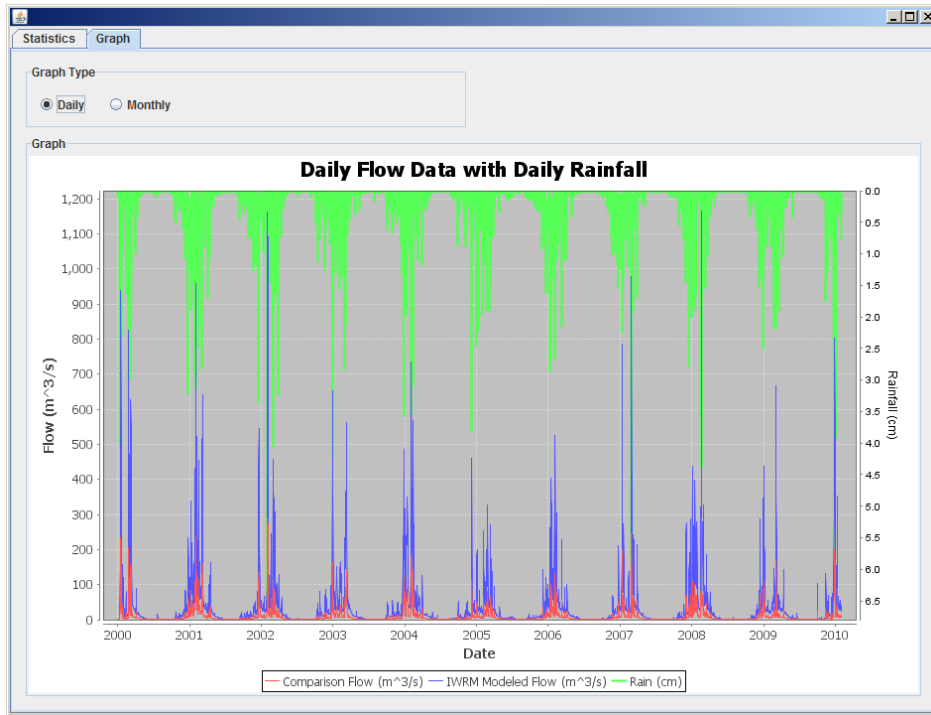


Figure 15. Daily simulated and observed hydrographs

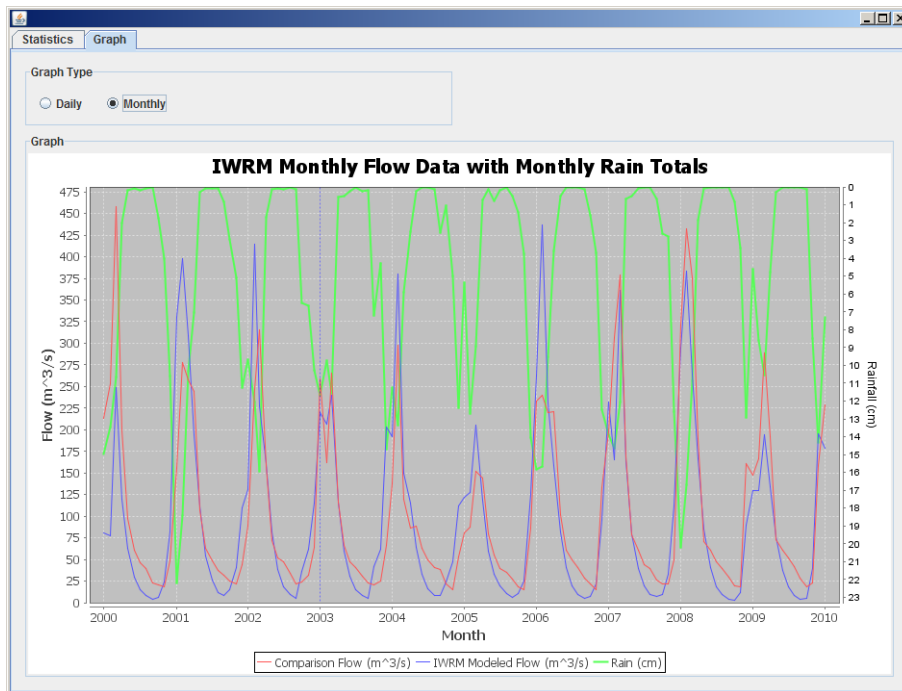


Figure 16. Monthly simulated and observed hydrographs

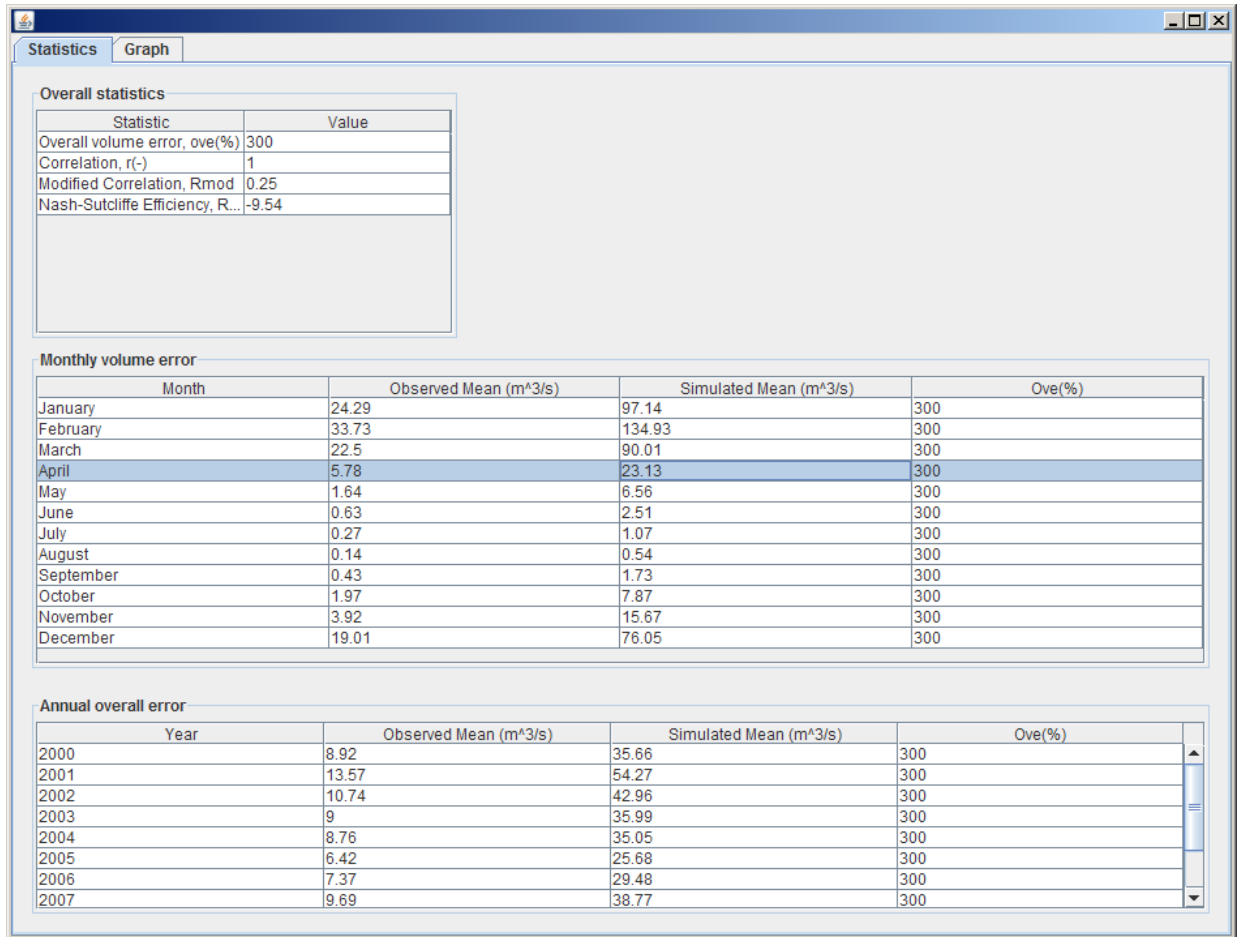


Figure 17. Model performance statistics

4.4 Hydro-BID Parameters and Modeling Options

In this section, we describe the input parameters of the Hydro-BID in detail and introduce several options that are available to model a watershed. Consider again the Set Up GUI shown in **Figure 18**.

The screenshot shows the IWRM Interface GUI with the following sections and parameters:

- Setup And File Options:**
 - Run Name: Sanfrancisco
 - Catchment: 314090000
 - Start date (dd/mm/yyyy): 1/1/2000
 - End date (dd/mm/yyyy): 31/12/2010
 - DB Location: SA.sqlite (with Browse... button)
 - Output Dir: out (with Browse... button)
 - Climate Data: (with Browse... button)
 - Climate Scenario: (dropdown menu)
 - Flows to compare: San_francisco_flow_monthly.csv (with Browse... button)
 - Cutoff Files Folder: controls (with Browse... button)
 - Output: Outlet catchment All catchments
- Climate Scenario:**
 - Temperature Adjustment (+/-): 0 (with Monthly Values button)
 - Precipitation Multiplier: 0.8 (with Monthly Values button) Use Precipitation Multiplier(s)
 - Precipitation Adjustment (+/-): 0 (with Monthly Values button) Use Precipitation Adjustment(s)
- Hydro Model Parameters:**
 - Stream velocity (m/s): .5
 - Latitude (degrees): -30
 - Start of growing season (day of year): 115
 - End of growing season (day of year): 210
 - Curve Number: Single Value Multiplier (0.9)
 - AWC: Single Value Multiplier (0.9)
 - R Coefficient: Single Value Multiplier (.005)
 - Seepage: Single Value Multiplier (0.02)
 - Grow season ET factor: Single Value Multiplier (1)
 - Dormant season ET factor: Single Value Multiplier (1)
 - Impervious cover percent: Single Value Multiplier (2)

Buttons: Go, View Stats and Graphs, Press Go to start

Figure 18. Hydro-BID interface – Set up

The input parameters shown in the above interface are described in **Table 10**.

Table 10. Input parameters

Setup and File Options:	Description	Suggested Value
Run Name	An identifier of run	
Catchment	Outlet catchment ID corresponding to the AHD specification	
Start date	Start date of simulation.	
End date	End date of simulation.	
DB location	Location of the database (provide full path). Example: C:/projects/ca.sqlite	
Output Dir	Location of output files. Example: C:/projects/out	
Climate Data	Input file for Climate data (daily precipitation and temperature data). These data are optional in case there are no spatially distributed climate data. The model uses these data for the entire extent of the basin under study. See example file for formats.	
Flows to Compare	Input file for observed flow time series. for comparison with the simulated flows. See example file for formats.	
Climate Scenario	Available projected climate scenario. See example file for formats.	
Temperature Change	Change of temperature from climate change. The value provided will be added/subtracted uniformly from daily mean temperature.	0
Precipitation Multiplier	Increase/decrease of precipitation proportional to daily values.	1
Hydro Model Parameters		
Stream velocity	Estimated average stream velocity.	0.5 m/s
Latitude	Location of the centroid of the catchment. This value can be obtained from AHD table.	
Start of growing season	The Julian day of starting day of growing season for the region.	
End of growing season	The Julian day of last day of growing season for the region.	
AWC	Available Water Content: This parameter can be either a single value applied to all catchments or a multiplier of catchment values. (The catchment values are available.)*	10 cm
R Coefficient	Recession Coefficient: This parameter can be either a single value applied to all catchments or a multiplier of catchment values. (The catchment values are not available *)	0.01

(continued)

Table 10. Input parameters (continued)

Setup and File options:	Description	Suggested value
Seepage	Seepage coefficient to determine the deep seepage from saturated layer. This parameter can be either a single value applied to all catchments, or a multiplier of catchment values. (The catchment values are not available.)*	0.005
Growing season ET factor	Evapotranspiration factor during growing season. This parameter can be either a single value applied to all the catchment, or a multiplier of catchment values. (The catchment values are not available.)*	1.0
Dormant season ET factor	Evapotranspiration factor during dormant season. This parameter can be either a single value applied to all the catchment, or a multiplier of catchment values. (The catchment values are not available.)*	1.0
Impervious cover percent	Estimated percent of impervious portion of the catchment in %. This parameter can be either a single value applied to all the catchment, or a multiplier of catchment values. (The catchment values are not available.)*	2%

**The individual catchment values for these parameters are not obtained directly and may be estimated from other properties of the catchment. Once they have been estimated and indexed, the multiplier option can be used.*

Setting File

Hydro-BID saves all the setting parameters provided in the GUI into a file (**Figure 19**). This setting file is named as Runname_setting.txt. The setting file allows an identical re-run of the model at any time in the future.

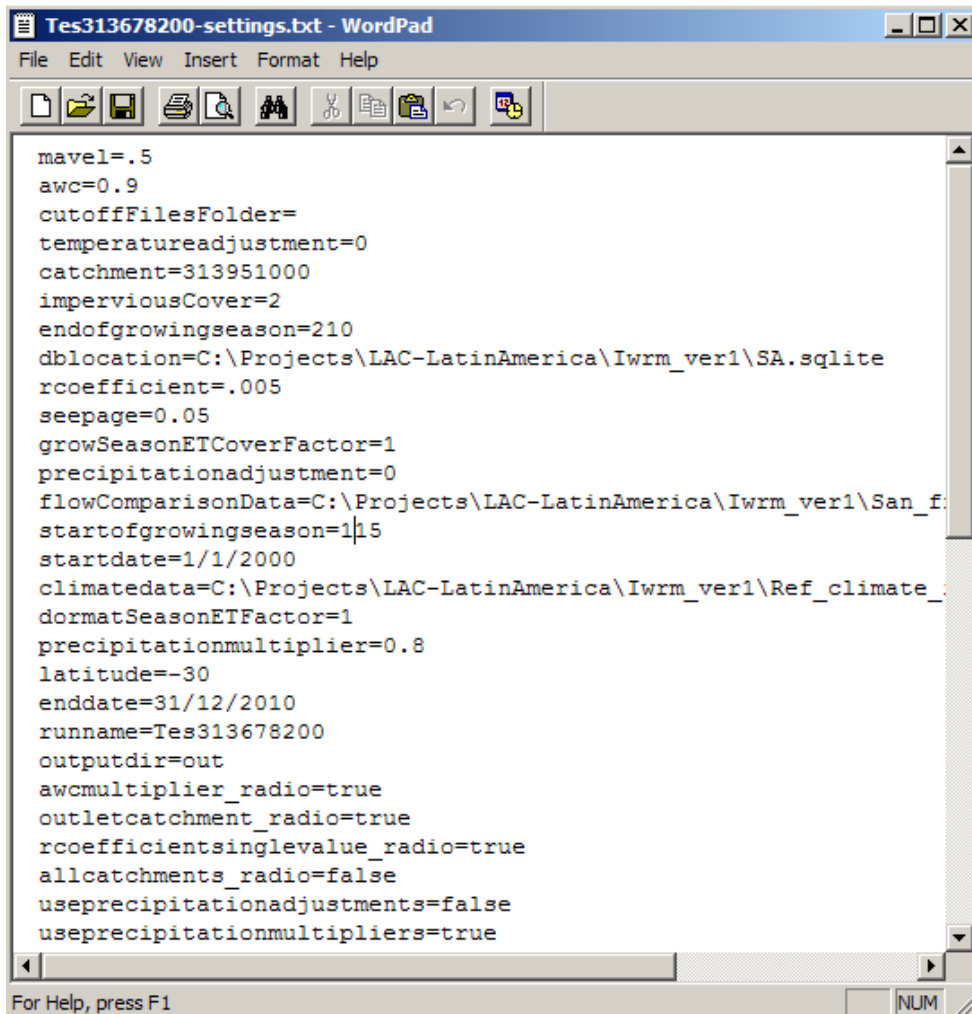
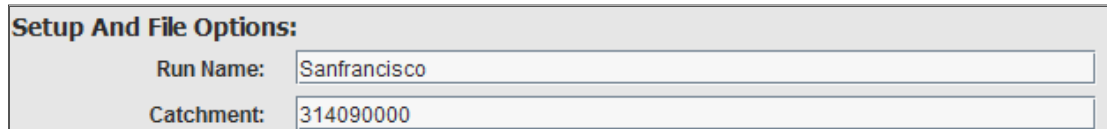


Figure 19. Setting file

4.5 Catchment Identification

Hydro-BID allows simulation of flows through basins of different sizes (i.e., varying numbers of catchments). To specify a basin for simulation, the system requires the identification of the most downstream AHD catchment. Once the downstream catchment is provided, the system navigates the database and collects all the catchments within the basin (i.e., catchments drain to the pour point). In the example shown below in **Figure 20**, the simulation is set up to model all catchments that drain to the output catchment (314090000), which corresponds to a gauge station for San Francisco River at Caimancito, Argentina.



Setup And File Options:

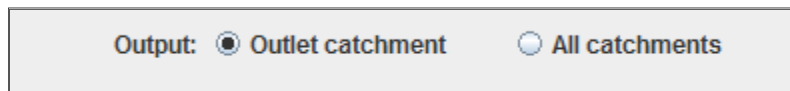
Run Name: Sanfrancisco

Catchment: 314090000

Figure 20. Catchment identification number

The catchment identification number can be found by using the GIS-based navigation tool described in Appendix A.

The system allows options to save the flows at all catchment outlets or at only the most downstream catchment (i.e., the pour point). In the example shown in **Figure 21**, the simulation output of only the downstream outlet is provided at the end of the simulation. This option is desired if the watershed covers a large number of catchments, as well as when the initial calibration is performed. In circumstances where one needs analyses of flows at interior catchments (for example, water supply diversion points), the final model should be run with the option “All catchments” specified. This will cause the model to output results for all catchments in the basin.

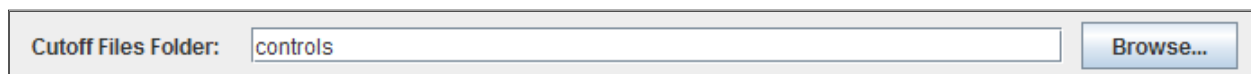


Output: Outlet catchment All catchments

Figure 21. Available output options

4.6 Cut-off Catchments

Though Hydro-BID is designed mainly to represent natural hydrological processes, we have enhanced the system to be used in areas where there is significant anthropogenic flow alteration. Such alterations include reservoirs. For instance, if an upper catchment of a large river contains a large reservoir and the release of the reservoir is known, the system can simulate the remaining catchments downstream of the reservoir. This is achieved by providing a time series of flows (releases) from the reservoir. A file that contains the time series should be saved in the folder specified as a Cutoff Files Folder, as shown in **Figure 22**.



Cutoff Files Folder: controls

Figure 22. Entry of the Cutoff File Folder

The format of the file is provided in **Appendix C**.

It should be noted that if there are reservoirs in several branches of the watershed, multiple cutoffs can be provided by saving the corresponding time series of releases. This enhancement allows application of the model in large basins with reservoirs. Further, the catchments upstream of the reservoirs can be modeled as separate catchments if the inflows to the reservoirs are required.

4.7 Model Calibration

Hydro-BID provides a number of initial parameters for hydrological simulations; however, as in all models, the parameters need to be calibrated to accurately simulate desired flows (**Figure 23**). To allow calibration within the system, Hydro-BID has an option to add the observed flow time series. The format for the flow time series is provided in **Appendix D**. Currently, the system requires a manual calibration in which the user selects and changes parameters in the model set up and reruns the model.



The image shows a software interface element with a label "Flows to compare:" followed by a text input field containing the filename "San_francisco_flow_monthly.csv". To the right of the input field is a button labeled "Browse...".

Figure 23. Observed flows

The hydrological parameters that can be changed are shown in **Figure 24**. Note that all of the parameters provided here apply to the entire basin identified by the most downstream catchment. In a future version, we expect to allow regionalized parameter set up. Also, we identify two sets of calibration parameters: single value and multiplier. A single-value parameter will be used in all catchments within the basin. Multiplier parameters are parameters that have initial estimates derived from AHD catchment level. The multiplier value is used to either scale up or down the spatially varied parameters by retaining the variability.

Hydro Model Parameters:

Stream velocity (m/s):

Latitude (degrees):

Start of growing season (day of year):

End of growing season (day of year):

	Single Value	Multiplier	
Curve Number:	<input type="radio"/>	<input checked="" type="radio"/>	<input type="text" value="0.85"/>
AWC:	<input type="radio"/>	<input checked="" type="radio"/>	<input type="text" value="0.85"/>
R Coefficient:	<input checked="" type="radio"/>	<input type="radio"/>	<input type="text" value=".005"/>
Seepage:	<input checked="" type="radio"/>	<input type="radio"/>	<input type="text" value="0.02"/>
Grow season ET factor:	<input checked="" type="radio"/>	<input type="radio"/>	<input type="text" value="1"/>
Dormant season ET factor:	<input checked="" type="radio"/>	<input type="radio"/>	<input type="text" value="1"/>
Impervious cover percent:	<input checked="" type="radio"/>	<input type="radio"/>	<input type="text" value="2"/>

Figure 24. Hydrological parameters

To evaluate the performance of the parameters, the output flow time series of each run is plotted against the observed flow time series. There are daily and monthly time series plots. In addition, overall statistics of the simulation are calculated based on the performance measures discussed in Appendix B.

4.8 Climate Data Options

Hydro-BID uses a database to store all of the required input and parameter data (**Figure 25**). Precipitation and temperature are provided in the Met_observation table. In watersheds where a gauge value is intended to be used, Hydro-BID allows the user to provide time series of precipitation and temperature. The format of the climate data file is provided in **Appendix E**.

Climate Data:

Figure 25. Climate data file

4.9 Climate Change Projections

Hydro-BID allows the following climate change scenario projections:

- direct use of daily precipitation and temperature within a single file;
- use of reference climate data with the ability to perturb the data by monthly future climate data;
- global increase/decrease of precipitation /temperature by a factor; and
- monthly increase or decrease factors.

The first two options are applied to a single climate input time series file, while the last two are applied to the database for all catchments in the model domain.

Direct Use of Daily Precipitation and Temperature within a Single File

Hydro-BID has an option to use a daily time series of precipitation and temperature. Climate projections obtained from general circulation models can be used directly if the daily values are considered to be accurate. However, the daily values from global circulation models based on coarse resolutions are often unreliable. Therefore, we recommend using monthly or annual precipitation and temperature data for future projections and generating daily values using historical daily time series, as described next.

Use of Reference Climate Data and Perturbation by Monthly Future Climate Data

The most commonly used climate projections are monthly and annual precipitation and temperature. Hydro-BID uses a monthly time series of future projection data with daily historical climate data to render daily projected climate data. The assumption in this method is that the daily variation of historical data is subjected to the proportional increase and decrease of future projections. The method also assumes that the daily sequences represented in the historical climate data will be repeated in the future.

To apply this method

1. Select historical data
2. Select future projection scenario from the list of available scenarios as shown in **Figure 26**.
3. Provide monthly future projections (see **Appendix F** for formats)

The system will produce daily climate data for the entire length of projection period.

In the current system, this method is available but can be applied only to a single time series of climate data within the basin of interest.

Climate Scenario: [Dropdown]

Flows to compare: CIRO GCM Scenario [Browse...]

 Hadly GCM Scenario [Browse...]

Cutoff Files Folder: [Browse...]

Figure 26. Climate scenario selection

Allow Global Increase/Decrease of Precipitation/Temperature

In the absence of future projected climate data, sensitivity analyses of impacts of a basin-wide change in climate can be studied. Hydro-BID allows an increase or decrease of precipitation by a percentage value and an increase or decrease of temperature by an absolute value (**Figure 27**). The increase/decrease can be applied to both the gridded climate data and gauge data.

Climate Scenario:

Temperature Adjustment (+/-): 0 [Monthly Values]

Precipitation Multiplier: 0.8 [Monthly Values] Use Precipitation Multiplier(s)

Precipitation Adjustment (+/-): 0 [Monthly Values] Use Precipitation Adjustment(s)

Figure 27. Setting climate scenarios

Allow Monthly Increase or Decrease Factors

Further, Hydro-BID allows capturing seasonal variability of future projected climate. For instance, if the climate projection models show a different change of precipitation in summer compared to winter or a monthly variation of precipitation/climate changes, the system can perturb the reference climate using specified monthly factors as shown in **Figure 28**.

Temp +/-		Precip Mult	
January:	<input type="text" value="1"/>	January:	<input type="text" value="0.8"/>
February:	<input type="text" value="1"/>	February:	<input type="text" value="0.8"/>
March:	<input type="text" value="1"/>	March:	<input type="text" value="0.8"/>
April:	<input type="text" value="1"/>	April:	<input type="text" value="0.8"/>
May:	<input type="text" value="2"/>	May:	<input type="text" value="0.8"/>
June:	<input type="text" value="2"/>	June:	<input type="text" value="1.1"/>
July:	<input type="text" value="2"/>	July:	<input type="text" value="1.1"/>
August:	<input type="text" value="2"/>	August:	<input type="text" value="1.1"/>
September:	<input type="text" value="2"/>	September:	<input type="text" value="1.1"/>
October:	<input type="text" value="1"/>	October:	<input type="text" value="0.8"/>
November:	<input type="text" value="1"/>	November:	<input type="text" value="0.8"/>
December:	<input type="text" value="1"/>	December:	<input type="text" value="0.8"/>

Figure 28. Monthly deviations

4.10 Model Outputs

The primary output of Hydro-BID is the daily time series of flow for the period of simulation. The length of the simulation depends on whether a user is interested in a historical period or future projections. The outputs for each simulation are saved as .csv files in a pre-specified output folder. The file name of the output is associated with the run identifier so that each simulation run can be identified correctly. **Table 11** describes the outputs of the model.

The output file contains additional information (see **Appendix G**), including the time series of mean areal precipitation, temperature, and several other model variables. Graphical and tabulated statistics are also provided for prompt evaluation of model performance.

Table 11. Model output

Field Name	units	Description
COMID		Outlet catchment ID
Run Day		Sequence of simulation days
Date	DDMMYY	calendar data
Rain	cm	Mean areal precipitation
Temp	°C	Mean areal Temperature
Runoff	cm	Mean areal precipitation
GwFlow (cm)	cm	Mean areal groundwater flow
Snow	cm	Mean areal snow
Melt	cm	Mean areal snow melt
Water	cm	Mean areal water (snow and rain)
Satstor	cm	Mean areal saturated storage
evapotranspiration	cm	Mean areal evapotranspiration
daylight hours	H	Day light hours
Percolation	cm	Mean areal Percolation
Unsatstor	cm	Mean areal unsaturated storage
inflow_rate	m ³ /day	Inflow to the catchments (COMID)
RTWR (M3/Second)	m ³ /s	Outflow from the catchment
RTWR (M3/day)	m ³ /day	Outflow from the catchment
deep seepage	cm	Mean areal seepage to deep storage
Observed_flow	m ³ /s	Observed flow at the outlet

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Appendix A: AHD Navigation Tool -- User Guide¹

Introduction to the AHD and the AHD Tools

The Analytical Hydrology Database (AHD) is a spatially explicit (i.e., geographic information system [GIS]-based) database of surface water. It serves as a regional spatial data platform for integrating data needed to support regional hydrography models. It provides a framework for parameterizing models in a consistent way; the upstream/downstream flow connectivity necessary for the models; and the data necessary for displaying results in map form.

The AHD has four key features enabling the development and implementation of tools that analyze water in the context of its movement in a network:

- a nested polygon catchment structure with a unique catchment identification scheme
- a corresponding line structure for the stream segments contained within the catchments
- descriptive attributes that create a linked network of upstream and downstream stream segments and catchments
- a database structure for populating and attaching additional model-specific attributes.

The AHD Tools are designed to assist users with visualizing and navigating on the AHD flowlines and catchments in the Quantum GIS (QGis) desktop application. The tools include simple menus to allow users to choose what features they want to navigate and then display information about the navigation results. The tools also contain specially designed symbols to improve the display of the AHD geometries and navigation results.

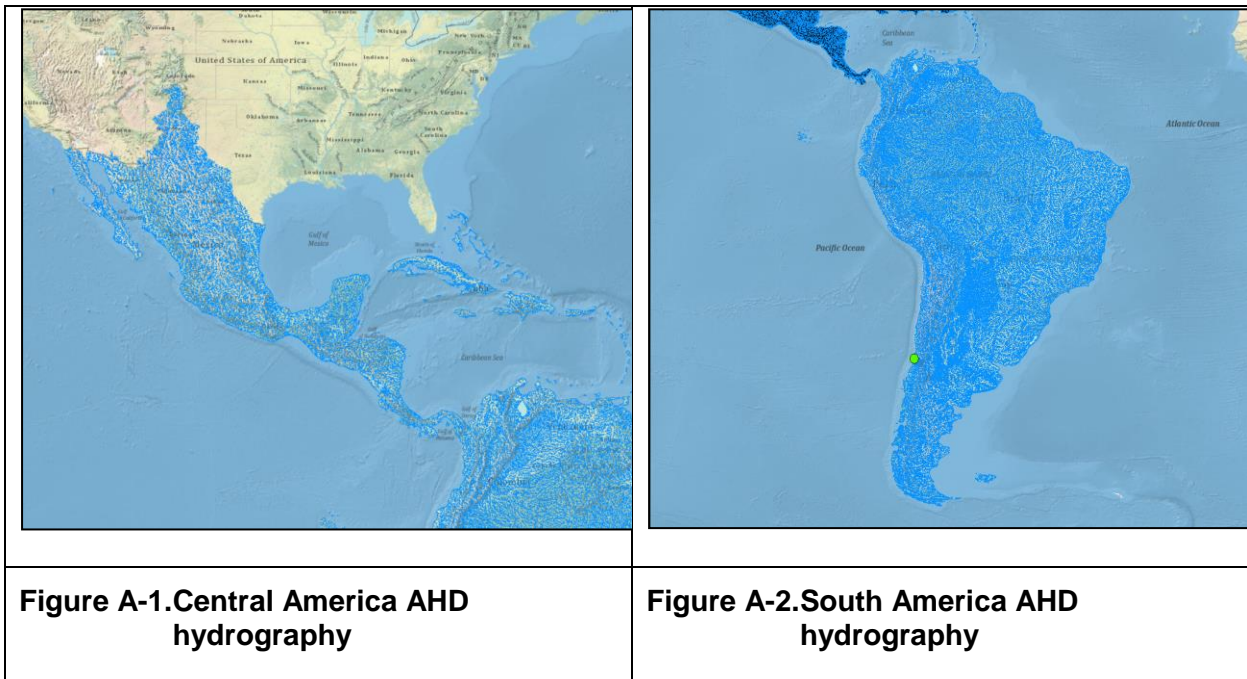
Using AHD in QGis

QGis software can be downloaded from <http://hub.qgis.org/projects/quantum-gis/wiki/Download>. It is available for Windows, Linux, Mac, Android, and other operating systems. The most recent version of QGis is 1.7.4. The AHD Tools have been tested in this version of QGis on the Windows XP and Windows 7 platform.

Once QGis is installed, users may want to install the QGis plugin “OpenLayers” if they want to use Google, OpenStreetMap, Yahoo, or Bing maps as a background image. Directions for installing and using OpenLayers is available from Spatial Galaxy at <http://spatialgalaxy.net/2012/01/14/qgis-plugin-of-the-week-openlayers>.

The AHD for Latin America and the Caribbean (LAC) was developed in two parts: Central America (**Figure A-1**) and South America (**Figure A-2**). The Caribbean is primarily included in Central America. The Central America AHD consists of approximately 37,000 catchments and stream segments. The average catchment area is approximately 83 square kilometers, and the average stream segment length is approximately 10 kilometers. The South America AHD consists of approximately 193,000 catchments and stream segments; the average catchment area is 92 square kilometers; and the average stream segment length is approximately 11 kilometers.

¹ This text is excerpted from Technical Note 1 (TN1): An Analytical Hydrology Dataset (AHD) for Latin America and the Caribbean, prepared by RTI International for the Inter-American Development Bank, January 2012.



The AHD for each region is available in Environmental Systems Research Institute (ESRI) shapefile format and other formats. Each region includes multiple shapefiles, each containing a particular set of lines, points, or polygons. The two shapefiles that are most important for navigation are the flowlines (hydrography/AHDFlowline.shp) and the catchments (Drainage/Catchment.shp). In addition to these two shapefiles, navigation using the AHD Tools requires use of the table containing the upstream/downstream relationship between each stream or each catchment. The table with this information is the AHD flow table (AHDFlow.dbf). Complete details about AHD data can be found in Technical Note 1, *An Analytical Hydrology Dataset (AHD) for Latin America and the Caribbean*; a description of these two shapefiles and the AHDFlow table are included in the Technical Note 1.

The flowlines, catchments, and flow table can be added to QGIS using the “Add Vector” menu.

Installing and Using the AHD Tools in QGIS

The AHD Tools are installed using the AHDTTools QGIS plugin, which is written in python. To install the plugin, obtain the “AHDTTools.zip” file containing all the software. Put a copy of the zip file in your personal QGIS plugin folder. In Windows, this folder is usually created as part of the installation process at C:\Documents and Settings\{yourusernamehere}\.qgis\python\plugins.

Extract the contents of the zip file in that folder. It should create a subfolder “AHD Tools” that contains a number of files. If the extractor does not create the subfolder, manually create the AHD Tools folder and move all extracted files to the subfolder.

Once the contents of the .zip file are extracted to the AHD Tools folder, start QGIS and add the AHD flowlines, catchment, and flow table to the canvas. Zoom in to your area of interest, and then save the QGIS project to make it easy to get back to this particular location.

From the QGIS display window, select the menu “Plugins” and then “Manage Plugins.” From the QGIS Plugin Manager window, find “AHD Tools Menu (0.02)” and check the box to enable it. Then close the manager menu by clicking the “OK” button.

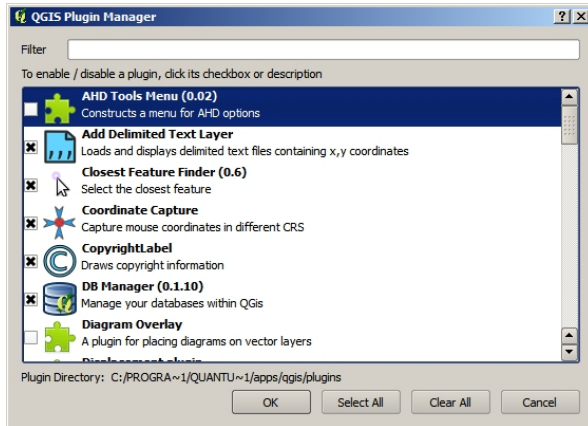


Figure A-3. QGIS Plugin Manager menu. Check the box beside AHD Tools Menu to enable the menu.

Once the AHD Tools Menu is enabled, there will be a menu option in the top bar of the QGIS screen that reads “AHD Tools” (**Figure A-4**).



Figure A-4. AHD Tools menu. The AHD Navigator allows navigation on AHD flowlines and catchments.

Click that menu to see the sub-menu with three choices “AHD Navigator,” “AHD Run IWRM,” and “About AHD Tools.” (The AHD Run IWRM menu is a specialized menu for running a particular hydrologic model. It may not be included in all versions of AHD Tools and is not needed for navigation.)

Select the AHD Navigator option to open the “RTI Analytical Hydrology Dataset Navigator” menu (**Figure A-5**).

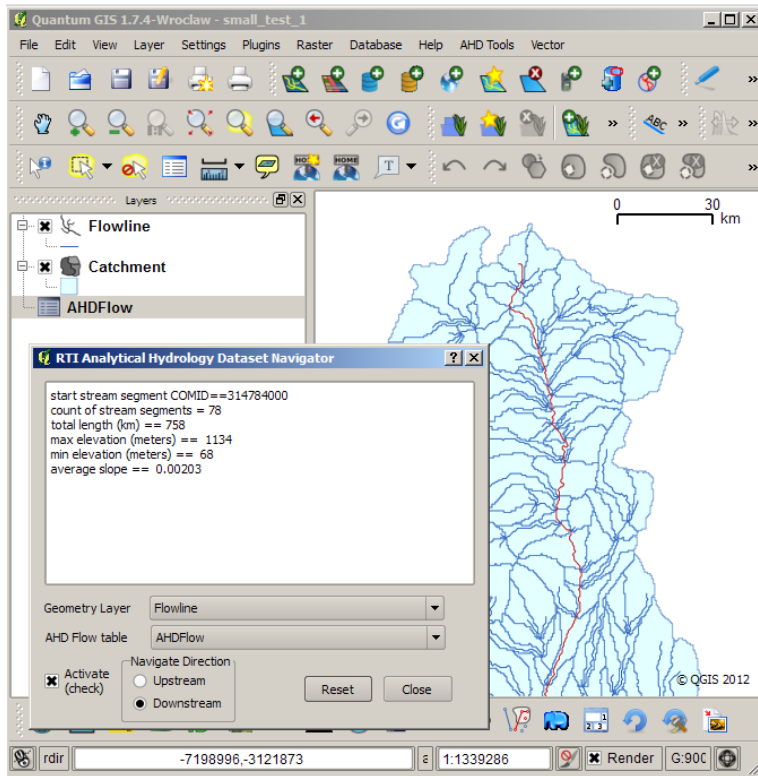


Figure A-5. RTI Analytical Hydrology Dataset Navigator showing downstream navigation of the flowline.

On the menu, check the “Activate” checkbox. Then select “Downstream” in the Navigation Direction option; then click somewhere on the Flowline layer.

You should see the selected stream downstream from where you clicked. Information about the navigated flowlines will also be shown in the menu, including the number of flowlines navigated, the length of all flowlines, the maximum and minimum elevation of all the flowlines, and the average slope.

Use the “Reset” button to unselect any selected flowlines. Use the “Geometry Layer” selection to change the navigation layer to “Catchment,” and to change the direction to “Upstream.” Then click somewhere on the Catchment layer. This will select all the catchments from the one you clicked on and all those upstream (**Figure A-6**).

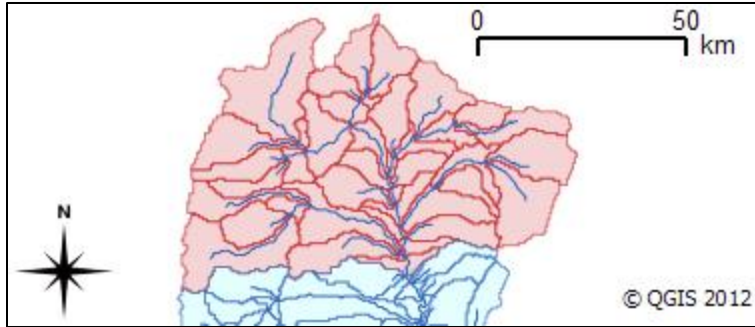


Figure A-6. Upstream navigation of the catchment layer

The AHD Navigator menu will display the count of catchments navigated and the total area in square kilometers.

Internally, the AHD Navigator uses the AHDFlow table to navigate upstream and downstream. To see what rows in this table are used in the navigation, open the table “AHDFlow” from the Layers menu. (Right click it and select “Open attribute table” from the menu).

In the Attribute table window, check the box at the bottom left that says “Show selected only.”

As you navigate upstream or downstream on either the flowline or catchment layer, the rows displayed in the AHDFlow table will change to just those taking part in the navigation.

Shift and Control Key Modifiers

For some modeling applications, it is important to remove parts of a basin from the navigation. For example, when a basin contains a reservoir, it may be important to model only the part of the basin below the reservoir and use the measured reservoir outflow as part of the calibration of the downstream part of the basin. To make this type of removal possible, the AHD Navigator allows you to hold down the Shift key while clicking the QGIS canvas and to remove the results of the navigation from the set of selected features (**Figure A-7**).

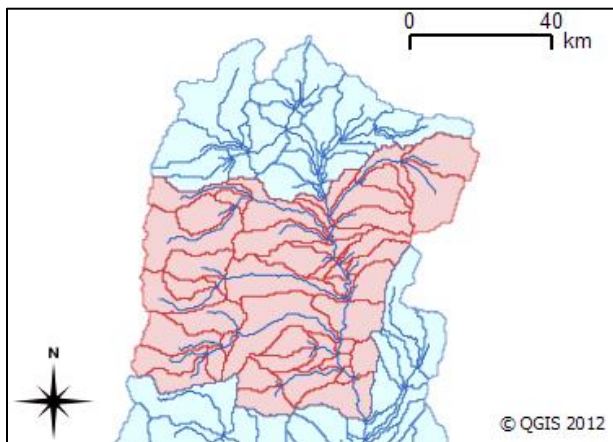


Figure A-7. The upstream part of the basin has been removed from the navigation by holding down the Shift key and clicking a catchment within the previously selected basin

Other applications require selecting multiple parts of a basin that might not necessarily be connected through normal upstream or downstream navigation. This type of selection can be made by holding down the Control key while clicking the QGIS canvas. The Control key prevents the AHD Navigator from starting a new navigation set with each click of the canvas.

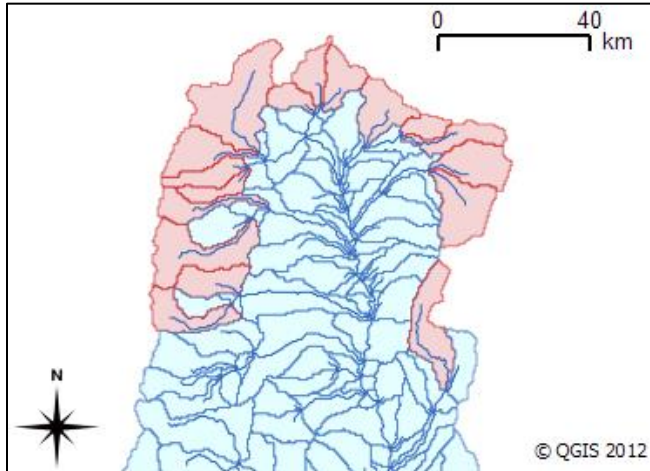


Figure A-8. The most upstream catchments along the outline of the basin have been selected by holding down the Control key and clicking the mouse in each catchment.

Using the Shift and Control keys, it is possible to create any arbitrary selection of catchments of flowlines from the AHD. It is possible to mix upstream and downstream navigation by switching the navigation direction and holding down the Control key during all mouse clicks.

If you click any of the QGIS menu items when the navigation window is open (like the zoom magnifier), you can hit the “Reset” button on the navigation window to resume using the navigator. This will clear any selected features.

You can also use the “Activate” checkbox to reset the AHD Navigator without clearing the selection. Just uncheck and then recheck the Activate checkbox. This turns the navigator back on, but does not reset the AHD Navigator. The reset only clears the selection from the layer selected in the “Navigation Layer” combo box so that you can have selected features in both the catchment and the flowlines.

Creating a Subset of AHD

Displaying all of the flowlines and catchments in Latin America simultaneously can cause QGIS to take a long time to refresh the screen. If a project only needs data for a particular basin or a rectangular area, it is useful to create a subset of the AHD that includes both the geometry layers and the AHDFlow table. This can be accomplished using any selection method to select features in either of the geometry layers and then selecting at least one catchment in the selected features using the AHD Navigator while holding down the Control key. This makes the AHD Navigator select all the rows from the AHDFlow table that are in any way related to the selected features. In QGIS, the selected features and the rows of the selected AHDFlow table can be saved into new

shapefiles by right clicking the feature in the Layers menu and selecting the “Save selection as…” menu.

Selected features from a geometry layer and the AHDFlow table can be saved into a new shapefile with a new name. The AHD Navigator looks for particular fields in any layer to determine if it is an AHD “geometry” or AHDFlow layer; it does not use the layer name so the layers can be given any name. It is useful to name basins selected using upstream navigation with the COMID of the most downstream feature, for example “Flowline.314927700.” This helps organize the set of flowlines, catchments, and rows from the AHDFlow table.

Symbol Layers

By default, QGis sets the color of lines and polygons using a random assignment. Polygons are always filled with solid colors. Selected features are shown in bright yellow. With the AHD data, this means that streams selected in a catchment that are also selected are not visible. The yellow of the steam selection color matches the yellow of the selected catchment color.

To improve the display of the AHD flowlines and catchments, custom symbol layers were developed. The custom symbol layers are “AHD Custom Catchment” and “AHD Custom Flowline.”

Users can change the display of flowlines and catchments by right-clicking the layer in the Layers menu in QGis and selecting the “Properties” menu. Then, in the “Layers Properties” menu, select the “Style” tab and click the “Change” button. This will open the “Symbol Properties” menu. Select the “AHD Custom Catchment” or “AHD Custom Flowline” from the Symbol Layer Type drop-down menu. These symbol types are only available if the AHD Tools plugin menu has been enabled.

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Appendix B: Hydro-BID Calibration Statistics

Hydro-BID produces stream flow time series at the catchment level. This output can be tailored to a specific application of the model. For example, for calibration purposes, the simulated flow time series are generated to compare to observed flow time series at gauged stations. The following statistical outputs are based on the simulated flow and observed flow time series.

Assumptions

- The observed flow series is assumed to have no missing value for the period of simulation
- The observed and simulated flows are both in cubic meter per second (cms)
- Both time series are on a daily time step
- To avoid the impact of the initial condition of the model simulation, the first year of simulation period will not be considered in computing performance statistics
- O_t = Observed flow on day t
- S_t = Model-simulated flow on day t

The following are the statistics computed after each run of the model:

1. Generate monthly average flow

For both observed and simulated flows, the monthly average flows $O_{(m,y)}$ and $S_{(m,y)}$ are computed as

$$O_{(m,y)} = \frac{\sum_{t=1}^{NDAYS} O_t}{NDAYS_{my}} \quad (E. 1)$$

$$S_{(m,y)} = \frac{\sum_{t=1}^{NDAYS} S_t}{NDAYS_{my}} \quad (E. 2)$$

where m is month y is year, and $NDAYS$ is the number of days in the month.

2. Overall volume error (ove)

$$ove = \frac{\sum_{t=1}^N S_t - \sum_{t=1}^N O_t}{\sum_{t=1}^N O_t} * 100 \quad (E. 3)$$

Where N is the number of days of the simulation without the first year. As described earlier, the $t=1$ starts at the first day of the second year of simulation.

3. Annual volume error (ave)

The annual volume error uses the same equation (E. 3), but computes for each year separately.

4. Monthly volume error (mve)

For each of the 12 months, compute monthly volume error using Equation 3. For example for the month of January, all flows in January of all years are added together.

5. Correlation - r

$$r = \frac{N \sum_{t=1}^N O_t S_t - \sum_{t=1}^N O_t \sum_{t=1}^N S_t}{\sqrt{\left[N \sum_{t=1}^N S_t^2 - \left(\sum_{t=1}^N S_t \right)^2 \right] \left[N \sum_{t=1}^N O_t^2 - \left(\sum_{t=1}^N O_t \right)^2 \right]}} \quad (\text{E. 4})$$

6. Modified correlation coefficient, r_{mod} (McCuen and Snyder, 1975)

$$r_{mod} = r \frac{\min(\sigma_{sim}, \sigma_{obs})}{\max(\sigma_{sim}, \sigma_{obs})} \quad (\text{E. 5})$$

Where σ_{obs} and σ_{sim} are standard deviations of the observed and simulated flow time series, respectively. See Equation 8 for computing standard deviations.

7. Nash- Sutcliffe Efficiency, R^2

$$r^2 = 1.0 - \frac{\sum_{t=1}^N (S_t - O_t)^2}{\sum_{t=1}^N (O_t - \mu_o)^2} \quad (\text{E. 6})$$

Where μ_o is the mean (average) of observed flow.

$$\mu_o = \frac{\sum_{t=1}^N O_t}{N} \quad (\text{E. 7})$$

$$\sigma_o = \sqrt{\frac{\sum_{t=1}^N (O_t - \mu_o)^2}{N - 1}} \quad (\text{E. 8})$$

Appendix C: Cut-off Catchments Format

Filename: comid.csv

Provide three columns: COMID, Date (Day/Month/Year), Flow (m³/s)

COMID is the unique Catchment Identifier where the cut-off catchment, such as a reservoir, is located.

Example format

COMID	Date	Flow (M3/Second)
314239700	1/1/2001	100
314239700	1/2/2001	100
314239700	1/3/2001	100
314239700	1/4/2001	100.3538551
314239700	1/5/2001	100.4935238
314239700	1/6/2001	100.0128607
314239700	1/7/2001	100.1432795
314239700	1/8/2001	116.5543028
314239700	1/9/2001	100.459333
314239700	1/10/2001	103.9216366
314239700	1/11/2001	100.0557632
314239700	1/12/2001	101.1451565
314239700	1/13/2001	119.5850988
314239700	1/14/2001	132.9346077
314239700	1/15/2001	135.98004
314239700	1/16/2001	100.3058625
314239700	1/17/2001	100.2916757
314239700	1/18/2001	100.5907081
314239700	1/19/2001	101.1154081

Appendix D: Observed Flow Time Series Format

Filename: name_of_station.csv

Provide two columns: Date (Day/Month/Year), Flow (m³/s)

Example format:

Date	Flow (m ³ /s)
1/1/2000	212.6011
2/1/2000	253.069
3/1/2000	458.0111
4/1/2000	199.819
5/1/2000	97.40111
6/1/2000	60.91778
7/1/2000	46.70125
8/1/2000	39.525
9/1/2000	23.19778
10/1/2000	20.04
11/1/2000	17.84857
12/1/2000	48.7475
1/1/2001	155.692
2/1/2001	277.3963
3/1/2001	258.175
4/1/2001	243.98
5/1/2001	107.396
6/1/2001	63.12
7/1/2001	48.955
8/1/2001	37.4475
9/1/2001	31.6425
10/1/2001	25.575
11/1/2001	22.19167
12/1/2001	44.50125

Appendix E: Historical Climate Time Series Format

Filename: name_of_station.csv

Provide three columns: Date (Day/Month/Year), Temperature (° C), and Precipitation (cm)

Example format:

Date	temp (° C)	precip(cm)
1/1/2000	12.6	0
2/1/2000	12.5	0
3/1/2000	12.1	0
4/1/2000	11.4	0
5/1/2000	11.8	0
6/1/2000	12.2	0
7/1/2000	13.1	0
8/1/2000	13.2	0.1
9/1/2000	13.8	0.95
10/1/2000	14.6	0.5
11/1/2000	14.8	0
12/1/2000	14.7	0
13/01/2000	15.4	0.3
14/01/2000	15	1.95
15/01/2000	14	0.45
16/01/2000	14.9	0
17/01/2000	15.4	0
18/01/2000	14.3	7.15
19/01/2000	15.3	0
20/01/2000	15.7	0

Appendix F: Projected Climate Time Series Format

Filename: name_of_station.sen

Provide two columns: Date (Month/Year), deltaT (° C), Precipitation (cm)

Note:

1. The file name extension should be “.sen”.
2. The projected monthly temperatures are provided as increase from a reference temperature.
3. The precipitation data are monthly totals in centimeters (cm).

Example format:

# GCM Scenario		
#Initial file from GCM on [date]		
#Date	deltaT (° C)	Precip (cm)
Jan-20	0.2	42.51
Feb-20	0.2	12.29
Mar-20	0.2	22.54
Apr-20	0.1	13.25
May-20	0.5	3.49
Jun-20	0.5	1.98
Jul-20	1	0.17
Aug-20	0.3	1.48
Sep-20	0.4	0
Oct-20	0.5	7.09
Nov-20	0.2	12.13
Dec-20	0.1	14.78
Jan-21	0.2	35.12
Feb-21	0.2	52.09
Mar-21	0.2	21.12
Apr-21	0.1	13.04
May-21	0.5	1.6
Jun-21	0.5	0.39
Jul-21	1	0.61
Aug-21	0.3	1.37
Sep-21	0.4	1.48
Oct-21	0.5	3.29
Nov-21	0.2	13.22
Dec-21	0.1	4.84

Appendix G: Model Outputs

Each model run produces four files, with the file name identified by the project name. The files are saved in the output folder.

Run_name-settings.txt

File name	Description
<i>Modelrunname</i> -settings.txt	Contains all the input parameters and model settings
<i>Modelrunname</i> -summary.csv	Contains a summary of simulation, total number of catchments, time of computation, and list of simulated catchments
<i>Modelrunname</i> -outlet.csv	Contains the simulated time series of output variables by catchment
<i>Modelrunname</i> -monthlySummary.txt	Contains monthly precipitation, temperature, simulated flow, and observed flow time series



2014